15. STRATIGRAPHY OF THE LACUSTRINE SEDIMENTATION IN THE BLACK SEA

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ABSTRACT

The history of Black Sea sedimentation recorded by DSDP cores includes: (1) black shale sedimentation during late Miocene (Tortonian); (2) periodic chemical sedimentation from late Miocene (Messinian) to early Quaternary; (3) terrigenous sedimentation since the middle Quaternary.

The black shale sequence, except for rare intercalations of dolomite, is practically free of carbonates. Its foraminifer faunas lived in the marine-brackish sea of the Paratethys. The palynological record indicates a warm climate,although a cooling trend had begun which,in turn began to kill off the *Engelhardia* flora in the regions around the Black Sea.

The interval of periodic chemical sedimentation started with a regression, when the Paratethys brackish waters flowed into the Messinian Mediterranean desert. Evaporative excess caused a drop of the Black Sea level, changing it into a saline lake, leading to the deposition of coarse clastics and supratidal dolomite at sites which now are situated on the edge of the abyssal plain.

The Black Sea was again flooded by marine brackish waters, probably at the start of the Pliocene, when aragonitic mud was precipitated. Increasing supply of fresh water accompanying a moderation in evaporation, led to a hydrological surplus and the desalinization of the Black Sea. While the marine-brackish organisms disappeared from the Black Sea, calcitic and sideritic sedimentation replaced the precipitation of aragonite and magnesian calcite. Terrigenous input was subordinate to chemical sedimentation, especially during warmer and drier periods. Lacustrine chalks (*seekreide*) were deposited when the aqueous climate of the Black Sea was comparable to that of Lake Zürich today. At still warmer epochs, sideritic sediments were formed, probably as a consequence of the relative abundance of iron in river waters draining deep-weathered lands of low relief.

A major influx of terrigenous clastics, perhaps related to the shift of the Danube to its present course some 1 million years ago, led to the deposition of the middle and late Quaternary detrital sediments. Climatic variations became shorter in periodicity but greater in amplitude. At glacial times, the Black Sea was a fresh-water lake. At interglacial times, its salinity tended to be brackish, either due to evaporative excesses, or due to the influx of marine waters, such as happened during the last (Eemian) Interglacial.

The climatic record of the regions around the Black Sea, as represented by pollen in the Black Sea sediments, shows that the continental glaciation started at or near the beginning of the Quaternary, some 1.5 to 2 million years ago. A long cold period (Alpha glaciation) lasted for more than one-half million years, to be followed by two interglacial (A, B), and two glacial (Beta, Gamma) stages. The pollen diagrams of the Black Sea cores can be correlated with the faunal indices (of climate) of the Equatorial Atlantic cores. However, it was difficult to correlate the Quaternary Black Sea events with those of northwestern Europe.

The rates for Black Sea sedimentation at Site 380 were 10 cm/thousand years or less during the preglacial epochs in which mainly chemical or black-shale sedimentation occurred. The average rate of terrigenous and chemical sedimentation during the Alpha glacial stage was about 30 cm/thousand years. The average rate doubled to about 60 cm/thousand years after the Danube took its present course. The rate during the Würm glacial was 90 cm/thousand years, and during the Holocene is 10 cm/thousand years, giving a glacial-plus-interglacial average of 50 cm/thousand years.

INTRODUCTION

The Black Sea today may be viewed as a super-sized lagoon of the Mediterranean. However, the drill cores obtained during the Leg 42B cruise left little doubt that the Black Sea was a lake during much of the Neogene. A lake is different from a lagoon in two major aspects:

1) The water level within a lake is not necessarily the same as the sea level.

2) The chemistry of lake water is an independent chemical system, little or not at all influenced by the sea water chemistry.

These differences render the lagoonal model of Black Sea, developed from studies of piston cores, not readily applicable, except perhaps for the topmost 100 meters. An understanding of the Black Sea history requires a model of lacustrine sedimentation.

The Black Sea sediments penetrated by Leg 42B holes are more than 1000 meters thick. Unfortunately, neither the studies of fossils nor of the sediments yielded any reliable absolute datum-planes. A stratigraphical interpretation of the sedimentation depends upon correlation with well-dated events outside of the Black Sea. Some correlations can be made on a sound basis and are not controversial; others are speculative, and may eventually have to be modified or even discarded after the paleomagnetic stratigraphy of the Black Sea cores is established. This paper is an attempt to provide a stratigraphical interpretation, and to stimulate further discussion and research.

SUMMARY OF HISTORY OF SEDIMENTATION

The late Tertiary-Quaternary history of Black Sea sedimentation can be subdivided into three stages:

1) Black shale sedimentation
2) Periodic chemical sedimentation
3) Terrigenous sedimentation

A graphical summary of the lithological successions at the three Black Sea DSDP sites is presented in Figure 1. The most complete section has been drilled at Site 380 (Figure 2). Unit V there consists of black shales. Units IV, III, and II were deposited at times of periodic chemical sedimentation, and Unit I includes mainly terrigenous sediments. Also shown in Figure 2 are fossil records at Site 380. Pollen are excellent indicators of past climate: the relative abundance of steppe pollen in an assemblage, expressed by steppe index, gives a measure of the extent of glaciation in regions around the Black Sea. Other fossils are salinity indicators. Nannofossils and foraminifers occurred at times when the Black Sea was brackish marine. Both marine-brackish and fresh-water species of diatoms and of dinoflagellates have been identified in the Black Sea cores, whereas the ostracodes and molluscs found are mainly fresh-water species.

Study of the stratigraphy and sedimentation revealed in the cores retrieved from the sea indicates that notable changes in environments and in the geographical framework of the Black Sea basin have taken place since the lat Miocene. An outlet to the Mediterranean may have been in existence during much of its past history. The outlet may have been either a stream draining a fresh-water lake, or a narrow strait opened to the influx of marine waters. There is, further, indication that the Black Sea may have been totally isolated at times when the large inland water-body was turned into a saline lake.

The ancient Black Sea was a deep-water body except for the time during an earlier phase of chemical sedimentation when supratidal dolomite was forming. The deep bottom was at times oxygenated, and populated by benthic organisms, or it was anaerobic or toxic as it is today. The Black Sea has been a fresh-water lake for much of the time during the last few millions years, but water salinities ranged up to brackish, to nearly marine, or even supersaline. Salinity increased because of evaporative excess or because of an influx of marine waters from the Mediterranean. The climate during this time also changed, first warmth, then a gradual cooling, eventually fluctuating between interglacial warmth and glacial frigidity. The interplay of all of these factors resulted in the accumulation of a complex body of sediments, divisible into five units and more than 15 subunits. The highlights of sedimentary history are summarized in the following sections.

Black Shale Sedimentation

The oldest sediments penetrated by drill, at Sites 380 and 381, are black shales. Thin layers of almost pure dolomite are intercalated; they constitute less than 1% of the bulk, but are abundant toward the top of the unit, in a transition to more frequent chemical sedimentation.

The shales contain brackish-marine benthic foraminifer fauna, with species which have been found in the upper Miocene formations of Paratethys basins on land. The climate was subtropical, but a cooling trend had set in, as witnessed by the extinction of the *Engelhardia* flora during this period.

The black shales are devoid of detrital carbonate, although the intercalated laminae of sandy silts contain some carbonate detritus (10% or less). Chemically precipitated carbonates are also rare; the Black Sea water was then undersaturated with carbonate, except at the time of dolomite formation which probably was precipitated during a more arid episode, when the Black Sea water momentarily reached supersaturation because of excessive evaporation. Chemical precipitation of dolomite took place in brackish lakes during the latest Messinian times in isolated Mediterranean basins (Hsü, Montadert, et al., 1977). Holocene dolomite precipitates are reported from lakes in arid (e.g., Deep-Spring Lake, Nevada) or warm and relatively dry regions (e.g., Lake Ballaton, Hungary) during an episode warmer than today.

Chemical Sedimentation

The times of chemical sedimentation at Site 380 can be subdivided into eight intervals, when different carbonate minerals were being formed:

- dolomite-aragonite-calcite (Unit IV_e)
- dolomite (Unit IV_d)
- aragonite + magnesian calcite (Unit IV_c)
- calcite (Unit IV_b)
- manganosiderite (Unit IV_a) with transition to alternative calcitic sedimentation near the top
- calcite (Unit III)
- siderite-calcite (Unit II, lower part)
- aragonite (Unit II, top)

Associated with some chemical sediments are biogenic diatomaceous ooze. Diatoms are particularly common in Units IV_b (calcite) IV_a (manganosiderite), and II (siderite-calcite), and are rare or absent in others.

The formation of chemical or biogenic sediments results either from an unusually high accumulation rate of such components, or from a scarcity of terrigenous influx, or from a combination of both. In the case of the Black Sea, such

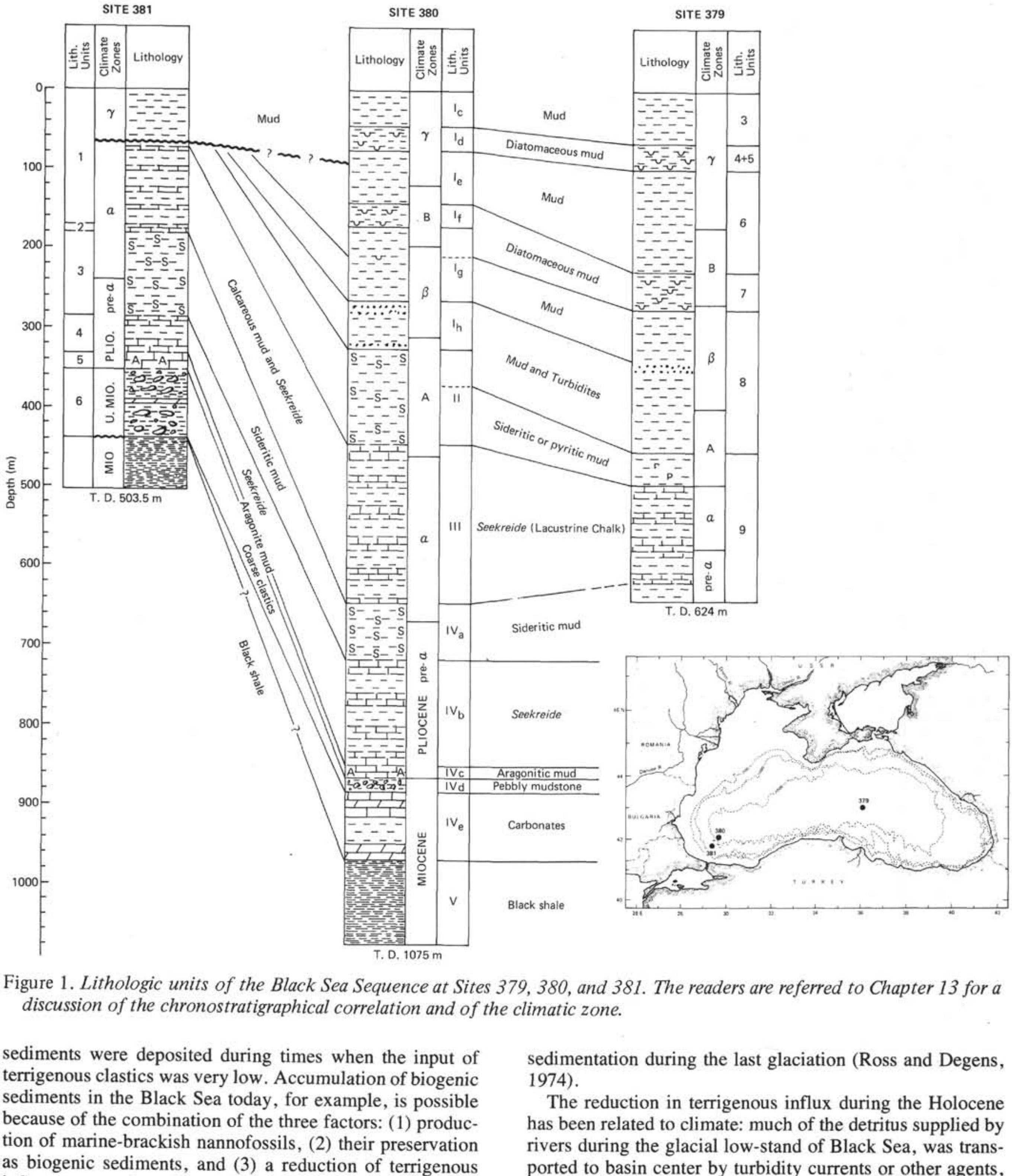

Figure 1. *Lithologic units of the Black Sea Sequence at Sites 379, 380, and 381. The readers are referred to Chapter 13 for a discussion of the chronostratigraphical correlation and of the climatic zone.*

sediments were deposited during times when the input of terrigenous clastics was very low. Accumulation of biogenic sediments in the Black Sea today, for example, is possible because of the combination of the three factors: (1) production of marine-brackish nannofossils, (2) their preservation as biogenic sediments, and (3) a reduction of terrigenous influx by an order of magnitude since the end of the last glaciation (Ross and Degens, 1974). Diatoms are also being produced in great quantity in the Black Sea today, but they are rarely preserved in the Holocene sediments (Maynard, 1974), having been eliminated by dissolution. Deprived of terrigenous influx, the Holocene nannofossil ooze has a very low sedimentation rate of 10 cm/thousand years, considerably less than the 90 cm/thousand years rate of terrigenous sedimentation during the last glaciation (Ross and Degens, 1974).

The reduction in terrigenous influx during the Holocene has been related to climate: much of the detritus supplied by rivers during the glacial low-stand of Black Sea, was transported to basin center by turbidity currents or other agents, but the detritus was retained more and more on the marginal shelf and in the estuaries as the sea level rose following the melting of glaciers (Ross and Degens, 1974). However, the climate could not have been the principal deciding factor during much of the Neogene, because the chemical sediments were deposited in both warm and in cold stages. There must have been another kind of sediment trap to reduce the terrigenous influx, and we believe that the change from the

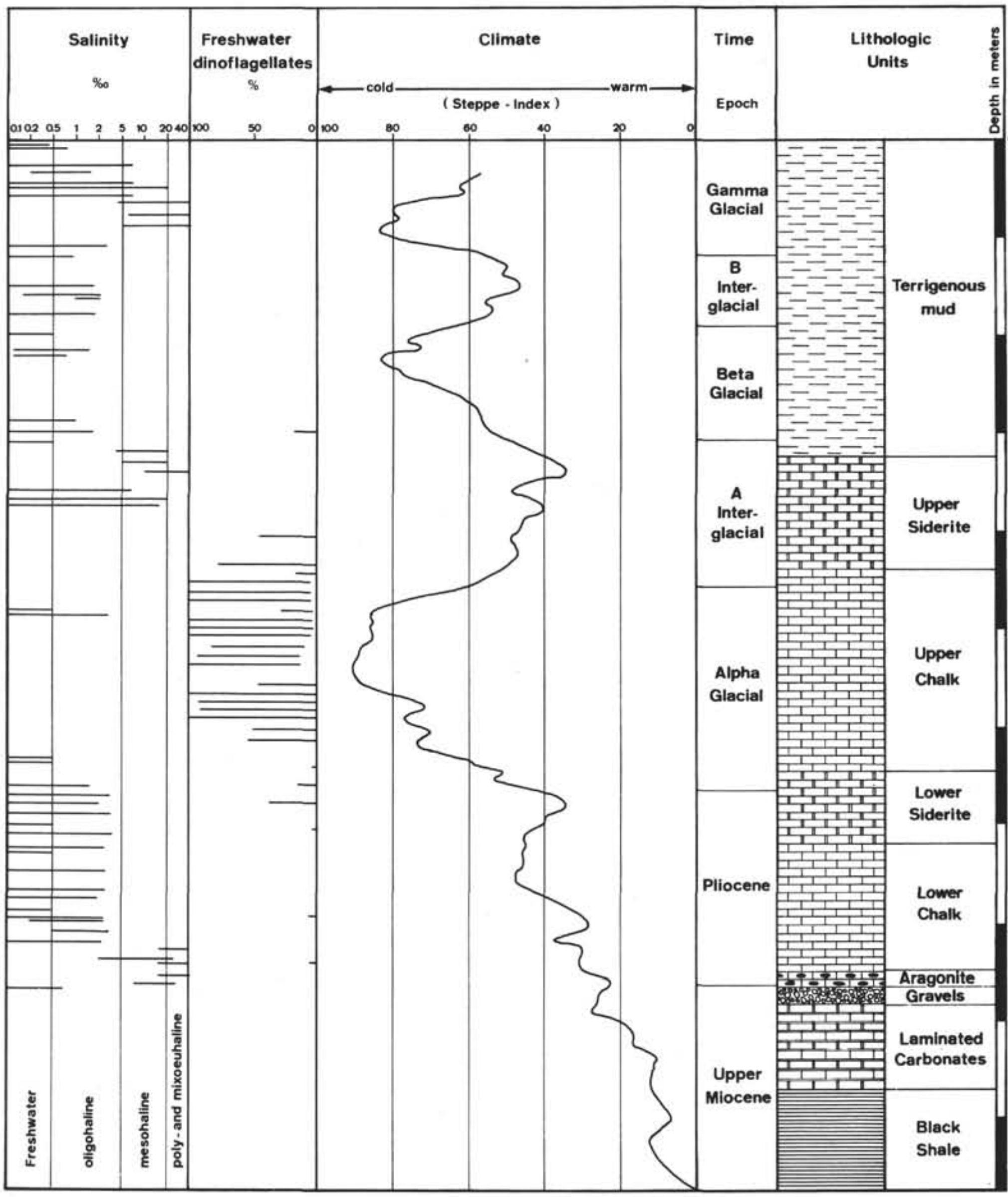

Figure 2. *Lithology. Climatic variation, and fossil record at Site 380. The sequence at Site 380 is divided into five units and 16 subunits (See Chapter 4, Site 380, lithology). The steppe index at the left of the column indicates climatic variation varying from 100 in coldest glacial to 0 in warmest preglacial times. The fossil occurrences of diatoms and dinoflagellates indicate changes in water-salinity.*

time of periodical chemical sedimentation to terrigenous sedimentation was caused by a significant reorganization of the river systems draining into the Black Sea.

Muds or clays are the dominant lithology in the sequence with intercalated chemical sediments. Carbonate-rich layers were precipitated, or formed by diagenesis, episodically or periodically. Varve-like carbonates, with individual laminae less than 1 mm thick, may represent annual precipitates. Carbonate-rich layers, varve-like or structureless, may occur in layers a few centimeters thick, alternating with muds several centimeters thick. The cause of such cyclical deposition is not known. Our studies of chemical sediments in modern Swiss lakes indicate that terrigenous influx has fluctuated in response to precipitation cycles: terrigenous sedimentation predominates during the wet years, whereas *seekreide* (lacustrine chalk) is laid down during the times of reduced rainfall (Kelts, in press). The carbonate cycles of the Black Sea may have a similar origin.

The precipitation of different carbonate minerals from the Black Sea must have been related to the chemistry of the lake waters. Unfortunately, ionic diffusion across concentration gradients has been altering the composition of interstitial waters, and we can only make some very general deductions on the chemical evolution of the Black Sea waters (Manheim, this volume). Modern lakes studies indicate that the precipitation of the different species of calcium carbonate is related mainly to the magnesium-to-calcium concentration ratio of the lake water: where the ratio is small, say less than 1, calcite is the precipitate. With increases of the ratio, magnesian calcite, and then aragonite would be precipitated (Berner, 1971). The precipitation of metastable $CaCO_3$ phases in magnesium-rich waters is commonly explained in terms of nucleation kinetics: the stable calcite phase is prevented from forming through the interference of magnesium ions.

River waters commonly have low magnesium-to-calcium ratios and fresh-water lakes, such as the peri-alpine lakes of Switzerland, are sites of calcite precipitation. The magnesium concentration of Black Sea waters may have increased because of evaporation and preferential precipitation of calcium carbonate, or surplus magnesian ions may have been brought in by seawater influx. The latter explanation is more probable because aragonite and Mg-calcite are common in sediments containing abundant marine brackish organisms.

The origin of dolomite is a problem of considerable uncertainty. We have mentioned that the dolomite intercalated in the black-shale unit may have been a chemical precipitate. The dolomite of Unit IV_e (Site 380), is present as thin intercalations in a sequence containing aragonite and calcite, may have a similar origin. On the other hand, the sedimentary structure and texture of the stromatolitic dolomite of Unit IV_d indicate a replacement origin, similar to those formed in supratidal environment today.

The origin of siderite is even more a mystery. Commonly, iron in reducing environments is combined with sulfide to form pyrite, and carbonate is combined with calcium to form a calcium carbonate. The formation of siderite takes place where the Fe/Ca ratio is 0.05 or higher (Berner, 1971), while at the same time the concentration of sulfide ions must be sufficiently reduced to prevent pyrite precipitation. Siderite is present in the Quaternary sediments of Lake Kivu (Stoffers, 1975) and also is found, as a diagenetic mineral in small quantity, in the sediments of Chesapeake Bay near river mouths (Bricker and Troup, 1975). The Black Sea siderite, forming nearly pure layers, seems to be genetically similar to the Lake Kivu deposit. The siderite layers are found in a unit which includes sediments yielding brackish diatoms, in contrast to the occurrence of the *seekreide* as freshwater lake deposits. Perhaps the increase in salinity leading to change from calcite to siderite deposition was related to evaporative excesses, and not caused by a marine influx which would have supplied considerable sulfate ions to the Black Sea. Also, rivers from the Balkan emptying into the Black Sea may have been particularly rich in iron then because of the prevailing weathering process under a warm and humid climate.

The history of periodic chemical sedimentation in a Black Sea lake seems to have spanned a considerable interval of the late Neogene. Carbonate-sedimentation (dolomite) began when the climate was still warm and nearly subtropical (Unit V). When the first *seekreide* (Unit IV_c) was precipitated, steppe pollen began to make up substantial proprotion of some assemblages. When the second *seekreide* (Unit IV_b) was precipitated, the cooling had progressed appreciably, as the steppe pollen for the first time constituted more than 50% of the total assemblage. At the time the principal *seekreide* (Unit III) was forming, the climate had reached a glacial stage; steppe pollen constituted more than 90% of many assemblages. The deposition of lacustrine chalks in the Black Sea during the cold periods and at times of maximum continental glaciation (Alpha Glacial Stage) seems to contradict our knowledge on the basis of studying the Holocene sediments of Swiss lakes: Lake Zürich *seekreide* is forming today, and it was precipitated during a warm and dry period shortly after the last glaciation during the Alleröd and Preboreal times (Kelts, in press). It is possible, however, that the depositional environment of the Black Sea during a glacial stage may have been similar to that of the Lake Zürich during an interglacial. The climate in the immediate vicinity of the Black Sea should have been mild since the cold steppes which supplied the abundant steppe-pollen to the Black Sea sediments were some distance away. Lacustrine chalk was probably precipitated under ranges of temperature and temperature-variations similar to those of Zürich today. At warmer times, when glaciers were as yet to form on, or disappeared from, the continent, the Black Sea was an environment favorable for siderite deposition; sideritic sediments are present below and above the main *seekreide* (Unit III), as preglacial or interglacial deposits.

The chemistry of the water in the basin underwent many changes. From an initial brackish-marine Black Sea, the water body may have evolved into a saline lake when magnesian calcite and aragonite (Unit IV_e) precipitated. The water depth of the lake also changed drastically. When stromatolitic dolomite (Unit IV_d) was being formed, Sites 380 and 381 were situated on the edge of a shallow lake in the bottom of the basin. As a consequence of the exposure of the steep banks of the basin, coarse clastics (Unit IV_d) were laid down at those sites near the foot of the western slope. The partial desiccation stage was followed by an influx of marine water; a *Braarudosphaera* flora was brought in and aragonite again precipitated (Unit IV_c). However, the connection with the open ocean was soon severed. With an excess of fresh-water influx from the rivers, the lake became less saline, with alternating conditions for *seekreide* and for siderite formation (Unit IV_b). The Black Sea basin hosted a deep freshwater lake at the time of the principal *seekreide* deposition (Unit III). There must have been considerable bottom circulation because benthic faunas, including burrowing organisms were present; most likely the lake had an outlet during this time when the lake water was being freshened. With the coming of the Interglacial Stage A, evaporation must have again exceeded influx; the lake level may have sunk below the outlet, leading to a gradual salinization of the lake water. Conditions were again ripe for siderite formation in a brackish environment. The time of periodic chemical sedimentation ended shortly after a brief episode of aragonite deposition, perhaps in connection with an influx of marine water with its *Braarudosphaera* flora (top of Unit II). It was followed by the predominately terrigenous sedimentation (Unit I) which continued until the Holocene.

Terrigenous Sedimentation

The onset of terrigenous sedimentation coincides more or less with the onset of the Glacial Stage Beta. However, the deterioration of the climate alone could not have been responsible for the change because the overall trend of periodical chemical sedimentation had not been interrupted during the preceding glacial stage. More likely the change was brought about in consequence of a drainage reorganization of the Danube (see next section).

Lenticulina sp., *Gyroidinoides octocametratus* (Cushman and Hanna), *Anomalina affinis* (Hantken), *A. granosa* (Hantken), *A. acuta* (Plumm.), *Globigerina eocaena* (Gumbel), *Globorotalia velascoensis* (Cushman), *Acarinina pentacamerata* (Subb.), *Nuttalides trumpyi* (Nutt.), *Acarinina crassaformis* (Gall and Wiss.), and *A. rotundinmarginata* (Subb.). These muds also contain, in addition to *Globorotalia inflata*, a considerable admixture of Eocene forms such as: *Globorotalia velascoensis* (Cushman), *Globigerina eocaena* (Gumbel), and *Acarinina rotundinmarginata* (Subb.), etc.

On the seismic profiles crossing the slope opposite to the Sinop, a lower non-laminated layer is overlain by an upper, evidently laminated unit (Ross et al., 1974, and Figure 3B).

Muds are the predominant lithology. Their detrital components are on the average coarser than those of the muds in underlying units. Also present are sandy and silty deposits, in laminae or thin layers up to a few centimeters thick. Some graded beds are apparently turbidites. Turbidite layers are thickest and most numerous near the base (Unit I_h) testifying to the youthful vigor of the newly integrated drainage.

Investigation of piston cores indicates rapid variations of sedimentation rate from 90 cm/thousand years during the last glacial stage to 10 cm/thousand years at the present (Ross and Degens, 1974). One might expect numerous occurrences of chemical or biogenic sediments for the interglacial or interstadial sequences when the rate of sedimentation should be as low as that of today. As a matter of fact, chemical sediments are very rare. Two *seekreide* laminae are found near the base of the terrigenous sequence (in Unit I_h); they were the last of relatively pure chemical sediments. Biogenic sediments are also uncommon. Laminae of chalk, consisting of *Braarudosphaera* pentaliths, are found in Unit I_d, deposited during a warm episode analogous to the present. However, similar biogenic sediments were not deposited during the many other interludes of warm climate.

A lagoonal model of Black Sea sedimentation, developed on the basis of studying piston cores, postulates that the Bosporus was a strait during the interglacial and that it was a spillway, or outlet, during the glacial time (Scholten, 1974; Ross and Degens, 1974). The model predicts that each interglacial or interstadial rise of sea should be represented by a marine or brackish marine deposit in the Black Sea sequence. This model may indeed be applicable to the uppermost 100 meters of Black Sea sediments (down to Unit I_d in Hole 380), but for older sediments there is no simple correlation of the indices of marine influence and of climate. The role played by the Bosporus was apparently far more sophisticated than was predicted by the model. During the glacial stages, the Black Sea level was probably higher than the sea level, when the lake could have been freshened (Figure 3[a]). The relationship during the interglacial may have been quite varied. The lake level could have been lowered below the Bosporus sill, with no communication to the open sea. Excessive evaporation of this inland lake could then have led to salinization. Alternatively, the Bosporus may have been open, with lake and sea levels about the same. Scholten (1974) has pointed out that whether or not the Mediterranean saltwater wedge could spill over the Bosporus sill into the Black Sea depends upon many factors, such as fresh-water influx, precipitation, evaporation, wind direction and strength, and finally sill-depth, which is related to the depth of erosion and to the stand

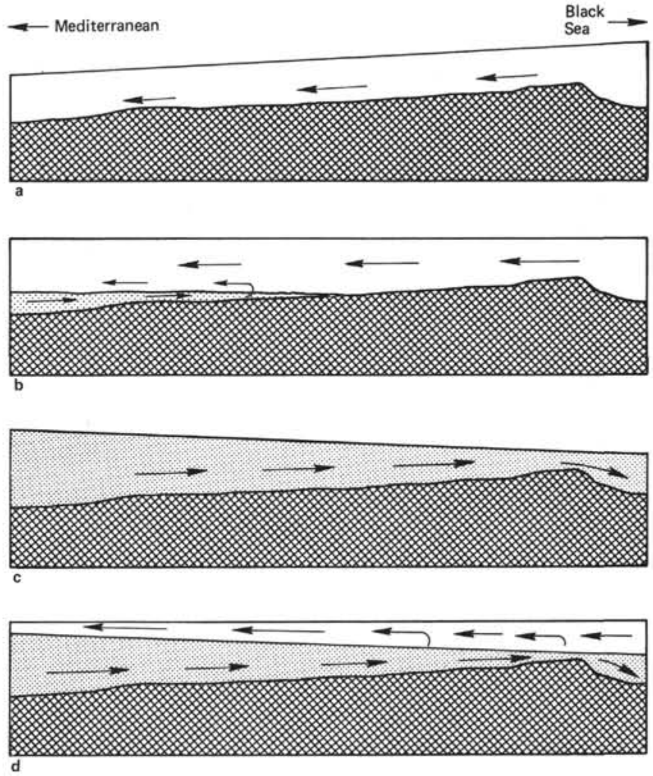

Figure 3. *Relation of the Black Sea to the Mediterranean. (a) At times when the Black Sea level was higher than the Mediterranean Sea level, the Black Sea fresh water flowed into the Mediterranean. (b) At times when the Black Sea and the Mediterranean Sea levels were about equally high, wind, current, and discharge may have been such that the fresh and salt water interface lay below the Bosporus sill. Fresh water flowed out of the Black Sea, and no marine influx was possible. (c) At times when the Mediterranean Sea level was higher than the Black Sea level, which had dropped below the Bosporus sill, marine water was spilled over into the Black Sea when sea-level began to rise above the sill. (d) At times, as it is now, the Black Sea and the Mediterranean Sea levels were about equally high, wind, current, and discharge may have been such that the fresh-saltwater interface lay above the Bosporus sill. Fresh water flowed out on top while marine water was spilled over at bottom.*

of sea level. A great surplus of fresh water and a shallow sill could prevent seawater invasion during some interglacial or interstadial stages (Figure 3[b]). We might conclude that a low lake level, consequent upon a long period of isolation and evaporative loss, combined with an unusually high sealevel stand during a very warm climate was the most favorable condition for the marine invasion of the Black Sea (Figure 3[c]). The periodic occurrences of *Braarudosphaera* floras, in the Black Sea sediments record three major marine invasions into the basin. The first two took place during the time of periodic chemical sedimentation, at the end of Unit IV_d, and of Unit II deposition. The lake had been isolated for some time and the water levels had been lower than sea level. The Bosporus, probably higher than the present, served as a divide (Figure 3[c]). The marine invasions took place when the sea level rose above the lowest point of the divide between the Black Sea and the Mediterranean. In contrast, the marine influx recorded by Unit Id took place during a brief episode of very warm climate. The Black Sea level prior to salinization was probably not abnormally low. Yet the saline wedge from the Mediterranean could spill over, for the firs time, into the Black Sea, despite the considerable outflow of fresh water (see Figure 3[d]). We might recall that Unit Id has been correlated to the Karangat beds (Chapter on Site 380; Koroneva and Kartashova, this volume). Scholten (1974) predicates that the Karangat marine invasion, which brought the Mediterranean molluscan faunas to the Black Sea shores took place because a northward-flowing bottom marine current could easily enter the Black Sea when the Bosporus was drowned under the high sea level of the Karangat interglacial (Figure 3[d]). In earlier warm or interglacial times, even if a connection to the Mediterranean existed, marine salinization of the Black Sea seemed to have been partially or totally hindered by the outflow wedge of fresh water.

If the sedimentation rate was low during those warm intervals as it is at present, the absence of chemical and of biogenic sediments needs to be explained. The presence of chemical sediments suggests that a spillway existed to prevent a concentration of dissolved ions in the lake water to rise above carbonate saturation. The absence of biogenic sediments indicates that the salinity was not high enough to permit bloom of calcareous nannofossils until a major marine invasion across the Bosporus spillway took place and the chalks in Unit Id were derived (Karangat Phase).

CHRONOSTRATIGRAPHICAL CORRELATION

The rarity of indigenous marine fossils renders accurate dating of the Black Sea cores difficult, if not altogether impossible; an ultimate tool is paleomagnetic stratigraphy. Meanwhile, some tentative dates are suggested on the basis of three different categories of criteria: (1) fossils of some chronostratigraphic value; (2) correlation of Black Sea events with those of adjacent regions where a chronostratigraphy is established; (3) correlation of climatic changes.

Fossil Correlations

The *Emiliania huxleyi* and *Emiliania huxleyi-Gephyrocapsa caribbeanica* floras are the only datable indigenous nannofossil assemblage of the Black Sea cores (Percival, this volume); they are late Quaternary in age and belong to NN-21 *Emiliania huxleyi* Zone of Martini. The uppermost 100 meters of basin-center sediments are thus not older than 0.7 m.y.

The only faunal assemblages of some chronostratigraphical value are found at the very bottom of Sites 380 and 381. The benthic foraminifer assemblages in Unit V of Site 380 are probably indigenous; at least they are present in normal superposition. Gheorghian (this volume) suggests that the *Paramysis kröyen-P. mihaii* assemblage in Cores 380A-70 and 76 are typical late Sarmatian, and that the *Quinqueloculina* spp. assemblage in Core 380A-77 are typical early Sarmatian. The age of the Sarmatian of the Paratethys basins is uncertain, but the faunas suggest correlation with the Tortonian stages of the Mediterranean (Senes, 1973) which range from 6.5 to about 11 m.y. (Berggren, et al., 1976). However, the K/A dating of the volcanics indicate a 10.8 to 12.5 m.y. age for the Sarmatian of Romania (Gheorghian, written communication), and an 11 to 14 m.y. age for the Sarmatian of central Paratethys (Senes, 1973).

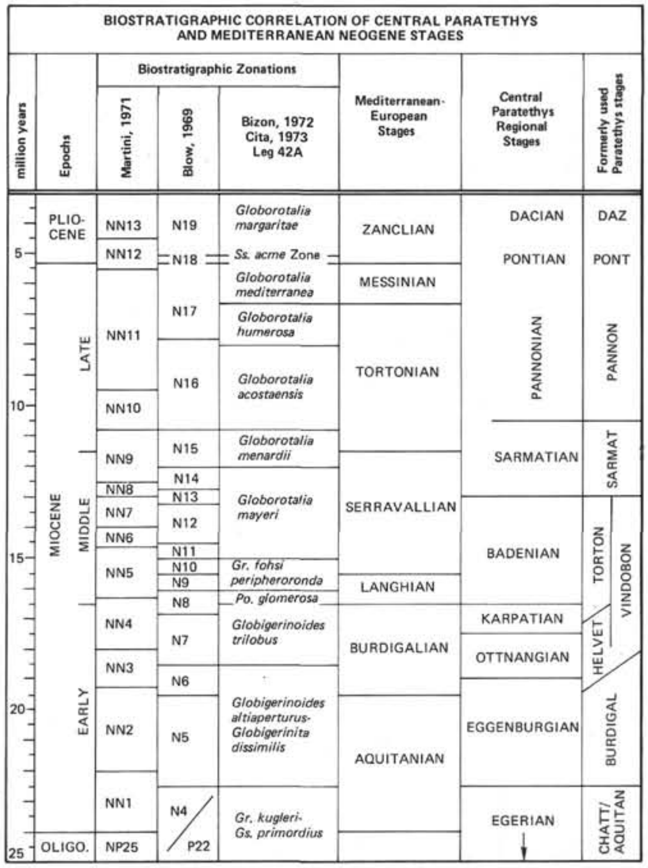

Figure 4. *Correlation of the Paratethys and the Mediterranean Neogene stages (after Rögl et al., 1977).*

Rögl et al. (1977) suggest a correlation of the Sarmatian with the Serravallian and early Tortonian of the Mediterranean (Figure 4). We might thus conclude that the oldest sediments penetrated by drill in the Black Sea are about 10 or 12 m.y.

Pollen assemblages also yielded some information on those sediments. Traverse (this volume) noticed that *Engelhardia* is present in Core 43 (396 m), and very abundant in Cores 48-54 (444-501 m) of Hole 381. This flora, according to van der Hammen et al. (1975) disappeared from northwestern Europe before the "Susterian" in response to a significant cooling of the regional climate; the "Susterian" was estimated to range from 6 to 10 m.y. In the Paratethys, *Engelhardia* are rare in sediments younger than the Sarmatian, although a similar form (cf. *Engelhardia*) has been reported higher up in the Pontian (Weyland et al., 1958).

Pollen studies of the Mediterranean DSDP cores show that *Engelhardia* was present during the late Tortonian (Blow Zone N.16), or some 7 to 10 million years ago, but its pollen were not found in the Messinian (Bertolani-Marchetti, 1977); the Tortonian *Engelhardia* and associated hardwood floras of Mediterranean Europe were largely replaced by conifer forests during the Messinian. It seems safe to conclude that the Black Sea sediments containing *Engelhardia* pollen were deposited some time before the onset of the Mediterranean salinity crisis at about 6 to 7 million years ago. We may further conclude that the pollen data seem to support the faunal study; the oldest Black sediments reached by drill at Site 381 are Sarmatian, some 10 to 12 m.y. old. The oldest sediments at Site 380 may be slightly younger, or 8 to 10 m.y. in age. This conclusion is confirmed by the finding of *Stephanodisus kanitzii* of late Miocene age in Core 380A-61 (Schrader, this volume).

Correlation of Unusual Isochronous Events

Having established that we should have at least a record of some 10 million years of the Neogene history of our Black Sea drill cores, we should search for vestiges of unusual events, which took place in adjacent regions on land, in Paratethys Basins, and in the Mediterranean.

Such an event was the Karangat phase of interglacial (or interstadial) marine invasion which left a record of high-standing terraces around the Black Sea. This was the last period of warm climate before the last glaciation which may be Würm II (Scholten, 1974), or the whole Würm. The latter alternative seems to be preferred by most workers, and the Karangat Terrace has been correlated to Riss-Würm (of central Europe) and to Eemian Interglacial of northwestern Europe (see summary by Frenzel, 1968); the Eemian spanned the interval of about 80,000 to 130,000 years B.P. (Montfrans and Hospers, 1969). The marine-brackish Unit I_d (Site 380) deposited during a brief warm interlude between two glaciations, has been correlated with Karangat beds, and the correlation is supported by the matching of climatic curves, to be discussed later. Accepting further the correlation of the Karangat with the Eemian, we might date the γ_a-marker, 70 meters subbottom at Site 381, to be approximately 100,000 years. This would imply a sedimentation rate of 70 cm/thousand years. Considering that the time span of 0.1 m.y. was mostly glacial, and that piston-core records give a rate of 90 cm/thousand years for the Black Sea sediments deposited during glacial times, the correlation is reasonable.

An earlier major event was the termination of periodical chemical sedimentation in the Black Sea. The event implies a sudden increase of terrigenous input. Meanwhile, an outlet to the Mediterranean was always present and the concentration of dissolved ions seldom exceeded carbonate-saturation. As a result, chemical precipitates did not accumulate even during the interglacial stages of presumably low sedimentation rate.

An analysis of the present terrigenous input and of the water-budget of the Black Sea drainage system indicates that the Danube River is the largest contributor of both (Shimkus and Trimonis, 1974). Yet borings in the Danube delta region indicate that the delta was geologically a young feature;it comprises only a thin cover of late Quaternary sediments above the Precambrian and Mesozoic basement.

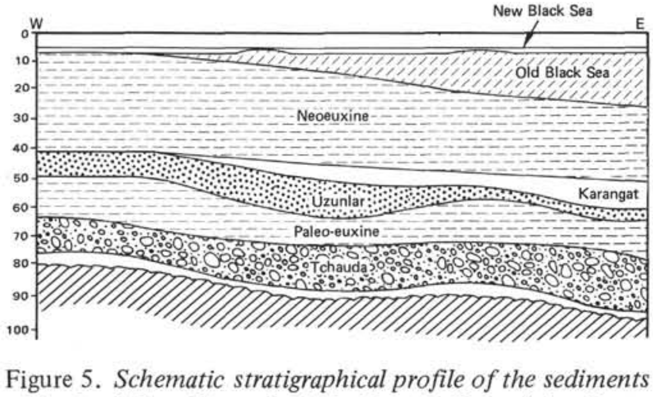

Figure 5. *Schematic stratigraphical profile of the sediments in the Sulina Channel of the Danube Delta (after Popp, 1968).*

A stratigraphic profile of the Quaternary sediments in the Sulina Canal of the Danube delta is shown in Figure 5. A thin veneer of clayey sediments is present at the bottom of the channel, but the coarse clastics marking the start of deltaic sedimentation of the present Danube has been dated as Tchauda. These gravels are overlain by sands and clays of the Paleoeuxine (Mindel), Uzunlar (Mindel-Riss or Holstein), Karangat (Riss-Würm or Eemian), Neoeuxine (Würm), and by the Old and New Black Sea deposits (Holocene). It is difficult to assign an absolute age to the earliest Danube gravels in Sulina Canal. The Tchauda stage of the Black Sea region has been referred to as an equivalent of Günz (Popp, 1968), or it has been correlated to pre-Cromerian deposits of northwestern Europe (Frenzel, 1968). In any case, we might conclude that the present Danube delta was a Quaternary creation, probably less than 1 million years old. Since there is no evidence of an ancient and abandoned Danube delta elsewhere along the west coast of the Black Sea, it seems that the Danube did not drain into the Black Sea until sometime in the Quaternary. This interpretation receives support from the studies of the Neogene of the Precarpathian basins, which are underlain by a Plio-Quaternary detrital sequence, with a composite thickness of more than 10 km. I visited the section, in the company of D. Jipa, west of Buzau, Romania. The sediments were deposited in an ancient lake, which served as a trap for detritus of westerly and of northerly origins. Indeed, paleogeographical reconstructions of the Paratethys in the Pliocene show that the Pannonian and Dacian basins effectively trapped the bulk of the sediment derived from central and from southeastern Europe (Figure 6), while the Black Sea received only the finest suspensions from rivers draining those parts of Europe. We can thus deduce that the uplift of the Precarpathian basins of Romania, and the subsequent integration of the Danube drainage, was the cause for the drastic change from chemical to terrigenous sedimentation in the Black Sea.

The horizon in the Black Sea cores recording this remarkable event is the base of Unit I_b at 332 meters subbottom at Site 380. As the record on land cannot be dated more accurately than mid-Quaternary, assignation a date of this event is better made on the basis of correlating climatic fluctuations (see next section).

An event affecting the area earlier than the cessation of chemical precipitation was the beginning of glaciation. The steppe index indicates an oscillating trend toward cooling during the early stages of periodic chemical sedimentation. Fully glacial conditions (Glacial Stage Alpha) did not prevail in Europe until the time represented by the Black Sea Core 380A-35, at about 650 meters subbottom, marking the transitional sideritic to *seekreide* precipitation. The start of glaciation in Europe is difficult to define. Deep-sea drilling in high latitudes suggests significant climatic cooling during the Messinian at about 5.5 million years B.P. (Van Hinte, personal communication). Glaciations probably took place on the continents of the Northern Hemisphere during the Pliocene and the cooling influence was felt in the Gulf of Mexico region at 2.8 million years ago (Beard and Lamb, 1968; Berggren, 1972; Briskin and Berggren, 1976). However, studies of deep-sea piston cores suggest that fully glacial conditions began in latest Pliocene or earliest Quater-

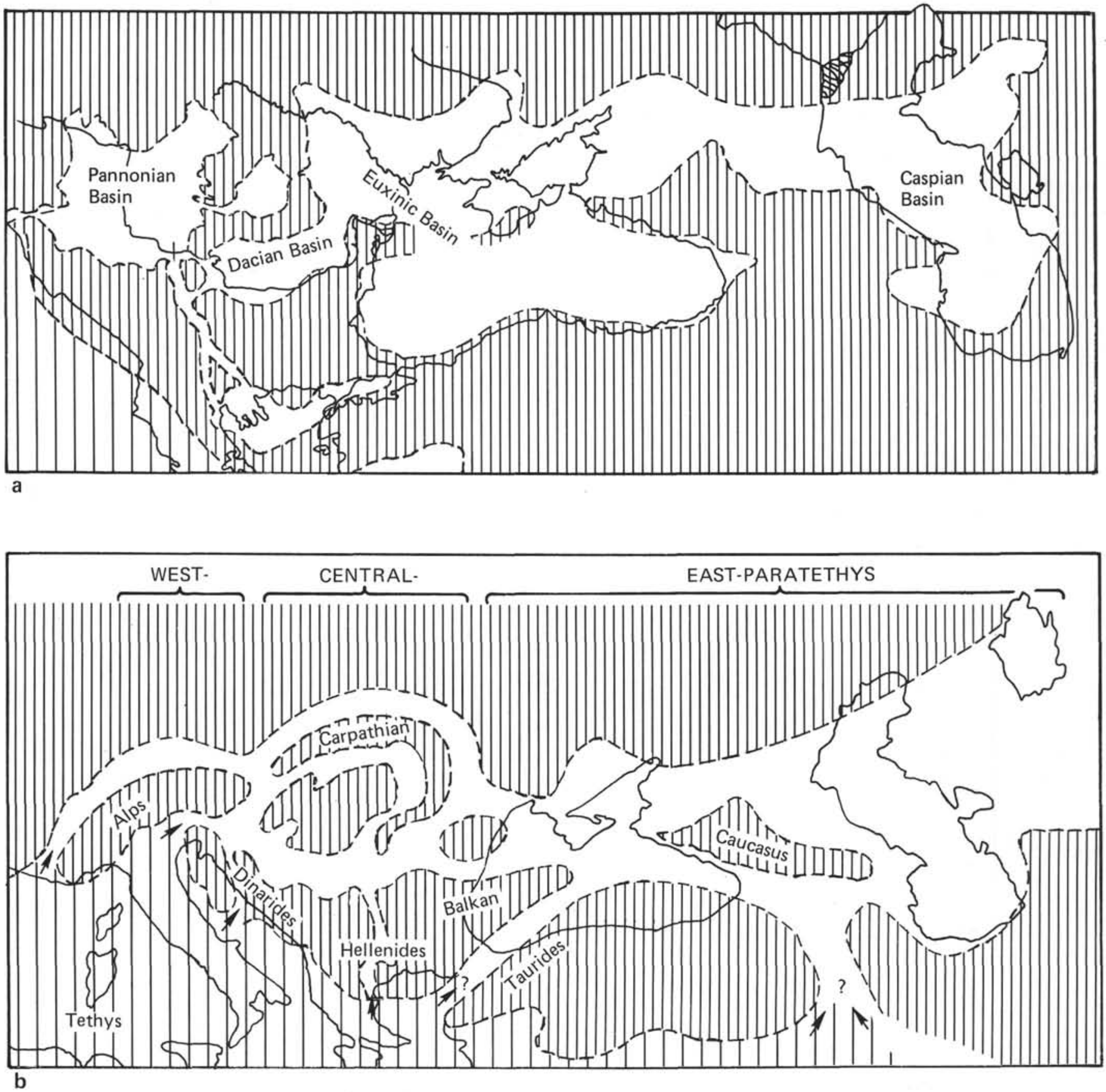

Figure 6. *Paleogeography of the Paratethys (a) Pliocene (after Marinescu, 1970); (b) middle Miocene (after Senes, 1973).*

nary, some 2 to 1.5 million years ago (Ericson and Wollin, 1968; Briskin and Berggren, 1976); this conclusion is supported by investigations of Quaternary chronology on land (Montfrans, 1971; Richmond, 1976). If we date the beginning of Alpha Glacial Stage as 2, or 1.5 million years, the sedimentation rate would be 33 or 43 cm/thousand years for the Black Sea during the glacial and interglacial times. This rate is slightly less than the average rate of 50 cm/thousand years between the Holocene low (10 cm/thousand years) and the Würm high (90 cm/thousand years), as it should be.

A still earlier event recorded by the Black Sea cores was the interlude of shallow-water sedimentation in the Black Sea basin, when supratidal dolomites and coarse clastics were deposited (Unit IV_d, Site 380). The occurrence of this sedimentary unit beneath overlying, deep water sediments is unusual and difficult to explain.

Degens and Stoffers (this volume) postulate a Mio-Pliocene shallow basin, followed by extensive Quaternary subsidence to account for the present (2000 m) depth of the Black Sea. However, geothermical studies reveal that the heat flows of the Black Sea are about normal, as typical of older oceanic basins (Erickson, this volume); young Neogene basins, such as the Balearic, Tyrrhenian, and Aegean basins of the Mediterranean, are characterized by heat flows twice or three times the normal flux (Ericson, this volume). Tectonic interpretations favor a Mesozoic origin of the Black Sea basin (Brinkmann, 1974; Hsü et al., 1977). I prefer to interpret that a deep basin was in existence when the coarse detritus and supratidal dolomites in question were laid down, but that the Black Sea water level had been lowered some 2000 meters because of evaporative draw-down; such a model I preferred for the desiccation of the Mediterranean (see Hsü et al., 1973). An evaporative draw-down requires either a dramatic change of climate, or fundamental change in hydrologic budget. Palynological data give no indication of dramatic climatic changes accompanying the sedimentation of Unit IV_d sediments. It seems more probable that the water deficit was caused by a reorganization of the drainage.

Deep-sea drilling of the Mediterranean during the Leg 42A cruise discovered that desiccated Mediterranean basins were partially covered, during the latest Messinian time, or about 5.5 million years ago, by fresh or brackish water (Hsü et al., in press). The sudden change from brine lakes and playas to brackish or fresh-water *Lago Mare* cannot be explained by a sudden climatic change. The only plausible explanation is to assume a sudden influx of fresh water from a large reservoir. The only great lakes nearby were the Paratethys, or the Neogene *lac mer.* Indeed, the stratigraphic record of the Paratethys indicates a period of major regression at the end of Pontian (Gagic and Sokac, 1970; Jiricik, 1975), which is correlative to latest Messinian (see Figure 5). The Pannonian Basin lost its connection to eastern Paratethys, its water became siphoned off, large parts were drained and exposed. It is reasonable to assume that some of that water found its way to the deep-lying Mediterranean desert.

The communication between the Tethys and the paratethys during the Neogene is a problem not yet clarified. Senes (1973) suggests four possibilities: (1) through the Rhone Valley, Swiss Molasse Basin, to the Vienna Basin; (2) through Istria to the Pannonian Basin; (3) through Bosporus to the Black Sea; and (4) through the Caucasus or eastern Turkey to the Black and Caspian seas. The first three connected the Paratethys to the Mediterranean, the last was an opening to the Indopacific. There was a good connection between Paratethys and the Mediterranean during the Oligocene and earlier Miocene. Fauna studies indicate that the connection was severed sometime during the middle Miocene, about 15 million years ago (Rögl et al., in press). The late middle Miocene faunas of the Paratethys show an affinity to some Indopacific faunas; apparently the marine influence may have come from the east after the western exits of the Paratethys were closed (Rögl et al., in press). During the late Miocene (Sarmatian and Pontian) the Paratethys stretched from the Vienna Basin to the Aral Sea; it was then a brackish marine inland sea somewhat like the Baltic today (see Figure 6). With the post-Pontian regression, the Paratethys disintegrated into a series of lakes.

During the late Messinian, a number of fresh-water lakes were present in depressions of southern Balkan. The peri-Adriatic provinces and the eastern Mediterranean basins hosted one, or a series of, large brackish water lake(s). Most probably a river draining the Balkan lakes threaded its way across the Dinarides to the Adriatic, as there is no evidence of a waterfall through the Bosporus (Hsü et al., in press). The reorganization of the drainage would have cut off the largest sources of fresh water to the Black Sea, and a hydrological deficit resulted, lowering its water-level until the margins of its abyssal plain became sabkhas, and sites for supratidal dolomite formation. This line of reasoning leads me to conclude that Unit IV_d at Site 380 should be dated as late Messinian, or about a little over 5 million years in age. The immediately subsequent brackish-marine invasion into the Black Sea, depositing the aragonitic sediments of Unit IV_e at Site 380, might thus be correlated to the early Pliocene marine flooding of the Mediterranean. This line of reasoning would date the contact between Units IV_d and IV_e at 864.5 meters subbottom in Hole 380A as the 5.2 million years datum, implying a 5 to 7 cm/thousand year rate for the Pliocene interval of periodical chemical sedimentation. This low rate for the preglacial times is, as it should be, comparable to the present low rate of 10 cm/thousand years.

The earliest major event of the Black Sea was marked by the disappearance of an endemic brackish-marine fauna from the Black Sea during the time when Unit V was being deposited at Site 380. The youngest brackish marine faunas of the Paratethys are Meotian (or late Pannonian), which is estimated to be about 8 to 9 million years (Senes, 1973). It is far from certain if the extinction of the marine Paratethys fauna was an isochronous event. If the marine connection was located in the east and the communication was with the Indo-Pacific, marine brackish conditions might have persisted longer in the Black Sea Basin, which is situated east of the Paratethys basins of southeastern Europe. On the other hand, this 8 to 9 million years date is not too much out of line with our estimate of 10 million years for the bottommost cores of Site 380. We might thus safely conclude that we did not penetrate beyond the base of late Miocene in our three deep-sea drilling holes.

Correlation of Climatic Changes

Numerous attempts have been made to construct curves of climatic variations on the basis of studying long piston cores from the Atlantic Ocean. Those cores were dated by paleomagnetic stratigraphy, and the climatic variations were estimated on the basis of interpreting foraminifer assemblages and on isotopic analysis.

Ericson and Wollin (1968) used the frequent occurrence of the *Globorotalia menardii* complex and the coiling direction of *Globorotalia truncatulinoides* to interpret changes as recorded by Atlantic piston cores. The cores have been dated by magnetic reversals whose ages are in turn determined by radiometric datings. They concluded that there have been four major glaciations during the last 2 million years. Briskin and Berggren (1975) chose one of the tropical North Atlantic cores studied by Ericson and Wollin, V 16-205, and made quantitative paleoclimatical analyses. Figure 8(b) shows their plot of climatic variation based upon the percentage of *Globorotalia menardii* complex in individual samples. Also shown is the variation of winter temperatures (three-point moving average of estimated temperatures) calculated on the basis of faunal composition. They identified the climatic zones first defined by Ericson (1961). They also found four major climatic cycles, with periodicities of about 500,000 years marking the Quaternary record of that core (Figure 7).

The absolute dating of the Black Sea cores by paleomagnetic method is still in progress, and that work will be reported in a forthcoming article (Giovanoli, in preparation). Provisionally, two datum planes have been recognized: a transition from normal to reverse polarity at 490 meters subbottom in Hole 380A and a positive event in a reversely magnetized sequence at 655-680 meters subbottom of the same hole. We

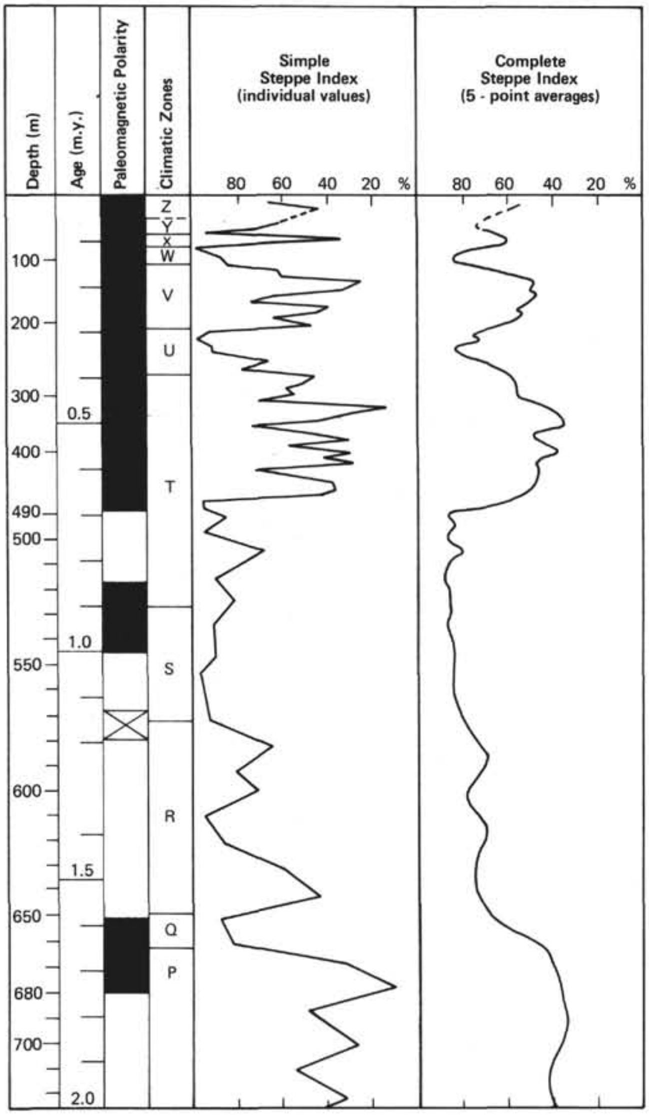

Figure 7. *Postulated climatic history at Site 380 on the basis of one interpretation of paleomagnetic data. The interval crossed by X shows positive and should be negatively magnetized according to this interpretation. This interpretation placed the basis of the climatic zones T, U, and V too high. We prefer the interpretation shown by Figure 6(a).*

can assume that the first is the Brunhes-Matuyama boundary, and that the second is the Olduvai event. We may further disregard the apparent positive polarity of the cores from 570 to 580 meters subbottom. Such a paleomagnetic interpretation permits the construction of a climatic curve (Figure 8a). The variation as shown by the plot of steppe index values of individual samples leads to a tentative recognition of Ericson's climatic zones, Q, R, S, T, U, V, W, X, Y, Z, and Zone P, defined by Briskin and Berggren (1975). The plot of five-point average values of the steppe index presents a rough comparison of the glacial stages Alpha, Beta, Gamma with the four glacial stages recognized by Briskin and Berggren. However, there are several serious shortcomings for such an interpretation:

1) The average sedimentation rate for the interval 0-490 meters Site 380 would be more than 70 cm/thousand years. This rate is a reasonable average for the glacial and interglacial terrigenous sediments of Unit I, but seems much too high for Unit II and upper Unit III, which include considerable thickness of slowly deposited chemical sediments.

2) Black Sea glacial stages defined by such an interpretation of the preliminary paleomagnetic results would lead to diachronous correlation between the climatic zones of the Black Sea with those of the Atlantic. For example, the beginning of Zone T would be 0.9 m.y. in the Black Sea instead of 1.0 m.y. in the Atlantic, and the beginning of Zone U would be 0.4 m.y. instead of 0.6 m.y.

3) The Brunhes-Matuyama boundary could not be lower than 475 meters at Site 379. The chronostratigraphically correlated horizon at Site 380 should be 415 meters. Therefore, the 490-meter transition in Hole 380 cannot be the Brunhes-Matuyama boundary on the basis of this correlation (see Hsü, this volume, on correlation).

Whereas the preliminary paleomagnetic results should not be completely disregarded, we also have to recognize the limitations of the method and should, therefore, not place too much reliance on their accuracy. One of the problems in paleomagnetic studies is illustrated by the work on Mediterranean DSDP cores: paleontologically dated early Quaternary samples which should have reversed polarity are mostly positively magnetized (Ryan and Flood, 1973). The cause of the imprint of positive NRM on sediments deposited during an epoch of reverse polarity is unknown. The diagenetic growth of magnetic iron minerals may account for such anomalies. Delayed magnetization during diagenesis can also be expected for the Black Sea cores, especially for the sideritic sediments of Unit II, which may have undergone considerable diagenesis of the iron minerals after their deposition. In addition, some of the lacustrine chalks studied may be slump deposits and their NRM polarity cannot be relied upon as indicators of past role positions. I have, therefore, tried out a second working hypothesis by accepting the correlation between Sites 379 and 380 that the Brunhes-Matuyama boundary should be higher than 415 meters in Hole 380. This alternative interpretation would (1) place the datum at 490 meters Site 380 as the end of the Jaramillo event, (2) place the datum at 680 meters as the end of the Olduvai event, and (3) assume that the positive polarity of cores from three intervals (as shown by Figure 8[b]) resulted from diagenesis or from slumping and, therefore, those results should be discounted. Plot of climatic changes based upon this working hypothesis of paleomagnetic dating are shown by Figure 8(b). As the illustrations show, correlation between the Black Sea and the Equatorial Atlantic data are remarkably close. Climatic zones of the Black Sea and those of the Equatorial Atlantic are practically synchronous, i.e., the beginning of Zone T at about 1.0 m.y. and of Zone U at 0.6 m.y. in both regions. Furthermore the Glacial Stage Alpha in the Black Sea can be correlated with the first two, and the Glacial Stages Beta and Gamma with the last two glacial stages as defined by the winter-temperature variations of Equatorial Atlantic (see Figure 8[b]). The climatic curves of the Black Sea also show that the warm interval indicated by the γ_a -marker is a brief, yet intensely warm episode in a major glacial stage, corresponding almost exactly to Zone X

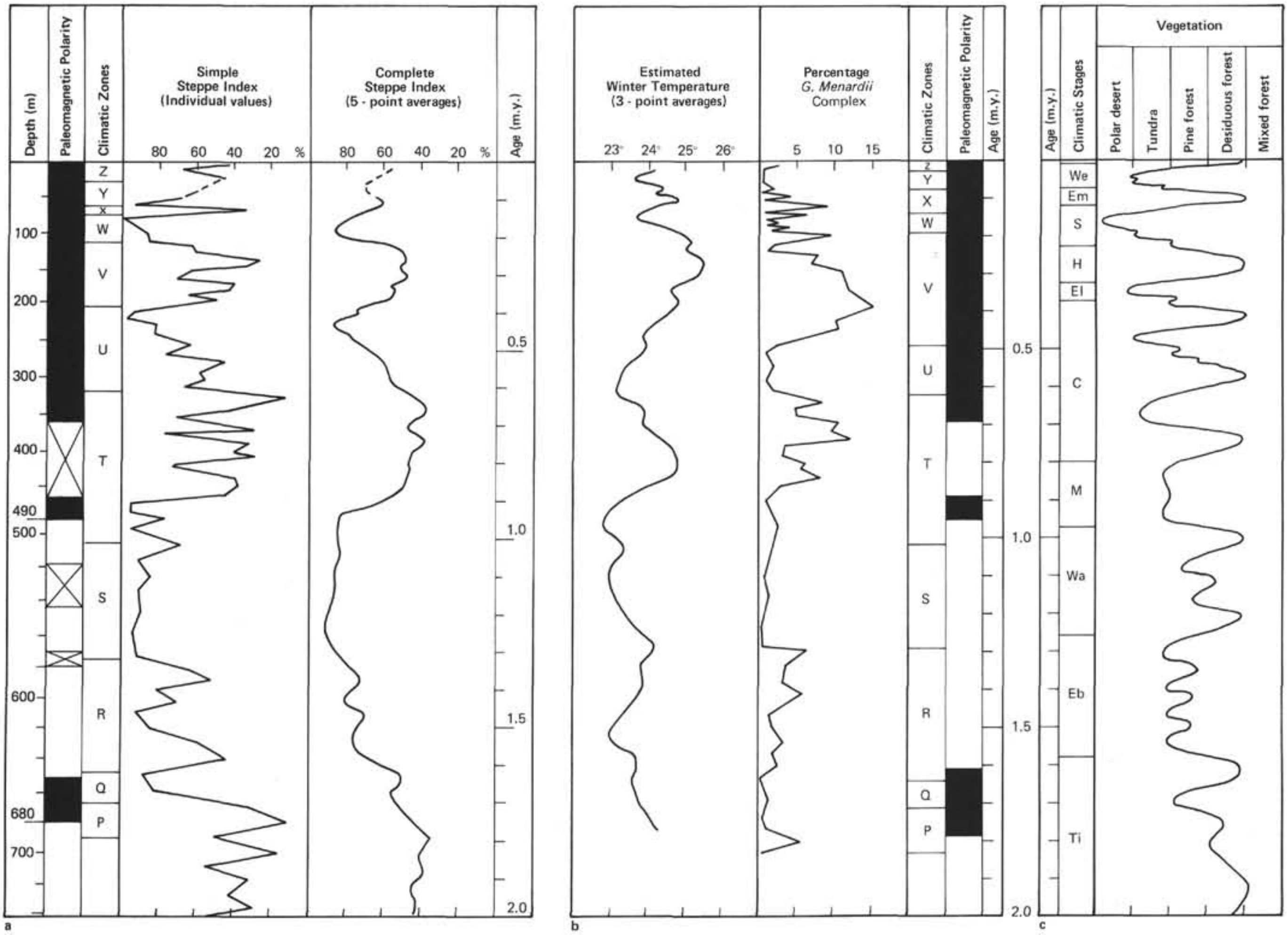

Figure 8. *Comparison of the climatic record of the Black Sea (a) with the Equatorial Atlantic (b) and with the Northwestern Europe Records (c). Note the good correlation between a and b, and the lack of correlation between a and c. (a) is the postulated climatic history at Site 380 on the basis of a second interpretation of paleomagnetic data. The intervals crossed by X include sediments deposited during the Matuyama Epoch, which for one reason or another have positive NRM polarity. (b) is replotted from figures in Briskin and Berggren (1976). (c) is replotted from a figure in van der Hammen et al. (1975).*

of Ericson and Wollin, 1968. The warm intervals B and A are, on the other hand, truly major interglacial periods; they correspond to the Ericson's Zones V and T.

The interpretation of the climatic changes around the Black Sea as shown by Figure 8(b) seems to confirm several conclusions by Briskin and Berggren on the basis of their study of the Atlantic cores:

1) The first glacial started in early Quaternary at the time marked by Olduvai event of the Matuyama reversed polarity epoch.

2) The early Quaternary climate was severe to mild and the amplitude of temperature variations was subdued. The late Quaternary climate varied greatly, with oscillations of great amplitude and short periodicity, and the climate was, on the average, warmer.

Whereas the climatic variation recorded by the steppe indices of the Black Sea cores is remarkably similar to that recorded by the faunal indices of the Equatorial Atlantic sediments, we find little correlation of those climatic records with that presented by Van der Hammen et al. (1973) for northwestern Europe (compare Figures 8[c] with 8[a], 8[b]). Only the climate Zone X of the Atlantic and the γ_a interstadial of the Black Sea can be correlated with the Eemian Interglacial of northwestern Europe; it is difficult to match the climatic variations beyond that datum horizon. The Cromerian should be correlated in part with climatic Zone T on the basis of paleomagnetic evidence; the Brunhes-Matuyama boundary falls within that complex (Montfrans and Hospers, 1969). If so, the Menapian and Eburonian cold stages might be equivalent in part to the Alpha glaciation of the Black Sea. Such a correlation does agree with our previous conclusions that the Quaternary climatic variations became shorter in periodicity and greater in amplitude. On the other hand, the Black Sea and the Atlantic records both indicate a colder early Quaternary, whereas northwestern Europe did not enter the coldest (polar desert) stage until late Quaternary time (Van der Hammen et al., 1973, p. 470). Perhaps the former are representative of global variations, where the latter registers more regional changes.

SUMMARY OF GEOLOGIC HISTORY

The DSDP Black Sea cores have been dated on the basis of largely circumstantial evidence, because reliable marine fossils for chronostratigraphy are absent. The conclusion is at best a working hypothesis, as numerous assumptions have to be made. It seems that the deepest sediments were obtained at Site 381, and are as old as Sarmatian (early late Miocene), or 10 to 12 m.y. old. At that time, the Black Sea was a part of the Paratethys, marine-brackish sea. Cut off from coarse clastics sources and devoid of biogenic sediments, black shales were the only sediments deposited in this deep-water body. At times, the water chemistry was such that dolomite formation became possible. Occasionally ashes, erupted from volcanoes of the Transylvanian or other Paratethyan basins, found their way here, but the Neogene volcanism soon died down and the youngest tuffaceous sediments of the Black Sea are found in Unit V of Hole 380A.

The gradual cooling of the global climate had advanced sufficiently by latest Miocene so that the warm, upland flora *Engelhardia* died out in the regions around the Black Sea (Table 1) and a major drainage reorganization apparently took place at the start of periodic chemical sedimentation (Unit IV_e, 380A). This event is believed to have taken place during Messinian time, when the Paratethys marine-brackish sea was drained off of much of its water. The endemic Paratethys marine-brackish foraminiferal faunas became extinct (Table 1). With an evaporative excess, the Black Sea water level sank below its outlet and it changed into a brackish to saline lake in which carbonate sedimentation took place. Eventually, evaporative drawdown was carried to the point where the edge of the Black Sea abyssal plain became dry land. Materials slumped from the freshly exposed slope were accumulated at Sites 380 and 381, as pebbly mudstones (Table 1). Reworking of coarse clastics led to the deposition of coarse beach sands on the lake shore. Meanwhile, exposure led to subaerial diagenesis and the formation of supratidal dolomites on the flat land fringing a shallow inland lake, which covered the central depression of the Black Sea basin.

This unusual period of shallow-water sedimentation was terminated, probably at the start of the Pliocene, when the desiccated Black Sea and Mediterranean basins were simultaneously inundated (Table 1). Aragonitic mud (Unit IV_c) was deposited in this marine-brackish Black Sea, in a water body sufficiently saline (>17%) to permit the population of the nannofossil species *Braarudosphaera*. Connection to the Mediterranean was soon severed, and the Black Sea again became a lake. The rivers draining into this lake brought in much fresh water and the gradual desalinization lasted through much of the Pliocene and early Quaternary times. The changing environments of the Black Sea supported diffe-

TABLE 1
Milestones of Geologic History of the Black Sea, as Recorded by the Sediments at Site 380

Depth (m)	Core	At or Near Base of Unit	Event	Stage	Estimated (m.y.)
1070	80A	V	Disappearance of *Engelhardtia* flora	Late Tortonian?	8-10
988	70A	IV_e	Extinction of endemic Paratethys marine-brackish foraminifer fauna	Messinian	6
883.5	59A	IV_d	Deposition of coarse clastics began; Paratethys water had been drained into Mediterranean; shallow Black Sea	Late Messinian	5.5
864.5	57A	IV_c	Marine invasion of Black Basin	Earliest Pliocene	5.2
718	56A	IV_a	Siderite sedimentation in brackish lake began	Pliocene	–
644	34A	III	Main epoch of *seekreide* sedimentation in deep, fresh lake began	Earliest Pleistocene	1.7
496	12A	II	Siderite sedimentation in brackish lake began	Pleistocene (Interglacial A)	
332.5	36	I_h	Chemical sedimentation practically ceased, Danube drained into the Black Sea, which was gradually turned into a freshwater lake	Glacial	0.6–
171	18	I_f	Salinization of Black Sea at times, perhaps Bosporus was eroded down to interglacial sealevel		
76	8	I_d	Major marine invasion during an episode of warm climate	Late Pleistocene Karangat Terraces	0.125
2	1	I_b	Old Black Sea		0.007

rent populations (see Figure 2). The nannofossil *Braarudosphaera,* which came in with the Pliocene marine influx, died out at the end of aragonitic deposition. The brackish foraminifers were gone and brackish diatoms began to flourish when the lower *seekreide* (Unit IV_b) was being deposited. Acritarchs were extinct and brackish dinoflagellates became rare when the first siderite was deposited, and the latter as well as the brackish diatoms also disappeared when the main *seekreide* (Unit III) began to be precipitated (Table 1): At that time, fresh-water *"Dinoflagellate 19-20"* and fresh-water ostracodes started to populate the completely desalinized Black Sea. Those became rare and eventually died out while the upper sideritic mud (Unit II) was being deposited (Table 1) when mollusks were the dominant fauna. The period of chemical sedimentation ended with a marine invasion which brought again nannofossils, foraminifers, and marine-brackish diatoms into the basin; this invasion coincided with the beginning of late Quaternary terrigenous sedimentation as the Interglacial Stage A came to a close (Table 1). The sudden increase of terrigenous influx at that time may be related to another reorganization of the drainage system of the Paratethys basins during the Quaternary when the sediments brought down by the Danube were no longer trapped by the Dacian basin, but were emptied into the Black Sea.

The overall cooling trend continued despite repeated oscillations, and continental glaciations began at about the same time as the beginning of the Quaternary some 1.7 million years ago. A prolonged glacial stage (Alpha), interrupted by several interstadial warm intervals, lasted for almost 0.8 million years. During the second half of the Quaternary, the climatic oscillations were characterized by shorter periodicity and greater amplitudes. The history of climatic variation of the region around the Black Sea shows a trend parallel to that recorded by the Equatorial Atlantic cores. It cannot be correlated with that of northwestern Europe until about the Eemian Interglacial some 100,000 years ago, when marine waters entered the Black Sea through the Bosporus to deposit the diatomaceous sediments of Unit I_d at Site 380 (Table 1). The Holocene (old Black Sea) sediments are found in the top core of Hole 380.

SEDIMENTATION RATE

The sedimentation rates of the late Quaternary Black Sea cores is about 10 cm/thousand years for the warm Holocene interval, and about 90 cm/thousand years for the Würm glacial stage. The sedimentation rates of the various intervals at Site 380 have been computed and the results give an approximate calibration of the adequacy of the postulated chronology. The computed rates are shown in Table 2. The uppermost 76 meters were deposited mainly during the glacial stage Gamma, but include also interglacial sediments; the average sedimentation rate is 60 cm/thousand years and is, as one might expect, less than the 90 cm/thousand years rate for the sediments that were deposited entirely during the time of continental glaciation. The interval 76-328 meters consists mainly of terrigenous sediments, some of which were laid down during the glacial and some during the interglacial time. The average rate is 50 cm/thousand years, exactly the same as the average of the late Quaternary glacial and interglacial sediments. The next interval down to 680 meters include sideritic and calcitic sediments interbedded with fine terrigenous clastics. The sediments were mainly deposited during the long glacial stage Alpha, but some, in the uppermost part of the interval, were laid down during the warm interglacial stage A. The average rate is 31 cm/thousand years. This rate is about half of that for the mainly terrigenous sedimentation during the glacial stage Gamma. Under an assumption that the terrigenous influx to the Black Sea was half as much as that of today, before the Danube took its present course, the computed rate is just about what is expected for this interval. The next interval (680-868 m) of terrigenous and chemical sedimentation during a warm preglacial epoch (Pliocene) yields an average sedimentation rate of 5.4 cm/thousand years, again just about half as much as the Holocene rate. The underlying Messinian units included not only terrigenous and chemical sediments deposited in a lake, but also some coarse clastics deposited during times of subaerial exposure. It is, therefore, not surprising that the sedimentation rate (10.3 cm/thousand years) is higher than that for other preglacial sediments. Finally, the rate of black shale sedimentation is 5.1 cm/thousand years if the late Miocene

TABLE 2
Sedimentation Rates at Site 380

Depth (m)	Age Stage or Epoch	m.y.	Units in Interval	Nature of Sediments in Interval	Average Interval Rate (cm/t.y.)
76	Eemian Interglacial	0.125	I_c, I_d	Terrigenous, mainly glacial	60
328	Near Top A	0.63	I_e, I_f, I_g, I_h	Terrigenous, glacial and interglacial	50
680	Base Alpha	1.75	II, III, IV_a	Terrigenous and chemical, mainly glacial, some interglacial	31
868	Base Pliocene	5.2	IV_a, IV_b, IV_c	Terrigenous and chemical preglacial	5.4
972	Messinian	6	IV_d, IV_e	Coarse terrigenous and chemical, preglacial	10.3
1075	Late Miocene	8 or 10	V	Black shale	5.1 or 2.6

sediments at the bottom of the hole are 8 million years, or 2.6 cm/thousand years if it is 10 million years of age. The latter alternative is more probable on the basis of the faunal evidence; also one would expect a lower rate when only very fine terrigenous and no chemical sediments were precipitated. We should note that the black shale was probably the typical sediments of the marine-brackish Paratethys and supported little or no planktonic life. At times of open-marine hemipelagic sedimentation, the terrigenous component may constitute one half or one-third of the bulk. With the addition of biogenic sediments, the estimated rate for pre-Tortonian sedimentation would be in the order of several to more than 10 cm/thousand years.

Seismic studies indicate that the total thickness of Black Sea sediments is about 6 to 12 km in the region of Site 380 (see Neprochnov et al., 1974, Fig. 6[a]). Since the age of the basin is probably Middle Cretaceous, or about 100 million years, the average sedimentation rate is 6 to 12 cm/thousand years. Our computations of rates are thus in general agreement with our knowledge of the age and sediment thickness of the Black Sea Basin.

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ADDITIONAL NOTES

Considerable progress has been made to work out the paleomagnetic stratigraphy of the Black Sea cores during the two years since the manuscript was first written. The final results will be presented in an article by F. Giovanoli, A. Traverse, and K. J. Hsü (in preparation). New findings relevant to the interpretations in this chapter are:

1. The Brunhes-Matuyama transition boundary is placed at 410 m in Hole 379A; the correlative horizon at Site 380 is about 370 m. This confirms the interpretation in this chapter, which placed the transition at 360 m at Site 380 (see Figure 8 [a]).
2. This chronological interpretation permits us to correlate climatic oscillations durings the Brunhes in the region around the Black Sea as shown by steppe indices of individual samples with those of marine climate as determined by oxygen-isotope studies (Shackleton and Opdyke, 1976, Geol. Soc. Am., Mem. 145, p. 445-464). The warm peak at 370 m sub-bottom in Hole 380 is the Warm Stage 19 in the marine record.
3. The 650 m datum at Site 380 is probably the beginning of the Matuyama-Gauss transition, not the top of the Olduvai event as shown in Figure 8(a) of this chapter. This new interpretation would place the beginning of Alpha Glacial Stage as late Pliocene (or about 3 m.y.), not early Pleistocene.
4. Some originally negatively polarized sediments may have acquired positive polarization because of the growth of greigite as diagenetic concretions during a normally polarized epoch. This observation supports the paleomagnetic interpretation (of the intervals crossed by X in Figure 8 [a]) in this chapter.