The Black Sea Flood Question:
Changes in Coastline, Climate, and Human Settlement
The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement

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A lengthy book does not need a lengthy preface, so these opening words will convey only some essential matters, including the circumstances that led to the present publication, some of the background to the research it contains, and thanks to those who helped in the effort.

The Black Sea is one of the largest marginal seas: as deep as 2250 m and over 420,000 km² in area. Its coastline visits seven nations and links Europe with Southwestern Asia, while its water is the product of Eurasian rivers and rainfall mixing with immigrant Mediterranean saline flowing in through the Bosphorus. Due to its semi-isolation from the world ocean, the Black Sea tends to amplify environmental changes, and thus its detailed and sensitive paleoclimatic record has become a focus of oceanographic research. It is also the world’s largest anoxic basin, enabling sophisticated studies of marine oxygen depletion and the exploration of ancient shipwrecks preserved in near pristine condition.

The earliest marine explorations in the Black Sea, dating to 1890–1891, were undertaken by the Black Sea Fleet’s R/V Chernomorets to study the basin’s hydrology and bottom sediments at water depths from 150 to 730 m (Andrusov 1890; Murray 1900). It quickly became clear that the bottom of the Black Sea is lifeless below the 150-m isobath, and that the sediments often contain shells of Monodacna and Dreissena, molluscan genera that no longer live in the Black Sea but are widely distributed in the slightly brackish limans, the local term for estuaries or submerged lower parts of river valleys.

Marine explorations continued under J.M. Shokalsky (hydrology) and A.D. Arkhangel’sky (sedimentology) on the Black Sea Fleet’s R/V “Pervoe Maya” between 1925 and 1927. Using a one-meter corer, Arkhangel’sky discovered that the character of the bottom sediments had completely changed during the most recent millennia (Arkhangel’sky 1927). This transformation was explored in detail over the course of the next marine campaign, undertaken on R/V “Pervoe Maya” and R/V “Hydrograph” between 1928 and 1933. A new, improved corer of 6 m length was introduced, and based on the results of numerous expeditions, the geological structure and history of the Black Sea was described, and the first stratigraphic scheme for the Quaternary was developed (Arkhangel’sky and Strakhov 1938).

Previously designated Euxinian sediments (Andrusov 1918) bearing brackish, Caspian-type fauna were divided by Arkhangel’sky and Strakhov (1938) into Neoeuxinian (Novoevksinskie) and Old Euxinian (Drevneevksinskie) beds, the former distributed below sea level and containing the molluscs Dreissena and Monodacna and the latter presently lying above sea level on tectonically elevated terraces and containing Didacna pontocaspia. In today’s terminology, Neoeuxinian deposits were laid down during the Middle to Upper
Würm, from Oxygen Isotopic Stage 2 to the beginning of Stage 1 (ca. 23 to 9.1 ky BP). The Old Euxinian is much older, Mindel and Mindel-Riss in date, ca. 400–260 ky BP (Yanko 1990). This initial stratigraphic framework was later improved by Nevesskaya (1965) based on molluscs and by Yanko (1990) based on foraminifera.

In 1970, a large-scale, systematic investigation of the floor of the Black Sea and Sea of Azov began under the authority of the USSR government to intensify the search for mineral, petroleum, and gas resources. Participating in the exploration were the USSR Academy of Sciences, the USSR Ministry of Education (Odessa and Moscow Universities), as well as various geological industries. At the about same time, western initiatives were undertaken, first in 1967 aboard the R/V Pillsbury of the Rosenstiel School of Marine and Atmospheric Science, Miami, and then in 1969 aboard the R/V Atlantis II of the Woods Hole Oceanographic Institution. The Atlantis II expedition was an extensive seven-week, two-leg cruise with international participation, results of which yielded additional information on the geological history of the basin that was widely distributed in the west (Degens and Ross 1974).

By 1997, a marine geological survey (1:500,000 to 1:10,000) of the Black Sea shelf had been largely completed by Eastern European scientists. Thousands of cores and tens of thousands of kilometers of high-resolution seismic profiles, taken across the shelf from the northern exit of the Bosphorus Strait in the west to the city of Batumi in the east, were studied as part of a multidisciplinary effort. A methodology for Black Sea shelf investigation was developed, and using it, the paleoclimatic, tectonic, and sedimentary history of the basin was investigated. A high-resolution Quaternary biostratigraphy was established based on molluscs and foraminifera, supported by hundreds of radiocarbon assays (Appendices 1 and 2, this volume), and sea-level dynamics were reconstructed (for the references, see Balabanov, this volume; and Yanko-Hombach, this volume).

In all this work, no evidence was observed for a rapid sea-level rise in the Black Sea during the Holocene. Thus, when marine geologists William Ryan and Walter Pitman of the Lamont-Doherty Earth Observatory, Columbia University, announced their discovery of an abrupt flooding of the Black Sea in the early post-glacial and linked it to the biblical legend about Noah’s Flood, the scientific community was surprised. It has now been a decade since they published their flood hypothesis. In it, they and their research collaborators proposed that, during the interval 14.7–10 ky BP (¹⁴C uncorrected), the Black Sea was a freshwater Neoeuxinian lake with a level about 140 m below that of today. A rapid rise of the lake during the early Holocene transgression, which they initially dated to around 7.15 ky BP, submerged more than 100,000 km² of exposed continental shelf, rapidly and permanently flooding human settlements along the coast. In their view, this catastrophe accelerated the dispersion of early Neolithic foragers and farmers into the interior of Europe and might have formed
the historical basis for the biblical story of Noah’s Flood (Ryan et al. 1997).

The “Noah’s Flood Hypothesis” triggered tremendous interest by the public, the scientific community, and the media. Major newspapers carried stories, based mostly on Ryan and Pitman’s popular book (1998) and conference presentations, and some religious people exulted in the prospect that scientific evidence for a major Biblical story had at last been found. Many archaeologists with knowledge of the Pontic region’s prehistory expressed skepticism that enough was known to link such a flood with the expansion of agriculture and Indo-European language spread, and many Near Eastern historians wondered how it could ever be proven that a Neolithic event taking place so far to the north was related to the growth of religious myth at the dawn of written history in Mesopotamia over 3000 years later. Many marine geologists were skeptical that such a flood had ever occurred, and a vigorous discussion over the matter ensued. The overall effect was salubrious to Black Sea studies in that the flood question very quickly aroused new interest in the region and encouraged fresh research ventures.

Unfortunately, the abundance of Black Sea data obtained by ex-USSR and former Eastern Bloc scientists was largely ignored in the global discussion. Neither the language barrier posed by the literature nor the general lack of west-east scientific dialogue could be overcome. Most of the information available in the west about the Black Sea came from western research initiatives. In addition, the flood problem was multi-disciplinary and needed a coordinated examination of both the geological and archaeological records by earth scientists and anthropologists. Such a strategy had not been implemented by the end of the 20th century, though some attempts had been made to do so on a small scale.

Ancient Mesopotamians would surely have agreed that astronomical alignments and favorable omens accounted for the coincidental planning of the conferences in the fall of 2003. V. Yanko-Hombach (with N. Panin) organized a meeting on late Pleistocene-Holocene climate and coastline migration of the Black Sea in Bucharest with NATO support in early October, and she assembled a topical session at the Geological Society of America’s Annual Meeting in Seattle in early November. A. Gilbert independently organized a conference for mid-October at Columbia University under the auspices of the University Seminars to examine the archaeological and geological implications of the flood. Only with the increasing overlap in participants as planning progressed did the parallel efforts become mutually apparent. The three meetings were eventually coordinated and, with the wide geographic spacing of venues, they accommodated researchers from Eastern Europe as well as other western scientists:

(1) the NATO Advanced Research Workshop “Climate Change and Coastline Migration” (October 1-5, 2003, Bucharest, Romania; http://www.avalon-institute.org/NATO_ARW.html);

(2) the International Conference “The Black Sea Flood: Archaeological and Geological Evidence” (Columbia University Seminar on the Ancient Near
East, October 18-20, 2003, New York, USA; http://www.columbia.edu/cu/seminars/special-event/black-sea-conference); and


Over 50 papers were presented; the original programs are provided in Appendix 3.

The present volume was initially contracted to cover only the Bucharest meeting with NATO subvention. The advantages of including the diverse papers from the other meetings convinced the backers and the publisher Springer to allow the book to accept wider participation. Though the intention was a speedy report of conference proceedings to be submitted in camera-ready form, the substantial issues at stake and the magnitude of the interpretive differences prompted participants to rewrite their papers, incorporating extensive data presentations and discussions. At the same time, other Eastern European scientists with significant research investment in Black Sea studies volunteered contributions though they had not been conferees at any of the meetings. Some of these papers had to be fully translated from the Russian. The inclusion of so much new information eventually outstripped the publication limits of the NATO Scientific Series, and so with NATO’s approval, a new contract was signed with Springer’s Geosciences division leading to the present expanded volume. In the end, the book was transformed into a much more extensive review of the problems, and it contained a long overdue introduction into the western literature of a substantial amount of data previously locked away behind the Cyrillic in which it had originally been published. The goal of bringing east and west together to share perspectives as well as findings succeeded beyond expectation.

This collaboration will continue to grow in the research programs of the individual scientists, but also in a new five-year IGCP Project 521 entitled “Black Sea-Mediterranean Corridor during the last 30 ky: Sea-level Change and Human Adaptation” (www.avalon-institute.org/IGCP), which will be funded by UNESCO and IUGS. Further testing of the catastrophic flood hypothesis is among the main tasks of the project, but it will be more far-reaching in examining issues of regional climate, dynamics of human settlement, economic resources, and future environmental stability.

This book brings together 35 papers on geological, hydrological, climatological, archaeological, and linguistic aspects of the Black Sea flood hypotheses. Data and discussions reflect efforts at discerning and understanding paleoenvironment, climate dynamics, sea-level changes and coastline migration, regional hydrological variations, active tectonics, and geomorphology as parameters influencing human adaptation to the Circum-Pontic Region since the Last Glacial Maximum. Only empirical evidence recovered through accepted scientific methods was considered, and speculative implications linking Black
Sea events to biblical narrative, as has increasingly happened in popular books and media reports, was avoided.

No final answer to the Black Sea flood question appears here. Each paper in this book marshals its own evidence and offers its own interpretations, and there is no summary at the end with an overall resolution. The goal has been to provide access to information on a broad scale that crosses previously impenetrable language barriers, so that new work in the region can proceed with the benefit of greater perspective. The three fundamental scenarios for late glacial to Holocene rise in the level of the Black Sea—catastrophic (Ryan), gradual (Hiscott et al.), and oscillating (Chepalyga and Yanko-Hombach)—are presented early in the book, with the succeeding papers organized by geographic sector: northern (Ukraine), western (Moldova, Romania, and Bulgaria), southern (Turkey), and eastern (Georgia and Russia), as well as three papers on the Mediterranean. We hope that the contributions of this volume will serve as a foundation for designing more inclusive collaborative investigations and building greater consensus about what the past century’s discoveries in the Circum-Pontic Region mean.

Each paper in the book underwent a lengthy review process (three reviewers as a rule per paper) and both language and graphics editing. Only one paper (W. Ryan) did not go through the reviews because it was submitted late. The complex editorial work (done mostly by Gilbert) took longer than expected, which accounts for why the publication was delayed over two years.

Acknowledgment must first be given for the financial assistance that made the conferences and book possible. First, the Avalon Institute for Applied Science provided much encouragement as well as release time to V. Yanko-Hombach for her conference organization and book editing. We thank NATO for supporting the Advanced Research Workshop in Bucharest and for kindly permitting recontracting of the present volume with Springer Publishers. Much of the cost of the Columbia University conference and many of the editorial expenses for graphics and translation were generously underwritten by the Office of University Seminars with the enthusiastic encouragement of its director, Prof. Robert Belknap, and the invaluable administrative help of Amanda Roberts, Alison Garforth, and Meredith Davis. Additional funding needed to cover travel and logistical costs incurred by the New York participants was provided by The Institute for Aegean Prehistory, The Trust for Mutual Understanding, The Joukowsky Family Foundation, Turkish Airlines, and one anonymous donor. The Geological Society of America also provided grant sponsorship to support several foreign presenters at the Seattle meeting. For all this financial backing, we express our sincere appreciation.

At various stages in the book preparation, we called upon the help of others. Russian translations were provided by Marianna Taymanova, Valentina Yanko-Hombach, Irena Motnenko, and Pavel Dolukhanov. All transliterations of cited sources in Cyrillic followed Library of Congress style for both
consistency and compatibility with the Online Computer Library Center’s World Catalogue, to maximize ease of location for the references in question. Most of this standardization was done by Kira Haimovsky of Walsh Library, Fordham University. The only exception has been with proper names, of people and some geographic places, where ‘y’ has been used instead of ‘ii’ or ‘i’ according to preference or a pre-existing Romanization in common use. Citations of already published sources containing a transliterated Russian name retain that transcription style, whether or not it follows the conventions of this book. All article and book titles cited in eastern languages have been provided with English translations for the reader’s convenience. The reader will also find among the papers two spellings of the Istanbul strait (Bosphorus and Bosporus), used according to author preferences. Radiocarbon dates appear often as ky BP, or thousand years before present, and are to be understood in this form as uncalibrated. When calibrated, they are rendered as ky calBP or ky calBC.

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REFERENCES

Andrusov, N.I.


Arkhangelsky, A.D.
1927 Ob osadakh Chernogo moria i ikh znachenii v poznanii osadochnikh goornikh porod [About the Black Sea sediments and their role in the investigation of sedimentary rocks]. *Biulleten Moskovskogo obschestva ispitateley prirodi*. Otdel geologicheskii 5(3-4). (In Russian)

Arkhangelsky, A.D., and N.M. Strakhov

Degens, E.T., and D.A. Ross, eds

Murray, J.

Nevesskaya, L.A.

Ryan, W.B.F., and W.C. Pitman III


Yanko, V.
INTRODUCTION

The Earth sciences and catastrophic flooding have been linked for a very long time. The *Oxford English Dictionary* reports the etymology of the word ‘geology’ as it serves to label a branch of science. The first use of the word was in the title of the 1690 book *Geologia: or, a Discourse Concerning the Earth Before the Deluge*, written by Erasmus Warren. Warren’s Geologia concerned the literal truth of the Book of Genesis. However, like biblical literalists before and since, Warren had to resolve a paradox: the mixing in Genesis of two very different accounts of the Noachian Debacle. In one account, The Flood derives from “foundations of the great deep” (Genesis 7:11). In the other, The Flood derives from “the windows of heaven,” such that it rained continuously for 40 days and 40 nights (Genesis 7:12). Warren privileged the first account, postulating that water burst from great caverns. It is interesting that modern biblical scholars (Cohn 1996) hold that the phrase “fountains of the great deep” can refer to underground waters, but so can refer to water from the world ocean. The latter source would be relevant to the controversy that is the subject of the present book.

Although the first geology was arguably “flood geology,” it soon became apparent that geologists would not be worthy of the appellation “scientists” (coined in 1840 by the Cambridge mineralogist, William Whewell) if their activity were to consist solely of bearing witness to authoritative pronouncements, including those presumed to come from a deity. It is unfortunate that today “flood geology” commonly refers to a branch of “creation science,” sharing with that enterprise an erroneous use of the word “science.” Science is no more and no less than an unrestricted inquiry into nature. To have its answers ordained in advance is a restriction on free inquiry, and the result is sham reasoning (Haack 1996), not science.

By the early nineteenth century, geology had evolved to a science concerned with observations of nature on a path to whatever could be discovered about causal patterns in regard to those observations. The inquiries of geologists had to be free to lead anywhere the observations and their implications required, unconstrained by prior notions of what was true, or even of what might be proper in the pursuit of that truth. Unfortunately, there also emerged confusion over the last point, and vestiges of that confusion linger even to the present day. This confusion involves the notion of “uniformitarianism” (another word coined by the famous polymath and logician, William Whewell). As a prohibition against the valid inference of cataclysmic processes, uniformitarianism is invalid as a concept in science, i.e., it blocks the path of inquiry (Baker 1998). Indeed, there is nothing wrong, scientifically speaking, with invoking cataclysmic flooding as a natural explanation, if the facts, rather than some preconceived belief, lead the
inquiry in that direction.

This volume was stimulated by just such a series of facts and the inquiry that followed. The fascinating thing, however, was that the inquiry led back to a geological conclusion, with similarities to the one that had been argued erroneously 300 years earlier. Based on remarkable marine science data from the Black Sea, W.B.F. Ryan and colleagues (Ryan et al. 1997) proposed that the Black Sea basin had been catastrophically flooded during the early Holocene, now thought to have been about 8400 years ago (Ryan, this volume). Ryan and Pitman (1998) subsequently elaborated that, prior to this flood, the Black Sea basin held an isolated freshwater lake, which was separated from the world ocean (then at a much reduced sea level) by the mountains of Turkey. Moreover, a large population of people inhabited the shores of this lake.

Rising world sea level eventually resulted in the breaching of the mountain divides that separated the freshwater lake of the Black Sea from the world ocean. As the water burst through the modern Bosporus Strait, the water rose 15 cm per day in the Black Sea, filling its basin in about 2 years. The human population that experienced this cataclysm was forced to disperse, carrying with it a memory of the great flooding, and conveying that story to the many other cultures that were encountered. Given that one of those cultures provided the Mesopotamian influence on the author(s) of Genesis, it was appropriate to label the model for this event, the “Noah’s Flood Hypothesis.”

The papers in this volume are all concerned, at least peripherally, with the “Noah’s Flood Hypothesis” of W.B.F. Ryan and colleagues. The current status of this hypothesis, modified from the original by Ryan et al. (2003), is defended by Ryan (this volume), who outlines seven observations that are key to his model of abrupt early Holocene saltwater flooding of the late ice-age lake that occupied the Black Sea basin. Hiscott et al. (this volume) present an alternative model, the “Outflow Hypothesis,” involving a gradual transition in salinity of the late Quaternary Black Sea. These authors do not accept the early Holocene evaporative drawdown of the freshwater lake in the Black Sea basin that preceded the 8.4 ky BP cataclysmic saltwater inundation of the “Noah’s Flood Hypothesis.” However, they do accept one of the modifications made in the original Ryan et al. model, specifically that late-glacial, meltwater-induced inflow to the Black Sea basin induced it to spill freshwater through the Bosporus to the Sea of Marmara. This late Pleistocene freshwater flooding was on an immense scale, such that Chepalyga (this volume) claims that “The Flood” was not the 8.4 ky BP saltwater inundation of the Black Sea basin (derived from the world ocean via the Bosporus, Sea of Marmara, etc.). Instead, there was an earlier, much larger catastrophe in which a cascade of spillings occurred from the Aral to the Caspian basins, and ultimately to the Black Sea via the Manych Spillway. Additional water was supplied by “superfloods” in the river valleys of European Russia, the Don, Dnieper, and Volga.

In the 1970s Mikhail G. Grosswald recognized that the Late Quaternary
ice-sheet margins of northern Eurasia, like those of northern North America, held huge proglacial lakes. Great spillways developed for the diversion of drainage. In North America immense flows were successively diverted into the Mississippi, Mackenzie, and St. Lawrence Rivers (Teller et al. 2002). A final outburst of the megalake Agassiz-Ojibway released about 160,000 km$^3$ of freshwater into the Labrador Sea via the Hudson Strait about 8400 years ago (Clarke et al. 2003). Grosswald (1980) envisioned Eurasian meltwater diverted to the south-flowing Dnieper and Volga Rivers, leading to the Caspian and Black Sea basins. However, he more controversially hypothesized impoundment of the great north-flowing Siberian rivers, the Irtysh, Ob, and Yenisei, by ice sheets that covered the modern Barents and Kara Seas. More recent work confirms these impoundments and ice sheets, though there remains considerable controversy over their extent, timing, and genesis (Mangerud et al. 2004). These flows would have contributed to the system described by Chepalyga (this volume), but the discharges would have been much larger than he proposes. Indeed, many of the late-glacial catastrophic flood systems had flows immensely larger than those proposed by Ryan and Pitman in the “Noah’s Flood Hypothesis” (Baker 2002).

With much of North America and Eurasia experiencing huge diversions of drainage by glacial meltwater flooding during the period of major ice-sheet decay, it is not surprising that many human cultures developed narrative traditions involving “world-wide flooding.” Certainly, “the world” for a local human society of 12,000 years ago involved a much smaller geographical extent than that word would convey to the global human society of today. There is no mystery that the most impressive events in the lives of many late ice-age cultures would have been “world-wide flooding.”

Was the Black Sea inundation the source of a flood myth, specifically one that inspired western Asiatic peoples to the beliefs that inspired the account of Noah in Genesis? The anthropological implications of the “Noah’s Flood Hypothesis” were greeted with considerable skepticism by many archaeologists. If the papers in this volume can be considered a test of the model, their conclusions range from equivocal (Chabai, this volume; Filipova-Marinova, this volume) to negative (Dolukhanov and Shilik, this volume; Anthony, this volume; Dergachev and Dolukhanov, this volume; and Bailey, this volume). Moreover, evidence for human dispersion after “The Flood” cannot be gleaned from language patterns (Nichols, this volume).

The physical aspects of the Ryan et al. model of early Holocene saltwater flooding of the Black Sea basin receive some support from Coleman and Ballard (this volume), Algan et al. (this volume) and Lericolais et al. (this volume). These studies document spectacular evidence for submerged paleo-shorelines, including drowned beaches, sand dunes, and wave-cut terraces. Some radiocarbon dates (Ryan, this volume) support the proposed early Holocene age for these presumed shorelines of the freshwater lake that existed prior to the catastrophic inflow of marine water. Other studies find no evidence in preserved
fauna or sediments that there was a cataclysmic flood (Yanko-Hombach, this volume; Kuprin and Sorokin, this volume; Shuisky, this volume; Shmuratko, this volume; Panin and Popescu, this volume; Balabanov, this volume; Glebov and Shel’ting, this volume).

Too much can be made in science of the current philosophical fad of testing (falsifying) hypotheses. As long recognized in geological investigations, hypotheses about past phenomena cannot function as propositions to be experimentally manipulated in a controlled laboratory setting. Because geologists study a past that is inaccessible to experimentation, they follow “working hypotheses,” testing for their consistency and coherence with the whole body of collected evidence. Applying methods described by T.C. Chamberlin, G.K. Gilbert, and W.M. Davis (see Baker 1996), geologists have long used their working hypotheses to advance a path of inquiry toward the truth of the past, while avoiding the blockage of that inquiry by privileging any particular take on that past. It is certainly within this tradition that the various studies in this volume have operated. For both its advocates and detractors, the “Noah’s Flood Hypothesis” of Ryan et al. has been a stimulus to further inquiry, made more productive by having a target to consider for the investigation. That the target involved considerable inspiration to the popular imagination just made the inquiry more intense and compelling. For what more could one ask in a scientific controversy?

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REFERENCES

Baker, V.R.

Clarke, G., D. Leverington, J. Teller, and A. Dyke

Cohn, N.

Grosswald, M.G.

Haack, S.


Ryan, W.B.F., and W.C. Pitman, III


Teller, J.T., D.W Leverington, and J.D. Mann

2002  Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in Climate change during the last glaciation. *Quaternary Science Reviews* 21:879–887.
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OXIC, SUBOXIC, AND ANOXIC CONDITIONS IN THE BLACK SEA

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Abstract: The Black Sea is the classic marine anoxic basin. It possesses an oxygenated surface layer that overlies a sulfide containing (anoxic) deep layer. This condition has evolved because the water column displays a strong density stratification arising because water with high salinity enters from the Bosporus Strait and mixes with water from an overlying cold intermediate layer (CIL). The CIL forms in the winter on the northwestern shelf and in the western gyre, and its rate of formation varies in response to changing climate. This mixture of Bosporus outflow and CIL produces the Bosporus Plume, which ventilates the deep layers of the Black Sea. New data about biogeochemical distributions of oxygen, sulfide, nitrate, and ammonium were obtained during R/V Knorr research cruises in 2001 and 2003. Oxygen is consumed by respiration of sinking organic matter, and sulfate reduction in the deep water results in the accumulation of hydrogen sulfide. Distributions in the upper layers reflect a classic example of the connection between climate forcing, physical regime, chemical fluxes, and biological response.

Keywords: suboxic zone, ventilation, temperature, salinity, oxygen, sulfide

1. INTRODUCTION

The Black Sea is located between latitudes 40° 55' and 46° 32' N and longitudes 27° 27' to 41° 42' E in the east-west oriented depression between two alpine fold belts, the Pontic Mountains to the south and the Caucasus Mountains to the northeast. The topography of the northwestern coast (except for Crimea) is relatively low. The Black Sea is the world’s largest semi-enclosed marginal sea, and its physical and chemical structure is determined by its hydrological balance (Neuman 1942; Caspers 1957; Sorokin 1983). Values for area, volume,
and depth are summarized in Table 1. The continental shelf is widest in the northwest, but the rest of the Black Sea is surprisingly deep for a marginal sea.

Table 1. Physical characteristics of the Black Sea.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Area</td>
<td>423,000 km²</td>
</tr>
<tr>
<td>Area of Northwestern Shelf</td>
<td>101,600 km²</td>
</tr>
<tr>
<td>Total Volume</td>
<td>534,000 km³</td>
</tr>
<tr>
<td>Deep Water Volume (&gt;50 m)</td>
<td>520,000 km³</td>
</tr>
<tr>
<td>Depth of Permanent Halocline</td>
<td>50 to 200 m</td>
</tr>
<tr>
<td>Maximum Depth</td>
<td>2243 m</td>
</tr>
</tbody>
</table>

The only pathway for water exchange between the Black Sea and the Mediterranean is the narrow (0.76–3.60 km) and shallow (<93 m) Bosporus Strait. The sill depths of the Bosporus are 32–34 m at the southern end and 60 m at the northern end (Gunnerson and Özturgut 1974; Latif et al. 1991). The seawater flowing northward out of the Bosporus Strait is the only source of salty water to the Pontic basin, and as a consequence, deep-water salinity increases to 22.33‰. Freshwater inflow from several European rivers (especially the Danube, Dniester, Dnieper, Don, and Kuban) keeps the salinity low in the surface layer (S = 18.0 to 18.5‰ in the central region), and for this reason, the water column is strongly stratified with respect to salinity, and thus density. The main water fluxes are summarized in Table 2. These values show that evaporation exceeds precipitation and that the surface outflow is about twice as large as the deep inflow through the Bosporus. The currents in both directions are very strong.

Table 2. Present-day water fluxes of the Black Sea.

<table>
<thead>
<tr>
<th>Flux Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>River Input</td>
<td>+350 km³ y⁻¹</td>
</tr>
<tr>
<td>Danube</td>
<td>250 km³ y⁻¹</td>
</tr>
<tr>
<td>Dniester</td>
<td>8</td>
</tr>
<tr>
<td>Dnieper</td>
<td>51</td>
</tr>
<tr>
<td>Don</td>
<td>28</td>
</tr>
<tr>
<td>Kuban</td>
<td>12</td>
</tr>
<tr>
<td>Precipitation</td>
<td>+300 km³ y⁻¹</td>
</tr>
<tr>
<td>Bosporus Inflow to Black Sea</td>
<td>+313 km³ y⁻¹</td>
</tr>
<tr>
<td>Average Salinity</td>
<td>34.9 ‰</td>
</tr>
<tr>
<td>Temperature</td>
<td>14.5°C–15.0°C in summer</td>
</tr>
<tr>
<td></td>
<td>12.5°C–13.5°C in winter</td>
</tr>
<tr>
<td>Evaporation</td>
<td>~353 km³ y⁻¹</td>
</tr>
<tr>
<td>Bosporus Outflow to Marmara Sea</td>
<td>~610 km³ y⁻¹</td>
</tr>
<tr>
<td>Slope of water surface</td>
<td>35 cm</td>
</tr>
<tr>
<td>along the Bosporus from north to south</td>
<td>~2 m s⁻¹ (surface)</td>
</tr>
<tr>
<td>Current</td>
<td>~0.5 m s⁻¹ (at depth, but reaching ~1.5 m s⁻¹ over the sills)</td>
</tr>
</tbody>
</table>
A consequence of the vertical stratification is that the surface layer (about 0 to 50m) is well oxygenated, while the deep layer (100m to 2000m) is anoxic and contains high sulfide concentrations. At the boundary between the oxic surface and anoxic deep layers, there is a suboxic zone (at approximately 50 to 100 m in depth), where the concentrations of both O₂ and H₂S are extremely low and do not exhibit any perceptible vertical or horizontal gradients (Murray et al. 1989; Codispoti et al. 1991; Jørgensen et al. 1991).

The suboxic zone in the Black Sea (Murray et al. 1989, 1995) is an important biogeochemical transition zone between the oxic surface layer and sulfidic deep waters. This layer, where O₂ and H₂S do not overlap, was first observed during the 1988 R/V Knorr Black Sea Expedition (Murray and Izdar 1989; Murray 1991). Its boundaries were chosen from the vertical distribution of oxygen and sulfide observed in the central gyre. After its discovery, these distributions were confirmed by others, and the processes controlling its origin and variability have been extensively discussed. When the suboxic zone was first observed, Murray et al. (1989) suggested that it might be a new feature resulting from reduced fresh water input from rivers. Subsequent research has shown that it is most likely a permanent feature of the Black Sea, at least since the early 1960s (Buesseler et al. 1994; Murray et al. 1995). The average thickness of this zone varies several-fold on a time scale of decades (Konovalov and Murray 2001), and this variability appears to be driven by variability in climate (Oguz and Dippner nd). The balance between oxygen injected due to ventilation of the thermocline with surface water and oxygen consumed by oxidation of organic matter governs the depth of the upper boundary of the suboxic zone (Konovalov and Murray 2001). The injection of oxygen into the upper part of the sulfide zone by water from the Bosporus is also an important control for the depth of the lower boundary, which marks the first appearance of sulfide (Konovalov and Murray 2001). Redox processes involving nitrate-manganese-sulfur are important for cycling of those elements in the lower part of the suboxic zone (Oguz et al. 2001).

The Black Sea is important to geochemists for several reasons.

(1) It is the classic anoxic marine ocean basin and is considered a prototype for the earth’s ancient ocean. The ocean was considered to be initially totally anoxic. As atmospheric oxygen increased, the ocean contained an oxic surface layer and anoxic deep water from about 2.5 to 0.7 bya (Holland 1984; Berner and Canfield 1989).

(2) It has a well developed suboxic zone at the interface between the oxic and sulfidic layers where many important redox reactions involving Fe, Mn, N, and other intermediate redox elements occur.

(3) Similar redox reactions take place in sediments throughout the world’s oceans, but they are easier to study in the Black Sea because they are spread out over a depth scale of 10s of meters (rather than cm or mm as in sediments). The various reactions have been shown to occur on similar density
(or depth) horizons from year to year, making them easy to study on repeated cruises.

(4) The Black Sea is an ideal site to study the effect of climate on ocean distributions. It is small enough in scale that variability in climate can vary physical forcing, and thus chemical fluxes and biological processes.

2. NEW DATA SETS FOR THE BLACK SEA

New hydrographic (T, S, and density) and oxygen/sulfide data were collected during two R/V Knorr research cruises to the Black Sea in 2001 and 2003. The cruises were divided into multiple legs, which allowed participation by 48 scientists from the US, Turkey, Ukraine, Russia, and Romania. One goal of these cruises was to analyze spatial and temporal variability in the suboxic zone in the southwestern part of the Black Sea in order to determine the effect on biogeochemical properties of the Black Sea caused by the intrusion of high salinity waters from the Bosporus (Konovalov et al. 2003). At the same time, new data were also collected at the northeastern coast of the Black Sea, near Gelendzhik, Russia, by researchers from the Southern Branch of the P.P. Shirshov Institute of Oceanology (SBSIO) (Yakushev et al. nd). The station locations were well situated to study the continental margin areas in the southwestern, northwestern, and northeastern regions.

Hydrographic data were obtained by standard CTD (conductivity, temperature, depth) procedures using SeaBird sensors. Oxygen and sulfide were determined by both wet chemical (volumetric) and electrochemical (voltametric) techniques (Luther et al. 2002; Konovalov et al. 2003). Nutrients were analyzed using standard autoanalyzer techniques. The vertical distribution of properties was sampled with rosette-CTD and pump profiling techniques (Codispoti et al. 1991; Konovalov et al. 2003). Charts of station locations, tables of participants, the analyses, and all data are available on the Knorr2001 and Knorr2003 web sites.1

3. HOW DOES THE BLACK SEA WORK?

Like the open oceans, the Black Sea possesses wind driven circulation with gyres, eddies, deep water thermohaline circulation, and shallower ventilation into the thermocline. Neuman (1942) described the surface circulation of the Black Sea as consisting of two large cyclonic (counterclockwise) central gyres that define the eastern and western basins. These gyres are bounded by the wind-driven Rim Current (Oguz et al. 1998), which flows along the abruptly varying continental slope all the way around the basin. The Rim Current exhibits large
meanders and filaments that protrude into the regions of the central gyres. The geostrophically calculated currents typically have speeds of 25 cm s⁻¹ along the axis of the Rim Current. Inshore or coastal of the Rim Current, there are several anticyclonic (clockwise) eddies (Oguz 2002) (Figure 1). Some of these eddies are permanently controlled by topography (e.g., the Sakarya Eddy located over the Sakaraya submarine canyon), while others are more temporally and spatially variable (e.g., the Sevastopol Eddy).

![Figure 1](chart.png)

*Figure 1. Chart of the Black Sea showing the wind-driven counterclockwise (cyclonic) Rim Current and several of the main anticyclonic gyres. The northwestern shelf and Rim Current are indicated.*

The Bosporus Strait is the Black Sea’s only connection with the Marmara and Mediterranean Seas, making it the only source of salt water to the Pontic basin. This salty water is also relatively warm (~15°C). The rivers are the main source of fresh water (300 km³ y⁻¹) and mostly drain onto the northwestern shelf. The surface water can become relatively cold in winter, especially on this northwestern shelf. On average, the lower layer inflow from the Bosporus to the Black Sea is about 300 km³ y⁻¹ and the upper layer outflow is about 600 km³ y⁻¹, which yields 300 km³ y⁻¹ for the vertically integrated transport driven by the Bosporus inflow (Özsoy et al. 1998) (Table 2).

These inputs result in strong vertical stratification with a fresh, lower density layer at the surface and a salty, higher density layer in the deep water. The keys for understanding the distributions are to remember that the only source of salt (and warm) water is through the Bosporus, and the only source of cold (and fresh) water is from the surface.
The Black Sea has an estuarine-type circulation, which means the water flows in at depth and out at the surface. Full scale (0–2200 m) salinity, potential temperature, and density (sigma-theta) are shown in Figures 2A, B, and C. These CTD data were obtained during a research cruise on the \textit{R/V Knorr} in the center of the western gyre in May of 1988 (Murray \textit{et al.} 1991). Salinity increases continuously from low values of about $S = 18\%$ at the surface to deep water values of over $S = 22.33\%$. Density ($\sigma$) is controlled primarily by the salinity, and it increases similarly. Temperature is seasonally variable at the surface and decreases with depth to a feature called the cold intermediate layer (CIL) with a temperature minimum at about 50 m (Figure 2B). The water in this layer forms in the winter on the northwestern shelf and in the center of the eastern and western gyres. Its extent of replenishment varies from year to year depending on the intensity of the winter (Oguz and Dippner). Below the CIL, the temperature increases continuously all the way to the bottom. The properties of salinity, temperature, and density are extremely uniform in the deep water, from about 1700 m to the bottom, and form a homogeneous bottom boundary.