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CATASTROPHIC FLOODING OF THE BLACK SEA

William B.F. Ryan,[1] Candace O. Major,[2] Gilles Lericolais,[3] and Steven L. Goldstein[1]

[1]*Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA: email: billr@ldeo.columbia.edu, steveg@ldeo.columbia.edu*
[2]*Laboratoire des Sciences du Climat et de l'Environment, CNRS-CEA, Domaine du CNRS, F-91198-Gif-sur-Yvette cedex, France: email: candace.major@lsce.cnrs-gif.fr*
[3]*IFREMER–Centre de Brest, F-29280 Plouzane cedex, France; email: gilles.lericolais@ifremer.fr*

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■ **Abstract** Decades of seabed mapping, reflection profiling, and seabed sampling reveal that throughout the past two million years the Black Sea was predominantly a freshwater lake interrupted only briefly by saltwater invasions coincident with global sea level highstand. When the exterior ocean lay below the relatively shallow sill of the Bosporus outlet, the Black Sea operated in two modes. As in the neighboring Caspian Sea, a cold climate mode corresponded with an expanded lake and a warm climate mode with a shrunken lake. Thus, during much of the cold glacial Quaternary, the expanded Black Sea's lake spilled into to the Marmara Sea and from there to the Mediterranean. However, in the warm climate mode, after receiving a vast volume of ice sheet meltwater, the shoreline of the shrinking lake contracted to the outer shelf and on a few occasions even beyond the shelf edge. If the confluence of a falling interior lake and a rising global ocean persisted to the moment when the rising ocean penetrated across the dividing sill, it would set the stage for catastrophic flooding. Although recently challenged, the flood hypothesis for the connecting event best fits the full set of observations.

PREFACE

The hypothesis of an abrupt flooding of the Black Sea arose from the results of a Russian-American expedition in 1993 that surveyed and sampled the continental shelf south of the Kerch Strait and west of the Crimea (Ryan et al. 1997a, Ryan et al. 1997b). Essential to this new and now controversial idea were (*a*) extremely-high-resolution seismic-reflection profiles, (*b*) cores precisely targeted on these profiles, and (*c*) dating by ^{14}C accelerator mass spectrometry (see Ryan & Pitman 1999 for a narrative text of the discoveries and the deductive processes). The reflection profiles revealed a ubiquitous erosion surface that crossed the shelf to depths of −150-m beyond the shelf break. The cores recovered evidence of subaerial mud cracks at −99 m, algae remains at −110 m, and the roots of shrubs in place in desiccated mud at −123 m. Each site lay well below the −70-m level of the Bosporus bedrock sill (Algan et al. 2001, Gökasan et al. 1997). The combination of evidence of a vastly shrunken lake, a uniform drape of subsequent marine mud on the terrestrial surface that was equally thick in depressions as on crests of dunes, and no sign of landward-directed onlap of the sedimentary layers in the drape that are generally produced by a steady transgression all suggested a drowning event. Mollusks tolerant to saltwater appeared in the base of the drape and in a thin layer of fragmented freshwater specimens eroded from the underlying desiccated mud beveled along the erosion surface. When sampled at five sites ranging from −123 to −49 m, the first marine species to colonize each location had an identical ^{14}C age of 7.14 ± 0.04 ky BP[1]. This age was assigned to the Holocene flooding event.

However, flooding precludes the possibility of outflow to the Sea of Marmara during the prior shrunken lake stage. Arguments for persistent Holocene outflow from the Black Sea to the eastern Mediterranean (Aksu et al. 2002a) and for noncatastrophic variations in Black Sea sea level during the ∼10 ky BP (Aksu et al. 2002b) have been recently presented to contradict the flood hypothesis. In order to evaluate the validity of the catastrophic model or its replacement by a continuous outflow model, our review cites many papers published in Soviet literature that contain pertinent observations and discussions not considered in arguments against catastrophic flooding.

OBSERVATIONS

The Black Sea is a large, deep, and semi-enclosed depression underlain by oceanic crust formed in a back-arc tectonic setting (Banks & Robinson 1997, Görür 1988, Letouzey et al. 1977, Zonenshain & Le Pichon 1986). Its sedimentary cover is thought to exceed 10 km in thickness (Malovitskiy et al. 1976, Neprochnova 1976). In fact, more than 300 m of mud and sand of the glacial Quaternary were deposited on the Euxine Abyssal Plain in the past one million years alone (Ross 1978). The large thickness of Quaternary and Neogene sediment, readily imaged by seismic-reflection profiling (Finetti et al. 1988, Letouzey et al. 1978) and representing near-continuous accumulation on the basin floor, contrasts with thinner deposits (Figure 1) of equivalent age beneath the margins (Robinson & Kerusov 1997).

The Continental Shelf

The Quaternary strata on the continental shelf thicken seaward as superimposed, unconformity-separated wedges or stratigraphic sequences (Myers & Milton 1996)

[1]In this paper the term ky BP stands for kiloyears before present without correction for reservoir age and without calibration to calendar years. In the Ryan et al. (1997a, b) and Ryan & Pitman (1999), ages were expressed in calendar years with 7.1 ky BP equivalent to 7.5 ky BP CAL. The usage of dates without corrections is now being practiced to facilitate comparisons between different studies.

Figure 1 The Black Sea with its broad northern and western continental shelf, its 2.2-km-deep basin floor, and its continental slope dissected by canyons. The Black Sea is surrounded by land and exchanges water today with the Marmara Sea and Aegean Sea through the narrow and shallow Bosporus and Dardanelles Straits, respectively (*arrows*). Note the incised drainage of the river networks.

that often display offlap toward the shelf edge (Figure 2, Table 1) (Aksu et al. 2002b, Esin et al. 1986, Khrischev & Shopov 1978, Okyar et al. 1994). Presumably, each wedge was deposited in response to sediment supply and accommodation space made available by subsidence and changing sea level. Because the location of the flexural hinge line lies landward of the present coast, Quaternary deposits are found, although thin, beneath the coastal plains of Bulgaria, Romania, Ukraine, and Russia.

Offshore drilling west of the Crimea penetrated a Quaternary series of clay, loam, sand, and coquina sequences with a thickness not exceeding 30 m before bottoming in Paleocene marls at a depth of 1.3 km (Chernyak et al. 1973). Similar Quaternary deposits were also sampled by drilling in the near-shore zone of the Anapa shelf (Figure 2, *middle*). At −85 m on the southwestern Black Sea shelf, exploration wells penetrated at a Quaternary series no thicker than 140 m (Can 1996).

Buried Channels

Buried channels are observed in the subsurface of the shelf (Figure 2, *bottom*) where they commonly have floors much deeper than the modern shelf break. Such channels on the Kerch margin have been interpreted as paleo-river valleys of the

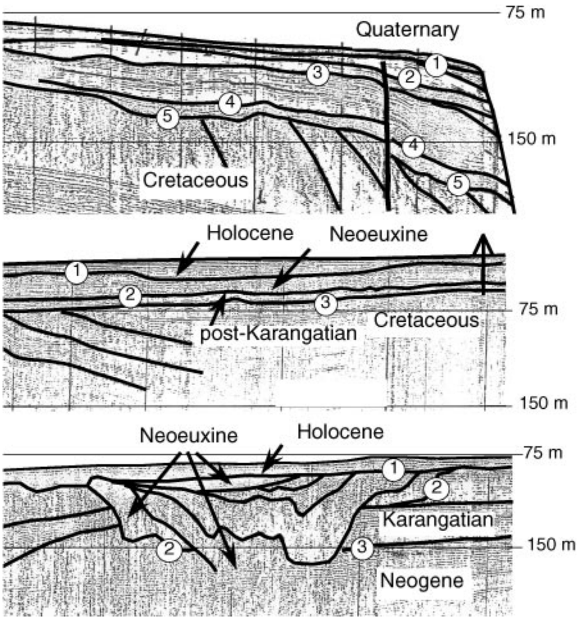

Figure 2 Unconformities (1–5, see Table 1) in Quaternary deposits on the northern Black Sea shelf in the Anapa to Novorossiysk region (adapted from Esin et al. 1986). A strong angular discordance cuts Cretaceous strata. The paleo-Kuban River flowed through the channel and cut into older Quaternary and Neogene shelf deposits as illustrated in the bottom section.

Don and Kuban Rivers (Esin et al. 1986, Popov 1973, Skiba et al. 1976). On the Romanian and Ukraine shelf, the buried valleys are more deeply carved into the surrounding substrate (Figure 3) than south of Kerch. Their floors lie hundreds of meters below the modern seabed (Gillet et al. 2000). These valleys either represent submarine canyons that have indented the shelf for extreme distances or

TABLE 1 Correlation of unconformities on the shelf with stratigraphic stages (Esin et al. 1996) and the correlative Marine Isotope Stages (Zubakov et al. 1988) that reflect changes in global ice volume and external sea level changes

Unconformity	Stratigraphic position	Marine isotope stage
1	Between the Holocene and Neoeuxine	1/2
2	Between the Neoeuxine and the Surozh	3/4
3	At the base of the Karangatian	5e/6
4	Pre old Neoeuxine	7/8
5	Uzunlar	9/10

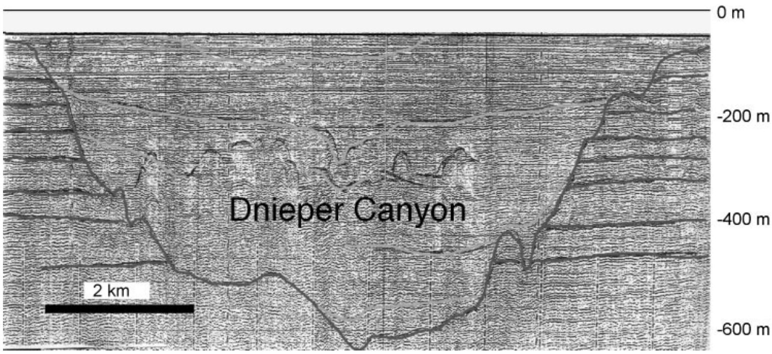

Figure 3 Cross-section of the Dnester-Dneper paleo-valley on the Ukraine shelf in a reflection profile from the 1998 BLASON survey. The valley bottom lies more than 600-m below the modern seabed, and the valley width from rim to rim approaches 10 km. The fact that the rims are just a few tens of meters below the seabed suggests that the incision and fill is young in age and not related to the Late Miocene regression 5.5 Ma ago (Hsü 1978, Hsü & Giovanoli 1979, Kojumdgieva 1983).

drainage across a former flood plain when rivers adjusted to a lower base level. Deep incision of river drainage is a characteristic feature of the modern landscape of Russia and Ukraine (Popp 1969) (Figure 1). Where survey line density at sea is sufficiently dense, the buried shelf valleys display sinuous pathways, suggestive, but not conclusive, of incision from meandering streambeds (Figure 4).

Drilling in the northern part of the Kerch Strait entrance to the Sea of Azov encountered a 5-km-wide ancient valley of the paleo-Don River whose floor lay at −62 m in a notch cut into deformed Neogene rocks (Popov 1973). The riverbed

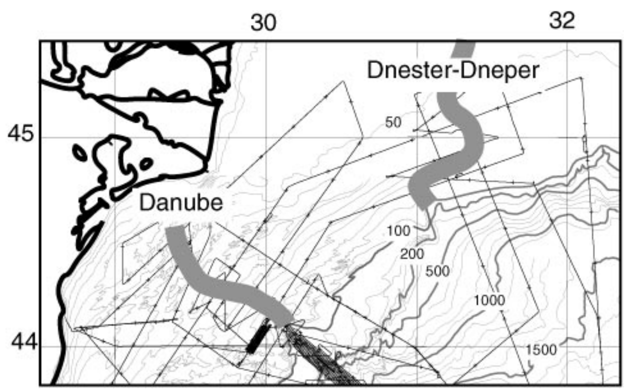

Figure 4 Paths (*stippled pattern*) of the buried Dnester-Dneper and Danube valleys mapped by seismic-reflection profiling. Bathymetric contours are light gray and are labeled in meters. Track lines are from the 1998 BLASON survey.

consists of gravel and pebbles with mollusks indicative of "greatly freshened water" and attributed to "a single alluvial complex consisting of channel, oxbow and floodplain facies" (Skiba et al. 1976). The whole area of the modern Azov Sea had been transformed into a vast alluvial plain through which tributaries of the ancient Don, Molochnaya, and Salgir rivers meandered (Shcherbakov 1961).

Buried Estauries

When the paleo-Don river drowned, its valley became an estuary. Deposits switched abruptly from fluvial gravel and sand to fine-grained clay with brackish species and also *Cardium edule* and *Chione gallina*, both euryhaline species. The appearance of these Mediterranean immigrants is coincident with the disappearance of freshwater Caspian species. The short-lived estuary rapidly transitioned into a marine strait. As its floor shoaled though sedimentation, the clay was replaced upward by coarse shelly detritus derived from the valley margins and then reworked into marine terraces and spits (Skiba et al. 1976). For a period of time known as the Old Black Sea stage of the Holocene (7–3 ky BP), the salinity of the Sea of Azov was higher and the fauna was richer in diversity than in the New Black Sea stage (3–0 ky BP) (Nevesskaya & Nevessky 1961). This suggests that the modern fluxes of evaporation and precipitation were established only in the past few thousand years.

Buried Coastal Lagoons

Exploration on the shelf south of the Kerch Strait has produced evidence of braided rivers that lead to a coast with long-shore bars blocking the river mouths to form lagoons (Figure 5) colonized by freshwater mussels and gastropods (Skiba et al.

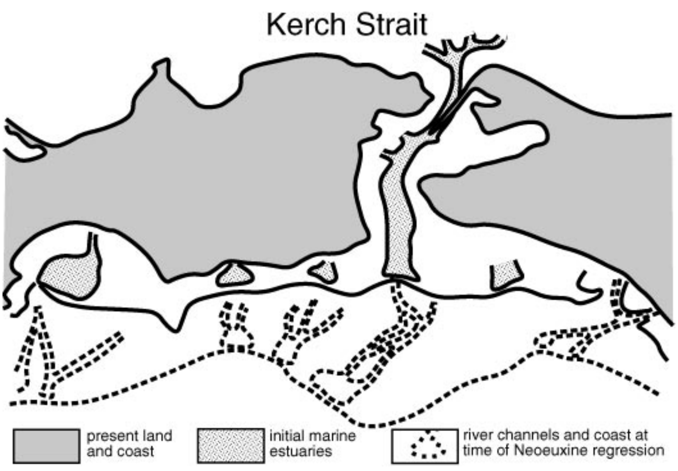

Figure 5 Interpretation of ancient coastlines, estuaries, and rivers in the Kerch Strait area both at the time of the freshwater Neoeuxine regression (*dotted lines*) and after the Black Sea became marine (*stippled pattern*) (Skiba et al. 1976).

1976). These lagoons are much like the modern Black Sea closed bays (liman) that become saline with evaporation. Chepalyga (1984) has reported salinity-tolerant fauna dated at 10 ky BP and indicative of hypersaline ponds that occupied the subarial Sea of Azov and Black Sea shelf in post-glacial time. The closed hypersaline estuaries are characteristic features of the modern northern coast. One for one, they are situated above valleys that ancient rivers cut in order to adjust lower lake levels. Similar drowned estuaries have been found in the interior of the modern Danube delta (Panin 1974, 1997).

In commenting about the postglacial transgression of the Black Sea, it has been emphasized that mud horizons rest directly on coarse-grained detrital deposits of the ancient coastal stratum. "Such a superposition could have been achieved as a result of rapid changes in the sea level" (Nevesskiy 1961). The emergence of most of the Black Sea continental shelf at the time of the maximum regression has been documented by dozens of sediment cores that penetrate into a former land surface (Figure 6) beneath its transgressive cover (Kuprin et al. 1974, Shcherbakov et al. 1978).

The regression occurred in a period of time called the Neoeuxine. Subaerial and near-shore subaqueous erosion combined to bevel older deposits on the outer shelf (Figure 7) whose remnants have been imaged in high-resolution seismic profiles (Major 2002, Ryan et al. 1997a). Although the erosion is ubiquitous across all Black Sea shelves (Aksu et al. 2002b, Demirbag et al. 1999, Okyar et al. 1994) and extends in many localities to depths beyond the −160-m isobath, this does not necessarily mean that the regression was that severe. Nevertheless, a paleoshoreline at a depth of −155 m has been discovered north of the Turkish seaport of Sinop, with its berm separating a cobblestone beach from the lake bottom and an offshore sandbar (Ballard et al. 2000). Rounded cobbles were sampled along the strike of the ancient beach. The cobbles were mixed with intact shells of *Dreissena rostriformis distincta* dated at 15.5 ky BP, which suggests that the beach was submerged and in a low-energy environment by that time.

Bosporus Strait

Reflection profiles across and along the Bosporus Strait reveal two ancient stream valleys that have been cut into the Paleozoic and Cretaceous bedrock (Gökasan et al. 1997). One stream runs north to the Black Sea from a watershed divide within the strait at ~ -70 m, and the other runs south from the divide to the Marmara Sea. Late Quaternary sediments (Neoeuxine and Holocene) have been recovered in cores from valley fill (Algan et al. 2001, Meriç 1995). These sediments contain *Dreissena* species indicative of freshwater lacustrine and fluvial environments dated between 16.6 to 32 ky BP, followed by forminifera, oysters, and mussels indicative of marine environments from 5.3 ky BP to the present (Algan et al. 2001). Electron spin resonance dating on shells gives the oldest marine age as 7.4 ky bp (Goksu et al. 1990). The freshwater sediments are thought to reflect deposition during episodes of Black Sea overflow to Marmara. The marine fauna are products of shell beds formed after penetration of Mediterranean water through

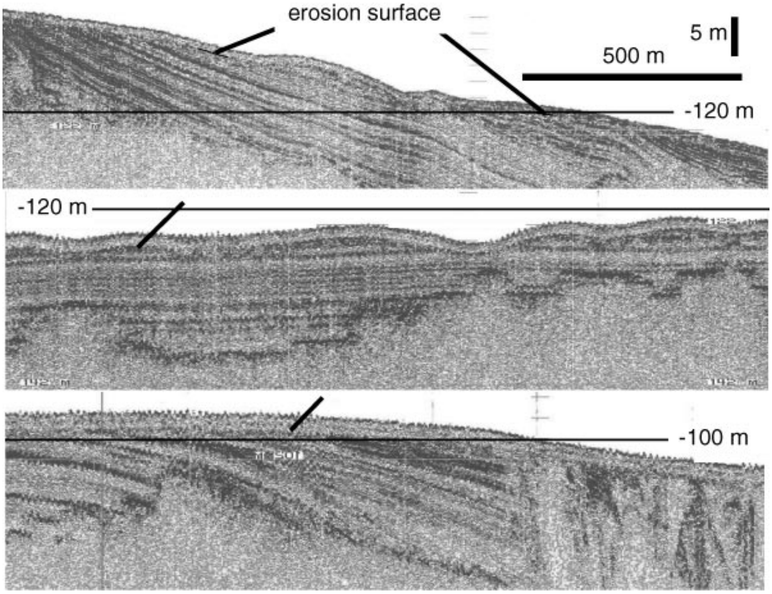

Figure 7 Reflection profiles on the outer Ukraine margin illustrating the ubiquitous erosion surface that crosses the entire shelf: (*top*) a dip-section with differential erosion of more-resistant and less-resistant, seaward-dipping, freshwater, glacial-age strata; (*middle*) a strike-section with channel incision; (*bottom*) a dip-section with truncated transitions from topset to foreset bedding (offlap breaks). The erosion surface is buried by a thin drape of mid- to late-Holocene mud whose salinity-tolerant fauna indicate a connection with the Mediterranean.

the strait to the Black Sea. Today the sediment sill is at ~ -35 m in the vicinity of the Golden Horn (Gunnerson & Oztuvgut 1974).

Terraces

Terraces have been recognized on many Black Sea margins, including the broad Danube (Figure 8) and narrow Caucasus shelves (Ostrovskiy et al. 1977, Shimkus et al. 1980). Based on their present water depth, some of the terraces can be tentatively correlated from region to region (Table 2). Shells belonging to past littoral environments from the vicinity of Black Sea terraces exhibit ages spanning 19 to 9 ky BP (Chepalyga 1984, Dimitrov 1982, Ostrovskiy et al. 1977, Shcherbakov et al. 1978).

Coastal Dunes and Barrier Islands

High-resolution seismic-reflection profiling has revealed large asymmetric bedforms on the outer shelf between the -60 isobath and the shelf edge (Figure 9). Crests reach 6 m in elevation. When surveyed in plain view on the Romanian

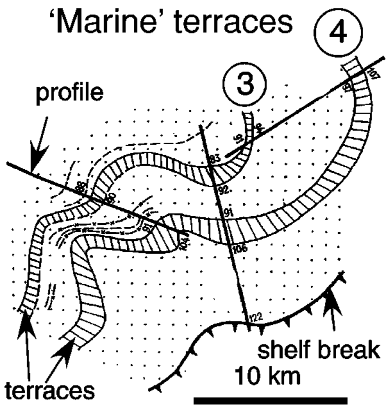

Figure 8 A sequence of wave-cut terraces (*top*) on the outer Danube shelf correlated from profile to profile (Shimkus et al. 1980). The two terraces shown here correspond to terraces #3 and #4 in Table 2. Landward of each terrace, one finds a set of small parallel ridges of 1- to 4-m relief and 100- to 500-m separation (*dashed lines*) that could be relic sandbars or coastal dunes (Vespremeanu 1989). In cross-section (*bottom*), each terrace displays an inflection typical of a terrace riser and ridge suggestive of a coastal foredune.

and Ukraine margin, the crest separation ranges from 200 to 1200 m. Here, these features occur in elongated fields that are adjacent to, parallel to, and landward of prominent wave-cut benches (Major 2002, Ryan et al. 1997b). On the southwest margin, the asymmetric bodies are even larger. Based on a prism shape with both steep, seaward-dipping faces and internal reflectors, and overall similarities with previously interpreted coastal deposits (Kraft et al. 1987), they are interpreted as barrier islands/beaches (Aksu et al. 2002b).

The bedforms on the paleo-Danube floodplain of the Romanian shelf are linear ridges that strike almost uniformly at an azimuth of $75 \pm 10°$. Steeper sides face southeast away from the ancient shoreline. At the base of the steep face

TABLE 2 Correlation of terraces between various Black Sea shelves based on their depths (in meters) (Shimkus et al. 1980)

	Danube	West crimea	South crimea	Kerch
Terrace 1			20–44	
Terrace 2		73–77	54–82	74–78
Terrace 3	83–92	80–101	84–89	83–88
Terrace 4	91–106	102–106		97–107
Terrace 5		108–121		104–115
Shelf break	*122*	*109–126*	*89–98*	*122–162*

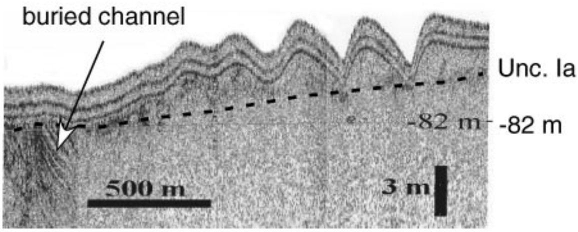

Figure 9 Dunes on the Ukraine shelf superimposed on the fill of former paleo-rivers incised into the landscape surrounding.

of many ridges, one finds depressions with diameters from 100 to 1800 m and a negative relief of 3 to 9 m. The depressions have a variety of configurations from nearly circular to kidney-shaped. Some appear to be strung together like pearls on a necklace and connect through shallow conduits. The depressions are cavities cut into the deposits of ancient riverbeds that meandered across an alluvial flood plain. In all cases, the ridges and depressions are covered uniformly by a mud drape containing at its base euryhaline mollusks (*Mytilus edulis* and *Cerastoderma edule*) representing the time after connection of the global ocean with the Black Sea. Material sampled by coring into the interior of the ridges includes frosted quartz of fine-grain sand size and abraded shell fragments of the fresh-water mussel *Dreissena* with dates of 8.6 and 10.2 ky BP. Mollusks from deposits upon which the linear ridges have migrated have ages of 9.6 ky BP.

In underwater environments, the asymmetrical linear ridges would be classified as sand waves or "large dunes" (Ashley 1990) that are products of sedimentary environments characterized by tidally driven bottom currents. In an essentially tideless Black Sea, either salty or fresh, such currents are lacking. On the other hand, if formed in a desiccated terrestrial environment around a shrunken lake, these ridges are likely to be coastal dunes. The dominate dune type in terrestrial sand seas is linear, with the crest parallel to the prevailing wind and resultant sand drift direction (Wilson 1972).

In subsea environments, small enclosed and unfilled depressions are rare. However, such features are quite characteristic of arid and windy terrestrial settings (Shaw & Thomas 1997) where cavities are eroded into the substrate by deflation processes (Laity 1994). Depressions at the scale of those mapped on the Romanian shelf would be called pans. Their initiation and growth depend on materials susceptible to deflation, such as material that curls, flakes, and blows away upon desiccation. Pans in dune settings often occur as a string of depressions aligned along a former river course and its braid plain (Lancaster 1998).

The Continental Slope

The continental slope of the Black Sea is widely incised by submarine canyons whose heads may indent the shelf edge and in the past were sometimes located within present-day land (Balabanov & Ostrovskiy 1979). Aligned side-by-side on the steep Crimea and Caucasus margins, these canyons leave little slope area unaffected by erosion. Consequently, much of the sediment delivered by rivers ultimately bypasses the slope to depocenters on deep-sea fans and the basin plain. Because many canyons do not occur on the prolongation of river valleys, their formation has been attributed predominantly to mass wasting by slumping and sliding (Peshkov 1983). Retrogressive slope failure has led to the development of a dendritic drainage pattern with second, third, and fourth order tributaries. Even steep canyon walls are gullied (Figure 10, *left*). Canyons with high-order tributaries also sculpt the continental slope west of the Crimea (Figure 10, *right*). Canyon heads that indent the shelf break mark the sites of ancient coastal embayment.

Stratigraphy and Chronology

Various bio- and litho-stratigraphic schema of the late-glacial and postglacial deposits of the Black Sea region are summarized in Figure 11. Common in the syntheses of different researchers is the distinction of a level around 7 ky BP that

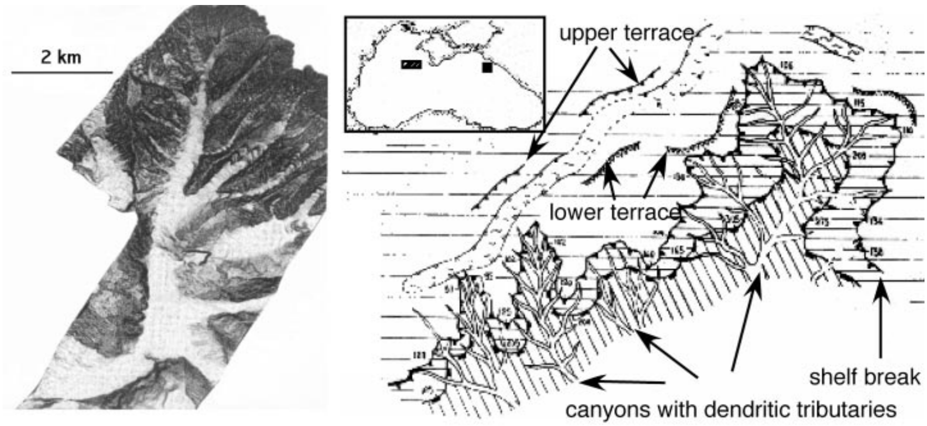

Figure 10 Dendritic drainage in a submarine canyon off Djubga on the Caucasus margin (*left*) (Nederland Survey Projecten en Apparatuur B.V. 1997). Dark shades indicate steeper slopes. Light shades are more gentle slopes. Gradients in the upper reaches approach 18 degrees. Some tributary heads cut through the shelf break all the way to the −50-m isobath. Spurs are sharp such that no part of the slope has escaped incision. The broad U-shaped valley trunk resembles those of the Nice canyons in the western Mediterranean through which boulder-transporting debris flows and turbidity currents have traveled in modern times (Malinverno et al. 1988). Geomorphological interpretation of canyon heads incised into the upper slope and shelf edge west of the Crimea (*right*) (Yu. Yevsyukov, personal communication, 1995). Two terraces are present: the upper at the −85-m isobath and the lower at the −105-m isobath. The shelf break varies from −107 to −140 m.

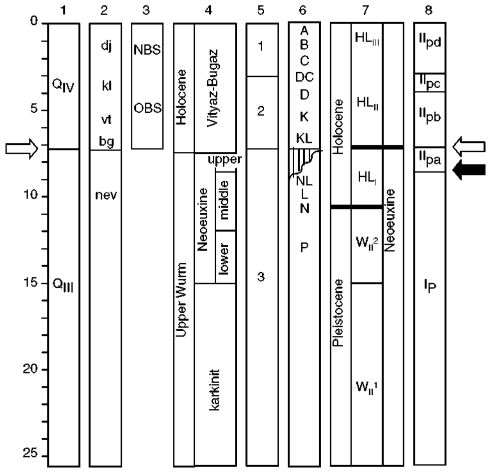

Figure 11 Various stratigraphic schemes developed for the Black Sea. 1. Stages commonly used for continental and marine stratigraphic correlation (Kuprin et al. 1974, Popov 1973, Popp 1969, Skiba et al. 1976). 2. Stratigraphic nomeclature based on distinct beds recognized in outcrop and cores: nev = Neoeuxine, bg = Bugaz bed (with marine fauna overlapping with fresh/brackish fauna), vt = Vityazevskian beds, kl = Kalamitian beds, dj = Djemenitian beds (Dimitrov 1982, Nevesskaya 1965). 3. OBS = Old Black Sea beds, NBS = New Black Sea beds (Markov et al. 1965, Nevesskaya 1965). 4. Subdivision of the Neoeuxinian deposits (Shcherbakov & Babak 1979). 5. Lithostratigraphic units in cores from the basin floor (Ross & Degens 1974). 6. Lithostratigraphic units in cores from the north and western shelf (Shopov et al. 1986). 7. Stratigraphy based on diatoms and pollen from deep-sea sediments (Shimkus et al. 1978). 8. Pollen assemblage zones in deep water cores from the western Black Sea (Atanassova 1995). Zone Ip = dominance of the herbs and grasses indicative of a dry, cold climate; IIpa = beginning of the enlargement of oak forests; IIpb = maximum spread of mixed oak forests; IIpc = some enlargement of herb communities; IIpd = formation the "longoz forests" along river valleys. The white arrow marks the first appearance of marine dinoflagellates (Wall & Dale 1974), whereas the black arrow points to changes in the *Dreissena* fauna, which is suggestive of the actual onset of salinification (Shcherbakov & Babak 1979).

separates the marine stage of the Black Sea from the prior freshwater stage. In the majority of the interpretations, the marine stage, identified at its base by the first appearance of Mediterranean species, defines the Holocene. However, in such usage, the beginning of the Holocene in the Black Sea is several thousand years younger than the conventional Late Pleistocene/Holocene boundary as established by the International Union for Quaternary Research in 1969. Scheme 7 in Figure 11 resolves this discrepancy by establishing the Black Sea Holocene as synchronous with the global chronology by placing its base at 10.5 ky BP (Shimkus et al. 1978).

In scheme 7, a freshwater early Holocene (stage HL_I) is separated at approximately 7.2 ky BP from the marine middle and late Holocene (stages HL_{II} and HL_{III}, respectively). Stage HL_I corresponds to the upper Neoeuxine stage of scheme 4 in which one observes the first appearance of *Dreissena rostriformis bugensis*, *Monodacna caspia*, and *Dreissena polymorpha regularis*, as well as a number of gastropods that can be interpreted as pointing to the onset of salinization (Shcherbakov & Babak 1979). In a deep basin core, the first sign of increasing content of the heavier O^{18} isotope in the oxygen of the Black Sea's waters (Deuser 1972) occur at a similar level (Ross & Degens 1974), dating to ~8.5 ky BP (by interpolation).

Sediment Composition and Isotope Geochemistry

The carbonate content and its oxygen isotopic composition has been measured in the a well-dated core on the continental slope at −378 m off Romania that extends back to 22 ky BP without interruption (Major et al. 2002) (Figure 12). The site is deep enough to have remained submerged throughout glacial and postglacial time. Six distinct sediment types are characteristic of this core, and numerous others, are described from slope and basin floor settings (Kuprin et al. 1974, 1981; Kuprin & Roslyakov 1988; Ross et al. 1970). These six types are from young to old: (*a*) lithology "M," a very fine-grain, organic-carbon-rich, carbonate-poor black sapropel clay with marine fauna and flora that dates from 0 to 7.2 ky BP (Jones & Gagnon 1994); (*b*) lithology "T," a coarse-grain, sandy light gray mud with shell fragments of brackish mollusks and increasing carbonate content from 7.2 to 8.4 ky BP; (*c*) lithology "C," two layers, C1 and C2, carbonate-rich, whitish freshwater silty-mud from 8.4–10 ky BP and 11–12.8 ky BP separating; (*d*) lithology "Y," a coarser-grain, low-carbonate, diatomaceous, dark-gray, freshwater mud from 10 to 11 ky BP; (*e*) lithology "B," a fine-grain reddish-brown, low-carbonate, freshwater clay from 12.8 to 15 ky BP; (*f*) lithology "G," another, low-carbonate, dark-gray, freshwater mud, similar to lithology "Y," from 15 ky BP to 22 ky BP at the base of the core (Major 2002).

Lithology "G" was deposited in glacial time. It is the deep-water equivalent of the prodelta clinoforms imaged on the continental shelf, and it passes upward to a reddish-brown clay delivered during the ice sheet melting. The reddish-brown clay has a high concentration in the mineral illite delivered from northern provenances (Müller & Stoffers 1974). The high-carbonate whitish silts reach 60% of the bulk composition of the sediment. The carbonate consists of euhedral calcite grains thought to originate by precipitation in lake environments (Hsü & Kelts 1978). The high-carbonate deposition occurs in two pulses bracketing lithology "Y" of Younger Dryas age. The black sapropel reflects an environment without oxygen.

The $\delta\ ^{18}O$ is light (−4 per mil) in the glacial mud and very light (−8 per mil) in the high-carbonate sediments. Such values confirm a freshwater condition for the carbonate precipitation (Deuser 1972). The $\delta\ ^{18}O$ becomes heavier in the brackish sediments of lithology "T" and approaches modern marine values in

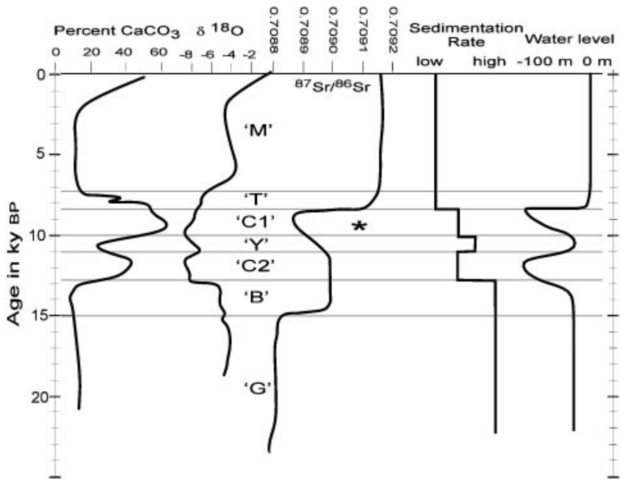

Figure 12 Variations in the lithology, carbonate, and isotopic composition of Black Sea sediments for the past 22 kiloyears. These measuremnts show the passage from glacial to post-glacial conditions at 15 ky BP, two carbonate peaks associated with subsequent calcite precipitation as climate warmed, the return to glacial condition in the Younger Dryas at 11 to 10 ky BP, and an abrupt transformation to modern ocean compositions at 8.4 ky BP. The $\delta^{18}O$ is measured on bulk carbonate (Major et al. 2002) and $^{87}Sr/^{86}Sr$ is measured on individual mollusks shells (Major 2002). The timescale is obtained from more than two-dozen ^{14}C dates and is used to calculate sedimentation rates. The level of the Black Sea's lake derives from the dated shorelines. The single $^{87}Sr/^{86}Sr$ outlier at 9.6 ky BP is from the shell of a salinity-tolerant mollusk recovered in sediments from the floor of pond that lay above the lake's shoreline. The sediment horizon lies below unconformity 1a and presumably reflects the $^{87}Sr/^{86}Sr$ composition of prior marine highstand sediment through which river meandered to the lake edge.

the marine sapropel. The $\delta^{18}O$ show a tendency to return to its glacial value in lithology "Y."

The $^{87}Sr/^{86}Sr$ ratio on shell calcite and bulk carbonate (Figure 12) is a useful proxy to trace the evolution of the Black Sea water composition from its stable baseline in the last glacial cycle. The earliest signal is at 15 ky BP with the input of the reddish-brown clay where it reaches an intermediate plateau from 14 to 11 ky BP. From there it returns toward its glacial baseline in lithology "Y," only to abruptly rise toward modern marine values at 8.4 ky BP (Major 2002).

Because of the substantially greater concentration of strontium in seawater relative to freshwater, $^{87}Sr/^{86}Sr$ is required to change abruptly to the composition of the external ocean even with small inflow. Signals prior to 8.4 ky BP require causative mechanisms other than reconnection. Changes in the relative inputs from rivers, the reorganization of drainage areas, and the weathering of soils and rock all have impacts. For example, the shift at 15 ky BP is because the reddish-brown clay has more radiogenic $^{87}Sr/^{86}Sr$ than gray glacial mud below.

DISCUSSION

Prior Models for Black Sea and Mediterranean Connections

The model that is the most widely cited for Black Sea-Mediterranean connections never addressed whether the surface of the Black Sea's lake ever dropped below its outlet (Deuser 1974). This early work considered a relatively shallow sill in the Bosporus Strait to account for the timing of the Black Sea's rise in salinity at ~9 ky BP (Degens & Ross 1972). It was obvious that the Black Sea followed the ups and downs of the global ocean whenever the later was at or above the Bosporus sill, but when the global ocean dropped below the outlet, it was assumed that the Black Sea stabilized at the outlet due to a persistent excess of water from rivers and precipitation as compared to that lost by evaporation (Kvasov 1975).

In order to account for deep shorelines discovered a few years later, this model was modified to deepen the sill to the level of the deepest shoreline, then recognized to be around −80 m (Chepalyga 1984, Kuprin et al. 1974). It thus became possible to fully synchronize Black Sea water levels and global eustacy and use the timing of the later to interpret sedimentary sequences on the Danube margin and fan (Winguth et al. 1996, 2000). However, two problems arose. The first conflict was that a sill as deep as −80 m should have permitted reconnection as early as 11 ky BP, yet the oxygen and strontium isotopes showed no evidence of salt water input to the lake until 8.4 ky BP. Although one could argue that Black Sea discharge to the Marmara Sea was so strong as to keep the saltwater out (Aksu et al. 1999), the Marmara Sea passes this same stream to the Mediterranean via the Dardanelles Strait. Yet the Marmara Sea did not keep the Mediterranean at bay but became marine at 11.7 ky BP as soon as its outlet was breached (Çağatay et al. 2000). The second problem was that ancient shorelines of the Black Sea's lake had been discovered as deep as −155 m (Ballard et al. 2000). Crests of features interpreted as barrier islands lay at −94 m (Aksu et al. 2002b). These depths clearly exceeded those of the Bosporus bedrock sill at −70 m (Gökasan et al. 1997) and the Dardanelles bedrock sill at −70 m (Aksu et al. 1999, Smith et al. 1995).

The only researchers to step back from the model of persistent outflow were those who discussed the possibilities of different climate regimes in the past. More arid climate could change the hydrologic regime and allow for episodic draw down of the Black Sea's lake by evaporation (Scholten 1974, Stanley & Blanpied 1980).

Paleoclimate

Because evidence is compelling that the level of the Black Sea's lake must have been below its outlet at the time of the deep shorelines, outflow had to have ceased.

Water levels in an isolate basin would then be subjected to a fluctuating balance between evaporation, river input, and precipitation. Pollen spectra dominated by *Artemisia*, *Chenopodaceae*, and *Poaceae* are characteristic of the freshwater sediments recovered from deep-sea cores on the Bulgarian slope (Atanassova 1995, Atanassova & Bozilova 1992, Filipova et al. 1983, Shopov et al. 1992). The continuous presence of *Ephedra distachia* in the pollen spectra points to extremely dry conditions. Accompanying flora, such as *Sueda maritima* and *Artemisia maritima*, grow today in salty soils and on sand dunes in coastal settings. Arboreal pollen, signaling the expansion of oak forests, along with elm and hazelnut forests, replaces the herbs and grasses at levels only after 7.2 ky BP (see schema 8 in Figure 9). Therefore, the aridity required for excess evaporation is compatible with the pollen analysis.

Marine Invasions

Cores obtained during leg 42B of the Deep Sea Drilling Project exhibit freshwater sedimentary environments of long duration reaching back for more than three million years and only punctuated by eight brief invasions of marine diatoms from the Mediterranean (Schrader 1979). The marine phases universally correspond to high global sea level during warm climates that produced wave-cut terraces now elevated on the Caucasus coast and drowned soils in coastal outcrops around the Kerch and Tamanian peninsulas (Arslanov et al. 1983). The sediments covering the soils are invariably marine. The intermittent saltwater pulses begin in the Uzunlarian regional stage (Arkhangel'skiy & Strakhov 1938) circa 0.6 Ma, with the Patray marine invasion carrying emigrants, such as the *Cardium*, *Pasphia*, and *Scrobicularia* mollusks families, and marine foraminifera such, as *Neogloboquadrinia pachyderma*, *Globigerina bulloides*, and *Globigerinoides ruber* (Zubakov 1988). The penultimate marine invasion is preserved in the Eltigenian beds of the Karangatian stage, dated at ∼129 ky BP by the uranium series (Arslanov et al. 1983). The Karangatian stage corresponds to the Eemian interglacial and marine isotope stage 5e (Shackleton & Opdyke 1973). The saltwater invasions amount to less than 10% of the duration of the combined freshwater phases. Thus, the Black Sea's outlet was sufficiently shallow to be above the level of the global ocean during most of the late Quaternary.

Six of the freshening episodes are associated with the spilling of Caspian water and fauna into the Black Sea (Zubakov 1988). Caspian overflow requires a swelling of that water body to more than one and a half times its present size in order to reach an elevation +25-m above the modern Black Sea and gain an exit through the Manych water gap into the Don River and from there to the Sea Azov and out through the Kerch Strait (Popov 1983). At times of Caspian outflow, it is almost certain that the Black Sea was also expelling water to the Mediterranean (Kvasov 1975). Strong freshening episodes trimmed the Black Sea's lake to the level of its spillway into Marmara, and Marmara trimmed its level to the Dardanelles spillway to the Mediterranean (Smith et al. 1995).

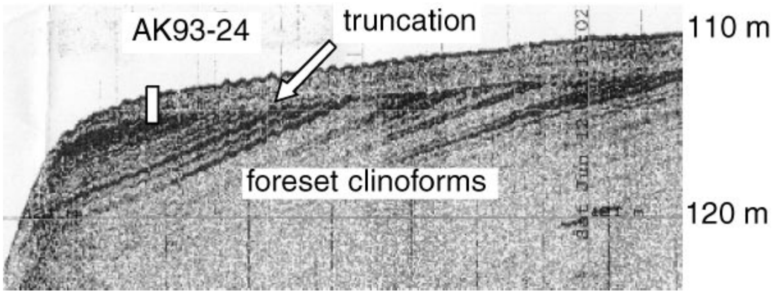

Figure 13 High-resolution reflection profile at the outer edge of the Black Sea shelf south of the Kerch Strait. The inclined bedding is attributed to truncated foreset clinoforms formed as the distal part of a glacial prodelta deposit fed by the paleo-Don River. At the time the truncation surface was exposed, the lake shoreline lay beyond the local shelf edge.

Level of the Spillway

Freshening episodes should correspond to sedimentation in river-fed coastal deltas, particularly those south of the Kerch Strait that would have been enhanced by the extra contribution from Caspian outflow. Clinoforms of the prodelta setting have been discovered using reflection profiles obtained in 1993 by the joint Russian-American expedition (Major 1994, Major et al. 1994). Core AK93-24 sampled inclined foresets of the paleo-Don delta and recovered desiccated mud and sand layers with plant material (Figure 13).

The foreset beds can be traced landward to where they transition into horizontal beds that make up the condensed topsets of the prodelta sedimentary prism. The summit of the prism sits roughly at −60-m below present sea level. Because young Holocene mud extends today practically to the shore zone, where it gives way to coarser silt and sand in the zone of wave action at depths on the order of −30 m (Shcherbakov 1979), one can apply this inferred wave-base to the glacial delta. Thus, the lake surface under which the topset beds formed may have been in the neighborhood of −30-m below present sea level.

Timing the Freshening

Core 1860 from the deep basin floor contains a layer rich in diatoms (Figure 14) that can be correlated to other nearby cores. Dominated (>80%) by *Stephanodiscus astrea* (Shimkus et al. 1973), the diatom assemblage resembles the time-equivalent "Stephanodiscus horizon" in the Caspian Sea (Zhakovshchikova 1968).

According to Shimkus (personal communication, 1996) "the Black Sea diatomaceous layer correlates with the top stage of the late Kvalynian transgression in the Caspian and marks an influx of Caspian waters into the Black Sea." Radiocarbon methods on bulk carbonate from the raised Kvalynian shoreline constrain the

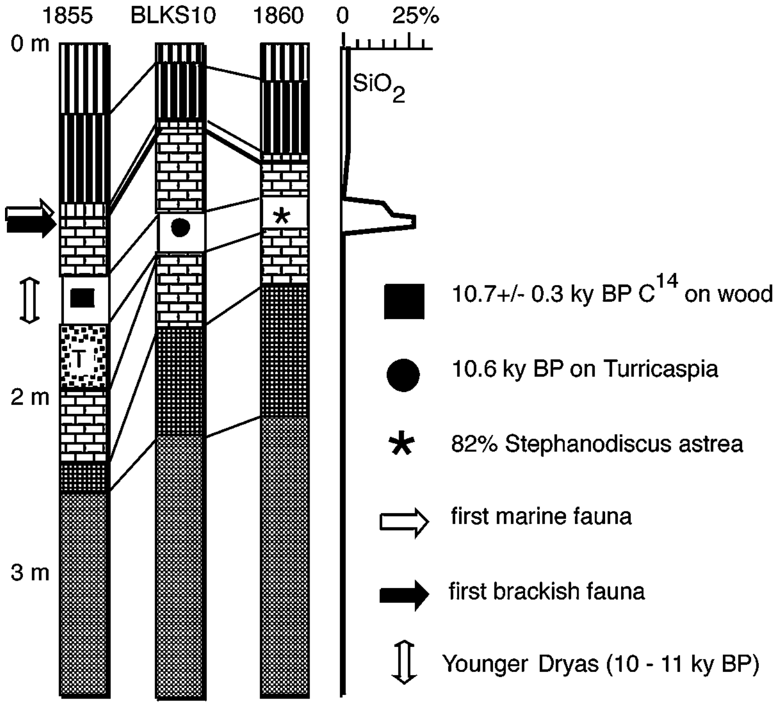

Figure 14 Deep-water cores from the western Black Sea constrain the age of a diatom-rich layer (Shimkus et al. 1973) that marks a freshening by Caspian overflow. The brick symbol represents calcite-rich mud. Verticle lines are sapropel, corresponding upward to the Bugas, Old Black Sea, and New Black Sea stages of the Holocene. The gray stippling in the lower part of the cores is glacial terrigeneous mud. The coarsely stippled pattern (marked by a "T") is a turbidite. Silicic skeletons, dominated by a single Caspian species, make up 25% by weight of the bulk sediment composition.

late Kvalynian transgression to somewhere between 14 and 9 ky BP (Kaplin et al. 1993). However, the Caspain discharge into the Black Sea can be better refined using fragments of wood and individual mollusk shells in the diatom deposit that have dates of 10.7 and 10.6 ky BP, respectively. Sediments of this age corrspond to the Neoeuxine transgression (Shcherbakov et al. 1978) and are widespread across the Black Sea shelf. They extend landward to the vicinity of the −30 m-isobath (Figure 6, *bottom*).

Timing the Regressions

With the Black Sea spillway constrained to be shallower than −30 m based on Younger Dryas overflow (Major et al. 2002), then any prior or younger shorelines below this level must correspond to intervals of excess evaporation and a shrinking lake. As regression exposed lakebed deposits, the combination of surf action, wind,

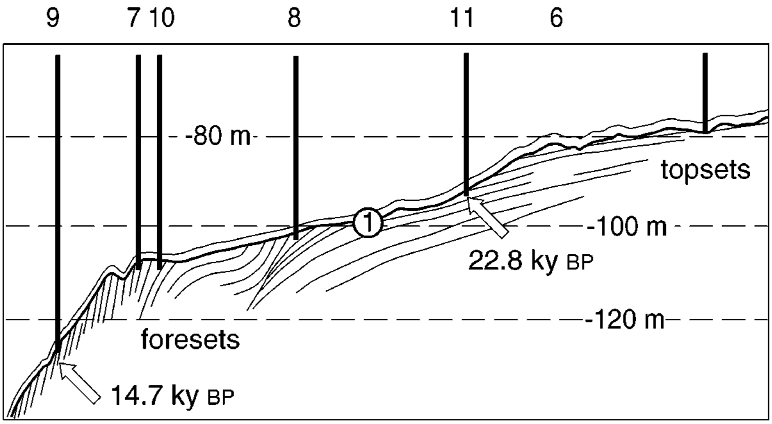

Figure 15 Line-tracing of a high-resolution reflection profile across the outer Ukraine shelf and slope break (Ryan et al. 1997b). Unconformity 1 truncates topset and foreset clinoforms deposited in late-glacial to early post-glacial time. These strata have been reached in all six cores on this profile. In all cores, the deposits are a dry mud with thin silt and sand lenses, rich in plant material, and covered by a thin layer of pulverized shells of freshwater mollusks, presumably concentrated from the material removed and left as a lag deposit. This thin layer has been recognized on the Bulgarian shelf where it is called a "wash-out surface . . . spanning considerable time " (Dimitrov et al. 1979, Shopov et al. 1986). Dates on bulk shell debris range from 10.2 to 11 ky BP (Dimitrov 1982).

and rain were then able to wash the surface and erode it. Thus, each regression left a corresponding unconformity as the result of either the removal of sediment or nondeposition. One of those shelf-wide exposures is labeled unconformity 1 in Figure 15. It correlates laterally to unconformity α on the southwestern shelf (Aksu et al. 2002b) and reflector R on the southeastern shelf (Okyar et al. 1994).

The single truncation seen in the reflection profile is actually comprised of two distinct erosion surfaces (Figure 16) separated by a thin layer of freshwater coquina (10–30-cm thick) that corresponds to the Unit N "lumashell" on the western Black Sea shelf (Shopov et al. 1986). Two stratigraphic gaps or hiatus bound this coquina. On the southwestern shelf, the gaps correspond to unconformity α (*below*) and α_1 (*above*) (Aksu et al. 2002b). In Figure 16, the gap below the coquina thins in the seaward direction as progressively younger strata appear at its base. The gap disappears only at depths below -165 m.

The youngest material sampled from below unconformity 1b is 14.7 ky BP. The oldest sediment is 22.8 ky BP. These ages show that the erosion occurred after almost all the glacial ice had retreated from the Black Sea drainage (Denton et al. 1999). Hence the regression that produced unconformity 1b was primarily a post-glacial phenomenon and took place when the regional climate started to warm.

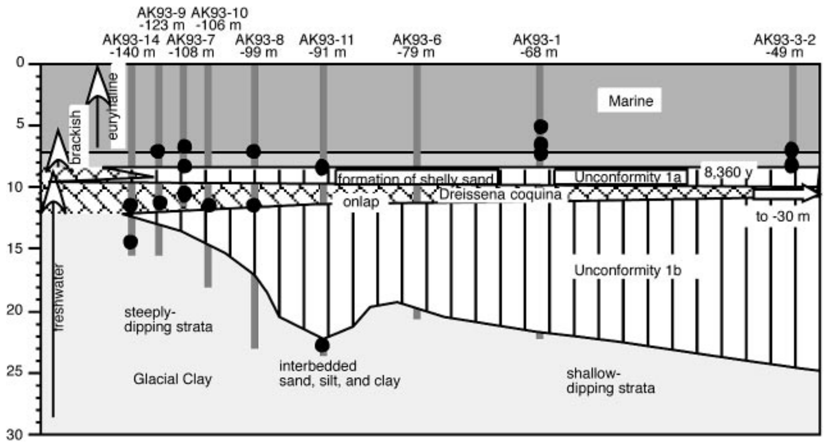

Figure 16 A Wheeler-type diagram constructed by combining the reflection data with dated sediments in cores taken along the profile. The vertical axis represents age in ky BP. The pattern of parallel vertical lines represent gaps where sediment has either not been deposited, or it has been removed by erosion. The dots are levels in the cores where ^{14}Cages have been measured on single shells. The glacial clay (*fine stipple pattern*) and the coquina (*inclined brick pattern*) are both indicative of freshwater conditions. They are separated from each other by unconformity 1b. Brackish fauna appear as intact whole shells in a thin layer of shelly sand (*intermediate gray stippled pattern*) on top of the coquina. The brackish fauna are younger than the shelly sand and its matrix. The brackish-water clam, *Monodacna caspia*, is essentially a colonizer of this sand with detritus once belonging to mollusks living in an earlier freshwater condition at the time of coquina deposition. Mud with marine fauna (*dark gray stippled pattern*) rest on the shelly sand and is separated from it by unconformity 1a. Some marine mollusks, such as the burrowing clam *Cardium edule*, also colonized the shelly sand.

Establishing the Presence of Former Terrestrial Landscapes

In freshly split cores, the sediment below the unconformities is low in moisture content ($<$20%) and high in bulk density ($>$2.1 g/cm^3). This condition is anomalous for shallow subaqueous burial of less than a few meters. Compaction produces such low water contents and high density only after hundreds of meters of overburden (MacKippop et al. 1993). Because plant roots and desiccation cracks are present in the top of the dry clay, the low water content is most likely the result of exposure to the sun. The fact that the roots and cracks are preserved right at the unconformity is evidence that this surface was unaffected by ravinement during the subsequent transgression.

Unconformity 1b associates with a wave-cut terrace (Figure 17) at −120 m that etched rivulets in prodelta bottomset deposits dated at 14.7 ky BP (Major 2002). This terrace is draped by *Dreissena* coquina dated at 10.7 ky BP. The coquina

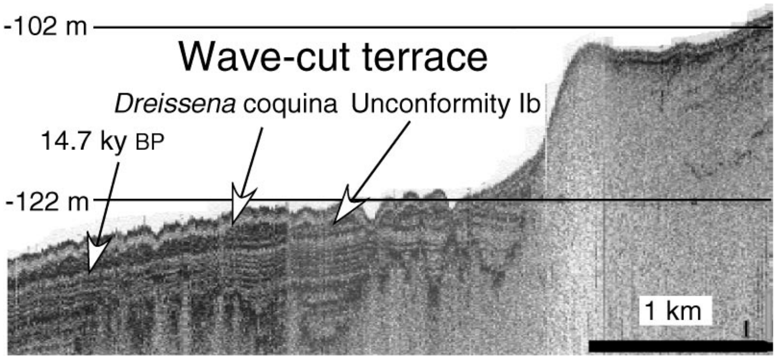

Figure 17 A wave-cut terrace at −120 m on the Ukraine margin associated with the earlier regression that produced unconformity 1b.

displays normal water contents (>60%) and bulk densities (1.6 gm/cm^3) only in cores taken from the continental slope below this terrace. The cusp of a remnant ridge, similar to the dune ridges described from the southwestern shelf (Aksu et al. 2002b), bounds the terrace on its landward side.

Asymmetric linear dunes form a 2-km-wide ribbon landward of and parallel to a second wave-cut terrace at −95 m (Figure 18). This terrace has a wedge-shaped sand body of the shape, size, and internal geometry of others imaged on the outer shelf of the Gulf of Lions in the western Mediterranean (Berné et al. 1998). Like

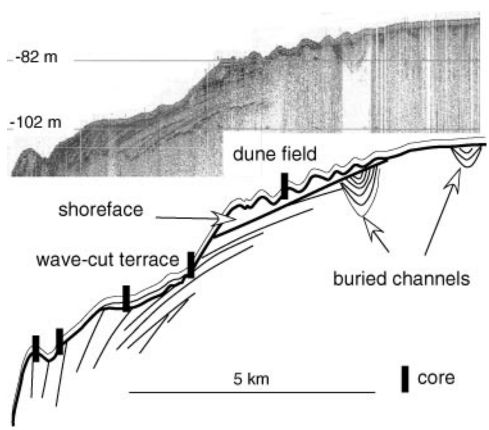

Figure 18 The upper terrace on the outer Ukraine shelf with its wedge-shaped, shoreface sand body and coastal dune complex overlying buried channels that lie below unconformity 1a. The dunes sit on remnants of the coquina layer and consist of materials eroded from the coquina and the deeper prodelta deposits.

those in the Mediterranean, the body on the Ukraine shelf, with its internal, steep, seaward-dipping reflectors, is interpreted as an ancient shoreface. From its berm, the inferred beach profile drops off to the wave-cut bench. A thin deposit rests on the terrace.

The dunes have built over the beveled fill of the underlying channels. In areas of dense survey coverage, many channels display meanders characteristic of rivers crossing a floodplain. A few others have little horizontal continuity and may have been cut by subaqueous currents ebbing and flooding through breaks in a coastal barrier leading to the interior of small lagoons as envisioned for the Kerch paleoshoreline (Skiba et al. 1976). The proximity of linear asymmetric bedforms with both buried channels and shorelines might indicate that the wind exploited fluvial and beach sand to build the dunes (Laity 1994).

In the deposit draping the dunes, intact fauna are no older than 8.4 ky BP (Major 2002). The only residue of the previous freshwater transgression is pulverized fragmented shell debris that is no younger than 10 ky BP.

Was the Drowning of the Ancient Shorelines Fast or Slow?

In order to consider the nature of how the ancient shorelines were submerged, the postglacial history of the Black Sea is summarized in six time slices (Figure 19). At time “a,” intensified melting of the Eurasian ice sheet and the Alpine ice dome filled both the Caspian and the Black Sea to their brims. The former spilled into the latter, and the latter overflowed into the Mediterranean. During time “b,” climatic aridity drew the water level down to the older shoreline by evaporation. Wave-action and exposure generated unconformity 1b. This regression reached a −105-m lowstand at time “c”. Cooling during time interval “d,” which corresponds to the Younger Dryas climate reversal (Alley 2000), changed the balance from evaporation to precipitation in both the Black and Caspian Seas. The latter sea swelled to its spillway during its Late Kvalynian transgression and discharged the *Stefanodiscus astrea* diatoms into the Black Sea. The Black Sea’s lake swelled to paint a layer of *Dreissena* freshwater coquina up to its −30-m isobath. At this time, the global ocean lay 20 or more meters below the Black Sea spillway. The Younger Dryas freshwater transgression produced the coastal onlap observed across unconformity 1b. As climate warmed in time interval “e” during the Bølling-Allerød, a new phase of aridity and evaporation drove the Black Sea down to its upper shoreline. The exposed *Dreissena coquina* was eroded into shelly sand and gravel. Calcareous beach sand, shell fragments of the exposed coquina, and quartz from dried riverbeds blew into coastal dunes. At 8.4 ky BP in the early Holocene, a connection with the Mediterranean triggered the terminal transgression that led to the modern snapshot sketched in “f.” The sediments deposited between 8.4 and 7.1 ky BP display a transition from brackish to marine.

Two transgressions occurred. The first produced a flooding surface during the Younger Dryas (10–11 ky BP) that extended from −105 to circa −30 m. The second produced a flooding surface at 8.4 ky BP, extending from −95 to circa −30 m. How rapid were these events?

The earlier transgression was climatically modulated. Although the onset of the Younger Dryas cooling was rapid and occurred in less than a century (Alley 2000), it is likely that the response of the Black Sea's lake to reduced evaporation was sufficiently gradual that an observable coastal onlap was formed at the base of the coquina deposit, as seen at depths below −85 m. This onlap geometry is also seen at the base of seismic subunit 1B on the southwestern shelf (Aksu et al. 2002b).

The younger transgression is confined to a narrow time window. Materials within the coastal dunes date to 8.5 ky BP and the dunes are drowned by 8.4 ky BP. In cores that span the depth range of −50 m to −90 m, the first intact fauna that colonize the submerged substrate give indication that salinization was underway. Does this mean that salt water flowing into the Black Sea through the Bosporus inlet produced a catastrophic flood (Ryan et al. 1997a)? Arguments in support of a rapid flood are the excellent preservation of the coastal dunes (Glennie & Buller 1983), the absence of a coastal onlap in the brackish to marine mud drape above unconformity 1a, and the observation that the Black Sea's coastal climate, as deduced from the pollen spectra, remained arid until after the initial salinization (Atanassova 1995, Filipova et al. 1983).

Criticisms of Catastrophic Flooding

The hypothesis of a rapid terminal flooding of the Black Sea has been criticized (Aksu et al. 2002a,b; Görür et al. 2001). The initial objection (Görür et al. 2001) noted the presence of 8.1-ky BP peat and 7.2-ky BP wood associated with brackish fauna (*Dreissena polymorpha* and *Monodacna caspia*) in cores from the Sakarya River and adjacent shelf. Deposits with these components at a depth of −22 m conflicted with a lake downed at 7.14 ky BP as originally proposed. However, a recognition from the strontium isotopes that the salinization was initiated earlier at 8.4 ky BP and that the 7.14 ky BP only reflected a threshold in salinity resolves the apparent conflict.

The second objection (Aksu et al. 2002a,b) is based on three arguments. The first is the formation of a sapropel deposit in Marmara, which, according to prior models for its origin (Aksu et al. 1999, Çağatay et al. 2000, Stanley & Blanpied 1980), requires a lens of freshwater presumably delivered by outflow from the Black Sea. The observation that the Black Sea did outflow during the Younger Dryas (Major et al. 2002) fits well with the initiation of the Marmara Sea sapropel at 10.6 ky BP (Çağatay et al. 2000). The second argument is the presence of a subaqueous delta in the Marmara Sea south of the Bosporus Strait, which was presumably constructed with sediments delivered from the Bosporus valley during persistent Black Sea outflow (Aksu et al. 2002a, Hiscott et al. 2002). This delta complex is not directly dated by samples within it, but its age is extrapolated from a core that stopped its penetration and recovery in a fining-upward sequence of sand. This sand is dated at 10.2 ky BP. Given that this core did not penetrate through the whole sand layer, concluding that the delta deposit was made by Black Sea outflow after

10 ky BP (Hiscott et al. 2002) seems premature. Until the age of the base of the delta complex is directly calibrated by sampling within the complex and through its base, all one can deduce from the available data is that the delta complex was still building at 10.2 ky BP. Thus, the outflow through Bosporus responsible for the delta could have occurred at the time of the Black Sea's Younger Dryas–age outflow. The third argument states, "We infer, based on extrapolated core dates, that lowstand shelf-edge deltas in the Black Sea were inundated by ca. 12-11 ka" (Aksu et al. 2002a). The age extrapolation starts at 6.6 ky BP in the marine mud cover and crosses erosional unconformities (Aksu et al. 2002a, Hiscott et al. 2002). Such extrapolation, based entirely on sedimentation rates in the marine cover, is speculative. This review has presented abundant evidence of a Black Sea shoreline well below a shallow Bosporus sill depth and developed between 10 and 8.5 ky BP during the time that there should have been persistent outflow. If the lake lay below its outlet, outflow is not possible. Persistent Holocene outflow would only have been possible with a deep Bosporus sill. However, a deep sill would not have made possible the Younger Dryas transgression across the Black Sea shelf to the −30-m isobath. Futhermore, a deep sill should have left a trace of earlier salization than the one recorded by the strontium isotopes.

CONCLUSIONS

There is a compelling, but not irrefutable, possibility that the Black Sea experienced a catastrophic saltwater flood at 8.4 ky BP. To build a tighter case, additional material is needed for dating from within upper shoreline coastal bedforms and from just below their base. Considering the dry and compact nature of these materials, this task may require either rotary drilling or piston coring with a large-diameter barrel and several tons of weight. Ten meters of penetration is adequate to reach the required targets. The facts that must be established are: (*a*) that the upper unconformity (1a) is a subaerial surface and (*b*) that the inferred dunes and beach deposits reveal ages that place them below the level of the global ocean at the time of their formation. Although there are existing dates from the dunes, from the materials below them, and from the materials above them to propose a post-Younger Dryas regression, these materials come from different sites on the shelf and were not recovered in a single core or borehole through the dunes and through the beach deposit.

The Black Sea regressions and transgressions appear to be modulated by climate. When not connected to the Mediterranean, the postglacial Black Sea has reacted akin to the Caspian Sea (Kvasov 1975, Svitoch 1999) by reaching highstand and outflow in cold periods and lowstand through evaporation in warm periods. The unconformities that extend well beyond the shelf break and the deep excavation of shelf valleys suggest that some Black Seas regressions in the earlier Quaternary were of substantially greater amplitude than those of the postglacial period.

Although the Black Sea witnessed at least eight marine flooding events in the past three million years, it is not possible from available data to argue that these were catastrophic floods analogous the Holocene event. However, in outcrops and shallow boreholes in the Kerch-Taman region, the marine deposits directly cover terrestrial soils (Zubakov 1988) not washed away by wave-action on a surface of the type that accompanies a typical marine transgression (Trincardi & Correggiari 2000).

Severe evaporation-driven drawdown and catastrophic marine flooding are real phenomena. The desiccation of the Mediterranean and the subsequent Pliocene flooding through the Gibraltar Strait are examples (Hsü et al. 1973, Iaccarino et al. 1999). When the Mediterranean penetrated through the Dardanelles Strait ~12 ky BP, Marmara was caught in a state below its outlet (Aksu et al. 2002a, Aksu et al. 1999). If today's global sea level were to rise another 25 m, there would be a catastrophic marine flood through the Manych Strait into the Caspian Sea (Lyell 1842). Thus, if rapid flooding did occur downstream of the Black Sea, is it unreasonable that it took place within the Black Sea?

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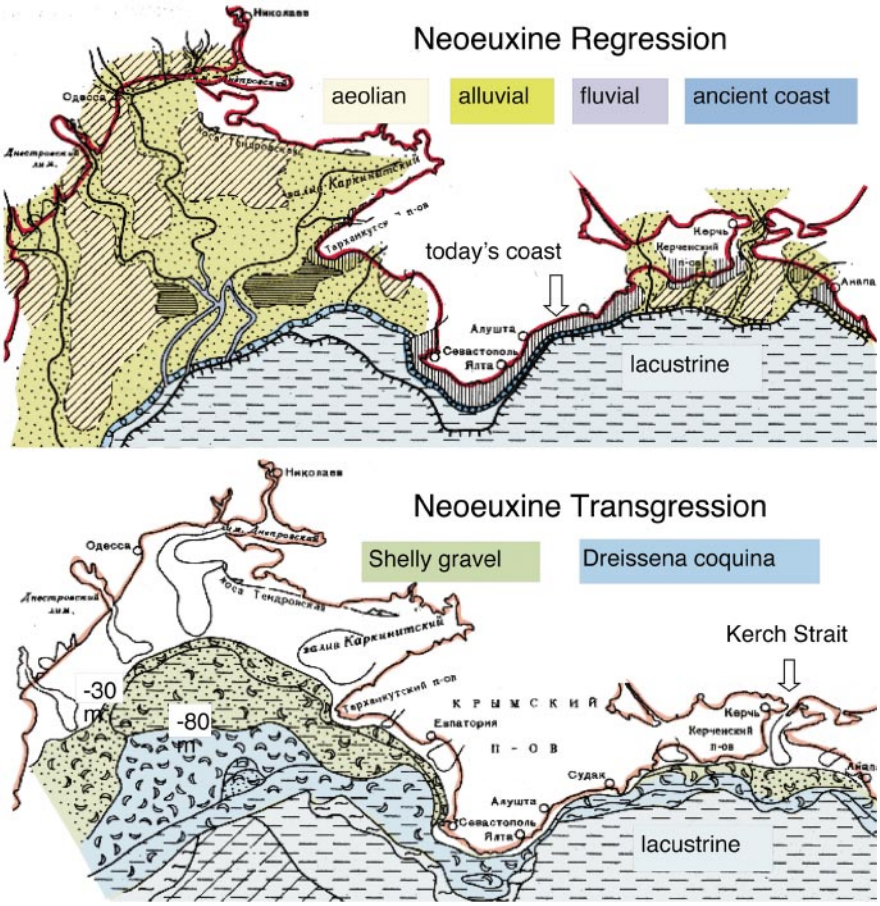

Figure 6 (*top*) The aeolian, fluvial and alluvial landscape of the Neoeuxine Black Sea shelf (Shcherbakov et al. 1978). The ancient shoreline, composed of shelly littoral deposits lay close to the present −100 m isobath. The horizontal and vertical hachure patterns depict Pliocene clays and older bedrock, respectively, exposed by erosion. (*bottom*) A subsequent transgression carried the shoreline to the vicinity of the present −30 m isobath.

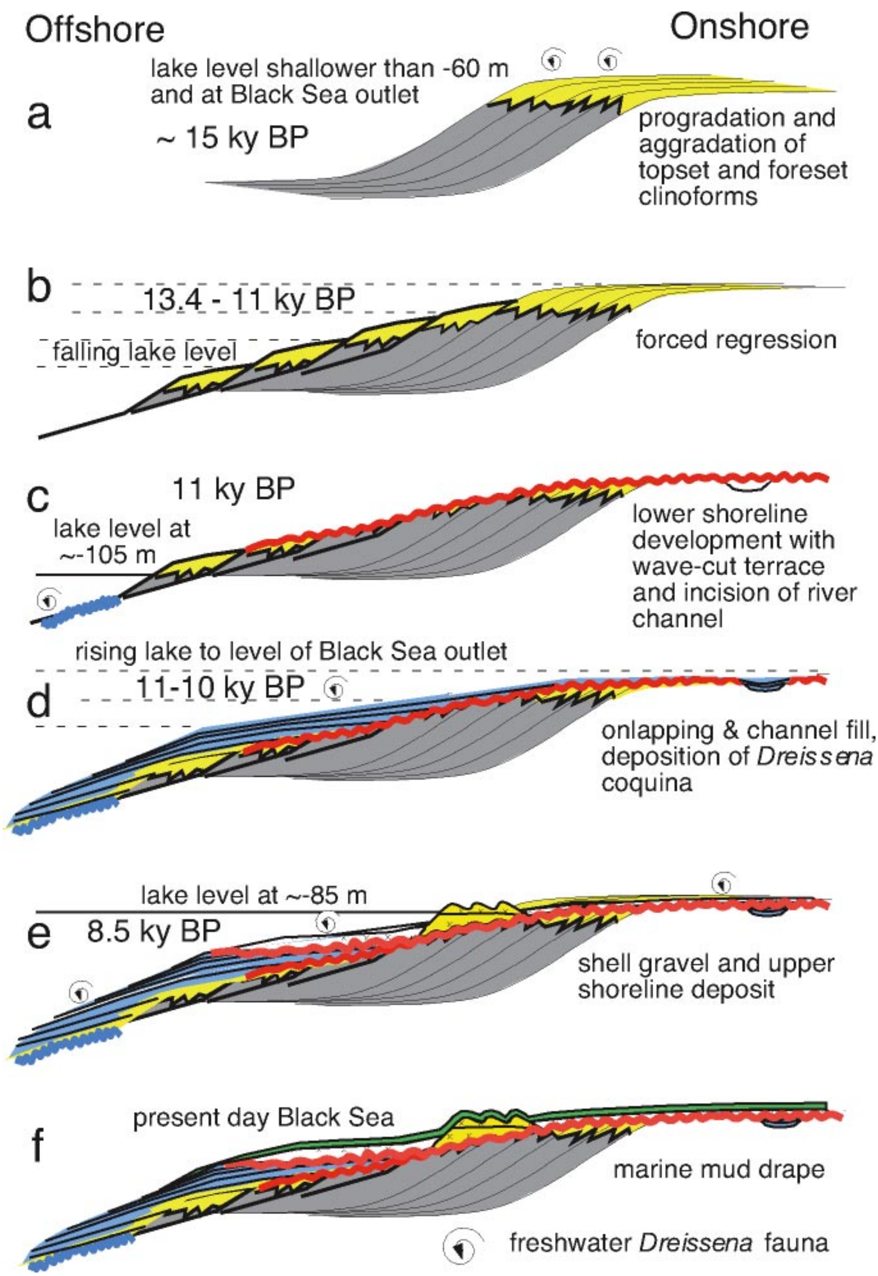

Figure 19 Six snapshots of the post-glacial Black Sea evolution on the outer Ukraine shelf from interpretations of reflection profiles calibrated by cores (Major 2002).

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ERRATA

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