43. THE ORIGIN OF THE MEDITERRANEAN EVAPORITES

Kenneth J. Hsü, Geologisches Institut, Eidg. Technische Hochschule, Zurich, Switzerland
Maria B. Cita, Institute of Paleontology, University of Milano, Milano, Italy
and
William B. F. Ryan, Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York[1]

INTRODUCTION

Prior to our cruise, one of us was asked by his colleagues to find in the Mediterranean the cause of the Pontian regression, which was one of the significant events in the Neogene history of Europe. Another of us was looking for a chance to continuously core a Neogene pelagic sequence, and thereby resolve the difficult Miocene-Pliocene boundary problem, and to establish a reference marine section for Neogene stratigraphers. The third had been puzzled by the almost ubiquitous presence of a strong acoustic reflector in the Mediterranean; he was hopeful by drilling, to determine its age, nature, and relation to the evolution of the Mediterranean basins. These three divergent lines of interest provided a basis for our eventual agreement through a shared belief that the Mediterranean evaporites owed their origin to the desiccation of a deep basin that had been isolated from the Atlantic.

The presence of a salt deposit under the Balearic Basin had been suspected since 1961 when diapiric structures resembling salt domes were identified on the seismic reflection profiles of *Chain* cruise 21 (see Hersey, 1965). Similar diapiric structures were known from the eastern Mediterranean, but there had been doubts whether these are indeed salt domes, or whether they are mud diapirs instead (H. Closs and D. Neev, personal communication).

The age of the Balearic salt had been a rather controversial problem; it had been postulated as Triassic (e.g., Glangeaud *et al.*, 1966), or as Tertiary (e.g., Cornet, 1968; Mauffret, 1969; Montadert *et al.*, 1970). Its genesis was even less certain. Comparing the Balearic deposits with those of the Rhine Graben and Rift valleys, the salt was thought to have been deposited in a rapidly subsiding basin, initially opened by rifting (Ryan, 1969; Schneider, 1970; Pautot *et al.*, 1970).

The presence of Upper Miocene evaporites in circum-Mediterranean countries has been well known, after their having been described from Spain, Italy, Crete, Turkey, Cyprus, Israel, North Africa, and other places, (see Kozary, *et al.*, 1968; Ogniben, 1957; Rios, 1968; Freudenthal, 1969; Tortochaux, 1968). A Late Miocene Mediterranean "salinity crisis" had been recognized (e.g., Gentil, 1918; Trevisan, 1958; Gignoux, 1960; Ruggieri, 1967), and even the isolation of the Mediterranean from the Atlantic had been postulated (Ogniben, 1957). However, none had envisioned desiccated basins thousands of meters below the worldwide sea level, nor had anyone ventured to correlate the Mediterranean reflector with an extensive evaporite formation covering the whole Mediterranean basin.

The presence of salt, not only halite, but also gypsum, anhydrite, and dolomite, in the Mediterranean was proven by DSDP drilling. Combining the drilling results with evidence furnished by geophysical records, the existence of an extensive evaporite unit of Upper Miocene age has been established. We propose to refer to this unit (a formation, a group, or a super-group as one may wish to view it) as the Mediterranean evaporite. Significance of the drilling results was not only to confirm the presence of halite under the Balearic Abyssal Plain, but to confirm that a major "salinity crisis" took place during the Late Miocene. It became apparent that the circum-Mediterranean evaporites of this age are not local deposits, but are uplifted fragments of a unit that once covered the whole Mediterranean Basin.

The origin of the Mediterranean Evaporite could be accounted for by three different models:

1) Evaporation of a deep-water Mediterranean basin, which received constant inflow from the Atlantic and Maintained its water level at or only slightly below the worldwide sea level.

2) Evaporation of a shallow-water Mediterranean basin, which received inflows from the Atlantic and maintained its water level at about the sea level.

3) Desiccation of a deep Mediterranean basin isolated from the Atlantic; evaporites were precipitated from playas or salt lakes whose water levels were dropped down to thousands of meters below the Atlantic sea level.

The first may be called a "deep-water, deep-basin model" (e.g., Schmalz, 1969), the second a "shallow-water, shallow-basin model" (e.g., Ogniben, 1957), and the third, a "desiccated, deep-basin model". The last is the one we prefer.

EVOLUTION OF THE DESICCATED DEEP-BASIN MODEL: A NARRATIVE

The idea that an ocean basin the size of the Mediterranean could actually dry up and leave behind a big hole thousands of meters below worldwide sea level seems preposterous indeed. We were reluctant to adopt such an outrageous hypothesis until we were overwhelmed by many different lines of evidence. When we first publicized our idea in press conferences at Paris and New York, we were greeted with much disbelief. We recall that our colleagues were vehement in their negative reactions; the idea was thought to be physically impossible. When we had a chance to present some of our evidence during a post-cruise conference at Zurich, in January, 1971, we found a few converts. Later, we presented oral reports at the First

[1] Lamont-Doherty Geological Observatory, Contribution No. 1861.

European Earth and Planetary Physics Colloquium at Reading, England, in March; the 1971 Annual Meeting of the American Association of Petroleum Geologists at Houston, in April; the 15th Congress of the International Union of Geodesy and Geophysics at Moscow, in August; the 8th International Sedimentological Congress at Heidelberg, in September; the 5th Neogene Conference at Lyon, France, in September; and the 1971 Annual Meetings of the Geological Society of America, at Washington D. C., in November. We also held seminars at various universities and research institutions. Our talks stimulated considerable discussion. We were very appreciative of the exchanges we had with our audience, for these helped us focus attention on the apparent difficulties. Nevertheless, many of our colleagues continued to be skeptical. Even today some of the most prominent authorities on Mediterranean geology remain most emphatically antagonistic. Faced with the task of gentle persuasion we thought the most effective avenue was to recount our own experiences and present a narrative in chronological order, of the many pros and cons that we had encountered before our ideas were crystallized into what we believe to be a solid working hypothesis.

Geologic Background

A prominent lithified layer within the Mediterranean Basin was discovered as early as 1953 by seismic refraction studies (Gaskell and Swallow, 1953). The upper surface of this layer has been adopted as the boundary between two distinct units of the Mediterranean sediments, and upper unconsolidated and a lower consolidated or lithified unit (Gaskell *et al.*, 1958; Ewing and Ewing, 1959; Moskalenko, 1965; Wong and Zarudzki, 1969).

Continuous seismic reflection profiling techniques were first applied to the Mediterranean in 1959 during R/V *Chain* cruise 7. Since then, the reflection studies have been continued and refined by Woods Hole, Lamont-Doherty, Monaco, Miami, Villefranche s.M., Bologna, Trieste, Israel, Brest, and others. A particularly prominent and widespread reflector was identified, and has been designated by Ryan as the M-Reflector. As late as December, 1969, when the paper by Wong and Zarudzki was published, it was clear that nobody knew what the reflector represents and that there was considerable controversy as to its age. Ryan (1969) considered layer M a lithified sediment of Early Pliocene age, based upon coring results near the outcrops of the reflector. Others assigned older ages. In fact this prominent reflecting horizon had been correlated to the top of the 4.3 to 4.7 km/sec layer to which a Cretaceous age had been ascribed (Moskalenko, 1966; Wong and Zarudzki, 1969).

The so-called M-Reflector has not only been observed under the abyssal plains (e.g., Hersey, 1965; Leenhardt, *et al.*, 1970; Mauffret, 1970; Montadert *et al.*, 1970), but is also present under submarine ridges and slopes (see Wong and Zarudzki, 1969; Ryan, *et al.*, 1971; Selli and Fabbri, 1971; Finetti, *et al.*, 1970). The reflecting surface is regionally flat under the abyssal plain, but rises and falls more or less conformably with the submarine topography, under the slopes and ridges (Figure 1). Near shelf areas, this strong reflector is lost because of multiple reflections on the seismic profiling record. Obviously the sediments constituting layer M were deposited in a topographic depression, which was not greatly different in its depth and the configuration of its basin floor from that of the present Mediterranean. In fact, the geometry of the reflectors resembles that of a pelagic sediment. One of the main tasks of our cruise was to identify this reflector, and to find the cause of its lithification.

Sampling the M-Reflector

The M-Reflector had not been positively identified in the Alboran Basin. We were not ready to tackle this problem when we drilled our first Mediterranean hole at Site 121. This reflector was, however, very clear on our reflector profiles when we steamed to our next site (see Chapters 4 and 5). It was our first chance to determine the nature of the M-Reflectors, but we soon ran into mechanical troubles when our drill string got stuck at the level where we should have encountered the subbottom level of this reflecting interface. It was depressing that we had to move to a new site. Meanwhile, buckets of gravel had been delivered into the core laboratory having been pumped out of the plugged coring tube. On the morning of 24th August, as the drilling crew was lowering the pipe to drill the next hole, the co-chief scientists found relief from their normal duties and passed some free time by sieving and washing the gravel. As the pea-size fragments were sorted out, they discovered, to their surprise, that the gravel was odd indeed. The following components were identified: (1) basic volcanics, (2) pelagic limestones, (3) selenite crystals, and (4) a fauna of pelecypods, gastropods, and other shells. Since no quartz, feldspar, nor lithic debris of continental provenance were found, it was difficult to assume that the selenite crystals were derived from the evaporite formations of the Ebro Basin on the Spanish Coast. The size-sorting and the nature of the faunas all suggested deposition in shallow waters. The presence of pelagic limestone, grains and the absence of continental debris implied that an oceanic terrane had been eroded as the source of the clastics. The occurrence of the volcanics suggested that the nearby basement high, shown on the reflection record, was a volcanic island when regression of the sea led to its exposure. The dwarfed fauna and the presence of selenite indicated that the gravels had accumulated in a restricted environment after an epoch of evaporite deposition. Thus, the lithology of the odd gravel was sufficient ground for us to suspect the improbable—that the Mediterranean was a desiccated deep basin during the Late Miocene. However, most of us did not favor so dramatic an interpretation on the basis of such flimsy evidence.

By the evening of the 24th, the crew brought in the outer drill bit from the abandoned hole (122). Stuck between its teeth were bits of bedded gypsum, which was the first confirmation we had that an evaporite deposit is present under the Mediterranean. A correlation of the drill depth with the seismic record showed that this gypsum must have constituted the top of the M-Reflectors.

Our next hole did not hit the M-Reflectors, but we did hit the top of the volcanic island. The evaporites and older pelagic sediments above the volcano had apparently been removed to provide the source for the gravel.

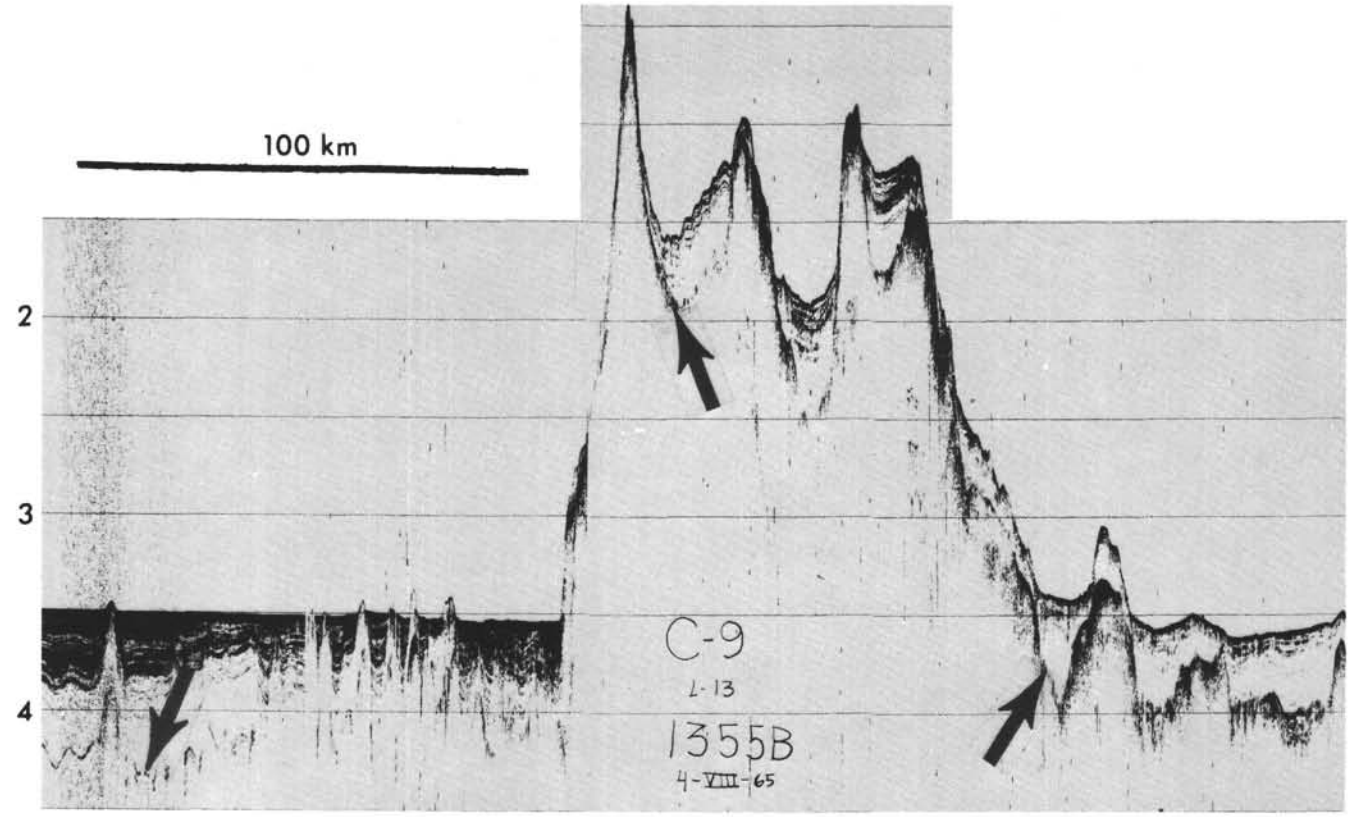

Figure 1. *Reflection profile depicting the continuity of Reflector M (arrows) and its relationship to the present sea bed. This reflector has been identified as the top of the Upper Miocene Mediterranean Evaporite. The air gun record from near the margin of the Balearic Basin which was made by the R/V* Robert D. Conrad *illustrates that the sea bed relief at the end of the evaporitic epoch was not too different than at present except for the absence of ponded turbidites. The growth of the diapiric intrusions seen at the left are clearly post Miocene in age and involve the piercement of halite through Horizon M into Pliocene and Pleistocene strata. Reflection time is in seconds (two-way travel time).*

As we steered our way through the Belearic Islands toward Site 124, we were already involved in a debate as to the origin of the evaporites, whose presence had only been established on the basis of gravel clasts and a bit sample. Ryan was in favor of a deep-basin hypothesis on the basis of his knowledge of the geophysical data. He gave us xerox copies of the recently published Schmalz (1969) article on the deep-water origin of evaporites. Pautot and Nesteroff favored a shallow-basin, shallow-water model, having apparently been influenced by the French school of thought on pericontinental flexures (see Bourcart, 1959). Those of us equally convinced by the geophysical evidence for a deep basin and sedimentological evidence for shallow-water deposition were forced to elaborate a desiccated deep-basin model.

Discovery of a Sabkha Facies

Drilling at Site 124 on the Balearic Rise soon established a firm correlation of the M-Reflectors with the Mediterranean evaporite. Having penetrated some 60 meters of this formation, we recovered many cores of anhydritic sediments. Their sedimentary structures are similar in all respects to those of recent and ancient sabkha deposits (see documentation in Chapters 6 and 22). Furthermore, the presence of anhydrite implies crystallization temperatures higher than those of deep-ocean waters. For those schooled in carbonate sedimentology, there was no longer any doubt that the evaporites were formed under a sabkha or in shallow waters. On the other hand, those who were familiar with studies of the Red Sea brines found the evidence less than compelling.

The desiccation model received a further boost when we recovered sediments containing abundant fresh- or brackish-water diatoms (see Chapter 34). A desiccated basin, isolated from the Atlantic, could be easily turned into a fresh- or brackish-water lake, if there had been an unusually high influx of fresh waters from surrounding lands. On the other hand, it was pointed out that the brackish-water diatoms could have floated about in a brackish surface layer. Only benthonic creatures could provide the critical evidence.

Cita offered another line of evidence in favor of the desiccation model when she discovered normal marine oozes between sterile evaporites in this Balearic Basin hole. Although the microfauna was less diversified than usual, the evidence was sufficient to prove that changes from evaporitic conditions to marine conditions, and vice versa, had been rapid and sudden. The paleontological criteria argued strongly against the deep-water model: How could we suddenly flush away all the brines of the Mediterranean and refill the deep hole with normal marine waters? At the same time, the facts also spoke against the shallow-basin, shallow-water model, for the oozes must have been deposited in an open sea of considerable depth where a normal marine planktonic fauna and flora could flourish.

Developing an Hypothesis

During the days when the *Glomar Challenger* steamed eastward, we had a chance to review our results. One of us would play the antagonist, the other the protagonist concering the desiccated, deep-basin model:

Q: If the basin had dried up, one basin full of seawater could not have deposited all the evaporites that we have in the Mediterranean.

A: The supply of salts undoubtedly relied not only upon the original basin full of seawater; the rivers as well as the several intervals of marine incursion must have brought in salts.

Q: If the basin had dried up, there must have been much clastic influx. Yet, we found very little terrigenous material in the evaporite sequence.

A: If the basin had been deep and had not dried up, we might expect the influx of turbidity-currents to have brought clastics into the abyssal-plain province. That we found no terrigenous clastics could be construed as evidence that the basin had dried up. Under the arid climate of a desiccated Mediterranean, debris from surrounding lands should have been deposited as alluvial fans at the foot of exposed continental slopes, and we should go there to look for it because little terrigenous materials would be transported across the flat plains of a dry lake (Figure 2).

Q: If the basin had dried up, we should have had carbonate precipitation. Yet, so far we have identified no carbonate minerals in the evaporite sequence.

A: Playa-evaporites are characterized by a bull's-eye pattern of zonation. The less soluble minerals, such as dolomite, should be found on the edge of an evaporating pan, and the most soluble minerals, such as halite and potash salts, should be present in the center (Figure 2). By drilling on the Balearic Rise we have hit mainly the intermediate zone of sulphate deposition. For halite, we must plan a drill hole on the Abyssal Plain. It was decided that perhaps we should check the cores of Hole 121 on the northern slope of the western Alboran Basin again, where we should have evaporitic dolomite.

Testing the Hypothesis

At this stage we took out the cores from that hole, and indeed found dense, primary dolomite in several sections of the Upper Miocene sediments there.

Our Italian shipmates called our attention to the similarity of our evaporites to the famous Messinian saline formation of Sicily, known locally as the *serie solfifera*

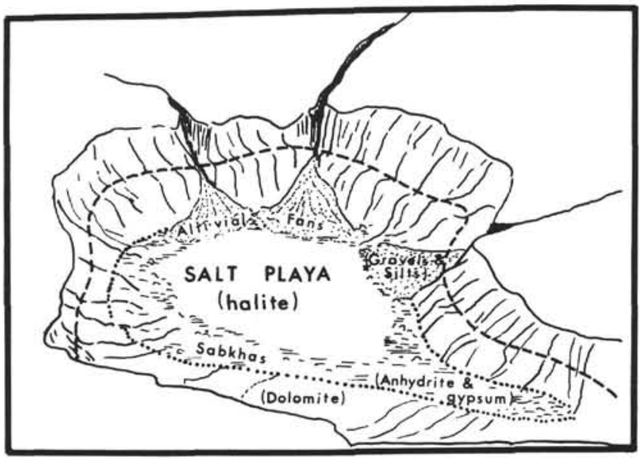

Figure 2. *Physiographic diagram portraying the bull's-eye pattern of facies distribution resulting from the desiccation of a deep basin. The dashed line depicts high-water stages when carbonates were precipitated. The dotted line delimits sulfate deposition.*

siciliana (Ogniben, 1957) or the *formazione gessoso-solfifera* (Selli, 1960). If our desiccation model was correct, the Messinian halite of Sicily should have been deposited in a dried-up marginal trench, rather than in a shallow basin, as commonly postulated. Such a suggestion was not unreasonable if we recall that the *solfifera* is localized in the "*avant fosse sicilienne.*"

The desiccation model would imply a sudden denudation of the basin and a rapid reestablishment of deep-marine conditions after the connection with the Atlantic was opened. Unfortunately, we missed strata recording this event in the Balearic Rise hole. However, the Messinian evaporites of Sicily are indeed transgressed by a globigerina ooze known locally as the Trubi formation. Ogniben apparently adopted the shallow-basin, shallow-water model to explain the origin of the *solfifera* and interpreted the Trubi as a shallow pelagic formation (1957, p. 258). Cita and our sedimentologist, Forese Wezel, regarded the faunal evidence there as being indicative of deep and open marine sedimentation. As we approached Site 125 in the Ionian Basin and scheduled continuous coring, we waited in suspense for evidence bearing on the termination of evaporite deposition in the eastern Mediterranean.

We again encountered considerable mechanical difficulties, but did manage to reach the M-Reflectors. Dolomite and gypsum were sampled, establishing that the M-Reflectors of the eastern Mediterranean constituted an evaporite formation like that of the west. Futhermore, we were able to make the time correlation of the Mediterranean evaporite with the *solfifera siciliana* of the Messinian stage because the evaporite deposition at both places of the Upper Miocene is succeeded by the open marine sedimentation of the lowermost Pliocene Trubi facies (see documentation in Chapters 40 and 47.1)

Search for Preevaporite Sediment

A further test for the desiccated deep-basin model depended upon a sampling of sediments older than the evaporites. We were frustrated in our attempts in Holes 124 and 125 to penetrate through the M-Reflectors. At site 126, we took advantage of the existence of a cleft in the Mediterranean Ridge, where post-Quaternary erosion cut through this layer. After penetrating rapidly through the soft fill of the cleft, we reached a Middle Miocene subcrop and sampled pelagic sediments of Serravallian age. We were eventually able to repeat the performance farther east at Site 129 on the wall of the Strabo Trench. The stratigraphical succession clearly indicated that the eastern Mediterranean topographic depression existed at least as early as Middle Miocene, when the basin was sufficiently deep to permit the deposition of an open marine facies. While the Middle Miocene Langhian sediments, subsequently found at Site 129, were deposited under conditions of free circulation, the Serravallian marls show signs of basin stagnation. This was due perhaps to the connection between the Mediterranean and the Indian Ocean being closed, and the Strait of Gibraltar getting narrower.

In Hole 129 we also cored sediments containing benthonic brackish-water ostracods of Messinian age. Since we might have drilled into a thrust zone or a melange there, the exact stratigraphic relation of this sediment with the Middle Miocene pelagic oozes could not be precisely determined. Nevertheless, the discovery of a bottom-crawling brackish fauna of the Messinian age dispelled any notion of a brackish surface layer above a brine pool; an eastern Mediterranean, filled with brackish water must have been completely isolated from the Atlantic. Our Italian colleagues recalled the existence of a brackish diatomaceous formation known locally as the Tripoli under the *solfifera siciliana*. It appears that after the Mediterranean was first separated from the Atlantic, the basin became brackish, when freshwater inflows apparently exceeded evaporation (Ogniben, 1957) or alternatively perhaps the Tripoli faunas are not reflecting brackish environments, but actually the initial salinity increase, since it is known that many oligotypical species also adapt ecologically to hypersaline or alkaline environments (see Chapters 36.2 and 40).

As we threaded our way again westward, we were convinced that the desiccated deep-basin model represented the only working hypothesis. The other two alternative ideas had already been set aside as untenable because of the evidence we already had. We only needed details to confirm and elaborate on, the picture. These details were to be uncovered in a rapid sequence during the last week of drilling.

Record of the Termination of the "Salinity Crisis"

At Site 132 in the Tyrrhenian Basin, we scheduled another hole of continuous coring. By then we were sufficiently experienced to choose a bit which gave us excellent recovery. Here we found positive evidence that the Mediterranean evaporite is Messinian. We also had a continuous section across the Miocene-Pliocene contact, and were thus able to reconstruct the terminating phase of the "salinity crisis." Above the gypsum and dolomite is a gray pyritic marl with intercalated silt which yielded a latest Messinian microfauna. The nature of the assemblage indicated the first return of marine waters, whose salinity may still have been somewhat other than normal. Directly above the marls is a "pseudobreccia", variegated in color, but mainly red and brown. Both, the "matrix" and the "clasts" of the "breccia" are a pelagic ooze and both include abundant lowermost Pliocene micro- and nannofossils (see Chapter 47). This breccia grades upward into gray oozes. The microfaunal succession in this hole is very similar to that of the Trubi in Sicily where the basal level is very rich in Sphaeroidinellopsis, spp.; is about 10 meters thick in both regions; and marks the lower boundary of the Pliocene. By now, we were able to conclude that the *solfifera* is not a local lagoonal deposit, but a part of the Mediterranean evaporite that was raised from the oceanic depths during the Plio-Pleistocene orogeny of Calabria and Sicily. The observations made on land are thus very relevant to our problem.

Continental Alluvium and Halite

It had been a troublesome problem that we had found no terrigenous clastics in the Mediterranean evaporite in the holes we drilled until then. The *solfifera* is known to have interbeds of a clastic facies, that includes silts, sandstones, and fanglomerates (Ogniben, 1957; Hardie and Eugster, 1971). The missing piece was to come to us in a dramatic fashion. At Site 133, we expected thin pelagic and evaporitic sequences above a volcanic basement and anticipated no difficulties in drilling. Yet, we found, under the thin veneer of Quaternary oozes, a variegated silt deposit, with scattered cobbles of phyllites and metagraywackes. One barrel after another of these barren sediments was hauled on deck as we drilled some 200 meters without reaching the basement. Futhermore, the poorly consolidated silts caved in easily and we eventually had another stuck pipe. Although there was no fossil evidence, the seismic record suggested a chronological correlation of this terrigenous deposit with the Mediterranean evaporite. We believed that we had finally found a clastic facies of the Messinian desiccation here in the lower reaches of the continental slope some 80 km from the west coast of Sardinia. These nonmarine variegated sediments could very well represent the floodplain silts and channel gravels on the rim of the Late Miocene Balearic salt pan.

Time was getting short for our port call at Lisbon. We would have liked to sample a piece of halite. Our model predicted that we should be able to reach halite if we could locate a site on the abyssal plain. The diapiric structures looked attractive, but were quite reasonably considered "forbidden fruit". Besides, drillers more experienced than we expressed skepticism that one could penetrate a halite formation through open-hole drilling and also that one could bring up a piece of halite before it dissolved in the circulation drill fluids. Futhermore, we had another more urgent objective, to determine the nature of the non-magnetic basement ridge under the western Sardinia slope.

We were lucky to find the Miocene-Pliocene contact in our seventh core at Site 134, for our odds were only one in three because of spot coring. But we were lucky indeed that we chanced upon halite at one of the few places in the Mediterranean where it could be reached by the drill string. The salt crystals from beneath the abyssal plain confirmed the "bull's-eye" distribution pattern of the Mediterranean evaporite and provided a logical explanation of why the diapirs had only been detected under the abyssal plains (Figure 3). In addition, we found an open marine foraminiferal ooze between two halite layers, with no transitional shallow-marine deposits.

The Gibraltar Floodgate

The only rational answer, it seemed to us, was to assume that the Strait of Gibraltar behaved like a floodgate.[2] When the gate was closed, the abyssal plain was a playa lake, but it would become deeply submerged as soon as the gate was temporarily opened. The floodgate was opened and shut repeatedly during the Late Miocene and was swung free for the last time near the end of the Miocene, permitting the deposition of the pyritic marl at Site 132. At the beginning of the Pliocene, the gate was crushed and all barriers were removed, and Mediterranean topographic depression was to remain a part of the world's ocean system to the present day. A "sudden-deluge" model seemed incredulous. Yet, the alternative was to adhere to the shallow-basin model and to postulate catastrophic basin-wide subsidence of some 2000 meters in less than ten thousand years.

Looking Back

At the conclusion of our cruise, we were surprised that the answer to our manifold question was simple indeed, since we had found the key. It now seemed that the cause of the Pontian regression was subaerial exposure of the Mediterranean sea bed when the base level of erosion was dropped 2 km below the worldwide sea level; that the search for a marine Mio-Pliocene transition in the Mediterranean countries would be in vain, since the Mediterranean was then dry; and that the M-Reflectors correspond to an Upper Miocene evaporite formation, deposited as the Mediterranean was being desiccated.

After our return, we received warm correspondence from numerous colleagues in various different fields of specialization. Each had his own paradox that could be resolved through the desiccated deep-basin model. These different lines of argument will be discussed briefly in a later section, and some are found in Chapter 44 of this volume.

This historical account serves to illustrate the relevance of the drilling results to the question of the Mediterranean evaporite. Many readers may continue to remain unconvinced because the cadence of a narrative precludes a succinct analysis. Since the question is one of considerable importance, we would like to further develop our thesis by enumerating the arguments for and against each of the three alternative hypotheses.

[2]Although we use the expression Strait of Gibraltar here, and later throughout the text, we are not certain if the western opening to the Atlantic had the same course as the present Gibraltar, whose existence could only be ascertained back to the beginning of the Pliocene. However, in order to facilitate our discussion, we shall use the abbreviated expression, Gibraltar, to denote the late Miocene connection opening to the Atlantic, and do not hold the view that the Late Miocene Strait was situated exactly where it is now.

THE CASE FOR DEEP-BASIN DEPOSITION

Deep-Basin Model

Quoting R. F. Schmalz, "There are no active deep evaporite basins today," (1969, p. 822). He nevertheless proceeded to formulate a most elaborate hypothesis for deep-water evaporite deposition. What motivated him and others to choose such a radical avenue? An analysis of their writings revealed that their hypothesis is based upon considerable evidence for the existence of deep, evaporite-depositing basins, and a tacit assumption that water level within such topographical depressions has always been at or near worldwide sea level.

The case for deep-basin salt is convincing. A most critical argument is derived from a consideration of the rate of salt deposition as compared to the possible rate of basin-floor subsidence.

> The problem imposed by this relation can be clarified by consideration of the Zechstein deposit of Germany, which contains 1195 meters of evaporite salts. The average rate of deposition inferred from stratigraphic evidence is 10 mm per year. If the basin floor subsided at a rate comparable to that of a geosyncline, 0.1 mm per year, the initial depth of the Zechstein Sea apparently could not have been less than 1185 meters, or slightly less than the mean depth of the Mediterranean Sea today. Even if the rate of subsidence were more that 15 times as great as the post-Miocene subsidence of the Gulf Coast Geosyncline, the thickness of the Zechstein deposit would require a basin not less that 600 meters deep initially. [Schmalz, 1970, p. 80l].

Schmalz's arithmetic is impeccable. But what about his "stratigraphic evidence"? The evidence lies in the occurrence of "varves" in evaporite sequences. Commonly, the varves consist of an alternation of halite laminae, centimeters thick, and anhydrite-carbonate laminae, millimeters thick as in the Zechstein (Richter-Bernberg, 1950) or in the Devonian Prairie Evaporite (Wardlaw and Schwerdtner, 1966). Rhythmic alternations of halite and sylvite (Fiveg, 1955), anhydrite and carbonate (Udden, 1924; Richter-Bernberg, 1960), or of other sediment pairs (Bourchert, 1959, p. 14) are also known. Practically all workers familiar with these sediments tend to regard them as seasonal varves, with Richter-Bernberg being their most enthusiastic advocate. Both he and Udden recognized not only annual rhythms in individual laminae, but also 11-year sunspot cycles in groups of laminae. Although a few authors did seek other explanations (e.g., Fulda and Rohler, 1921; Vortisch, 1930), their arguments proved contrived and unconvincing, as discussed by Lotze (1957) and by Bourchert (1959) in their excellent reviews of the question. In fact, Bourchert, after a painstaking consideration of the pros and cons, stated almost unequivocally that the Zechstein salt basin must have been deep when salt deposition first began.

Paleogeographical reconstructions also yielded evidence that evaporite basins represented topographical depressions of considerable depth (e.g., Adams, 1944; King, 1947, for the Midland Basin; McCamie and Griffith, 1967, for the Devonian Basin of Alberta; Peterson and Hite, 1969, for the

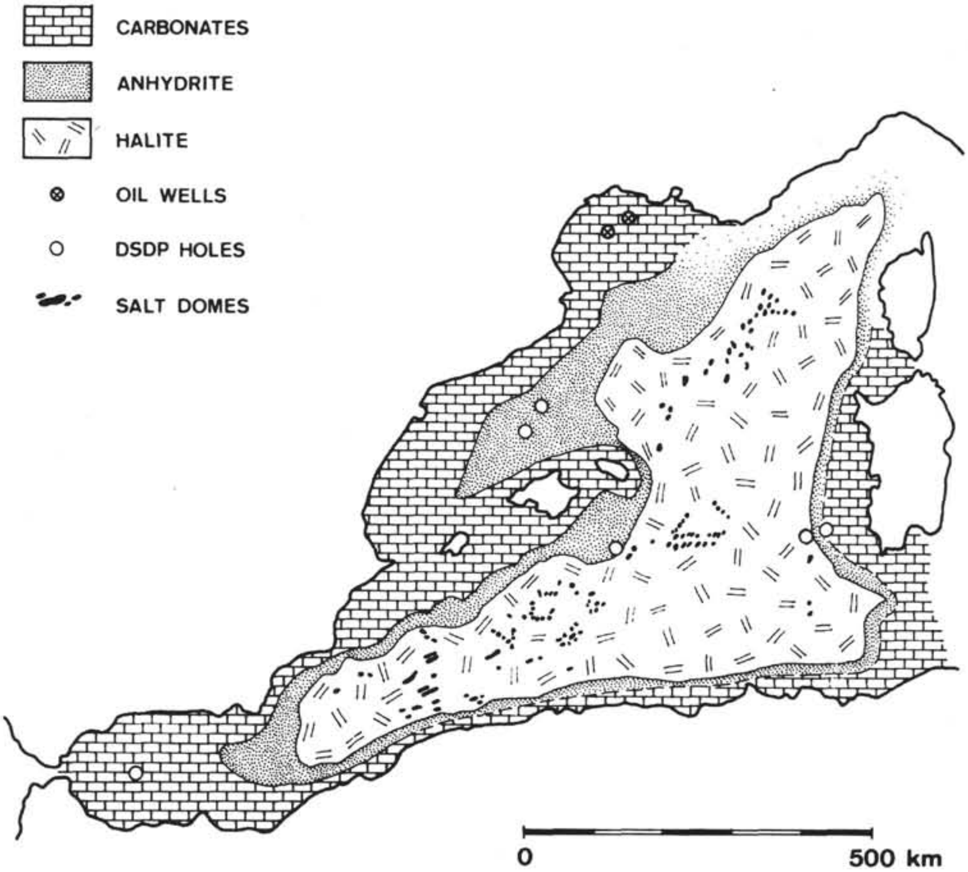

Figure 3. *Inferred facies distribution of the Mediterranean Evaporite in the Balearic and Alboran basins.*

Paradox Basin). Stratigraphic records afforded additional clues. Ancient salt deposits commonly include intercalations of euxinic sediments, such as black shales, which could be considered evidence of deep-water deposition (e.g., Schmalz, 1969; Peterson and Hite, 1969). It seemed reasonable to assume that salts were deposited in the same deep depressions as the intercalated deep-water sediments.

Finally, a most persuasive argument for the deep-basin hypothesis was furnished by the results of DSDP Leg 1 when the existence of a salt formation under the Gulf of Mexico was proven for all practical purposes (Ewing, *et al.*, 1969). Since the Gulf of Mexico is underlain by a thin oceanic crust, isostatic considerations demand that the floor of the salt-depositing basin should have been thousands of meters below sea level, unless the crust had been thinned or "oceanized" by some unknown process after salt deposition there.

Thus it seems that we have considerable evidence for the postulate of evaporite deposition in ancient deep basins. However, none of the criteria discussed above could be construed as an explicit indicator that these salts were deposited in deep *waters*.

The Late Miocene Mediterranean Basin

We could use the same classical arguments enumerated above as evidence for the deep-basin origin of the Mediterranean evaporite. For example, Ogniben (1957) recognized saline varves as well as intercalations of euxinic sediments in the *solfifera siciliana*. However, we need not rely on such somewhat controversial criteria. The Mediterranean evaporite is unique, we believe, because the topographical depression hosting the salt pans is still there, except it is now covered by marine waters.

As we mentioned, the geophysical evidence led us to conclude that the Late Miocene Mediterranean had a configuration not greatly different from that of today. The key was furnished by basin-wide distribution of an acoustic reflector (Figure 4, see also Wong and Zarudzki, 1969) which has been identified by drilling as the top of the Mediterranean evaporite.

There has been local deformation of the Mediterranean evaporite. The evaporites of Sicily (*solfifera*), of Marche-Abruzzi, of Crete, of Cyprus, etc., may represent uplifted segments of the evaporite formation in regions of active Plio-Pleistocene tectonics. Elsewhere, the evaporite may have subsided under isostatic load. Yet a careful study of the seismic profiling records revealed no evidence that the evaporite was deposited on a shelf near sea level and was downwarped or downfaulted to its present depth. In fact, as illustrated by Figures 1 and 5, the reflector conforms more or less to the contours of the intricate submarine topography, indicating that the Mediterranean basin had already been created when the evaporite was being deposited.

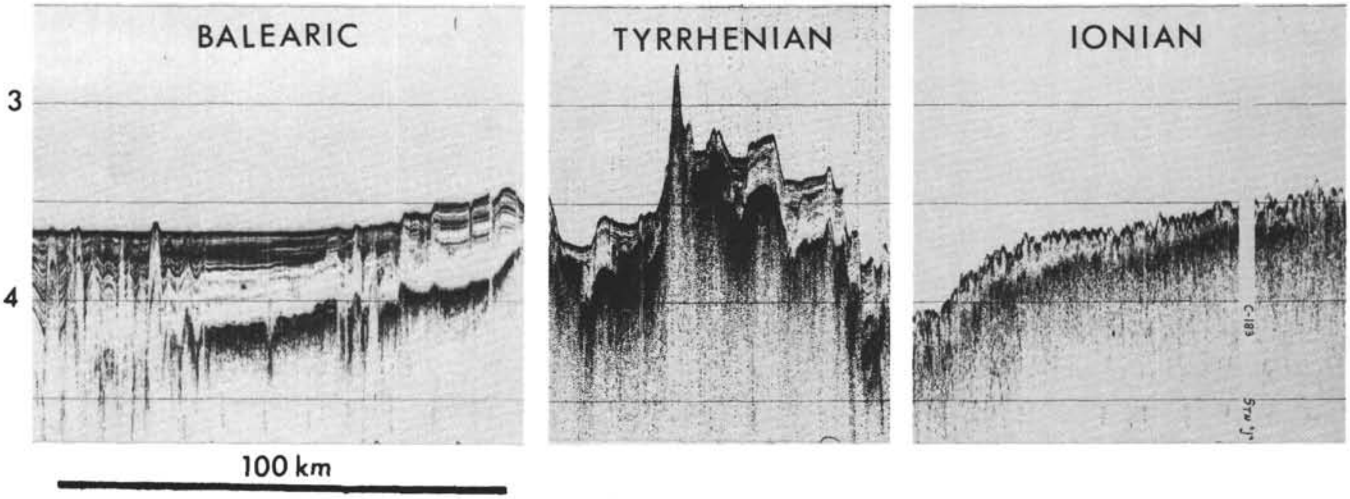

Figure 4. *Idealized distribution of evaporite facies in a partially enclosed basin, after Schmalz (1966), illustrating a teardrop pattern with the most soluble salts at the distal end of the basin.*

The available stratigraphic record clearly indicates that a deep-marine Mediterranean Basin existed prior to, during, and immediately after the epoch of evaporite deposition. Pelagic sediments older than the Mediterranean evaporite have been found at Sites 126 and 129 in the eastern Mediterranean as well as in the islands of Gavdhos and Cyprus, and turbidites have been found on Cyprus (Weiler,

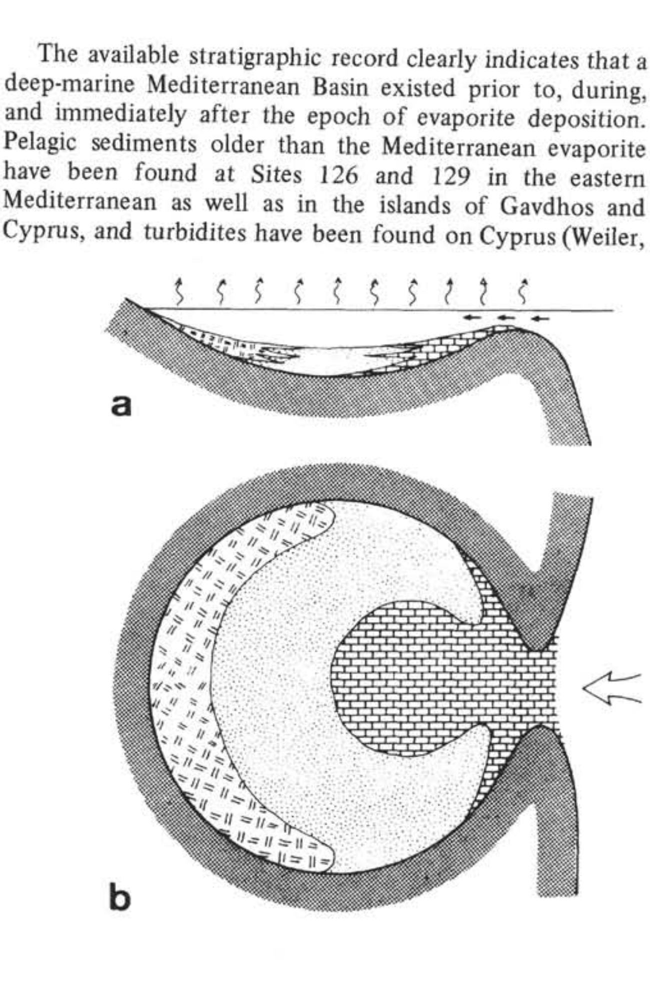

Figure 5. *Correlation of the pan-Mediterranean Reflector M, as illustrated in three segments from the* Robert D. Conrad *profiling record; each from a different basin. Vertical scale is in seconds (two-way travel time), and vertical exaggeration is ≈ 55:1.*

1970). Deep-marine middle Miocene pelagic sediments are also known on the Island of Pianosa in the western Mediterranean (see Dallan, 1964). Pelagic oozes of Late Miocene age have been found intercalated between the anhydrite at Site 124 and between the halite at Site 134. Finally, the sediments directly overlying the evaporite are pelagic oozes.

Depositional Environment of the Post-evaporite Strata

Pelagic oozes are also intercalated with, and immediately overlie, the solfifera. The base of the Pliocene Trubi marks the end of evaporite deposition. Ogniben (1957) and Hardie and Eugster (1971), among others, regarded this pelagic ooze, as relatively shallow marine shelf deposits, using the time-honored argument by Walther (1897) that pelagic sediments do not necessarily indicate deep water. Yet, neither a shelf fauna, nor any feature of shallow-water sedimentation was ever found in any of the oozes below, above, and intercalated with the Mediterranean evaporite. These pelagic oozes are no different in their general sedimentological and paleontological aspects from those deposited in the deep Mediterranean today.

Our confidence was further bolstered by Benson's study of the habitat of the marine ostracod fauna in the earliest Pliocene ooze. He (1971, p. 114) reported:

> Three diagnostic species of "bathyal" psychrospheric (deep-sea) ostracods were found in the Pliocene and lowermost Pleistocene strata of a core (DSDP Hole 132) obtained from the floor of the Tyrrhenian Basin. This particular deep-sea assemblage is most likely to occur living in the open ocean at depths between 1000 and 1500 meters (bottom temperatures between 4°C and 6°C). It is known from outcrop sections of Neogene age in Italy and Crete and is believed to have become extinct in the Mediterranean during the early Pleistocene (Calabrian) . . . [This] discovery . . . suggests that in the past the opening that now forms the Gibraltar sill was much deeper and wider. The fact that the oldest of the Pliocene specimens in DSDP Hole 132 were only a few meters above a Messinian (upper Miocene)

evaporite sequence suggests that radical changes in threshold depth in the western opening took place in a very brief geologic time span.

Benson related the extinction of the deep-sea ostracods in the Mediterranean to the shoaling of the Gibraltar Strait during the Pleistocene when the deep and cold Atlantic waters could no longer flow across the sill; the present minimum bottom temperature of the Mediterranean is 13°C, considerably above the tolerance limit of the psychrospheric fauna. For a few million years during the Pliocene, however, not only the sill, but the Mediterranean basin itself must have been deep enough to permit a population of such deep-living creatures to exist.

Foraminiferal evidence is in direct agreement with that afforded by the ostracods. The occurrence of the deep-water planktonic species *Sphaeroidinellopsis* as the dominant component (up to 90%) of the microfauna supports our postulate for a deep Mediterranean in the earliest Pliocene (see Chapter 47).

We have also tried to study the problem by the stable isotope method, but the results are not conclusive because of the inherent difficulties involved in translating oxygen isotope values into paleotemperatures. However, if the Pliocene Mediterranean sea could be assumed to have the same isotopic composition as the Atlantic Ocean, the average Mediterranean water must have been very cold (12°) and thus must have filled a deep basin (see Chapter 30).

Another line of evidence for the existence of a deep late Miocene Mediterranean basin was presented by Parea and Ricci Lucci, members of the staff of a school where our desiccation model was not accepted. They (1971, p. 75) reported, "The evaporites (of the Peri-adriatic Trough—eastern Emilia, Romagna, Marche and Abruzzi) underwent repeated gravity displacement by submarine slides and turbidity currents and are preceded and followed by terrigenous facies of considerable depth, both turbiditic sands and normal pelagic muds . . . " They added that the turbidites are interbedded with "laminated gypsum and pelites which were deposited in place". We gladly accept their conclusion that a deep peri-Adriatic Trough existed during the Late Miocene. However, we do not agree with their presumption that the deep basin was always covered by a body of deep water. The evidence they presented only proves turbidite sedimentation in deep water and hence the existence of a deep basin, but does not negate our contention that the deep basin could have been desiccating, when the laminated gypsum was deposited.

THE CASE AGAINST DEEP-WATER DEPOSITION

Based on the assumption that the "marine evaporites" had a restricted connection with the oceans, it was tacitly assumed that evidence for deep-basin sedimentation constituted evidence for deep-water evaporite deposition. The discovery that salt domes may exist under the deep waters of the Gulf of Mexico gave further impetus to the idea that evaporites could be crystallized out from supersaturated brines filling a deep basin. Earlier models proposed by King (1947) and Scruton (1953) did not particularly advocate evaporite basins of great depth and both presumed a continuous outflow, or "reflux", of high-density brines along a basin floor. These models were recently modified by Schmalz (1969), who became a champion for deep-water evaporites. His model demands particular attention because the geographic and climatic environment of the present day Mediterranean was considered a representative setting for the formative stage of an evaporite basin. An analysis of the applicability of this model is thus particularly relevant, although many of our arguments could also be applied to discredit other deep-water models.

Water Mass Budget

The Mediterranean Sea, exclusive of the Black Sea, has an area of 2.5 million km^2, and a water volume of 3.7 million km^3. The water balance can be stated in the following equation (Lotze, 1957, p. 142):

$$E - (P + R) = I - O$$

where

- E, the annual volume loss by evaporation, is 4.69×10^3 km^3.
- P, the annual precipitation, is 1.15×10^3 km^3.
- R, the annual volume delivered by river inflows, is 0.23×10^3 km^3.
- I, the estimated inflow from the Atlantic, is 55.2×10^3 km^3.
- O, the estimated outflow to the Atlantic, is 51.89×10^3 km^3.

The evaporative loss of the Mediterranean amounts to 3310 km^3 annually; this loss is compensated for by inflow from the Atlantic.

If, for some reason, evaporative loss should become more severe, or the basin should become more restricted, the Mediterranean waters would become increasingly more saline; surface water, particularly in the more distal parts of the basin, would become sufficiently concentrated to allow the surface precipitation of gypsum (Schmalz, 1969, p. 804). Meanwhile, heavy brines would sink to the bottom and eventually the basin would be filled to its sill depth with a brine saturated with gypsum. Gypsum crystals would continue to sink and accumulate on the basin floor while the dilute brine produced at the surface would "float" out of the basin above the deeper, denser brine. With increasing salinity, conditions for halite deposition would set in. Evaporite precipitation would only be terminated by a major change in geography, in climate, or after the basin had been completely filled up.

This model is completely hypothetical. No such deep-water evaporite basins exist, unless we consider the Red Sea, where anhydrite has been deposited in local pockets of trapped brines. The genesis of the Red Sea brines and evaporites is closely related to hydrothermal activities (see Degens and Ross, 1969), and the Red Sea model of local deposition could hardly be applied to explain the thick and extensive Mediterranean evaporite. Yet, the simplicity of the deep-water model, and the logical arguments so very elegantly advanced by Schmalz, had gained him many adherents, including one of us. It seems attractive because one need not postulate vertical movements of large magnitude since the late Miocene. Secondly, the problem of supplying marine waters for salt deposition and of disposing of the residual brines is neatly solved. However, the model has some inherent difficulties even in its theoretical aspect.

The present Mediterranean has been considered to represent the formative stage of such an evaporite basin. Yet the inflow of Atlantic and river waters and the outflow of brines through the Strait of Gibraltar have apparently kept this inland sea in a steady state for millions of years to allow normal marine sedimentation since the beginning of Pliocene. What has kept the Mediterranean from evolving into a brine-filled basin such as Schmalz postulated? Would we need an increasing rate of evaporation? Or, should we reduce the freshwater inflow from rivers? Schmalz's model is qualitative; he presents no compelling physical arguments why the Mediterranean should not be forever arrested in its present "formative stage" as long as a Strait of Gibraltar is there.

The deep-water model could also be questioned on hydrodynamical grounds. What are the effects of convective transfer, bottom currents, turbidity currents, or upwelling on the hydrology of such a basin. Could dense brines ever really be trapped in a basin as large as the Mediterranean? If so, could such a brine ever become so saline as to permit halite deposition? Finally, could the water level within the evaporating basin be kept at the worldwide sea level to permit the reflux of brines?

These theoretical questions have no easy answers. However, the geological implications could easily be tested by our drilling data.

Distribution Pattern

The distribution pattern of the Mediterranean evaporites is not at all what has been predicted on the basis of a deep-water model. In an excellent review, Schmalz (1970) pointed out that such a model would result in a tear-drop lateral distribution pattern (Figure 5), rather than the bull's-eye pattern typical for the salina type of evaporite deposit (Figure 2). The latter is well known (Hunt *et al.*, 1966; Jones, 1965; Hardie, 1968). A gradual desiccation of a playa would result in concentric zones of evaporite distribution—the outermost carbonate being the first salt to precipitate from a brine, and the inner core the most soluble salt. In contrast, a restricted marine basin with an opening at one end would have less soluble salt deposited near its opening and the more soluble at its far end. Applying this concept to the Mediterranean, one would expect to find potash salts and halite in the eastern Mediterranean but only gypsum and/or dolomite in the western basins. The drilling results show no evidence of such a tear-drop pattern. In fact, drilling confirmed the suggestions of seismic profiling that halite lies in the deepest part of the deeper Mediterranean basins (Figure 3); for example, in Hole 134 under the Balearic Abyssal Plain, which is far closer to the Strait of Gibraltar than is Site 125 in the Ionian Basin where Miocene dolomite was found.

The sequential distribution of Mediterranean evaporites is also not like that predicted by the deep-water model. With a basin trapping increasingly saline brines, the vertical sequence would start with dolomite and/or gypsum, grading upward into the halite and potash salts. We found no indication of such a succession in any of the holes we drilled.

An evaporite deposited in deep water could be expected, like all other pelagic deposits, to have lateral continuity and to show all the sedimentological features of deep-sea sediments. Although some of the Mediterranean evaporite beds (e.g., the laminated dolomites) may have some lateral continuity and may have been deposited in deep water, other evaporite sediments (e.g., the nodular anhydrite) have sedimentary structures completely foreign to the deep sea.

The common absence of turbidites in the Mediterranean evaporite is also not what one would have predicted on the basis of a deep-water model. Mediterranean abyssal plains today are traps for turbidites (Norin, 1958; Hersey, 1965; Ryan *et al.*, 1965; Stanley *et al.*, 1970). There could be no good explanation why a deep-water Upper Miocene basin, surrounded by steep slopes and lands of high relief on all sides, would not receive turbidity currents. At least we could expect deposition from turbidity overflows or interflows even if the high density of the trapped brines should prevent such currents from continuing indefinitely as underflows. Yet, except for turbidites in pericontinental troughs in Italy and on Crete (Parea and Ricci-Lucci, 1971; Freudenthal, 1969), we found no Upper Miocene turbidites in the DSDP Mediterranean holes.

Our studies on the stable isotope composition of the evaporite minerals also argue against a deep-water basin model. From a single basin with trapped brines one would expect a relatively uniform chemical and isotopic composition of the brines. Yet, the isotope values for identical facies of anhydrite rock vary greatly from bed to bed; apparently they were not deposited from one huge, homogeneous reservoir of supersaturated brines (see Chapter 30), but from brine solution which varied greatly in time and space.

Consideration of the mineralogy furnished us with another argument to reject the deep-water model. The widespread presence of anhydrite in laminated and nodular forms is striking indeed if one recalls that anhydrite is the stable phase of calcium sulphate at temperatures much higher than those at the bottom of a deep ocean. Latest studies on the gypsum-anhydrite equilibrium gave a transition temperature of 58°C for an ideal solution, and a range of 25° to 40°C for brines supersaturated with calcium sulphate (Hardie, 1967). This equilibrium relation explains why recent "primary" anhydrite has only been reported from places like the sabkhas (supertidal flat) of the Persian Gulf (Curtis *et al.*, 1963), where ground temperatures above 35°C prevail. Indeed, thin anhydrite beds, up to 20 cm thick, of deep-water origin were found in the Atlantis II Deep of the Red Sea (Bischoff, 1969). However, the areal extent of these brine pockets is only a few square kilometers. Even the most optimistic of us would hesitate to postulate that the whole Mediterranean basin was filled up to the brim with hot water during the Late Miocene.

Brackish-Water Interludes

The paleontological evidence is even more condemning. Intercalated in the evaporites are fossil-bearing fresh- or brackish-water deposits. The occurrence of planktonic forms, such as the diatoms, in Hole 124 could be explained away by assuming the presence of a brackish-water wedge on top of the trapped brines, a somewhat shaky assumption when we consider the richness of the flora at a site very distant from any large river. The presence of benthonic forms, such as the ostracods in Hole 129A, left no doubt that the fresh or brackish water extended, at least at times, thousands of meters down to the bottom. A basin full of hot brine could not have existed then. That the Mediterranean could be temporarily turned into a fresh- or brackish-water lake (like the Caspian Sea) indicates that isolation from the Atlantic upon occasion must have been complete.

In summary, we repeat that speculative models of deep-water evaporites are not founded on compelling evidence. The available facts are not what could have been predicted on the basis of deep-water models. Several lines of critical evidence speak strongly against such models. Finally, we should not lose sight of the fact that the deep-sea models were specially tailored to rationalize the presence of evaporites in a deep basin. We cannot apply this hypothesis to explain any of the other geological data we gathered from the Mediterranean or have known from the circum-Mediterranean countries. On the basis of these considerations, we are convinced that the idea of evaporite deposition in deep-waters does not have to be invoked to explain the genesis of the Mediterranean Evaporite.

THE CASE FOR SALINA OR PLAYA DEPOSITION

Salina Model

The site of deposition of modern halites is commonly an embayment or a lagoon near the sea coast or a playa in an intermontane basin. It is interesting to note that halite is being deposited in the marginal lagoons of the Dead Sea, but not from the deep waters of its north and south basins (Neev and Emery, 1967). Modern salinas and playas are located in hot, arid regions. Water depth ranges from a few centimeters to a few meters, and emergent conditions prevail from time to time. During periods of emergence, the exposed salt flat is characterized by resolution, and by the new growth of clear halite replacing earlier chevron or zoned crystals (see Chapter 22.2). The moist salt surface further affords an excellent trap for windblown dusts.

Even advocates of deep-water model recognizes that ancient marine evaporite deposits are similar in their mineralogy and inferred depositional rate to modern salina deposits (e.g., Schmalz, 1969; Richter-Bernberg, 1960). The bulk of salina evaporites is halite and calcium sulphate (commonly anhydrite) with subordinate amounts of carbonate (commonly dolomite) and potash salts, and they are deposited at annual rates ranging from a few to 15 cm (Lotze, 1957).

These considerations alone would lead uniformitarians to adopt a salina model for the genesis of ancient salts. Why then should there be any misgivings? The main argument against the salina model is provided by the evidence discussed previously; that is, that ancient formations appear to have been deposited in preexisting topographic depressions of considerable depth. Few had recognized the flaw of the tacit assumption that a deep basin must hold deep water.

True, the intercalation of presumably deep turbiditic and euxinic sediments in an evaporite sequence provides evidence for deep-water deposition. However, these sediments are not evaporites even though they might locally include clasts of detrital evaporites (Parea and Ricci-Lucci, 1971) and could have been deposited in a different setting. The question of whether a particular body of evaporites has been precipitated from a deep body of layered brines or from a desiccating shallow pool must be settled through a study of the evaporites themselves.

In a recent article to advocate the shallow-water origin of the *solfifera*, Hardie and Eugster (1971, p. 188) cited several categories of sedimentological evidence to strengthen their arguments:

> Current activity is indicated, for instance, by halite cross-beds described by Dellwig and Evans (1969), biological activity by the presence of algal mats in gypsum-halite accumulations (Masson, 1955; Moore and Hayes, 1958), groundwater gradients by the growth of gypsum or anhydrite nodules at or near the water table (Kinsman, 1966; Hardie, 1968), and recycling by annual dissolution and reprecipitation (Eugster, 1970).

To this list, we might add the occurrence of oolitic carbonates (Stewart, 1954), of ripple marks in halite (Lotze, 1957, p. 206), the existence of salt-filled, polygonal, shrinkage cracks in associated anhydrite (Dellwig, 1968), and the evidence of solution and reprecipitation of halite under apparently emergent conditions (Fuller and Porter, 1969).

In fact, mineralogical evidence by itself would tip the balance in favor of the salina model. As we have discussed, the dominant sulfate in saline formations is anhydrite, the high-temperature form commonly found in sabkhas or salinas, but not gypsum, which is accumulating on the deep bottom of the Dead Sea (see Neev and Emery, 1967).

Certain deductions concerning brine depth can be made on the basis of the changing bromide content in halite layers, because progressive crystallization of halite leads to an enrichment of bromide in residual brines and thus to a corresponding increase of the bromide content in a halite crystallized from such a residual brine. After a given volume of salt deposition, the salinity, and consequently the bromide content of the residual brine in a shallow pond, should become greater than that in a deep pool. On the basis of this principle, Kühn (1955) devised a formula to relate the rate of increase of bromide in halite samples from a vertical profile to the depths of brines from which these halites were crystallized: the more rapid the upward increase in bromide, the less the depth of brine involved.

The applicability of Kühn's formula is uncertain, because of the possibility of brine influx during halite deposition. Nevertheless, computations rarely yielded indications of halite deposition from waters of great depth. For example, Wardlaw and Schwerdtner (1966, p. 337) found that halite from the lower part of the Devonian Prairie formation should have been precipitated from a brine pool with an initial depth of only 62 cm. They dismissed the calculated value as "unrealistically small", probably because they subscribed to the hypothesis of a deep-water evaporite basin.

Late Miocene Mediterranean Playas

The case stated by Hardie and Eugster (1971) for the shallow origin of the *solfifera siciliana* is very convincing and need not be repeated here. However, they could not know, and had no evidence to determine, where their sabkha was situated with respect to worldwide sea level, and they had no objection if we found independent criteria to place their "lagoon" and sabkha at the bottom of a deep pit thousands of meters below the geoid (Eugster, personal communication).

The mineralogical, petrographic, sedimentological, and geochemical investigations of the DSDP samples yielded convincing evidence of shallow-water evaporite deposition. The anhydrite in the Mediterranean evaporite is the calcium-sulphate formed by primary precipitation or by penecontemporaneous diagenesis, as is witnessed by the 60-meter section penetrated by the Balearic Rise hole. Secondary gypsum was encountered in holes at higher topographic elevations; such gypsum replaced anhydrite, probably on those parts of the sabkhas where diagenesis was caused by groundwaters at temperatures below that of the phase.

The petrographic criteria for a shallow-water or desiccation model have been documented in Chapters 6, 13 and 22. Structures, such as anhydrite in nodular, and "chicken-wire" forms, stromatolic laminations, etc., indicate deposition in supratidal and intertidal environments. Evidence for periodic subaerial exposures of the Balearic salt pan is provided by the occurrence of desiccation cracks, the intercalations of cross-laminated, windblown, foraminiferal silt, and by an observation that euhedral salt crystals have been partially replaced by clear and anhedral halite.

The results of stable isotope investigations support the hypothesis of playa deposition. Negative carbon isotope values were found in all evaporitic carbonates, suggesting the influence of freshwater influx into partially desiccated Messinian playas. Variations in oxygen isotope values of the Miocene anhydrite indicate that the sulfate was of both marine and freshwater origin (Chapter 30). The highly negative oxygen isotope values of calcite associated with gypsum bear witness to groundwater diagenesis. This interpretation has been further supported by chemical and isotopic analyses of the interstitial waters in the evaporites, and by the isotopic composition of the crystallization water in a gypsum sample (see Chapter 30.2); all indicate the influence of a significant freshwater influx during the Messinian desiccation.

The facies distribution, of the Mediterranean evaporite is consistent with our postulate of a desiccation model. Seismic reflection studies show that the salt domes of the Balearic Basin are largely restricted to the abyssal plain and the Rhone delta provinces (Figure 5); the latter was probably a part of the Late Miocene abyssal plain before it acquired its constructional topography after the deposition of Plio-Pleistocene submarine fan sediments (Menard *et al.*, 1965). Halite was cored at about 3220 meters below sea level in Hole 134 on the Balearic Abyssal Plain. Evaporite minerals less soluble than halite (anhydrite, gypsum, dolomite) were found in more peripheral holes at depths of less than 3000 meters below sea bed.

Apparently we can conclude that the chloride stage of evaporite deposition at the end of the Messinian did not begin until the water level was dropped down to 3000 meters, or if we make an isostatic correction for post-Miocene subsidence, down to 2000 meters below Atlantic sea level. We certainly need to drill more holes to map the facies boundaries, yet, the available data fit a bull's-eye pattern typical of saline deposition in totally enclosed basins (Figure 4).

The occurrence of terrigenous clastics in Hole 133 provided an additional clue (see Chapter 25.1). These variegated silts and interbedded gravels resemble continental flood-plain deposits, and may be compared to the alluvial-fan deposits of the *solfifera*, which have been described by Hardie and Eugster (1971).

The evidence for shallow-water deposition of the Mediterranean evaporite has been so clear that we have encountered hardly any skeptics among the sedimentologists who have examined the cores. A casual examination was sufficient to convince the majority of our friends of the similarity between the Mediterranean evaporite and the modern sabkha sediments. Yet, as we have shown, the evidence for a deep-basin regional framework is just as good. Confronted with these two sets of facts, we were forced to conclude that the Mediterranean evaporite was deposited from shallow-water bodies occupying topographic depressions thousands of meters below worldwide sea level.

A DESICCATED DEEP-BASIN MODEL

Material-Balance Considerations

If the Strait of Gibraltar were closed today, the present Mediterranean with its 3.7 million cubic kilometers of salt water would be evaporated dry in a little over a thousand years because the annual evaporative loss amounts to 3.3×10^3 km^3 per year. Shown in Table 1 are approximate values of major salts precipitated isochemically from one liter of seawater, and the corresponding thickness of evaporites that could be deposited by a basin full of Mediterranean waters (averaging 1500 m depth).

TABLE 1
Volumes and Thicknesses of Salts Precipitated (after Schmalz, 1969)

Salt	Volume in 1 Liter of Seawater (cm^3)	Volume in Average Evaporites (cm^3)	Thickness from 1500 m of Seawater (m)
MgCl	1.48	0.02	2.2
KCl	0.43	0.23	0.65
$MgSO_4$	0.94	0.30	1.41
NaCl	12.87	10.89	19.31
$CaSO_4$	0.59	4.29	0.89
$CaCO_3$+ $CaMg(CO_3)_2$	0.06	1.04	0.18

At Sites 124 and 132, we cored more than the 18 cm of carbonates and 89 cm of sulfates required from a single drying up of the Mediterranean. Even though our drilling technique did not permit us to penetrate more than a few meters of halite, the seismic evidence, as well as the stratigraphy of *Solfifera* suggest that the halite thickness might reach a few kilometers under the Mediterranean abyssal plains. Obviously, one basin full of the Mediterranean water was not sufficient to produce all the salts of the Mediterranean evaporite. The discrepancy is accounted for in the following ways:

1) **Mineral Zonation**. Assuming isochemical evaporation, three main stages of evaporite deposition should be recognized i.e., carbonate, sulfate, and chloride stages. Halite should be deposited in the deepest part of a salt pan. If halite deposition was restricted, for example to one-third of the basin area, three times the normal thickness, or some 60 meters of halite could be precipitated from one basin of Mediterranean water. This line of reasoning might explain an abnormally thick local occurrence. However, more than one basin full of water was necessary to supply the salts for regional deposits comprising hundreds of meters of carbonates and sulfates and thousands of meters of halite.

2) **Fresh Water Influx**. The present influx of the river waters to the Mediterranean is 0.23×10^3 km^3 annually (Lotze, 1957). The average salt content is uncertain; Clarke (1924) showed that the dissolved solid contents in rivers depend upon the climate ranging from about 0.1 g/l for rivers in very wet climate to 0.7 g/l for those in arid climate. Since the climate in circum-Mediterranean lands should have been rather arid, we might assume for sake of a simple calculation a salt content of 0.5 g/1. Recognizing that the duration of the Messinian did not exceed 2 million years (see Chapter 47), the total salt contribution during this epoch from the rivers would amount to less than 2.3×10^5 km^3. Distributed over an area of 2.5×10^6 km^2, the salts from rivers could form an evaporite 100 meters thick. These salts, from arid or semi-arid lands are, however, mainly carbonates and sulfates (Clarke, 1924). Much of the carbonates and some of the sulfates in the Mediterranean evaporite were probably brought in by river waters into an enclosed Mediterranean. Such contributions might also account for the fact that the average evaporite deposits have proportionally more carbonates and sulfates than one would expect from isochemical evaporation of seawater (see Table 1). Important as the river contributions are, they could not furnish enough chloride for a very thick halite deposit.

3) **Steady Seawater Influx.** We might assume that the Strait of Gibraltar was never completely closed during the Messinian. The influx of seawater found its way through a narrow strait and descended into the desiccating Mediterranean across a huge waterfall. Assuming this water had the same discharge rate as Victoria Falls (the largest waterfall in the world at present), or some 200 km^3 per year (see Keilhack, 1930), the influx would still be less than 10 per cent of the annual evaporative loss of 3310 km^3 per year. After one or two thousand years, the Mediterranean might reach a steady state when the basin would be desiccated in summer and partially covered with shallow water in winter. If this process had continued for half of the Messinian time, or some 1 million years, the total salt supply would amount to 6×10^6 km^3. This would result in a halite deposit more than 2 km thick. Such a model is more than adequate to take care of the material balance problem. However, geological evidence is not sufficient to support such an idea. Steady-state influx of normal seawater should bring in considerable plankton and other marine life from the Atlantic. Stella (1900) did describe marine microfossils from "*roccie a solfo*" in the *solfifera*, but it is not very clear whether these fossils are contained in the evaporites or if they are present only in intercalated marine marls. So far, hardly any marine fossils have been found in the evaporites of the DSDP cores, although foraminifera and nannofossils are common in interbedded oozes. The sterility of the evaporites seems to negate the postulate of a steady-state waterfall. Nevertheless, influx during the transient infilling or desiccating stages, may have been considerable (see section on "Final Deluge"), and such an influx may account for an appreciable part of the materials deposited.

4) **Periodic Seawater Influx.** The presence of marine intercalations in the Mediterranean evaporite proves the occurrence of periodic influx. However, some thirty full basins of marine waters would have to be postulated if they were brought in instantaneously and if one-third of the Mediterranean is underlain by 2 km of salt. How many times might the dried Mediterranean basins have been drowned during the Messinian by invasions from the Atlantic?

Unfortunately, we were not able to core a complete section of the evaporite in any of our holes, and thus we can not judge the exact frequency of Messinian marine incursions. The record of the Sicilian section, however, may yield the answer. Some eleven marly intercalations are present in the cores of the gypsiferous part of the *solfifera* (Ogniben, 1957, p. 114). It is not certain, but we believe that some of those intercalations might correlate with the pelagic oozes we encountered in DSDP holes. The marine microfauna described by Stella (1900), for example, came from such marl intercalations in gypsum. Assuming that all eleven marl intercalations were deposited during marine interludes, would the number of incursions suffice?

Possibility of Evaporative Loss During Filling

The total water influx of each marine incursion into a desiccated Mediterranean would have had to be greater than the basin volume unless the basin was filled up instantly. The excess would have been needed to offset evaporative losses during the transient stage of basin infill. As we shall enumerate later, it probably took one or two thousand years each time before the Mediterranean could be filled up again. The evaporative losses during those years would amount to one, or two, times the basin volume. In other words, the total water influx should be two or three times the basin volume, and the salt influx per refill should be two or three times more than the theoretical value given in Table 1. If the latter was the case, materials for a layer of halite 60 meters thick (20 m $\times$ 3) should be brought in by each refill. If this salt was laid down only in the deepest parts of the Mediterranean that had one-third of the total basin area, the basinal halite deposited by each marine incursion would reach 180 meters in thickness (60 m $\times$ 3), and an aggregate thickness of 2 km Messinian halite would require only eleven interludes.

In summary, the evidence seems to suggest that the thick halite layer, believed by us to exist under the Mediterranean, required repeated marine incursions to supply the chloride. Influx during infilling or desiccating stages must have contributed considerable salts. Freshwater influx can not account for enough chloride, but may explain the presence of relatively thick carbonates and sulfates.

History of Desiccation

Under present conditions, a closed Gibraltar Strait would lead to a complete drying up of the Mediterranean basins. The evidence from Sicily has been interpreted (Ogniben, 1957) to indicate frequent alternations between the brackish and nearly marine conditions in earliest Messinian times of Tripoli deposition before the basin desiccation produced the *solfifera* evaporites.

Assuming that the regional climatic conditions were not greatly different during the Messinian from what they are today, the presence of a brackish-water body in the Mediterranean basin requires a freshwater influx considerably more than that of the present. A survey of the geological literature suggests that such a large influx could have taken place; at least this idea can be entertained for the eastern basins.

It is well known to stratigraphers that a very large fresh- or brackish-water body existed in eastern Europe during the Late Miocene. This "lake" which can be traced on the basis of lacustrine sediments, extended from Yugoslavia to the Aral-Caspian provinces of USSR, and was so large that Gignoux (1960, p. 597) coined the term *lac-mer* to characterize its existence.[3] The last remnants of this lake are the Black and Caspian Seas of today.

If this *lac-mer* drained into the Mediterranean at an influx rate much greater than its evaporative loss, then the Mediterranean Sea could have been converted into a brackish-water lake when the Strait of Gibraltar was too high or too shallow to permit the inflow of Atlantic waters. The mechanism postulated to explain the alternation of marine and freshwater conditions of the Black Sea (Degens, Ross, Scholton, and other personal communications of work in press) could then be applied to explain the interbedding of brackish and marine sediments in the Tripoli. However, we can also entertain the idea that the euryhaline faunas of the Tripoli are recording the initiation of the "salinity crises", since, as mentioned earlier, many of the "so-called" brackish-water species are known to ecologically adapt to hypersaline environments as well. We note that the impoverishment of planktonic foraminifera occurs with the commencement of Tripoli deposition.

The change from brackish-water to supersaline deposition requires that the faucet be turned off, namely the influx from the *lac-mer* be stopped or drastically reduced. While the early Messinian restriction of the western entry might be related to uplift in the Rif-Gibraltar area, the clue for this later Messinian closing has to be sought in the mountain building records of Greece and Dalmatia. When the sum of freshwater supply and the trickle of seawater across the Gibraltar could no longer replace evaporative loss, desiccation ensued. It was interesting for us to find out from our colleagues that this phase of the Miocene coincided with major orogenic uplift of the Carpathians, which in turn would have provided the dam to block the outflow from the *lac-mer.*

Through our drilling efforts, we learned that brackish-water sediments occurred also at times in the Messinian other than the very beginning (i.e., the diatomaceous sediments of the Site 124 cores as discussed in Chapters 6 and 34). It seems that freshwater from the *lac-mer* had periodically managed to find its way to the various Mediterranean basins. We might entertain an alternative to the idea of a pan-Mediterranean great lake if we envision a chain of local inland lakes strewn across the depressed floors of the Mediterranean basins with water levels considerably below worldwide sea level. Deposition of lacustrine deposits at various sites may not necessarily have been synchronous since the existence of individual lakes would have depended upon complex drainage systems from the *lac-mer*, the presence or absence of connections with the Atlantic, and upon local climates in the isolated deep depressions.

Both stratigraphical evidence and material-balance considerations lead us to believe that marine waters crossed the Messinian Gibraltar Isthmus repeatedly. The influx never reached catastrophic proportions during the Messinian. There should have been times of complete isolation when sterile sediments were deposited. The cause of periodic influx is unknown. Worldwide eustatic sea level rise resulting from the desiccation of the Mediterranean should have been about 11 meters, enough to usher in a new epoch of influx if the Isthmus was only 10 meters high at the time of complete isolation. Or one might postulate eustatic changes caused by Late Miocene glaciation and deglaciation, which has been postulated on sedimentological evidence (e.g., Curtis and Echols, 1971). Or one could attribute the closing and opening of the floodgate to the complex interplay between orogenic uplift and erosion.

Upon isolation of a basin, carbonates would be the first to precipitate. The precipitation of calcium sulfate should begin after 68 per cent evaporative loss. By then, water level within the closed Mediterranean would have receded to a level down to the lower continental slope. Halite deposition would not have started until the pan was 90 per cent dry, when only the abyssal plain and perhaps the lower part of the continental rise were covered by the brines. This model can be used to predict the evaporite zonation in the Mediterranean.

The latest Messinian playa-bottom can be assumed to be represented by the top of Reflector M corresponding to the salt layer in the Balearic Basin, some 3350 meters below sea level. Since the post-Miocene infill of marine waters would have caused subsidence under load, we should reduce the

[3] It is interesting to note that earlier stratigraphers used the term "Sarmatian" to designate the fish-fauna of the Tripoli in Sicily (see de Stefano, 1918), yet more recent studies indicate that the Type Sarmatian actually predates the Messinian (van Couvering and Miller, 1971).

figure by a factor of one-third as an isostatic correction. In other words, playa-bottoms could then have been 2500 meters below the Late Messinian worldwide sea level. Using this approach we have computed that sulfate precipitation should begin when the water level was dropped to 1700 meters below the Messinian sea, or about 2500 meters below the present sea level, and that halite should precipitate at 2250 meters below the Messinian sea level, or be found at greater than 3000 meters subsea depth by drilling. We have not drilled enough wells to determine the boundary between the carbonate-sulfate zone in the Balearic playa. Hole 121 is the only hole in which sulfate is not encountered in the Upper Miocene, but the seismic record suggests that a large part of the Messinian has been removed by erosion (see Chapter 3). The sulfate-chloride zonal boundary has been roughly delineated by seismic profiling as well as by drilling: gypsum was sampled at 2300 meters in the Valencia Trough Hole; anhydrite was cored at 2650 meters subsea in the Balearic Rise Hole, and halite at 3220 meters subsea in Hole 134, spudded on the Balearic Abyssal Plain. These results are consistent with the postulated zonal boundary at about 3000 meters below present sea level.

Phases of a Desiccation Cycle

The model of progressive desiccation suggests anhydrite-formation on "sabkhas" and halite in salt lakes and/or on playas. However, there were periods of deep-water sedimentation during the Messinian. The brackish-water diatomites were probably laid down in a relatively deep lake, or *lac-mer*; the extremely fine horizontal laminations of these sediments indeed indicate accumulation on a quiet bottom (see Chapter 6). Some of the gypsum deposits in *solfifera*, particularly the reversely graded layers described by Ogniben (1955), might have been deposited in the deeper part of the salt lake when anhydrite was forming on the "sabkhas". We should recall that the Mediterranean salt lake was about 500 meters deep when the first anhydrite began to form on its peripheral shore flats, while at that time gypsum might have been precipitated in the basin center like the modern Dead Sea. Finally, deep-water sedimentation generally prevailed during times of marine submergence; pelagic oozes were laid down on the open-sea bottom while turbidites were accumulating in the nearshore troughs of Italy and Crete.

History of the Final Deluge

When the Gibraltar Strait finally opened at the end of the Miocene, Atlantic waters rushed into the dry Mediterranean. However, this influx of water probably did not constitute a catastrophic flooding because truly catastrophic floods reach speeds of tens or even hundred of kilometers per hour and often pave their paths with scattered boulders (Malde, 1968). We have as yet found no evidence for so dramatic an event. On the contrary, the end of evaporite deposition in Sicily was marked by the accumulation of a mollusk-ostracod coquina, up to 1 meter thick locally (*zone a congerie*), followed by a terrestrial clastic layer of variable thickness (*arenazzolo*). These transitional sediments are overlain by the Trubi ooze (Ogniben, 1957). At the neostratotype locality for the Messinian in central Sicily, the transition sediments include neither the *strati a congerie* nor the *arenazzolo*, but are represented by pyritic marls. (Selli, 1960).

The record of the Miocene-Pliocene boundary is not complete in DSDP Holes 125 and 134, where current action either prevented deposition, or removed sediments of the earliest Pliocene (see Chapters 7 and 15). We did note, however, the same pyritic marl in the uppermost Messinian as Selli noted in the neostratotype locality. Fortunately, the stratigraphy of Hole 132 records continuous sedimentation and permits a reconstruction of the dramatic event, which we shall call "the Final Deluge".

Immediately overlying a sterile dolomite is a 15-cm-thick unit of gray, pyritic marl with interlaminated terrigenous silt (Figure 6). The marl is definitely marine, but still carries a restricted microfauna of latest Messinian age (Chapter 13). Immediately above the marl is the truly open marine earliest Pliocene ooze, carrying a *Sphaeroidinellopsis* microfauna and psychrosphaeric ostracods.[4] The sediments of the *Sphaeroidinellopsis* Acme-zone are about 10 meters thick in Hole 132 and in Sicily, and are overlain by other oozes of Early Pliocene age.

The Gibraltar Waterfall

This stratigraphic evidence suggests that the filling of the Mediterranean was not a catastrophic event. Perhaps we should reconstruct the geological framework in the latest Miocene. The Mediterranean was separated from the Atlantic by an isthmus tens of kilometers wide. After long years of headward erosion a westward flowing stream might be turned into a tidal inlet, which eventually might have cut a gap through the divide. Unlike an artificial dam in which the first crack would precipitate a total collapse, the natural barrier might have remained effective to restrict the first inflow. The discharge rate would have been related to the width and depth of the gap. The first spillovers could have been only trickles, supplying salts to the evaporating pans east of the Strait. Eventually the gap would have widened and deepened. Atlantic waters flowing through the strait would have cascaded down the eastern escarpment as a majestic waterfall of saline waters. Still, the discharge rate would have been restricted by the dimensions of the Strait.

We have shown that even if the "Gibraltar Fall" had as large a discharge rate as the Victoria Falls of the Zambesi, the 200 km^3 influx would not have been sufficient to replace the evaporative loss. The latest Messinian waterfall must have had a discharge rate at least 15 times as great! Concurrent with the infill of the basin would be isostatic sinking; this process would increase the volume of the

[4] In contrast to the gray Trubi ooze in Sicily, the earliest Pliocene ooze in this Tyrrhenian hole is red. The red ooze is altered along veinlets to a sediment in pale brown color. Also, dark gray patches of irregular shape are present and separated from the red by sharp boundaries (Figure 6). We were first misled to interpret this sediment as a flat-pebble conglomerate. Yet we found that both the "matrix" and "flat-pebble" carry exactly the same microfossil assemblages. We now believe this sediment to be a "pseudo-breccia"; the breccia-like appearance might be due to changed colorations when this ooze was altered diagenetically by brines ascending from the evaporites below.

catchment basin and further delay the equalization of water levels. As long as the water level of the Atlantic and those of the various Mediterranean salt lakes remained unequal, the partially evaporated water from the Mediterranean could not return to the Atlantic. A microfauna might still survive in the somewhat supersaline waters, but both their numbers and diversity would be restricted. The fast currents of the inflow might have brought along terrigenous debris and deposited them as clastic interbeds. This period of sedimentation is perhaps represented by the gray pyritic marl of Hole 132 (Figure 6), and by the *zone a congerie* and *Arenazzolo* of Sicily. At the same time, channels would have been cut, draining the waters from higher salt lakes into lower ones, as the Atlantic waters would have found their way through the Balearic and Tyrrhenian basins into the Ionian and Levantine basins. This channel system of post-Miocene, pre-Pleistocene has been recognized in many of our seismic profiling records (Figure 7). In fact the cleft on the Mediterranean Ridge at Site 126, which cut through the Mediterranean Evaporite, might represent a deep canyon funneling the salt waters from the Ionian Basin to the Hellenic Trough.

While the basin water level rose, the erosion of the Strait might have continued and caused the retreat of the Waterfall. Since the upstream reservoir of a salt waterfall is for all practical purposes infinite and since its upper surface will not be depressed, downcutting of the sill leads to progressively greater discharge rates.

Time the Basin Would Take to Fill

A guess as to the duration of infilling can be made on the basis of the gray pyritic marl in Hole 132. The marl unit is 15 cm thick, of which some 5 cm are terrigenous silts. The microfauna is restricted to dwarfed forms (see Chapter 40), and productivity was probably less than normal. If we assume a low sedimentation rate (low for Mediterranean biogenic sediment) of 1 cm per thousand years, the infilling stage should have lasted some 10,000 years. This would mean a net annual gain of 400 km^3 water and would require the Waterfall at Gibraltar to have delivered some 3700 km^3 of Atlantic waters per year in order to make up for the evaporative loss.

This line of reasoning has a major flaw because the tolerance of marine life in supersaline waters is not unlimited. The preceding model suggests that some 80 per cent of the seawater influx should have been evaporated, leaving a brine almost saturated with halite behind. Obviously, neither the microfauna found in Hole 132, nor the mollusks and ostracods of Sicily could have survived in such brines. If we take the other extreme and assume that the influx rate was so much greater than the evaporative loss, that the average salinity of the Mediterranean was increased only 10 per cent (to permit the survival of shallow-marine faunas), an inflow rate of some 34,000 km^3 per year would be required, and the Mediterranean would be filled up in 100 years. Such a model would require that the gray pyritic marl of Hole 132 be deposited at a very high rate of 1 meter per thousand years.

The answer might lie somewhere between these two extremes. The Mediterranean is not a simple single drying dish, but consists of several hydrographic basins. It is

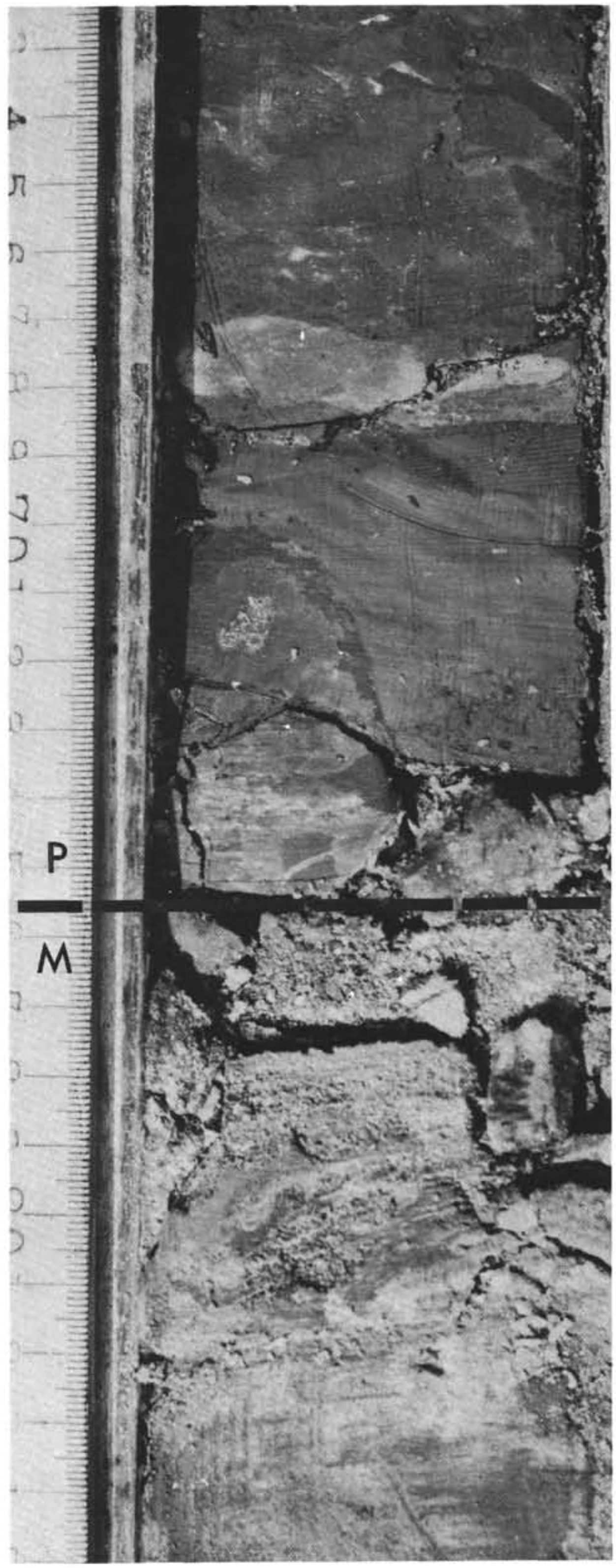

Figure 6. *Contact between the Pliocene pelagic ooze above and Messinian pyritic marl, cross laminated silt, and dolomite below in Hole 132 at 183 meters below bottom. This is reproduced in color in the frontispiece of this volume.*

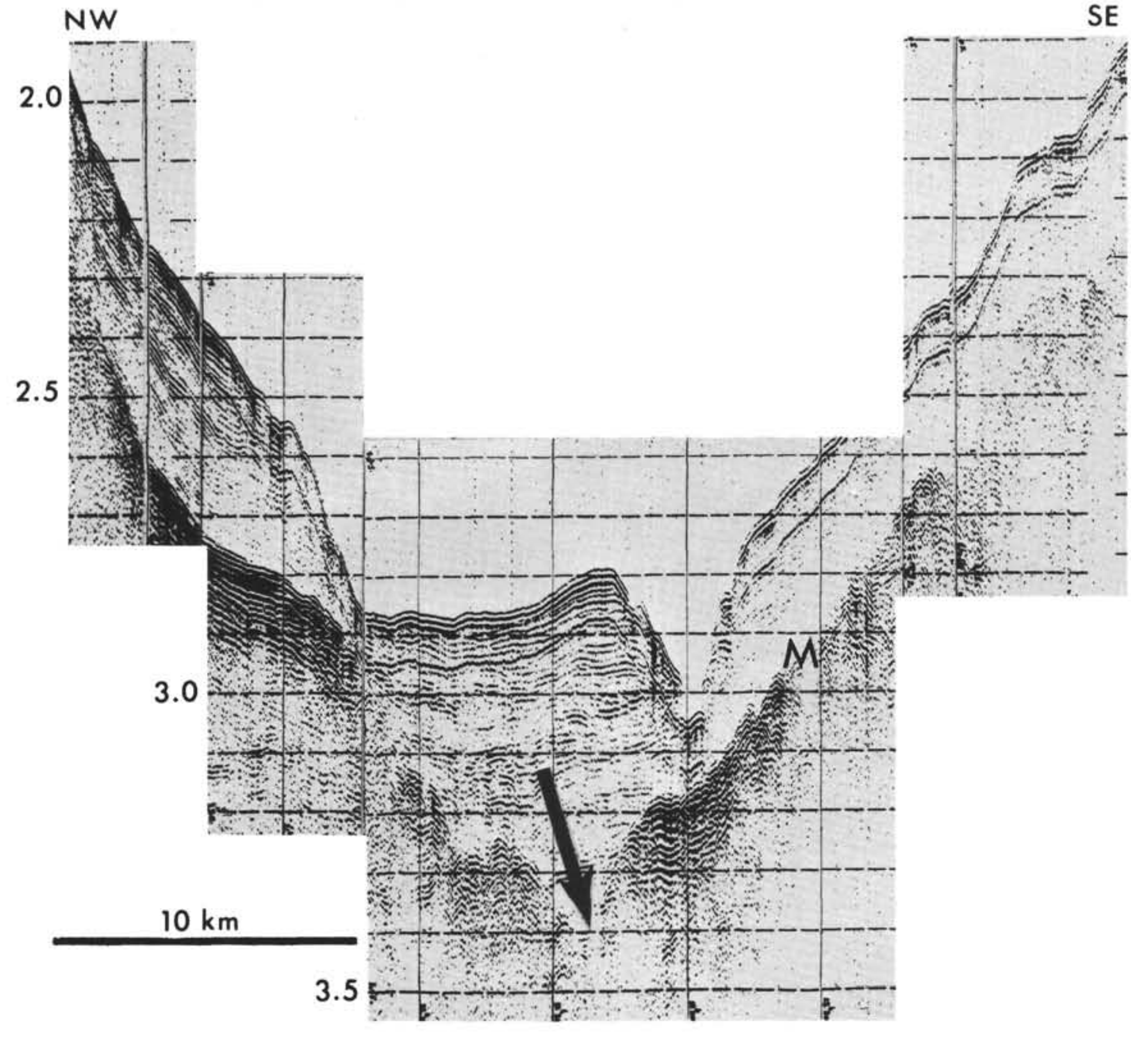

Figure 7. *Reflection profile between Sardinia (left) and Tunisia (right) showing an excavation into Horizon M inferred to have been produced by the exchange of flood water between the Balearic and Tyrrhenian basins. This record made in 1968 by the M/S* Amazon *is from Auzende (1969) and has a vertical exaggeration of* $\approx$ *30:1. Vertical scale is in seconds (two-way reflection time).*

probable that some of the supersaline brines in the west could find their way to the eastern basins, so that the Balearic Basin remained normal marine while the Ionian Basin was desiccating. Or, it could be assumed that the dense brines were trapped below the basin sills which permitted the survival of plankton in the nearly normal marine surface layer. These lines of reasoning could permit a range of models. One of these would require the filling of the basin in a thousand years or so. The inflow rate would have been about 7000 km^3 per year and pelagic sedimentation would have proceeded at 10 $cm/10^3y$. Such rates seem reasonable.

This type of infilling, by a waterfall descending from the Gibraltar Strait, must have also taken place during the Messinian to permit deposition of the intercalated pelagic oozes, and to supply chlorides for the evaporites. What distinguishes the "Final Deluge" from its predecessors is the fact that desiccating conditions were never resumed. Beginning with the Trubi, the Mediterranean has since been the site of normal marine deposition.

The Opening of a Deep Portal

At the beginning of the Pliocene, deep-marine waters from the Atlantic entered the Mediterranean, and open marine faunas and floras flourished in the Mediterranean waters. The implications are (1) the existence of a deep sill to permit the inflow of cold Atlantic waters, and (2) the equalization of water levels to permit return of the partially evaporated, and denser Mediterranean brines to the Atlantic. What was the nature and cause of the event?

One could postulate that the retreat of the "Gibraltar Fall" westward finally cut the last shallow barrier down to about 1000 meters below sea level. Or there might have been a tectonic event, such as rifting movement along the Azores-Gibraltar plate boundary, to produce a large gap. We have no evidence to reconstruct what exactly happened. Nor do we know how much of the basin was filled before the final breakdown of the Gibraltar Barrier. The evidence does show, however, that equalization of the water levels must have taken place at practically the same time as the invasion of deep waters, because the earliest Pliocene sediments give no evidence of restricted circulation; that is, the way for the brines to find their way back to the Atlantic must have been established as soon as the deep strait was opened.

The changed conditions seem to have resulted in a system of strong bottom currents in the Pliocene Mediterranean. These currents may have locally prevented the deposition of earliest Pliocene sediments and caused bottom erosion, as witnessed by the presence of Pliocene submarine channels and pre-Pleistocene unconformities (see Chapters 4, 5, and 6).

The Gibraltar sill must have subsequently shoaled enough to cut off the supply of deep Atlantic waters, leading to the extinction in the early part of the Pleistocene of the cold Mediterranean benthonic fauna, such as the psychrospheric ostracods (Chapters 36 and 47). Yet, the Strait is still open enough to permit the reflux of partially evaporated waters so as to keep the salinity of the Mediterranean only slightly above that of the open ocean.

IMPLICATIONS OF A DESICCATED MEDITERRANEAN

A good theory has many attributes. First of all, it has an ability to predict. The finding of halite in Hole 134 fulfilled our prediction that such soluble salt would be found in the deepest part of the evaporating basin.

The desiccated deep-basin model has also proved its worth through its ability to correct omissions in data gathering and to sort out errors in data analyses, for these omissions and errors were very conspicuous contradictions of our theory. On board ship we were puzzled by the apparent absence of carbonate minerals in the Mediterranean evaporite. We found gypsum and anhydrite, but not dolomite, which is almost ubiquitously associated with calcium sulfates. We did note the presence of a very fine-grained mineral, which was tentatively identified as an "oolitic anhydrite", based on visual comparison with a photograph in some publication. The question was raised: how could a body of water evaporated to dryness fail to precipitate any carbonate?

As mentioned, one explanation was provided by the zonal distribution of saline minerals. We searched and found evaporative dolomite in the Alboran hole that had been overlooked. Still, the apparent absence of carbonates in other holes continued to puzzle us, until X-ray analyses by Nesteroff in shore-based laboratory study identified the so-called "oolitic anhydrite" as a very fine-grained dolomite (see Chapter 21), and thus an apparently serious objection to our model turned out to be based upon a mistaken mineral identification.

A good working hypothesis also has the ability to change a piece of apparently unfavorable evidence into a friendly witness. A fact which puzzled us greatly was the absence of clastic interbeds in the Mediterranean evaporite. After we found the floodplain silt and channel gravel at Site 133, we realized that our previous sites had been situated too far away to receive terrigenous clastics. Later we learned the existence of interbedded Messinian clastics and evaporites in the *solfifera siciliana* (Hardie and Eugster, 1971), in northern Italy (Giannini and Torgiorgi, 1959), in Spain (Rios, 1968), in the Mistral hole of the Gulf of Lyon (P. Magnier, personal communication), and on the Island of Crete (Freudenthal, 1969). Finally, even colleagues not sympathetic to our theory were able to furnish us a critical piece of evidence, the existence of Upper Miocene turbidites in the Marchi-Abruzzi evaporitic sequence (Crescenti *et al.*, 1969; Parea and Ricci-Lucci, 1971).

It should be emphasized that our model is not a specially tailored hypothesis, innovated only to explain the genesis of the Mediterranean evaporite. Adoption of the desiccated deep-basin model could interrelate many different facets of European geology. We would like, therefore, to explore some of the implications of a desiccated Mediterranean.

Pontian Regression

A desiccated Mediterranean implies a lowered base level of erosion, particularly for coastal streams of the circum-Mediterranean countries. Shelf seas should withdraw from continental areas. Coastal plains and newly exposed continental terraces should be dissected by rejuvenated streams. They should cut canyons of steep gradients, hundreds of meters deep into older marine sediments, and leave alluvial gravels and terrestrial clastics in these gorges. Such a stream system should be drowned during the "Final Deluge" of the earliest Pliocene.

In southern France a marine sequence, ranging up to Tortonian in age, has been cut by a deep channel system. The channels are filled with alluvial gravels, which, in turn, underlie marine Pliocene sediments. The event recorded by the channel cutting has been known to stratigraphers as the Pontian regression, and is described and discussed more thoroughly in Chapter 44.5. The exact age of the Pontian has been somewhat uncertain, but the documented channel cutting occupies the same stratigraphic interval as the Messinian. In hindsight, we might conclude that the geologic history of the Pontian regression in France is exactly what one could have prophesied if he had formulated a model of a desiccated Mediterranean. In fact, we later learned that the French geologist Densiot (1952) did formulate such an hypothesis without the benefit of drilling results.

Pontian regressions have also been reported from other circum-Mediterranean lands; but the details are less well known. For example, when oil geologists in Lybia found a system of Late Miocene alluvial channels cutting deeply into the Lybian continental margin down to a level of some 900 meters or more, they had to postulate a corresponding lowering of the Mediterranean. Nobody believed them, and their results did not find their way into publication until we welcomed the inclusion of their manuscript in Chapter 44.4 of this volume. Meanwhile, we received a communication from a Soviet colleague who indicated that the Late Miocene base level of erosion in Egypt and Syria was probably a thousand meters or more below present sea level (I. S. Chumakov, written communication, 1970) an observation in accordance with our hypothesis (see Chapters 44.2 and 44.3). The Pontian regression is also known on the Island of Cyprus; the Late Miocene erosion of the Troodos Massif might well be related in some way to the desiccation of the Mediterranean (F. Vine, personal communication).

We realize, of course, that many observations are yet to be analyzed properly or documented in print; new chapters can be written on "Pontian" geology. What is relevant to our argument is, however, the fact that the theory demands a Late Miocene circum-Mediterranean regression, and this regression did indeed take place.

Submarine Channels and Canyons

When the Mediterranean was desiccated, the river channels should not only have cut the shelf-margins, but they should have continued down toward the flat bottom of the Messinian playas, and extended 2000 to 3000 meters below present sea level. Extensive survey work has been carried out by the French in the Gulf of Lyon, south of France. Many submarine canyons have been found, with the channels directed to the southeast and cutting the seaward margin of the shelf. The slopes of the canyon floors seaward of the Gulf vary from 1:50 to 1:25, and are locally much steeper. Lacaze Duthier Canyon, which extends southeast from the western part of the Gulf, has been studied in detail (Bourcart *et al.*, 1948). The canyon was cut in Miocene limestones, then filled with Pliocene and Lower Quaternary marls and sands. The present canyon has been recut into Quaternary sediments. Farther east, the submerged continental margin is very narrow, and is dissected by numerous canyons and valleys, even steeper than those of the Gulf (Figure 8). In some instances the canyons strike east-west, parallel to the coast.

Eastward from Cape Antibes toward Genoa the morphology of the continental shelf and slope changes again. From the Ligurian Trough eastward, the continental margin may be divided into a narrow shelf (down to 500 m), a broad flat plateau (500-1000 m), and a steep slope (1000-2000 m) leading into the basin. The most striking features in the region are the two deep linear canyons extending SSW in the Ligurian Trough from Genoa into deep waters (2600 m).

Corsica is fringed on its north and west side by a submerged platform, 500 to 600 meters in water depth. Numerous submarine canyons with channels directed westward into the deep depression of the Ligurian Trough cut the western margin of this platform and extended down to more than 2000 meters depth. Dredging and coring have established that the sea floor on the margin contains a thick series of Upper Miocene limestones overlying metamorphic rocks (Bourcart, 1959). The submarine canyons of Corsica and Sardinia generally are continuations beneath the sea along valley courses established on land. The continental slope west of Corsica probably represents an erosional land surface, which was subaerially exposed during Miocene time, and has been modified by the invasion and trapping of marine Pliocene to Recent sediments in the topographic depressions.

The submerged continental margin of North Africa is narrow and is cut by numerous transverse canyons, many traceable to depths of 2000 meters and more (Bourcart and Glangeaud, 1954; Rosfelder, 1955). Most of the submarine valleys can be traced continuously into landward extensions. Bourcart and Glangeaud (1954) suggested that the canyons here were initially sculptured by subaerial erosional processes.

This brief outline of the morphology of continental margins around the Balearic Basin fulfills the prediction of the desiccated model perfectly. What is more amazing is the fact that this description is not a post-mortem account written after we had formulated the desiccated deep-basin model. These passages are taken almost verbatim from a dissertation one of us completed in 1969, a year before our cruise. Only the conjectural interpretations were left out. What were the conjectural interpretations before the Mediterranean drilling?

Bourcart (1959) pointed out that the morphology of the shelf and slope south of France dated from the Miocene. It originated prior to the Pliocene transgression. He also concluded that canyons and channels were largely carved by subaerial processes. Yet he could not then have had the hindsight that the whole Mediterranean had dried up. He could only postulate the less outrageous hypothesis that the circum-Balearic channels owed their present position to a down-bending (continental flexure) of the continental margin since late Pliocene time. Only a few (e.g., Denziot, 1952) considered the evidence sufficiently convincing to postulate a desiccation of the Balearic.

Although some of our French colleagues are still inclined to combine Bourcart's hypothesis with the shallow-basin, shallow-water model of evaporite deposition (see Chapter 21), the evidence we have discussed so far has led us to reject these ideas. In fact, the channel morphology and the gravel infill indicate that the gradients of the coastal streams were steep during the Miocene. If the Miocene salt pan was situated near present sea level, there would be no reason for streams on flat coastal plains to cut deep canyons and to deposit coarse gravels. Furthermore, if there had been downbending, the timing could not have been Pleistocene or Pliocene as postulated by Bourcart (1959) and Selli and Fabbri (1971). Even if the Mediterranean had been shallow in latest Miocene, the earliest Pliocene sediments from the western Mediterranean basins are deep, pelagic oozes. So, if these basins had subsided since the Messinian, the event had to be represented by the Trubi transgression at the beginning of Pliocene. Accepting the evidence of Benson (1971), the transition from the evaporites to Trubi would represent a basin-wide subsidence of 1000 to 2000 meters. The transitional period, as we discussed previously, is represented by some 10 cm of pelagic sediments, which might have been deposited in about a thousand years or less. This would require the Balearic sea floor to have sunk at an incredible rate of 1 or 2 km per thousand years. This is far greater than normal subsidence rates of ocean floors, which are in the range of centimeters per thousand years (see Menard and Ladd, 1963; Hsü and Schlanger, 1968; Maxwell *et al.*, 1970; Fox *et al.*, 1970). Even the local maximum rate of isostatic rebound in Fennoscandia reached only about 10 meters per thousand years (Gutenberg, 1941). A consideration of high viscosity of the asthenosphere would rule out this somewhat exaggerated postulate of catastrophic subsidence. Some of Bourcart's former students, who first clung to his hypothesis, are now persuaded by the merit of our desiccation model. Had Bourcart been alive today and had the facts which we now possess, we are convinced that he would have come to the same conclusions as we did.

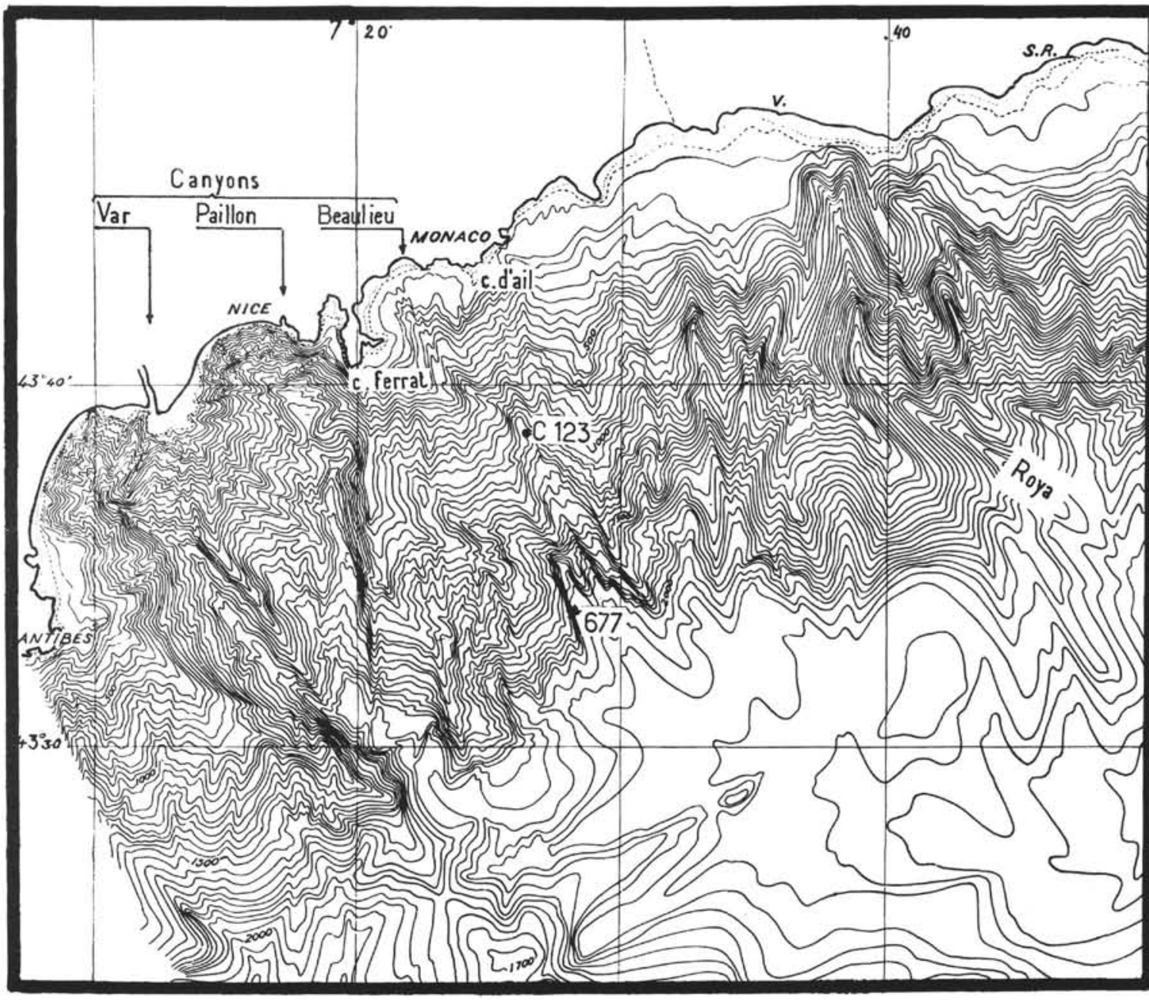

Figure 8. *Bathymetric contours depicting the canyon-dissected continental margin off the Cote d'Azur, France. From Bourcart* et al. *(1958) reprinted in Gennesseaux (1963).*

Submarine canyons exist on the continental margins of the Tyrrhenian and in the eastern Mediterranean basins also. Many of the canyons of the Tyrrhenian region seem to terminate at depths ranging from 1000 to 1500 meters. Ryan *et al.*, (1971) noted the presence of "numerous deeply incised canyons along the Malta Escarpment, which attest to periods of direct sediment-embouchment over the edge of the shelf". We now could postulate that these periods were times of Messinian desiccation. Steep submarine channels are present off the Levant coast. Goedicke (1971) traced some of these from the coast of Lebanon to a depth of some 600 meters, where his echo-sounder stopped sending back signals. Similar submarine valleys were found on the south side of Rhodes, Crete and around the island of Cyprus (Goedicke, personal communication).

In the Nile Cone area the Upper Miocene morphology is masked by a thick Quaternary deposit (Chapter 12), and is criss-crossed by a system of meandering deep-sea channels. These channels originate from the Alexander Canyon and then descend seaward to the Herodotus Abyssal Plain. Their present channel and levee systems were built in late Quaternary times and one can only speculate on their Late Miocene heritage.

We recognize that many of the Mediterranean submarine valleys registered on echograms are Quaternary, and some may not even have a Messinian history. We do not propose that the maximum seaward extension of these channels should be indiscriminately used to determine the level of the Messinian desiccation; we must consider the blanketing effect of the Pliocene and Quaternary sedimentary cover as well as changes due to tectonic movements, particularly in the Tyrrhenian, Adriatic, and eastern Mediterranean regions. At the same time, we should not lose sight of the fact that Miocene submarine channels do exist just as the theory would have predicted. A careful mapping of subsurface channels may yield useful data for the reconstruction of post-Miocene tectonic history.

Subsurface Solution

Subsurface dissolution of carbonates and sulfates depends on hydrodynamic movements, which continuously bring in undersaturated solutions. In regions where the subsurface water is static, dissolution is not possible. On an island such as Malta, situated in the middle of the Mediterranean, the zone of hydrodynamic circulation is limited to within a few hundreds of meters of the surface. It was thus a great surprise to everyone, that in an oil well

(BP Noxxar No. 2) drilled on the island some ten years ago, "lost-circulation" was encountered down to a depth of 2600 meters. "Lost-circulation" intervals are zones of very high porosity; drilling fluids pumped down from the derrick find their way into the porous formation and do not return to the surface. Why should there be such porous intervals of such thickness and at great depth?

The samples and well-logging records of the BP well indicate that the porous interval is a section of extensively leached Mesozoic carbonates and sulfates. The dissolution cannot have been caused by hydrodynamic movements under the present hydrologic regime. The puzzle could be resolved if we accept the Messinian desiccation theory. A lowering of sea level by 2500 meters would make the Island of Malta a high peak rising above the Ionian Basin floor. The descent of vadose and phreatic waters through a carbonate sulfate terrain should lead to extensive solution even if the climate were arid or semi-arid.

This line of reasoning could lead us to wide speculation. Could we attribute the early failures of oil exploration on the Lybia Coast to the fact that oils from pre-Miocene reservoirs have been flushed out by Messinian ground-waters? Perhaps the genesis of karst topography in Yugoslavia can be viewed with a different perspective if the Dalmation Coast were a leaky dam separating the Messinian Mediterranean desert from the "Sarmatian *lac-mer*"

Genesis of "Cobblestone Topography"

Echograms of the Mediterranean Ridge Crest and areas to the north of this crest show characteristic traces of numerous overlapping hyperbolic returns (Figure 9). These areas have been referred to informally as the "cobblestone terranes" (Chapter 37). The name is misleading, as it seems to imply the presence of cobblestones on the bottom. Actually, the echograms are a result of diffractions from "numerous closely spaced hills mostly less than 100 meters high and forming a very distinctive topography" (Emery *et al.*, 1966).

The width and height of the individual echo traces varies from place to place along the Ridge (Figure 9a). In some instances the crests of the hyperbolic echo traces are tangent to a line drawn parallel to the regional topographic slope (Figure 9b). Elsewhere the echo traces are completely jumbled and the whole composite may occupy up to 1/4 of a second of the echo return (Figure 9c).

One could conclude from the echogram pattern that the bottom topography is rough, and locally very irregular. The sea floor may consist of numerous blocks of material or sculptured irregularities which are able to reflect and scatter sound from within the whole effective cone of reception of the ship's hull-transducer. Unfortunately the dimensions of these features producing the hyperbolic echo returns are too small to be individually delineated by normal echo-sounding techniques and too large to be identified by bottom-photography. However, bottom photographs at several stations along the Ridge show tiny cracks, ridges, and sedimentary blocks (Figure 10). One of the objectives of drilling Hole 125 was to identify the nature of the "cobblestone terrane".

Drilling results at Site 125 did not give an obvious answer to the genesis of the "cobblestone terrane". The Pliocene and Quaternary sediments seem to be conformable and little disturbed. We did not find any exotic blocks, but we did prove that the Mediterranean Ridge is underlain by an evaporite series, including dolomite and gypsum. Furthermore, the gypsum seems to have been altered from anhydrite by ground-water diagenesis (see Chapter 7). These are the clues we needed to formulate a dissolution model to explain the "cobblestone topography". We have already discussed paleogeographical reconstructions for the late Messinian which show that northeastern Europe was a fresh- or brackish-water *lac-mer* when the eastern Mediterranean was being desiccated. At the last stage of desiccation, when the bitterns were being drained into the lowest depressions, the higher part of the Mediterranean Ridge would have stood considerably above the level of the salt lakes of the Sirte, Messinian, Antalya, and Herodotus Abyssal Plains. Hydrodynamic movements originating from the humid northeastern Europe would have found their way to the northern, crestal parts of the Ridge and caused extensive leaching of sulfates, leading to the formation of caverns. The collapse of the roofs of the caverns would have formed sink holes and a rough topography. The leaching and caverning could only have happened during the Messinian when those parts of the Ridge were subaerially exposed. However, roof-collapse under sedimentary load could have continued long after the ridge was again submerged under the sea. The tiny faults shown by bottom-photographs are now believed by us to be related to gravity collapse of very recent origin.

Dolines and Hums

Sink holes of solution origin are known as *dolines* (von Engeln, 1954, p. 569-575). A typical doline of the Adriatic karst has the form of a funnel top. The dolines vary in size and form from mere chimney-like shafts, to the representative funnel-shaped occurrences ranging up to 130 meters in diameter and 25 meters in depth. They commonly dot the landscape in numbers of up to hundreds or more to the square mile. Among the dolines one may find residual conical summits, which resemble haystacks and are called *hums* in the Adriatic expression. Steep-walled dolines and sharp-crested hums have a range of sizes that are too small to be individually delineated by normal echo-sounding techniques, though they have possibly been recognized in bottom photographs (Figure 11). Could the "cobblestone" area be underlain by such partially covered dolines and hums?

Area distribution of the "cobblestone terrane" suggests that extensively leached zones occur only in the northern and the more crestal part of the Mediterranean Ridge, close to a source of the groundwater and at elevations sufficiently high above the abyssal plain to have experienced frequent subaerial exposures during the Messinian. The southern boundary of the "cobblestone terrane" might well mark the farthest penetration of the "Sarmatian" Aquifers from the *lac-mer* (Figure 12).

We recognize the very speculative nature of our "*doline*-and-*hum*" hypothesis and are not ready to stake our desiccation model on the basis of such a wild postulate. However, we can not refrain from pointing out that another mystery might well be solved on the basis of our knowledge

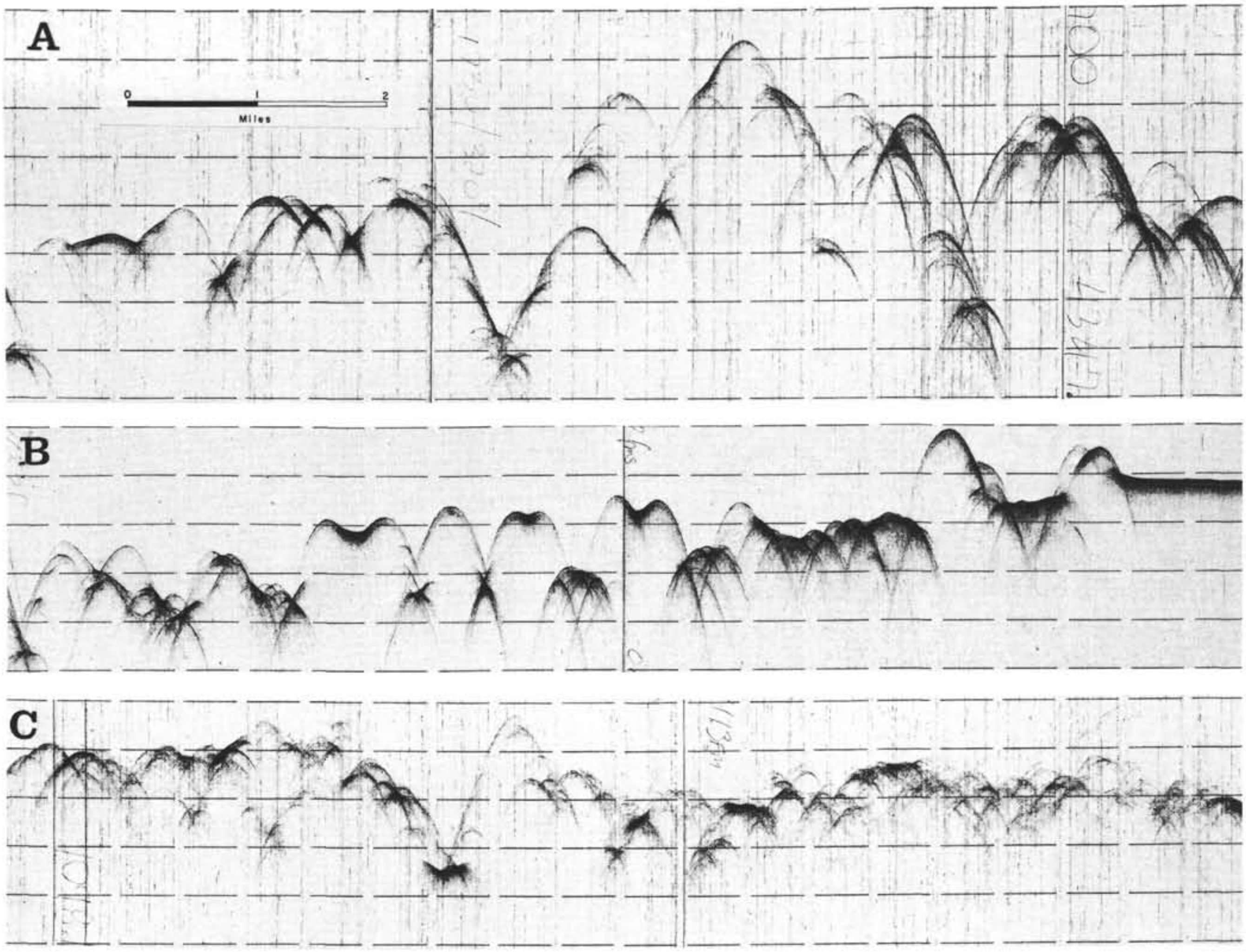

Figure 9. *Examples of the "cobblestone terrain" on the Mediterranean Ridge, interpreted by us as a* doline-and-hum *karst topography. The vertical spacing between scale lines represent 20 tau or approximately 36 meters. The multiple crescent echo sequences are produced by very irregular, small-scale, blocky relief that acts as numerous point scatters.*

that the Mediterranean must have been periodically dry during the Messinian. The crux of the matter is that our theory predicts extensive dissolution and leaching in the subsurface of the Mediterranean lands, and that this prediction is confirmed by evidence provided by investigators working in other fields of specialization.

Late Miocene Faunal Crisis

A desiccated Mediterranean must have led to the extinction of its marine life. A new assemblage might have evolved to adapt itself to the conditions of restriction or of isolation. Finally, the Pliocene Mediterranean fauna should represent a return of the refugees, accompanied by new immigrants from the Atlantic.

After our return from Lisbon, Professor Ruggieri of Palermo sent us reprints of his article of 1967 in which he deduced "the Miocene and later evolution of the Mediterranean Sea" on the basis of his faunal investigations. We would like to cite the following paragraphs from his work, which stated a conclusion almost in complete agreement with that of our own.

At the end of the Middle Miocene, . . . communication with the Atlantic Ocean, previously assured by two wide arms of water, the North Betic Strait, and the South Rif Strait was . . . reduced to the latter and this was itself constricted. . . .

Communication with the Indian Ocean, which had previously existed across Syria, had already ceased in Lower Miocene times. From the Vienna basin eastwards to the Caspian and beyond, there extended an immense closed sea, 'Paratethys'[5], in irregular communication with the Mediterranean across the Balkan Peninsula and Turkey.

The Parathethys was populated by a distinctive fauna, the *Sarmatic fauna* . . ., which occurs sporadically in the Peloponnese and in Eastern Sicily. Communication with the ocean became more difficult, and the circulation of water within the Mediterranean also deteriorated, until at the end of Miocene times a clearly evaporitic situation arose, with

[5]"Paratethys" is another expression for the *lac-mer* discussed previously.

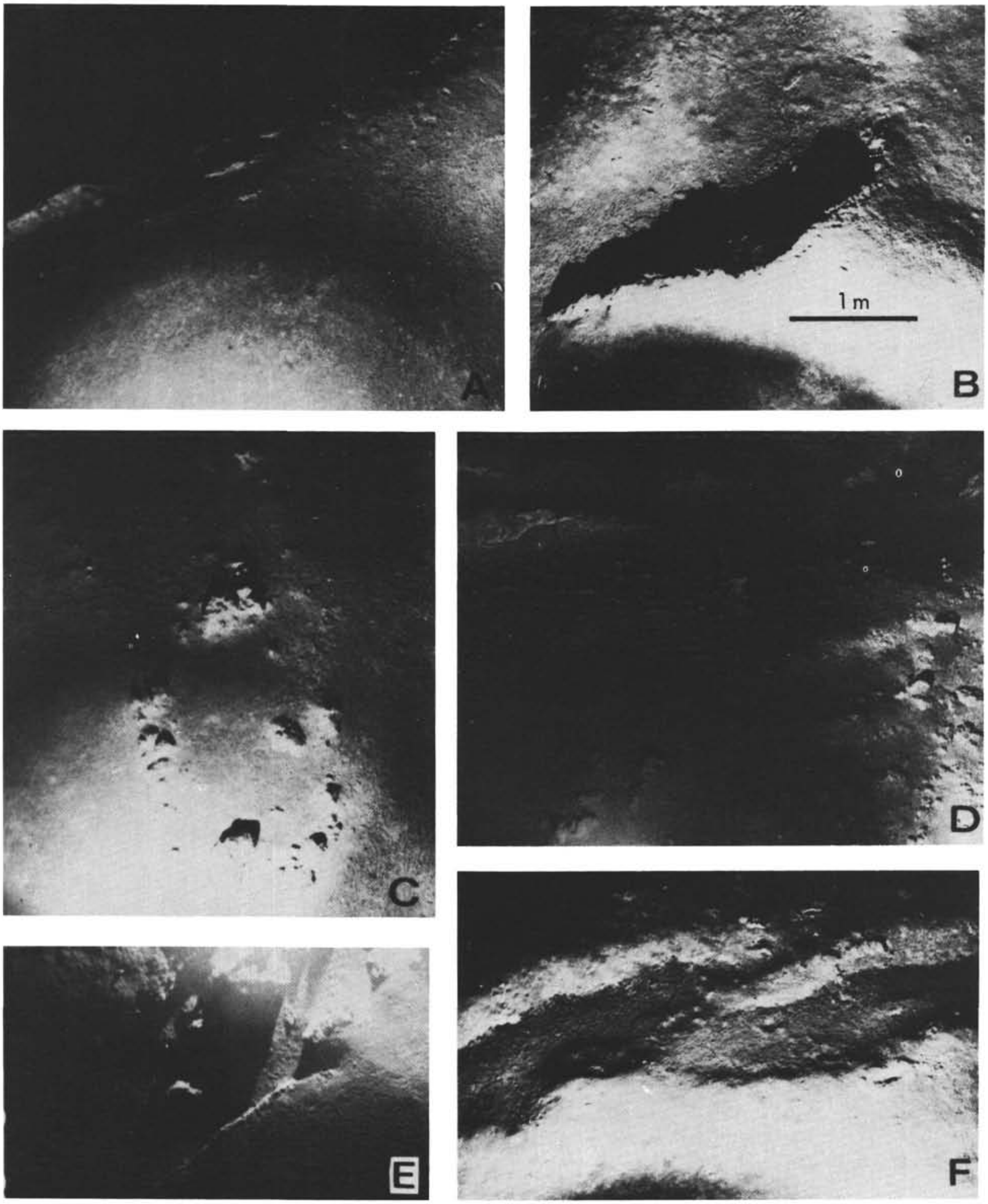

Figure 10. *Visual evidence of small-scale deformation of the sediment carpet on the Mediterranean Ridge. We infer that these youthful cracks, furrows, and ridges are produced through gravity collapse of Quaternary sediments into solution caverns in the underlying evaporite formation. The bottom photos were taken aboard the* Robert D. Conrad *in 1965, and are reproduced here through the courtesy of Maurice Ewing.*

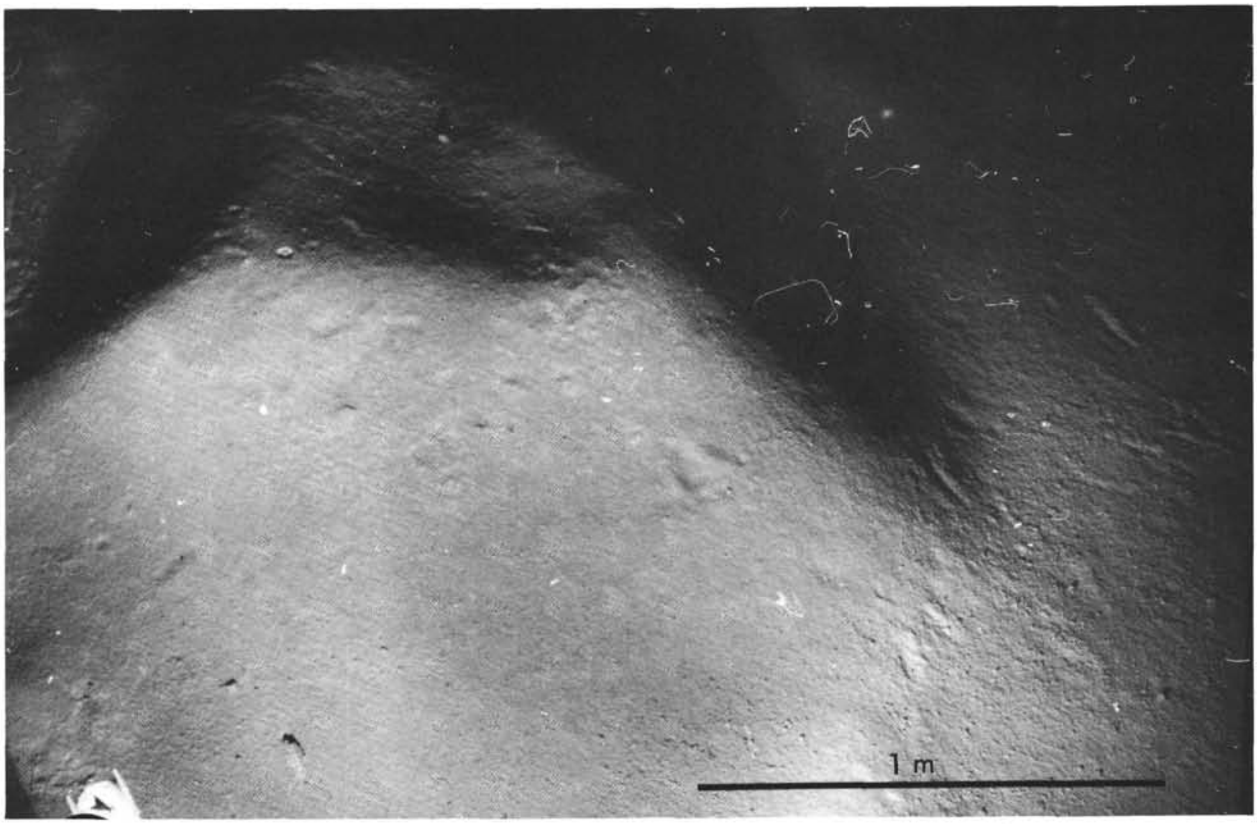

Figure 11. *Is this miniature pyramid on the sea bed of the Ionian Basin the partially buried tip of a hum? Photograph taken at 35° 53'N and 21° 11'E, water depth 3675 meters, during Cruise 61 of the R/V* Chain, *courtesy E. F. K. Zarudzki.*

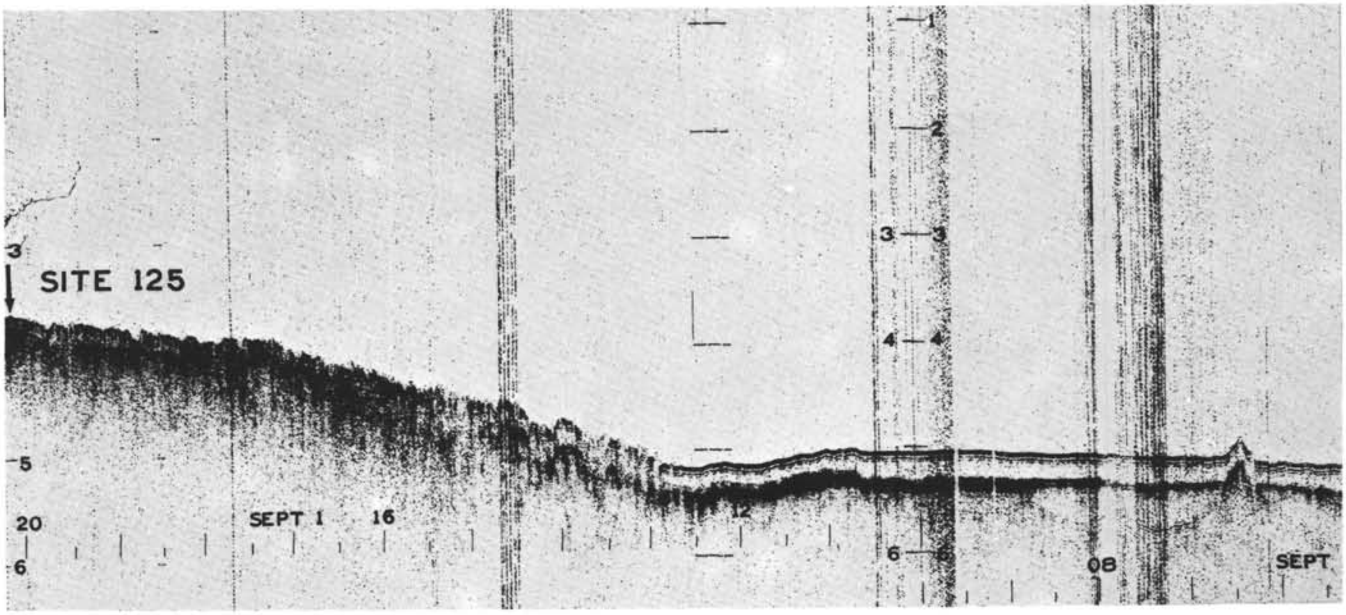

Figure 12. *The development of "cobblestone topography" on elevations in the Ionian Basin. We infer that the change in bottom and subbottom fabric in the center of the reflection profile relates to the fact that the Mediterranean Ridge at the left was subaerially exposed above the level of playa lakes during the Messinian desiccations and its evaporite strata were subject to groundwater leaching leading to the genesis of a karst morphology. We believe that the acoustically transparent Pliocent and Pleistocene pelagic oozes have failed to mask the subsurface relief on the Ridge because of continuing collapse of subterranean cavities under the accumulating overburden.*

gypsum and salt sedimentation extending almost throughout the western Mediterranean. Before the onset of evaporitic sedimentation, the depth and circulation in various places was reduced, with the accumulation of mud rich in organic material. This led to a natural enrichment in H_2S. The latter, oxidized by sulphur bacteria, has given rise to a conspicuous sulphur mineralization interpolated originally in the lowest part of the evaporite sequence, but which was migrated successively higher.

Toward the end of the Miocene, communication with the Atlantic Ocean ceased completely (Gentil, 1919; Gignoux, 1950), and the Mediterranean was transformed into a series of lagoons, which either dried up, or became gradually desalinified, as in the present day Caspian. *These basins of reduced salinity are characterized in the western Mediterranean by gastropods of oligohaline, warm-water facies, belong to the genus Melanopsis.* The Melanopsis fauna is found in North Africa, Catalania, Sicily and the Italian peninsula (in Tuscany, and along the Alpine and Apennine margins of the Po Plain). It is possible that the marine Miocene fauna was able to survive in some parts of the Mediterranean, but *it seems much more likely that it was totally destroyed by the adverse environmental conditions (Ruggieri, 1962).*

Meanwhile, the tectonic deformation of the Betic-Rif massif continued until eventually the Straits of Gibraltar opened, and the waters of the Atlantic Ocean poured anew into the Mediterranean, destroying the *Melanopsis* fauna and reestablishing truly marine conditions. *Those elements of the Miocene fauna that had persisted in the Atlantic outside Gibraltar were thus reintroduced to the Mediterranean together with new species previously absent from the area in Miocene times. This important event is regarded as coinciding with the start of the Pliocene.*

In the areas previously characterized by *Melanopsis* lagoons, the Pliocene "transgression" is manifest in a sudden change in fauna, with the marine, predominantly planktonic fauna, taking the place of pre-existing oligohaline fauna. Where, on the other hand, the floor of the Mediterranean was dry, *the sudden appearance of marine sedimentation, often deep-water, has resulted in the curious phenomenon of deep-water corals (Isidella) occurring immediately above a plane of transgression.*

The Mediterranean Pliocene fauna (was) originally the product of a reintroduction of the Atlantic fauna from the area facing the Gibraltar straits (probably the true asylum for the Indo-Pacific relicts during the salinity crisis of the Upper Miocene) . . . [italics ours]

This extensive quotation represents another loose end tied up. A paleontologist using entirely different criteria and pursuing another line of arguments reached a conclusion which is almost exactly what one could have predicted on the basis of our model of Messinian desiccation.

Abyssal Oil Fields

The occurrence of euxinic and diatomaceous sediments as source beds in a salt dome province where leached carbonates are reservoirs under halite seals represents an ideal setting for an extremely rich oil province. Quoting Schmalz (1969, p. 822), "The deep-basin model offers a direct explanation of the petroleum, natural gas and base-metal sulfide deposits, which are commonly associated with the evaporites". To this statement, we agree wholeheartedly except we wish to add that a desiccated deep-basin model offers even a better explanation. It provides not only an explanation for the origin of the source beds, for the genesis of the traps, for the deposition of the seals, but also accounts for the occurrence of the leached reservoirs. The western Mediterranean is particularly attractive as a potential petroliferous province as the source beds there have probably been altered to yield mature hydrocarbons under the prevailing steep geothermal gradients (Erickson, 1970).

The potential of a great reserve in the Balearic region is hinted at by an oil-show in Hole 134, where gas-condensates, migrating up-dip from a deeper reservoir, have been trapped in a porous foraminiferal ooze between two halite layers (Chapter 32). A petroleum reserve in the Mediterranean is a two-edged sword. On the one hand, the building of dynamically positioned exploration vessels and the design of deep-water production techniques have made oil exploration and production beyond the continental shelf a distinct possibility within the next decade. A discovery of Mediterranean oil fields should have unforeseen economic and political consequences. On the other hand, ecologists would be alarmed at the prospect of a greatly accelerated pollution of the Mediterranean waters when and if abyssal oil fields become a reality. Furthermore, the hydrocarbon potential of the Mediterranean basins renders future scientific drilling by vessels without blowout-prevention measures a very risky undertaking.

Perhaps we should not be sidetracked by this discussion of economic and political issues, apparently devoid of scientific relevance. Nevertheless, the presence of large oil reserves in the Mediterranean is one more geological implication of our desiccated deep-basin model and this prediction still has a chance to stand the test of time.

CONCLUSION

So far, we seem to have emphasized the positive aspects of our idea. Is our model perfect? If so, why do so many of our colleagues continue to remain unconvinced? During the numerous discussions following our oral presentations, the only objections they voiced, other than those we have already considered, are intuitive reactions against an improbable event. An improbable event is not an impossible event, although these two kinds of events are all too often confused. The issue was clearly defined by Gretener (1967, p. 2197):

> The *impossible event* by this definition is one either invoking a new, present unknown physical law, or violating a known such law . . . providing that no observational or theoretical evidence is furnished to justify such action. Whereas such a possibility cannot be ruled out, it nonetheless furnishes no working hypothesis, and the rejection of such explanations is well justified. . . .
>
> The *improbable event*, on the contrary, is one that is physically possible, but requires the rare coincidence of several favorable happenings, and consequently is highly unlikely.

Our postulates do not violate any physical law, nor do we invoke an unknown physical process in our formulation. Nevertheless, a question could be asked if the consequence of a desiccated Mediterranean would lead to a physically impossible situation and would thus constitute an impossible event.

One of our geophysicist friends did indeed raise such a question. "It was physically impossible", he reasoned intuitively, "the loss and the sudden infill of waters from such a large hydrographical basin should have so disturbed the earth's isostatic equilibrium that it would have had a dire consequence on the rotation of the earth."

Nonetheless, the negative load of a desiccated Mediterranean is less than half as large as the maximum load of the Pleistocene Fennoscandia Ice Sheet. The Mediterranean (exclusive of the Black Sea) has a volume of 3.3 million cubic kilometers. The Fennoscandia Ice Sheet had a volume of about 8 million cubic kilometers (see Flint, 1948, p. 305). The North American Laurentian Ice Sheet was even larger. The creation of these unbalanced loads has not greatly affected the motion of the earth.

Also, the rates of load application were not greatly different. We have shown that the Mediterranean was not filled in one day, although the duration of the refill was probably less than 1000 years. In comparison, the larger mass of the Fennoscandia Ice Sheet took several thousand years to disappear. Thus, the rate of weight-transfer during the "Final Deluge" may have been a few times greater than that during the final melting of the Fennoscandia Ice Sheet. The effect on the angular momentum of the earth caused by the Gibraltar saltwater Fall may have been large enough to cause an imperceptible lengthening of the day, but it was far too trivial to seriously interfere with the rotation of the earth.

The single oft-repeated argument left is based upon a misinterpretation of uniformitarianism; that is, that *none of the desiccated interior basins existing today are comparable in size or in depth to a desiccated Mediterranean.*

Desiccated deep basins are known. The Dead Sea is an 80-km-long saline body 400 meters below sea level, inside a 600-km-long and 20-km-wide depression. The basin floor is some 800 meters below mean sea level (Neev and Emery, 1967). The Dead Sea basin is thus considerably smaller than the Mediterranean. The Tarim Basin of Sinkiang, China is comparable to the Mediterranean in size, yet its floor has been elevated by basin fill to such an extent that only local depressions remain below sea level.

The argument that the Mediterranean could not have been desiccated because basins of similar dimension do not exist today constitutes "substantive uniformitarianism" which is founded on the unacceptable premise that conditions at or near the earth's surface have remained relatively constant throughout geological history (see Gould, 1965). What one did not experience in one's life time, or what was not recorded in the short span of Holocene history may be considered a rare event, but certainly not an impossible event. A rare event is, by definition, not an event which should have necessarily happened during the last few thousand years of human history.

For example, small landslides are common occurrences in the mountains. The chances for major landslides may range from 10^{-1} to an improbable 10^{-4}. The Flims Slide of the Swiss Alps, which deposited a debris tongue some 600 meters thick and some 20 km long, represented such an improbable event. Yet at odds of 10^{-4}, 100,000 such "super-slides" should have occurred during the last billion years, even though no human has ever encountered such a dramatic event during the last 5000 years.

Evaporite deposition in salinas a few square meters in extent are daily occurrences. Deposition of salts in basins as large as the Dead Sea, some 1000^2 km in extent, would represent a rare event. Deposition of salts in basins more than 1 million square kilometers in extent represents even a more improbable event. The Devonian Prairie Salt of Canada, the Permian Zechstein, and the Mediterranean evaporites represent three such occurrences in our geological history. There might have been a few more, but certainly the total should be less than 10 during the last billion years. Let us call such super-sized evaporites "saline giants". If the life span of an average saline giant is 2 million years, the probability of our ever encountering one would be 1 in 500. The existence of a modern "saline giant" is thus rather improbable, and we can hardly expect to find a modern salt-pan as large as the Mediterranean to satisfy the demand of substantive uniformitarians.

Drilling revealed the improbable – that an area as large as the Mediterranean is underlain by an evaporite deposit. The Messinian event is an improbable event, regardless of whether the basin was deep or shallow, deep-water or desiccated. Whatever explanation we should offer would thus seem improbable. On the other hand, improbable is not impossible. It seems appropriate that we should close our story with a quote from a master "detective," Arthur Conan Doyle, alias Sherlock Holmes:

> "It is an old maxim of mine that when you have excluded the impossible, whatever remains, however improbable, must be the truth."

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