AN ABRUPT DROWNING OF THE BLACK SEA SHELF AT 7.5 KYR BP

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Abstract: During latest Quaternary glaciation, the Black Sea became a giant freshwater lake. The surface of this lake drew down to levels more than 100m below its outlet. When the Mediterranean rose to the Bosporus sill at 7.5 kyr BP[1], saltwater poured through this spillway to refill the and submerge, in less than a year, more than 100,000Km^2 of its exposed continental shelf.

Key words: continental shelf, erosion surface, climatic condition, faunal succession, radiocarbon data, Neoeuxine Lake, Black Sea

INTRODUCTION

The earliest written accounts on the Bosporus and Dardanelles Straits, date to the Roman era[2-4] and chronicle a catastrophic breakthrough of the sea. The winding course of both straits, their terraced cross-sections, and their dendritic tributaries were interpreted by nineteenth century geomorphologists[5, 6] as indicative of a stream origin. Today the channel is deeply submerged and partly filled with sediment[7-10] to a sill depth of-33 m[11]. It hosts a two-way exchange of water between the partly marine Black Sea and the fully marine Mediterranean Sea[11-16]. In fact, the northward-flowing undercurrent[17] had long ago been known to mariners who lowered baskets laden with rocks into its core to tow their vessels upstream toward the Black Sea[18].

Dated fossil coral reefs in the Caribbean[19-21] show that, at the time of the maximum expansion of continental ice sheets around 20 kry BP, the surface of the global ocean was at -120 m. Thus prior to the glaciers, the Black Sea was without connection to an external ocean (Fig.1). In the absence of a saltwater inlet it had transformed itself into a giant freshwater body[22, 23], dwarfing any modern lake in area and volume.

NEOEUXINE LAKE

Lacustrine deposits of glacial and postglacial age, assigned to the local Neoeuxine[23-25] stratigraphic stage of the late Quaternary, have been cored at a large number of sites on the floor of the Black Sea extending from the continental shelf[26-28] to the center of its basin plain[26, 29-31] at a depth of 2.2 km. The freshening is deduced from the ecology of the fossil molluscs[25, 32, 33], dinoflagellates[33] and diatoms[34, 35], from strongly negative $O^{18/16}$ isotopic ratios in the carbonate component of the sediments[36], and from the chemistry of pore waters drawn out of the Neoeuxine-age strata[37-39].

Near-shore littoral deposits[26, 27, 40, 41], with radiocarbon ages of the mollusc shells spanning 19 to 9 kyr BP, have been found at depths between -93 and -122 m. Linear steps that resemble the profiles of beach terraces have been mapped for tens of km along the outer shelf between -90 to -110 m. A substantial lowering of the past lake level to at least -110 m has also been inferred from the discovery of formerly entrenched river valleys[42-45] which are now partly filled in with estuarine deposits under the beds of modern rivers as they approach the coast. Boreholes in the Kerch Strait[46, 47] have recovered coarse gravel with fluvial fauna at -62 m in the stream bed of the ancient Don River > 200 km seaward of the present river mouth. Mud, silt and sand on the basin plain dated between 9 to 7.5 kyr BP[48] contain a significant component of reworked molluscs[49], microfossils[50] and plan detritus[33] washed downslope from coastal swamps. The contamination of former proximity of wetlands to the heads of the submarine canyons which indent the shelf edge and act as conduits for sediment transport to the basin plain. The inferred relocation of the coastline in the vicinity of the current shelfbreak is shown in Fig.2, along with the ubiquitous distribution of loess and alluvial soils on the broad and emerged continental shelf south of Ukraine and throughout the Sea of Azov[27].

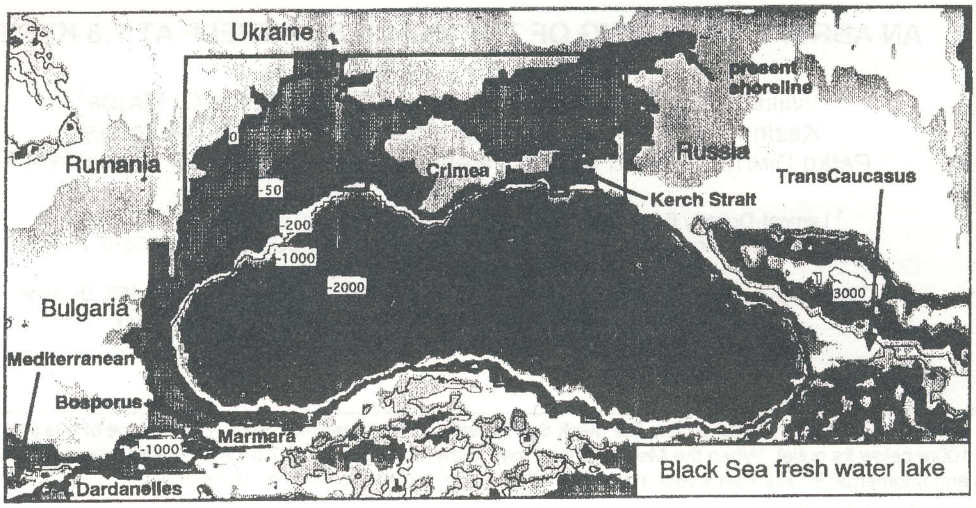

Fig.1 The Black Sea lake with its reconstructed 9 kyr BP shoreline (blue/green boundary) at -120 m below the modern coastline (bold line). The regression portrayed here has exposed the entire continental shelf and the Sea of Azov, thereby reducing the region covered by water to two-thirds of its present extent.

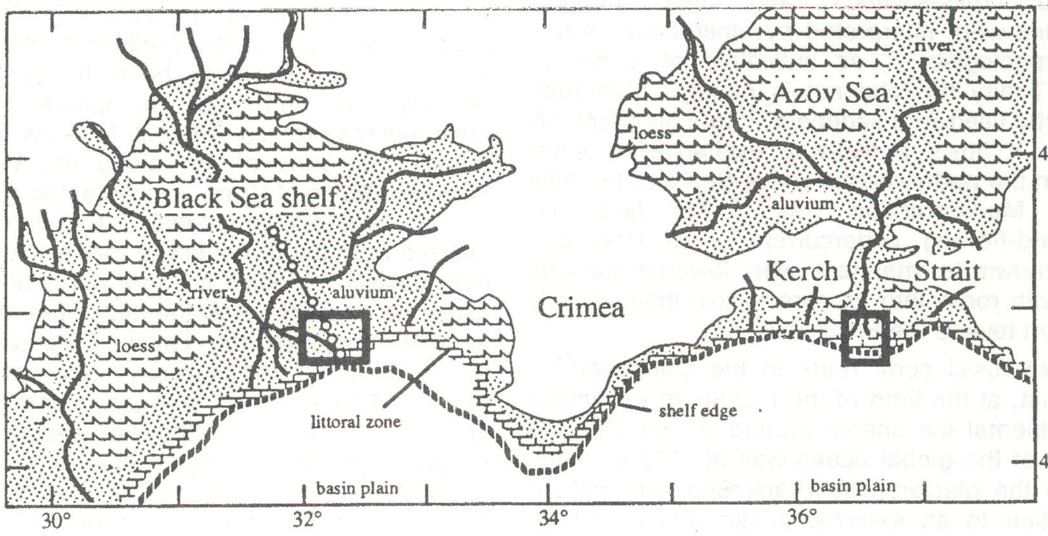

Fig. 2 The arid landscape of the Neoeuxine stage in the Black Sea deduced from the lithologies of more than 250 sediment cores[26, 27]. The soils of the emerged shelf are dominated by wind-blown loess (wavy pattern) and the alluvial deposits (stippled pattern) of meandering rivers that flowed hundreds 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/US expedition in 1993. The line with small circles extending north-west from the survey west of the Crimea indicates a transect of new cores whose lithologies and ages are portrayed in Fig. 6.

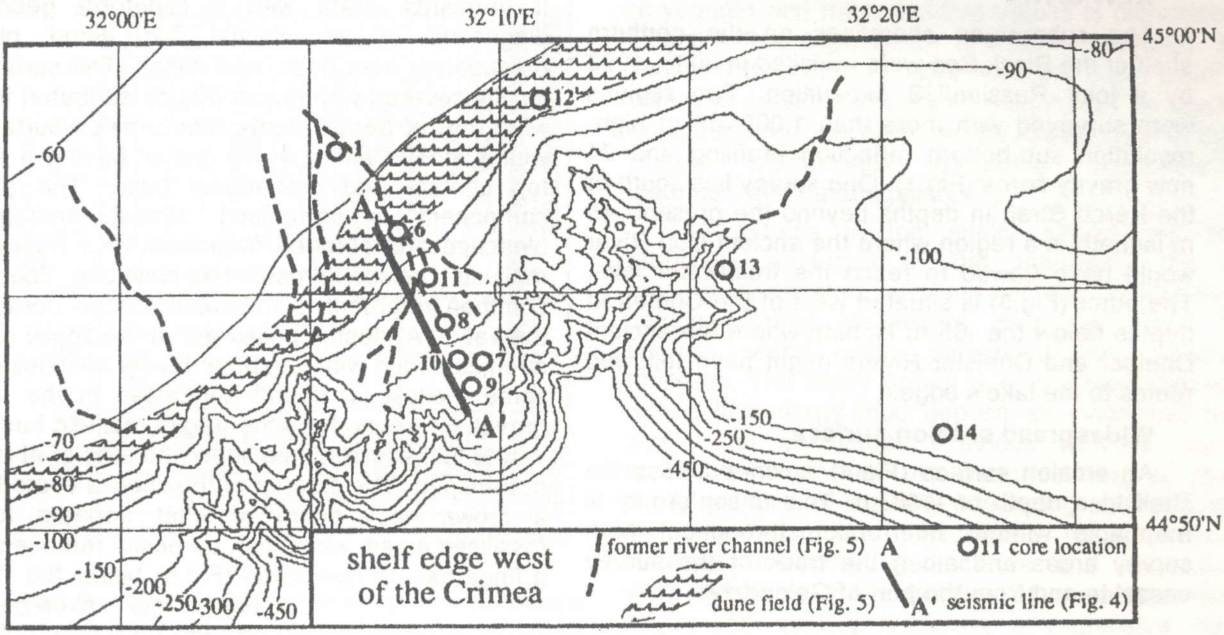

Fig.3 The west Crimea survey, contoured in meters below present sea level. A belt of dunes lies between the -70 and -80 m isobath. Core 14 at- 140 m contains an erosion surface formed by emergence of the lake bottom.

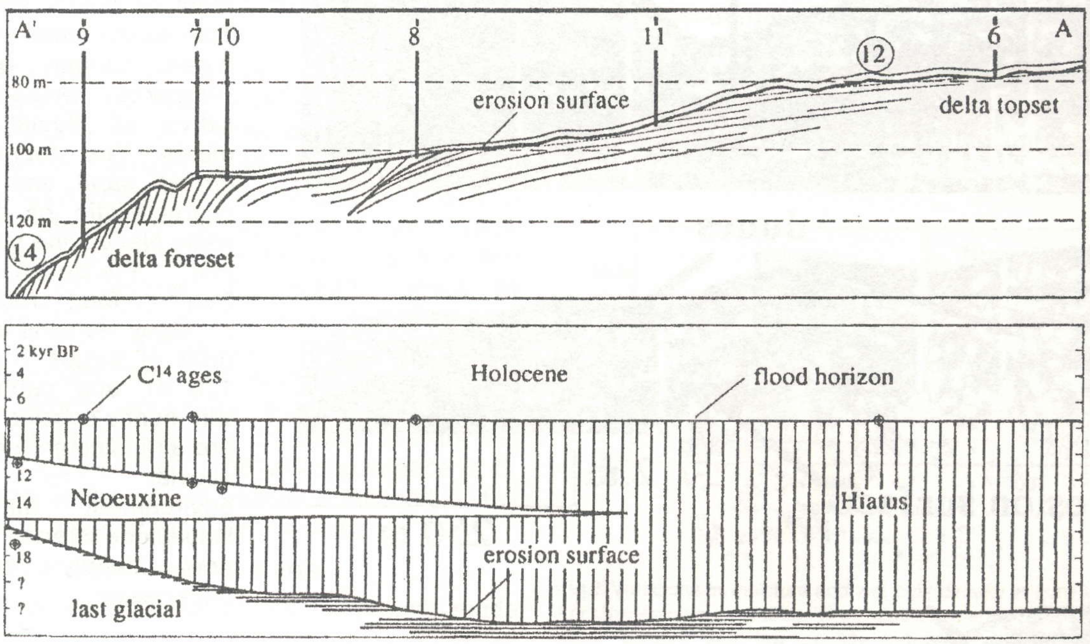

Fig.4 Interpretation of seismic profile A-A" illustrating an erosion surface (bold line) which has truncated an underlying glacial-age deltaic deposit and which is ubiquitous in the west Crimea survey everywhere above the- 156 m isobath. The cores obtained in 1993 are projected onto the profile (lines showing the depth of penetration are those cores close to the profile, circled numbers are those further away). In the bottom half of the figure the reflection profile has been projected into an age-distance space to emphasize the major hiatus (outlined in bold) formed by the regressions of the lake. The diamond symbols locate AMS radiocarbon-dated levels in the cores. Two transgressions are apparent, one starting about 15 kyr BP and the second at 7.5 yr kyr BP. The latter drowns the shelf from -123 to-49 m in the diagram in an interval, which appears to be instantaneous given the resolution of the AMS dates.

NEW DATA

The submerged shorelines on the northern shelf of the Black Sea were revisited in June, 1993 by a joint Russian/US expedition. Two regions were surveyed with more than 1,000 km of high-resolution sub-bottom reflection profiling and 24 new gravity cores (Fig.1). One survey lies south of the Kerch Strait in depths beyond the present -45 m isobath in a region where the ancient Don River would have flowed to reach the freshwater lake. The other (Fig.3) is situated west of the Crimea at depths below the -65 m isobath where the ancient Dneiper and Dneister Rivers might have followed routes to the lake's edge.

Widespread erosion surface

An erosion surface (Fig.4) reaches across the shelf to a depth of -156 m. This unconformity is mappable without interruption throughout both survey areas and along the track of the survey vessel to and from the port of Gelendzhik.

It truncates strata with a clinoform geometry diagnostic of an alluvial fan, flood plains, meandering river beds, and deltas. The surface is locally covered with dunes (Fig.5) attributed to the wind drift of beach sands. The erosion surface is widely strewn with a shelly gravel having a sharp top contact and gradational base. The gravel component is comprised almost entirely of bleached and abraded fragments of a freshwater mollusc (*Dreissena rostiformis distincta*). The most common fragment is the robust hinge portion of the valve. At depths below -95 m the shelly gravel overlies a mud with sand-rich layers containing the same mollusc as found pulverised in the shelly gravel. However, here the fragile mollusc has both valves still attached and shows no sing of abrasion or transport. The exterior of the shell is coated with a brown hairy scum of what appears to be fossilised algae, which can be easily removed with a fingernail. In five cores (Fig.6) below the -95 m isobath this shell-bearing sand rests on a firm, dry clay in which one could identify desiccation cracks filled with plant detritus and surrounded by the preserved roots of plants and shrubs. The sand, mud and clay layers contain gastropods (*Viviparus viviparus*) indicative of fluvial environments. The fauna in the gravel, sand and mud are characteristic of the freshwater Neoeuxine stage of the late Pleistocene Black Sea[25,51]. Mud cracks at -99 m, algae remains at -110 m, roots of shrubs in place at -123 m, and pebble gravel with neritic species to -140 m are all indicators of a former alluvial to coastal environment during the Neoeuxine interval in regions now deeply submerged under water.

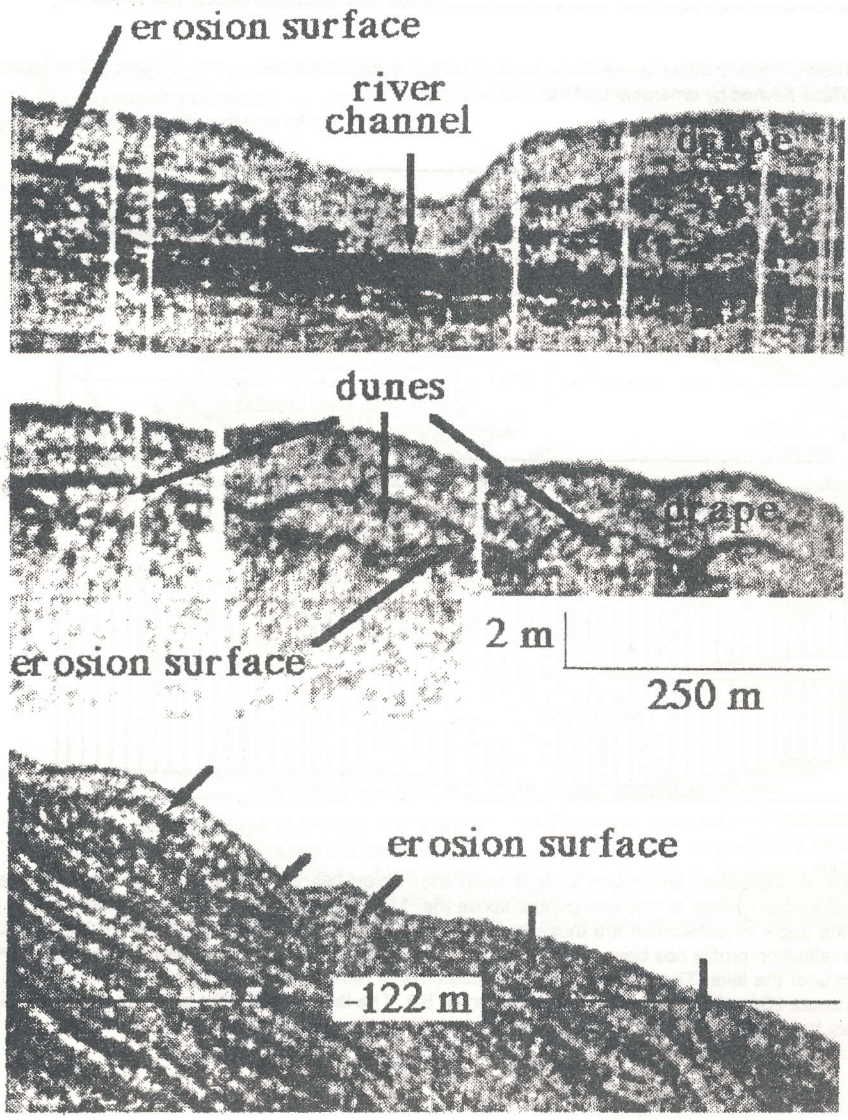

Fig.5 Seismic profiles illustrating examples of a buried river channel incised into the erosion surface (top), asymmetrical sand dunes on the erosion surface (middle) and the marked truncation of steeply incline delta foreset deposits (bottom). In every case, there is a uniform drape of Holocene mud with no evidence of reworking by surf zone of a gradually transgressing shoreline.

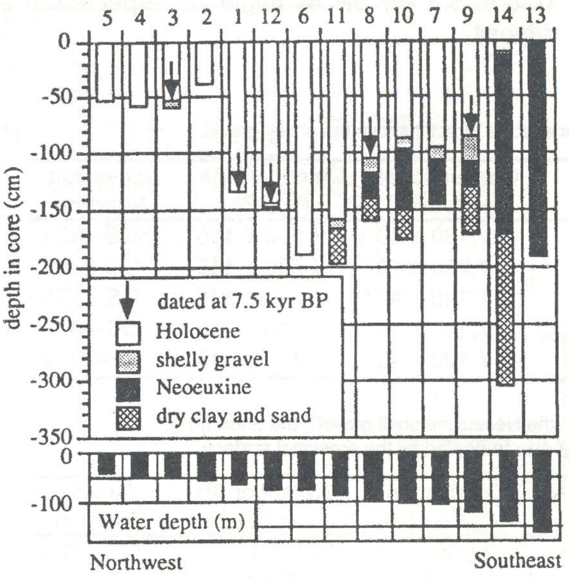

Fig.6 The transect of new cores whose locations are shown in Fig.2, and which extend from -49 to -160 m below present sea level. The base of the marine Holocene Black mud, where dated, is everywhere 7.5 kyr BP. The freshwater Neoeuxine sediments onlap the erosion surface and the underlying stiff clay and have been partly preserved from erosion below -90 m in the survey are. The shelly gravel is the subaerial weathering product of the Neoeuxine coquina-rich sands and mud.

Faunal successions

The sediment overlying the erosion surface is a dark organic rich mud with abundant brackish (*Monodacna caspia*, *Dreissena polymorpha*) to more marine (*Cardium edule*), molluscs. The latter species is an emigrant from the Mediterranean. A few cm above the shelly gravel, the briefly flourishing brackish-water molluscs disappear and are replaced with a few hundred years by additional marine species that prefer still higher salinity, e.g., *Mytilaster lineatus*, *Mytilus galloprovincialis*. The first appearance of marine species directly above the shelly gravel defines the stratigraphic datum in the Black Sea for the base of the Holocene[25]. The last appearance of *D. rostiformis* in the gravel indicates the end of the Neoeuxine stage of the Late Pleistocene[24,46].

Physical and chemical shifts

Moisture and bulk density measurements made shipboard on the fresh cores (Fig.7) show an abrupt change from high-water-content and low-density Holocene dark mud above the shelly gravel to significantly more-desiccated and higher-density values for the underlying Neoeuxine-age gravel, sand, mud and clay layers. The dry clay is stiff and can be cut only with difficulty using a knife. The stable isotopic ratios of $O^{18/16}$ measure on individual mollusc valves in the Holocene black mud are significantly more positive (-1 to 0 ‰) than those from the Neoeuxine sand and mud (-4 to -8 ‰). This shift from older and more negative to younger and more positive values is coincident with the first appearance of marine molluscs. A similar shift occurs in cores from the basin plain[52] where an offset of the same magnitude[51] is again abrupt and accompanied by the appearance of the marine microfossils (including coccoliths[50], diatoms[34] and dinoflagellates[33]).

The detritus in the shelly gravel can be artificially produced in the laboratory by a moderately-agitated washing of the underlying coquina-bearing Neoeuxine mud and sand, a process which easily pulverised the delicate molluscs. The shelly gravel is everywhere draped with a low-energy mud deposit as evidenced by shells that are intact. Previous workers have invariably associated the manufacturing of the shelly gravel with a slowly advancing shoreline of the Late-Pleistocene - Holocene transgression. However, it's desiccated nature and abundant plant debris is not indicative of a subaqueous origin and instead suggests a regressive lag deposit.

AMS radiocarbon dating

The timing of the onset of the Holocene deposition has been determined with Accelerator Mass Spectrometer (AMS) radiocarbon dating methods. Ages have been obtained in a suite of cores by sampling only single intact molluscs (both valves still articulated) which were removed from the initial 0.5 cm of the black mud on top of the shelly gravel.

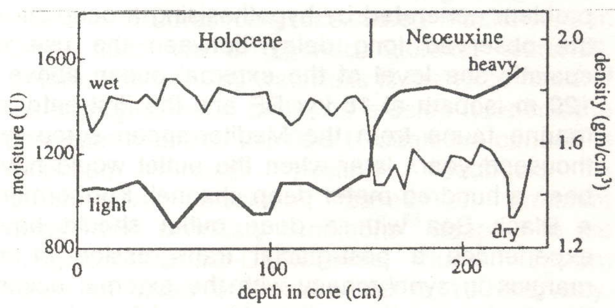

Fig.7 Variations in moisture and wet bulk density in core AK24-93 from the Kerch survey area. The Holocene marine mud has a high water content and low density indicative of a subaqueous sediment, whereas the Neoeuxine shelly gravel and stiff clay has been dewatered through subaerial exposure. The water content is measured by a nuclear resonance method and its units are the period of vibration.

The calibrated[53] radiocarbon ages (Table 1) are indistinguishable from each other (7.5-7.6 kyr BP) to within the tabulated error ranges (± 45 y) over water depth range from -49 to -123 m. Thus, the apparent marine intrusion across the continental shelf is virtually identical in timing to the onset of anoxia throughout the basin[48, 54]. The dates in the

Neoeuxine sands and mud (Table 2) range from 14.7 to 10.0 kyr BP. Those in the shelly gravel have stratigraphically inverted ages in the range of 10.8 to 8.3 kyr BP as might be expected in a lag deposit.

Table 1 AMS radiocarbon dates[1] of Holocene fauna directly above the shelly gravel.

Core	Water Depth(m)	Depth in Core(cm)	Species Analysed	Conventional Age (yr.BP)	Calender Age (yr.BP)	Accession Number
AK3-2-93	49	49	*M.caspia*	7,130 ± 40	7,500 ± 115	OS-2321
AK1-93	68	134	*M.caspia*	7,220 ± 40	7,580 ± 115	OS-2357
AK12-93	78	144	*C.edule*	7,140 ± 40	7,510 ± 115	OS-2325
AK8-93	99	104	*C.edule*	7,140 ± 40	7,510 ± 115	OS-2322
AK9-93	123	92	*C.edule*	7,100 ± 40	7,470 ± 115	OS-2323

Table 2 AMS radiocarbon dates[1] from fauna in the Neoeuxine shell gravel*, the underlying Neoeuxine sand and mud layers⁺ and the stiff clay truncated by the erosional surface⁼.

Core	Water Depth(m)	Depth in Core(cm)	Species Analysed	Conventional Age (yr.BP)	Calender Age (yr.BP)	Access. Number
AK10-93	106	145⁺	*D.rostriformis*	11,350 ± 45	12,800 ± 50	OS-2324
AK7-93	108	95-97*	*D.rostriformis*	10,400 ± 55	11,400 ± 160	OS-2357
AK7-93	108	100-104*	*D.rostriformis*	8,250 ± 35	8,617 ± 80	OS-2358
AK7-93	108	140-145⁺	*D.rostriformis*	10,800 ± 65	12,200 ± 120	OS-2359
AK14-93	140	20⁺	*D.rostriformis*	10,000 ± 50	10,800 ± 100	OS-2326
AK14-93	140	215⁼	*D.rostriformis*	14,700 ± 65	17,100 ± 95	OS-2360

The documentation of Neoeuxine shorelines along the shelf edge of the Black Sea brings into doubt the scenario, proposed by many researchers[55-59], of a flow-through glacial-age freshwater lake with a continuous outlet. For steady discharge the floor of this outlet is required to have been as far below the present sea surface as the ancient shorelines[60]. However a major problem generated by hypothesising a deep sill is the observed long delay between the rise of eustatic sea level of the external ocean above -120 m isobath at 18 kyr BP and the first entry of marine fauna from the Mediterranean some ten thousand years later when the outlet would have been a hundred meter deep channel. Furthermore a Black Sea with a deep outlet should have experienced a post-glacial transgression of its margins in synchroneity with the external ocean, thereby leaving the sedimentary and faunal record of a progressive landward advance of its coastline across the shelf. Instead, one observes only the abrupt appearance 7.5 kyr BP age black mud on top of the severely desiccated Neoeuxine shelly gravel.

Arid Climatic Conditions

However, if one considers that the lake level might have dropped upon occasion below its outlet[11, 39, 61], the rise and fall of its shoreline would not need to be coupled with the external ocean. Such a drawdown requires a negative hydrologic balance comparable to neighbouring present-day Caspian Sea. Given adequate time and sufficient evaporation, the lake's content of bi-carbonate will increase. The mollusc *Didacna moribunda*, found in the Neoeuxine deposits is thought to be an indicator of such increasing alkalinity[59]. A negative water balance could occur if the river supply to the Black Sea had diminished for reasons other than local precipitation. Radiometric dates of moraines of the Barents and Scandinavian continental ice sheets record their retreat between 15 and 10 kyr BP[62,63]. Their peri-glacial lakes did not maintain drainage to the south. Beginning 12-13 kyr BP these lakes found alternate outlets, either to the west where they fed a large lake in the Baltic region with a spillway to the North Sea, or to the Arctic via gaps between the ice sheets. The Younger Dryas (12-11 kyr BP) is an interval in Europe and the Near East of marked cooling and aridity[64-67]. Elevated levels of wind blown dust from Asia and Europe are found as far away as the Greenland ice cap[68-70]. In the Caspian Sea the Younger Dryas coincides with the Mangyshlak regression to -133 m during which the Caspian shrank to 30% its present surface area[59, 71] transforming the exposed northern shelf into a desert landscape with wind-blown sand dunes. A belt of semi-desert terrain extended to the west along the northern and southern sides of the Crimea, blanketing the exposed Caspian and Black Sea shelves with loess deposits. The parched conditions reached into Romania where fossil sand dunes are still preserved on terraces of the Danube River[72]. In Syria, the material remains of human sedentary occupation during the

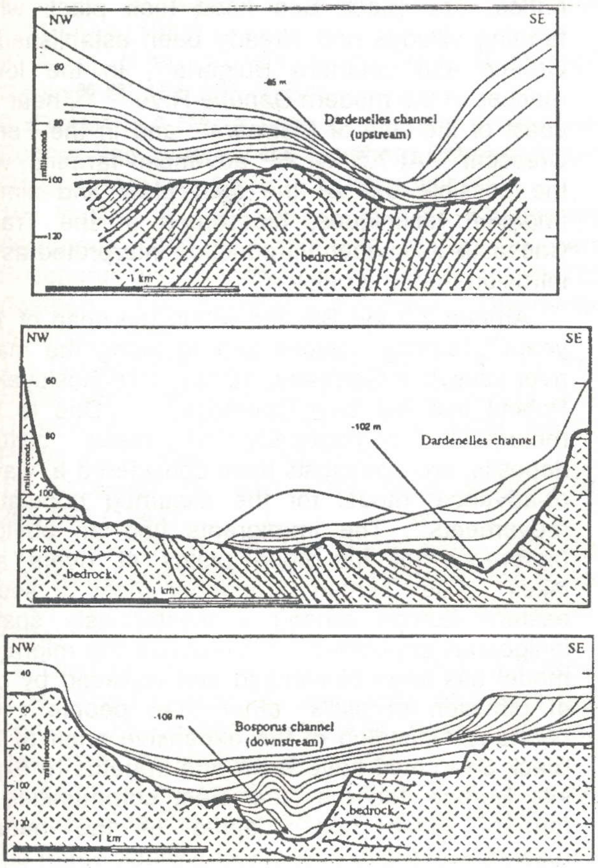

Fig.8 Interpreted seismic reflection profiles across the Dardanelles and Bosporus. Straits showing the erosion of the Paleozoic bedrock[13] and its subsequent cover with inferred Holocene deposits as calibrated by drilling in the axis of the Bosporus near Istanbul[9, 79, 80,96]. The base of the bedrock gorge deepens in the direction of the Black Sea and reaches -110 m in the Bosporus Strait.

Natufian stage of the late Palaeolithic carry a record of a severe impoverishment in diet leading to an abandoned of sedentary villages on the banks of the Euphrates River[66]. Pollen studies in cares from Lake Huleh in the Levant indicate an episode of post Younger Dryas aridity lasting to at least 10 kyr BP[73]. Loess accumulated in the southern Ukraine to 9.0 kyr BP[74]. Cores from the Black Sea shelf east of Bulgaria have an abundance of herbaceous pollen of steppe communities with Chenopodiaceae and the sagebrush *Artemisa* in proliferation[75] right up to the first appearance of marine molluscs. The synchronous deposition of mud with marine fauna directly on top of the low-moisture shelly gravel over a documented minimum elevation change 74 m implies a rapid submergence of the type which would have occurred if the Mediterranean Sea had broken its way into the Black Sea via the Bosporus at 7.5 kyr BP. A massive input of saltwater is expressed in the abrupt shift positive shift with a magnitude of 4 to 6 ‰ in the oxygen isotopes[52] and in the formation of a density stratification in the water column that quickly turned the sea anoxic everywhere below -200 m[54]. A fast submergence of the landscape would explain the preservation of shelf-edge river channels and sand dunes from the destructive processes of the surf zone. The migration of the coast far inland would also have caused the observed simultaneous shutdown in the delivery of detrital carbonate and reworked materials to the shelf and the basin plain at the time of the marine invasion and for the. That the inundation was by water with an already increased salinity is corroborated by the fact that, unlike the deep-basin sediments, there is only a very slight depletion of interstitial chloride with depth in the subsurface of the shelf[76]. Apparently the transgressing sea percolated directly into the open pore space of the highly permeable and dry Neoeuxine shelly gravel and sands[39].

A catastrophic deluge through the cataracts of a narrow inlet is fully capable of cutting into the bedrock of the Bosporus and Dardanelles Straits (Fig.8). Where drilled and sampled in the Bosporus Strait, the initial fill on the eroded bedrock in the bottom of this gorge contains large blocks and boulders of the adjacent Devonian and Carboniferous bedrock[13] floating in a gravel matrix[77] with Holocene-age euryhaline benthic foraminifera (*Ammonia beccarii, Elphidium crispum*)[78] and brackish water molluscs (*Corbula gibba, Cerithidea insulaemaris*)[79] dated at 7.4±1.3 kyr BP in age[80].

Sudden inundation of depressed, enclosed basins are rare but real events. At the beginning of the Pliocene the drastically desiccated Mediterranean Sea[81] filled via a gigantic Gibraltar waterfall. Common to oceanic waterfalls is the fixed head of the supplying water body. As erosion deepens the upstream cataract, the flow through the conduit is amplified through positive feedback. A conservative calculation based on turbulent fluids[82] with boundary conditions[83] adapted to the Bosporus-Marmara-Dardanelles flume system yields an inflow of water of 50 to 100 km^3/day. This flux rate, several hundred times greater than the world's largest waterfall and a thousand times exceeding the present undercurrent, is sufficient to have raised the level of the Black Sea 30 to 60 cm each day or to have topped up the basin in a year (Fig.9). On flat regions of the shelf and in the river valleys the sea might have advanced landward at almost 1 to 2 km per day. The roar of the waterfall, radiated by air and ground waves, would have broadcast the enormity of its cascade to any humans settled or wandering within 100 km of the inlet.

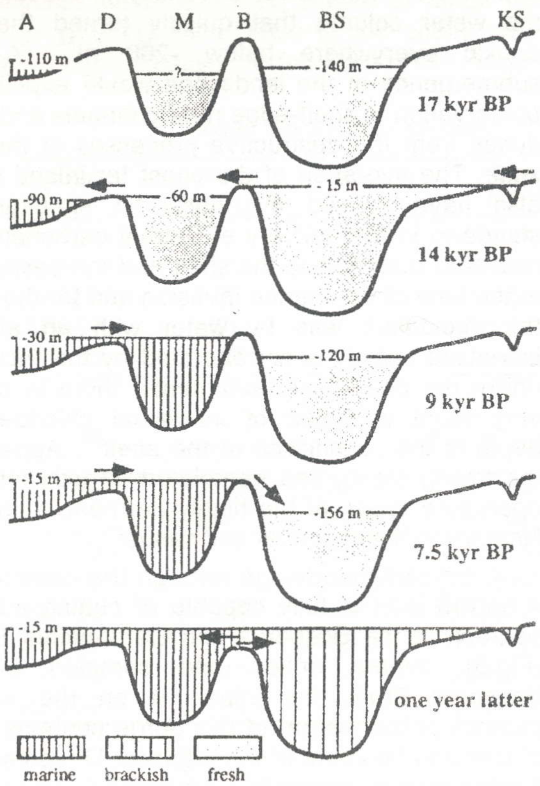

Fig.9 Reconstructed lake and sea levels in the Aegean (A), Sea of Marmara (M), and Black Seas (BS), and their connections/isolations via the Dardanelles (D) and Bosporus (B) Straits. An entrenched stream bed of the ancient Don River Passes though the Kerch Strait (KS). Sea level in the Aegean tracks the rise of the global ocean[9-21]. The sedimentary record of the Black Sea reveals two intervals of isolation, during which much of its vast continental shelf was emerged land. A brief Neoeuxine transgression takes place between 15 and 12 kyr BP, triggered by large flux of melt-water, supplied from the retreating Barents and Scandinavian ice sheets[62] and delivered by the Don and Dneiper Rivers and by an overflow from the Caspian Sea[39, 58,71]. This time of high lake level coincides with Melt-Water Pulse 1 of ref (18). The flooding of marine water into the Black Sea at 7.5 kyr BP is catastrophic, and is accompanied by the erosion of a gorge along the inlet. In the span of a year, the Black Sea is topped up the level of the Aegean and is launched on its way from a freshwater lake to an anoxic brackish sea.

Possible human response

The geological evidence of an injection of saltwater into a depressed Neoeuxine lake via a Bosporus cataract lends credence to the ancient accounts of a bursting of the sea though this orifice. The Black Sea flood took place when farming villages had already been established in Greece and southern Bulgaria[84], in the lower reaches of the modern Danube River[85, 86], near the coast of the Sea of Marmara[87] and in the Fertile Crescent[88]. At 7.5 kyr BP advanced farming, with the possible use of the light plow and simple irrigation techniques, blossomed in the Trans-Causasus its sudden introduction interpreted as an intrusion from the outside[89].

Around 7.4 kyr BP and within the span of 100 years[85] farming villages spread along the major river valleys of Germany, Austria, Czechoslovakia, Poland and the Low Countries[90, 91]. Due to the remarkable homogeneity of these cultural deposits, archaeologists have considered a "wave-of-advance" model for the assumed population movements[92]. The immigrants had an obvious preference for the flood plains of rivers and lakes[93]. They settled throughout most of south-eastern Europe among a mysteriously sparse indigenous population[94, 95]. Although the migration model has been challenged and replaced by one of diffusion of skills rather than people[84], the permanent flooding of the expansive shelf of the Black Sea could have been and impetus to expel into Europe and the Near East communities of farmers which had adapted to the natural resources of the late Neoeuxine Black Sea, i.e., its arable loess soils, the seasonal irrigation of its entrenching rivers, and the fresh moist loam along the retreating shoreline of its vast freshwater lake potentially exploitable for the springtime growing of domesticated food crops.

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