54. MESSINIAN EVENT: SEISMIC EVIDENCE

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ABSTRACT

The distribution of Mediterranean Messinian evaporites is recognized on the basis of numerous seismic profiles and land data. Seismic character and stratigraphy are described for the different basins. Different structural settings, thresholds and straits, and differences from one basin to another are noted. A depositional model for the North Balearic Basin is as follows: a relatively deep Miocene basin existed before evaporite deposition; a thick salt layer filled the major depressions during a significant regression which is marked by an erosion surface; the upper evaporites which extend beyond the salt layer and are deposited under shallow-water conditions. The Messinian-Pliocene-Pleistocene subsidence is a continuation of the Miocene subsidence of the basin. Although each Messinian evaporitic basin has its own geodynamic evolution, this depositional model is valid in the other deep evaporitic basins of the Mediterranean area.

INTRODUCTION

Late Miocene evaporitic layers are exposed in an area more extensive than the present deep-sea basin (Figure 1). On land they are limited to small basins where they have little thickness and considerable variation of facies. Sedimentologic and stratigraphic studies of these onshore deposits support our concept of the Messinian Event.

Initially, workers concentrated on obtaining seismic data on the Mediterranean salt diapirs (Hersey, 1965; Glangeaud, 1966). More recently seismic profiles of more than fifty thousand kilometers throughout the entire Mediterranean have been collected which give a clear picture of the general distribution and volume of the evaporites.

Results of drilling during DSDP Legs 13 and 42A complement the data obtained from offshore drilling. These include those for the Algerian Margin (Burollet et al., this volume); Levantine margin (Gvirtzman, et al., this volume); and north Aegean (Byramijee et al., 1975) and Turkish margin.

DISTRIBUTION OF MEDITERRANEAN EVAPORITES

Onshore Messinian deposits include sulfates, chlorides, phosphates, carbonates, pelagic marls and diatomites, terrigenous layers, and even biostromal limestones. In, and between, each basin, local conditions and difference in time of deposition have caused these facies variations. A vertical and horizontal evolution of evaporitic facies is generally observed. Chloride members are mainly located in the central part of the main basins and in the middle part of the sequence (Sicily, Cyprus, [see Pantazis, this volume], and the Adana Basin). Alternation of sulfates, terrigenous sediments, and marls is usually found at the bottom and at the top of the sequences, and more generally in all small basins around the present Mediterranean deep basins. On the margins of these limited basins and on some highs, sulfate beds change to marly terrigenous or carbonates facies (chemical, oolitic, or reefoidal) with alternating brackish and marine conditions. On the margins, erosional surfaces between Pliocene and Miocene sediments are very distinct and include, in some cases, conglomerates.

Some onshore basins extend offshore toward deep areas. The results of drilling in the offshore Adana Basin show a thick (600 to 800 m) upper Miocene "salt layer." This salt layer, composed of thin laminations of halite and anhydrite, lies between a sulfate and a carbonate facies with marls and sands. On the margin of this basin, the salt layer pinches out, and only gypsum marls or limestones crop out on land. Seismic profiles clearly demonstrate the broad extent of evaporites from the shelf to the deep basin.

The occurrence of evaporites in offshore basins is established by the nature of the seismic reflection, interval velocity analysis, and DSDP drilling. Bear in mind that the determination of evaporitic layers by seismic prospecting is possible only when the thickness is more than a few dozen meters. Thin layers are generally impossible to detect. Figure 2 shows that the velocity contrast induces strong reflectors between evaporitic layers (3.5 to 4.6 km/sec) and the Pliocene-Quaternary sequences (1.6 to 3.5 km/sec).

Nevertheless, in some cases, particularly where recent deposits are very thick and compaction induces high acoustic impedance at the bottom of the Pliocene or where in the basal Pliocene alternating layers are numerous, the contact is not well defined.

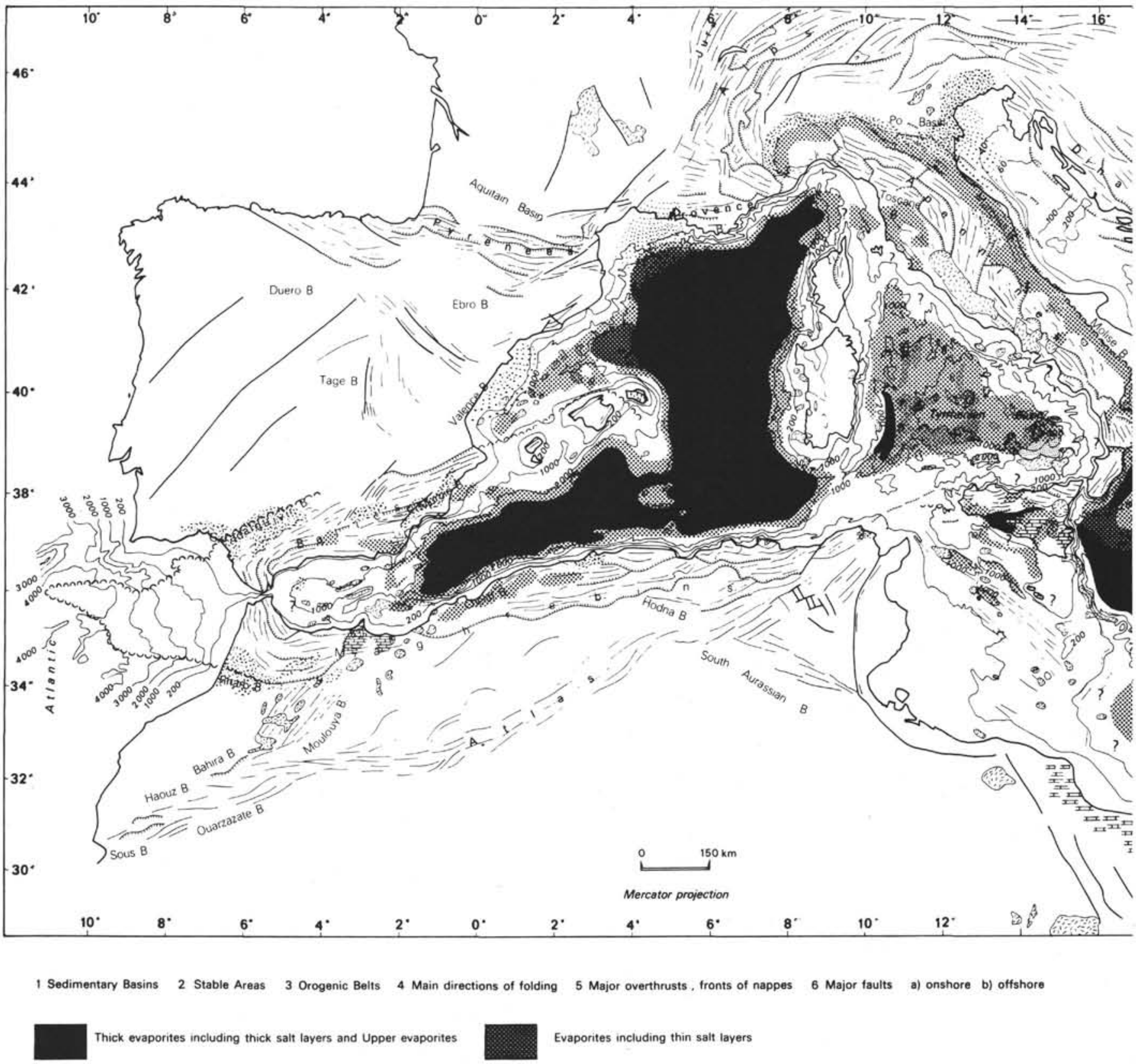

Figure 1. *Messinian evaporites in the Mediterranean area.*

"Upper Evaporites," made of evaporites and marls encountered in DSDP boreholes, correspond on seismic profiles to strong, often parallel, reflectors with an interval velocity of 3.5 km/sec (Mauffret et al., 1973).

The presence of one or several thick salt (halite-anhydrite ?) layers is characterized by halokinetic phenomena, pull-up, and a mean interval velocity of 4.5 km/sec. In some cases, intermediate reflectors appear in the salt member which are interbedded or have lateral facies changes.

At the bottom of the salt layer, mainly in the eastern Mediterranean, strong continuous reflectors may indicate lower evaporites or limestones as found in boreholes (Sicily, Adana Basin). Often a negative acoustic-impedance contrast appears between the evaporitic sequence and underlying series.

Generally, the "upper evaporites" extend further than the salt, onlapping pre-salt deposits. In some cases they overlie an erosional surface and are conformably overlain with marine transgressive series. Contrary to the opinion of some authors, the central part of different basins is marked by a concordance between infra-salt layers, evaporites, and Pliocene deposits (Figure 2). Figure 3 shows that the evaporitic sequences defined by seismic data are very different from one place to another, with various thicknesses (up to 4000 m south of the Florence Rise). The evaporites are thickest in the central part of the basins. The comparison between the different sections clearly shows that the vertical successions vary greatly. The western Mediterranean Basin succession, characterized by "lower evaporites" (?), a "salt layer" and "upper evaporites," is

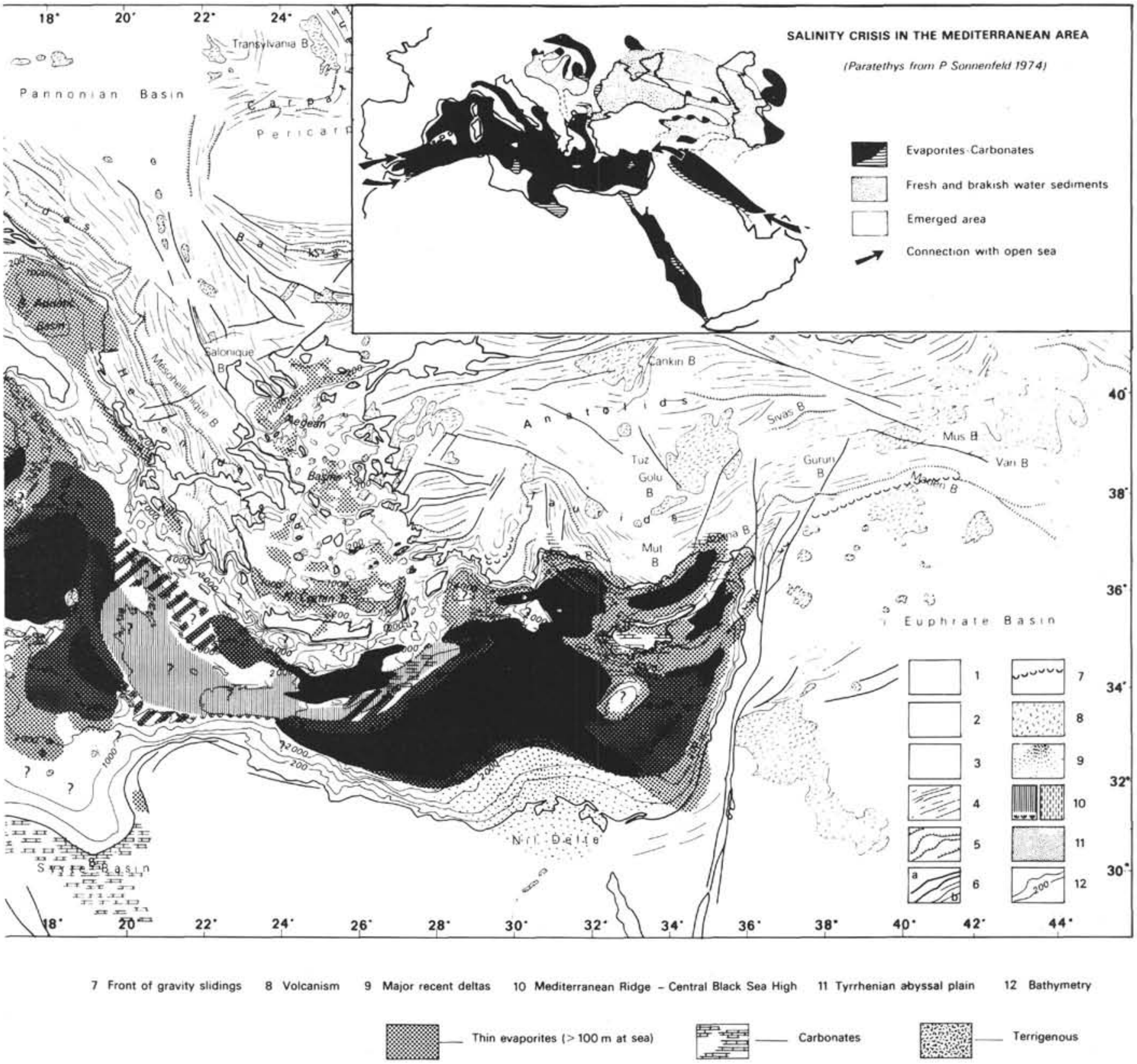

Figure 1. *(Continued).*

not so well defined elsewhere. The present depth of the evaporitic layers is very different from place to place (Figure 3), as previously noted by Sonnenfeld (1976). It is from 8000 meters below sea level in the Herodotus Abyssal Plain to several hundred meters on land. This is mainly a result of the very different geodynamic settings of the various sub-basins.

We have utilized all the seismic data to map the evaporitic distribution (Figure 1). Three major basins can be distinguished which corresponds to the main present abyssal plains (Western, Ionian, and Eastern Basins). They are connected to small peripheral basins offshore and onshore. Because thin layers cannot be followed from the seismic data and because of the erosional process, the connection between these basins and the exact initial extent of evaporitic basins is obscure.

The tectonic setting of each basin is different. The Western Basin was created by spreading during the early Miocene. The Ionian and Eastern basins are on an old African margin in front of, and on top of the active Alpine margin. All the tectonic processes were active before, during, and after evaporitic deposition (Biju-Duval et al., this volume).

Because of the total volume of the evaporites and the occurrence of pelagic marls with nannoplankton and foraminifers (Rouchy, 1976), we know that there must have been at least temporary communications with open seas (Atlantic and Indian oceans). We need to determine location and thresholds of straits connect-

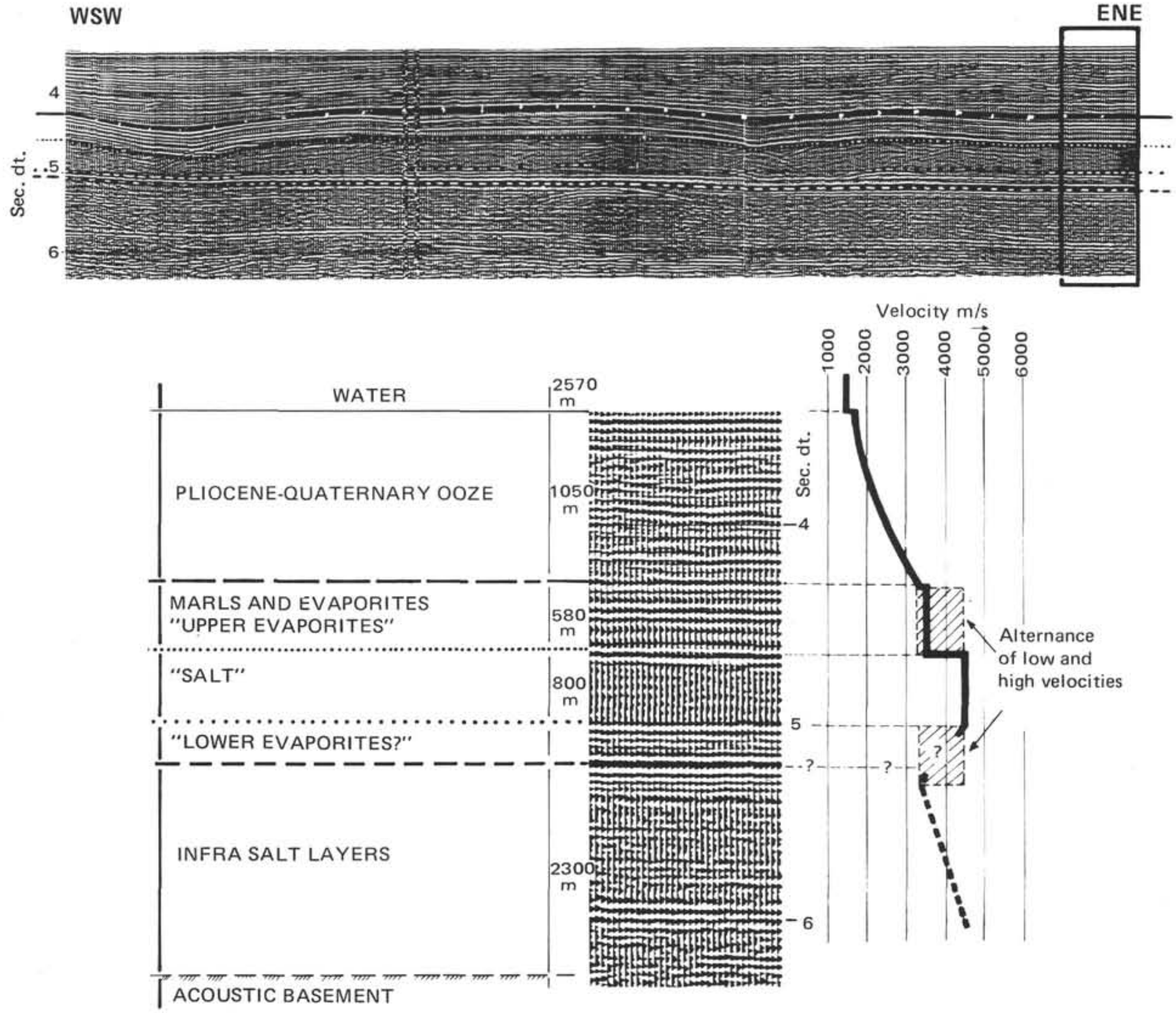

Figure 2. *Typical seismic section of the evaporite sequence in the Western Mediterranean (Gulf of Lion, Abyssal Plain).*

ing basins with open sea (especially for the interpretation of a deep desiccated basin).

The opening of the Strait of Gibraltar is a recent phenomenon and consequently was not the connection to the Atlantic during the late Miocene. The connection may have existed either in the North Betic domain or in the south rif area where Messinian reefoidal limestones occur between Atlantic marls and Mediterranean evaporites. A connection with the Indian Ocean existed sometime after Burdigalian time north of the Syrian platform, but the Misis Bitlis overthrust, which is Pliocene in age, obscures a possible Messinian communication. DSDP Leg 23 results show that the connection with the Red Sea existed at that time, but because the Aden threshold was closed, there was no connection with the Indian Ocean. The closure of the Gulf of Suez corresponds to the Pliocene opening in the south of the Bab El Mandeb Strait.

Seismic profiling in the Black Sea clearly shows the absence of an evaporitic layer during the Miocene, although these layers are well developed in the Aegean Sea and even include salt (Thassos oil field, Byramjee et al., 1975). During all this time, the Black Sea water was probably highly subjected to fresh water inflows (see Volume 42B, in press). Determination of communication with the "Paratethys" through the Salonika Basin is mainly a stratigraphic problem made difficult because of the different stratigraphic scales applied in the different regions.

Note also that in some cases land exposures of evaporites occur in peripheral basins which were deposited before Messinian time (Tortonian in Spain; Serravallian in Israel; Paratethys; Euphrates Basins, North Turkey; early Miocene to late Miocene offshore in the Red Sea).

In order to indicate the extent of the Messinian deposits and lateral facies changes, and to present a coherent sedimentological analysis, we would need to apply a very precise chronostratigraphic scale to the Messinian event. But such a scale is not yet available. In land sections the Messinian has often been defined by the presence of an evaporitic facies, but typical

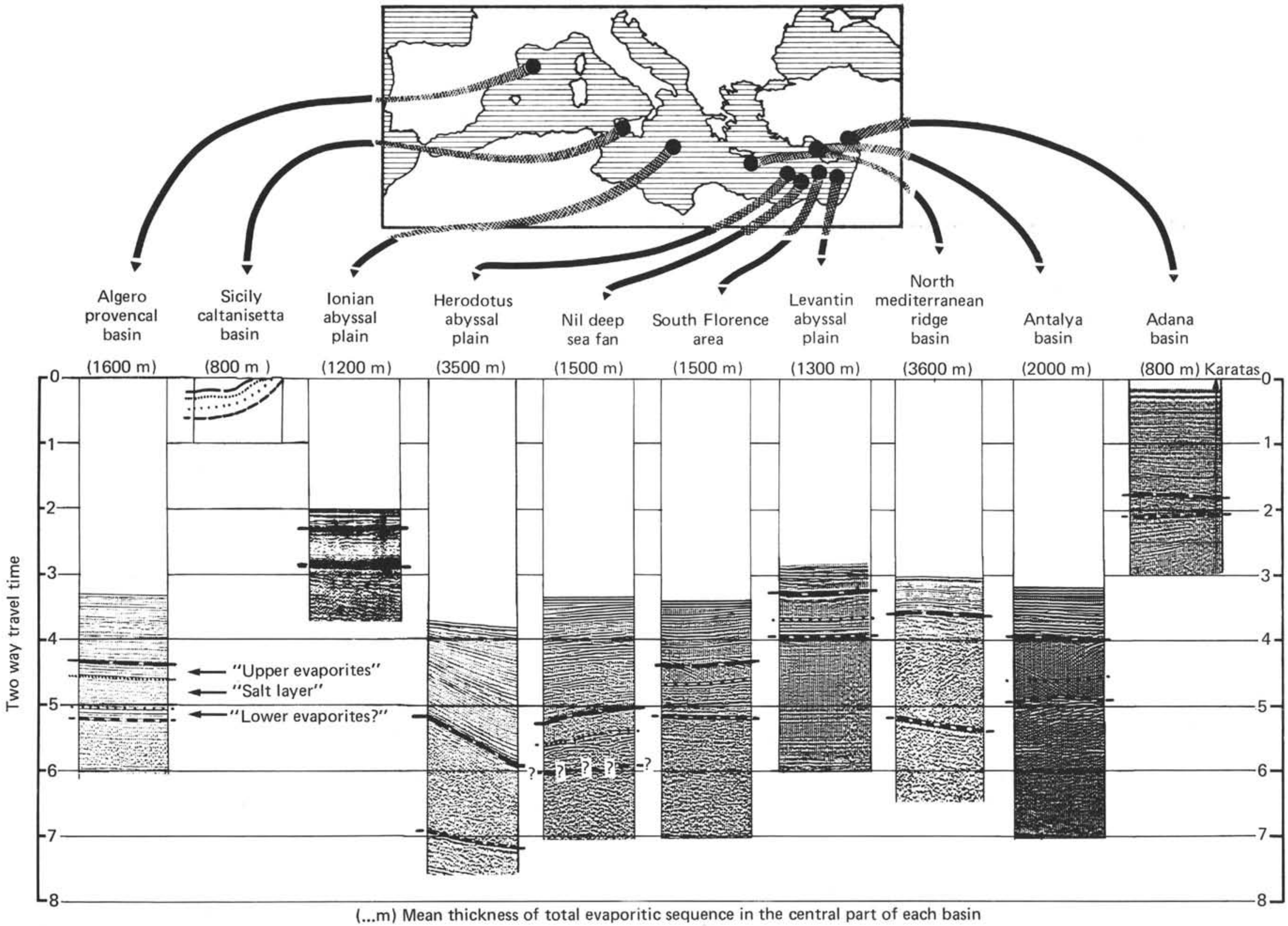

Figure 3. *Seismic facies of the evaporite sequence in the central part of different Mediterranean basins.*

Messinian planktonic foraminifers (*G. mediterranea*, etc.) occur in pelagic marls below the first evaporites. We have no more chrono-stratigraphic data from before the Pliocene pelagic marls for the entire evaporitic sequence in the Mediterranean.

The "salinity crisis" and the salt basins correspond to special sedimentological conditions which occurred during the evolution of different previously initiated basins; some basins existed since the Mesozoic, others since Oligocene-Miocene times.

In conclusion, if one does not take into account the role of tectonic disturbances, salt deposition is located in the center of Tortonian basins. Major Pliocene subsidence and the present abyssal plain are also superimposed on these previous structural units (Biju-Duval et al., this volume). Nevertheless, during the late Miocene, the Mediterranean area was not a single basin, but was a succession of more or less separate basins in which straits and thresholds played an important role. Subsidence, sedimentation rates, and depositional environments varied. All around the three major basins in which thick salt was accumulating, the small basins were marked by a reduced rate of subsidence and sedimentation, reduced depths and were more generally influenced to local conditions (terrigenous influx). Present onland evaporitic basins correspond to these latter ones.

GEOPHYSICAL EVIDENCE FOR INTERPRETING THE MESSINIAN EVENT TAKEN FROM THE NORTH BALEARIC PROVENÇAL BASIN

As shown before, the Messinian evaporites are related to an event which affected the entire Mediterranean superimposed on a geodynamic evolution that is very different in different areas.

This geodynamic evolution may be especially complicated in the areas where compressional tectonics affected the deep basins before, during, and after the Messinian "event." Thus we think that in using geophysical data to interpret the event, we have to choose an area that was relatively stable during that time—one mainly affected only by local vertical movements. The North Balearic-Provençal Basin, especially on its western side, is the best area on which to make this kind of interpretation. Indeed this area corresponds to a basin that was created by rifting, some drifting, and subsidence in a realm not affected by the Miocene orogeny which was active southward including the Balearic Islands.

Three main hypotheses have been proposed to explain the Messinian event:

1) Deposition of the evaporites in shallow water in a shallow basin. This was the most conventional explanation and implies that the basin was shallow before evaporite deposition and that active subsidence occurred during the Pliocene-Pleistocene. The Mediterranean basins were thus considered as having been formed after Miocene.

2) The "deep water-deep basin" hypothesis accepted the existence of a deep basin before evaporite deposition, but denied that the evaporites drilled by *Glomar Challenger* were deposited in shallow water. This model has often been used to explain the existence of very thick monomineralic evaporitic layers in old basins. Note that such a thick body of halite exists in the Mediterranean evaporites.

3) The "deep-desiccated" model of Ryan, Hsü, et al. (1973) was proposed from evidence obtained during DSDP Leg 13 drilling, i.e., deposition of shallow-water evaporites overlain by deep-water Pliocene sediments.

We think now that the numerous geophysical data and the new sedimentologic and biostratigraphic data from Leg 42A impose many more geological constraints upon hypotheses concerning the evaporite deposition and allow to choose one of the preceding hypotheses.

Here, we consider mainly the geophysical evidence and accept the findings of Legs 13 and 42A which interpret the upper evaporites as deposited in shallow water and the pre-evaporitic deposits as deposited in deep water (Mauffret et al., 1973; Garrison et al., this volume; R. Wright, this volume).

The following points are critical to the understanding of the Messinian event:

1) Physiography of the basin prior to the deposition of the evaporites.

2) Seismic stratigraphy, extension and limits of the evaporites, related events on the margins close to the Miocene/Pliocene boundary.

3) Subsidence, especially during Pliocene-Pleistocene time.

Physiography of the Pre-Evaporitic Basin

The evidence of a pre-evaporitic deep Miocene basin and margins have already been shown by Montadert et al. (1970) and Mauffret et al. (1973). New seismic data and a re-examination of older profiles have provided new evidence about the pre-evaporitic deep basin. On the margins of the deep basin, we can distinguish two types of escarpments:

1) Old escarpments covered by Miocene, Messinian, and Recent deposits, which were not rejuvenated after the Messinian. These escarpments were created by horst and graben tectonics as a result of Oligocene rifting of the North Balearic-Provençal area.

2) Escarpments where the pre-Miocene basement outcrops, which generally correspond to Oligocene-early Miocene escarpments rejuvenated during Pliocene-Pleistocene times.

The main new evidence of a Miocene deep basin is the existence of Miocene sedimentary wedges along these old escarpments. These wedges thin toward the basin and are covered by younger Miocene layers. Several examples demonstrate this. North of Majorca (Figure 4) the thickness of the wedge near the escarpment is about 1000 meters. The same thickness has been established on the "old" margin at the approach to the Gulf of Valencia (Figure 5). Similar features are also observed on the Catalonia margin (Figure 6) and probably in the Gulf of Lion (Figure 7).

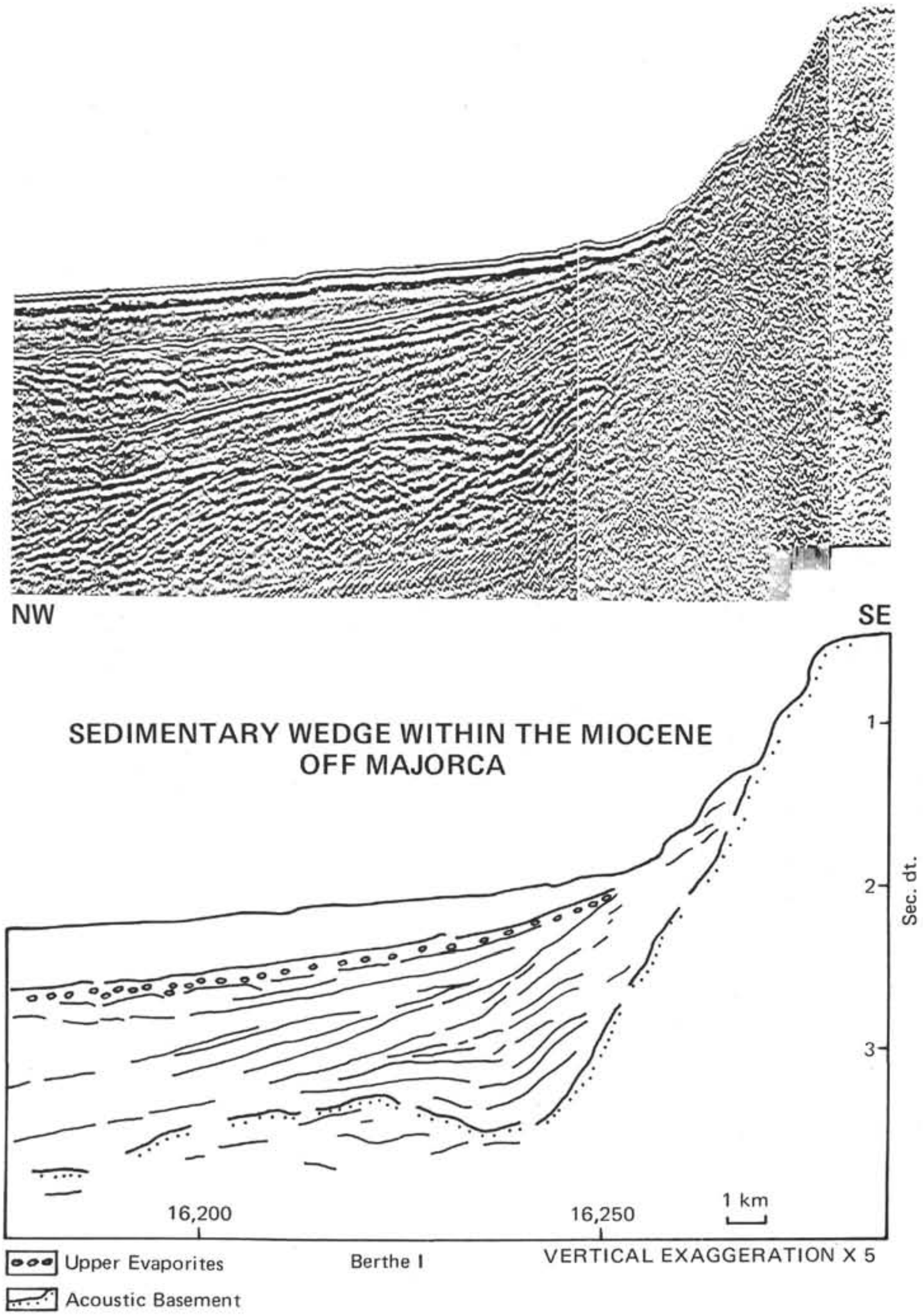

Figure 4. *Sedimentary wedge within the Miocene off Majorca.*

Thus, geophysical data clearly indicate the existence of a pre-evaporitic basin on the basis of sedimentary wedges at its margins, but they, of course, cannot indicate the depth of the basin at that time. It could have been around 1000 meters as suggested by the thickness of the Miocene wedges (Figure 4). The only indication for this depth now available is provided by the benthic fauna of Hole 372 which indicate that the upper Miocene marine deposits were deposited at a depth of at least 1500 meters (R. Wright, this volume). In contrast, holes drilled on shelves indicate deposition of mainly platform deposits (Cravatte et al., 1974; Stoeckinger, 1976; Burollet et al., this volume).

Seismic Stratigraphy, Setting of the Evaporites, Related Events on the Margins

Previous publications (Montadert et al., 1970, Auzende et al., 1971; Finetti and Morelli, 1972; Mauffret et al., 1973; Biju-Duval et al., 1974; Morelli, 1975) and the first part of this paper, demonstrate that, especially in the western Mediterranean, two main sequences can be distinguished in the Messinian evaporites:

1) A thick (0.5 to 1.5 km) seismically homogeneous layer of salt filling the main depressions of the basin (Figure 3).

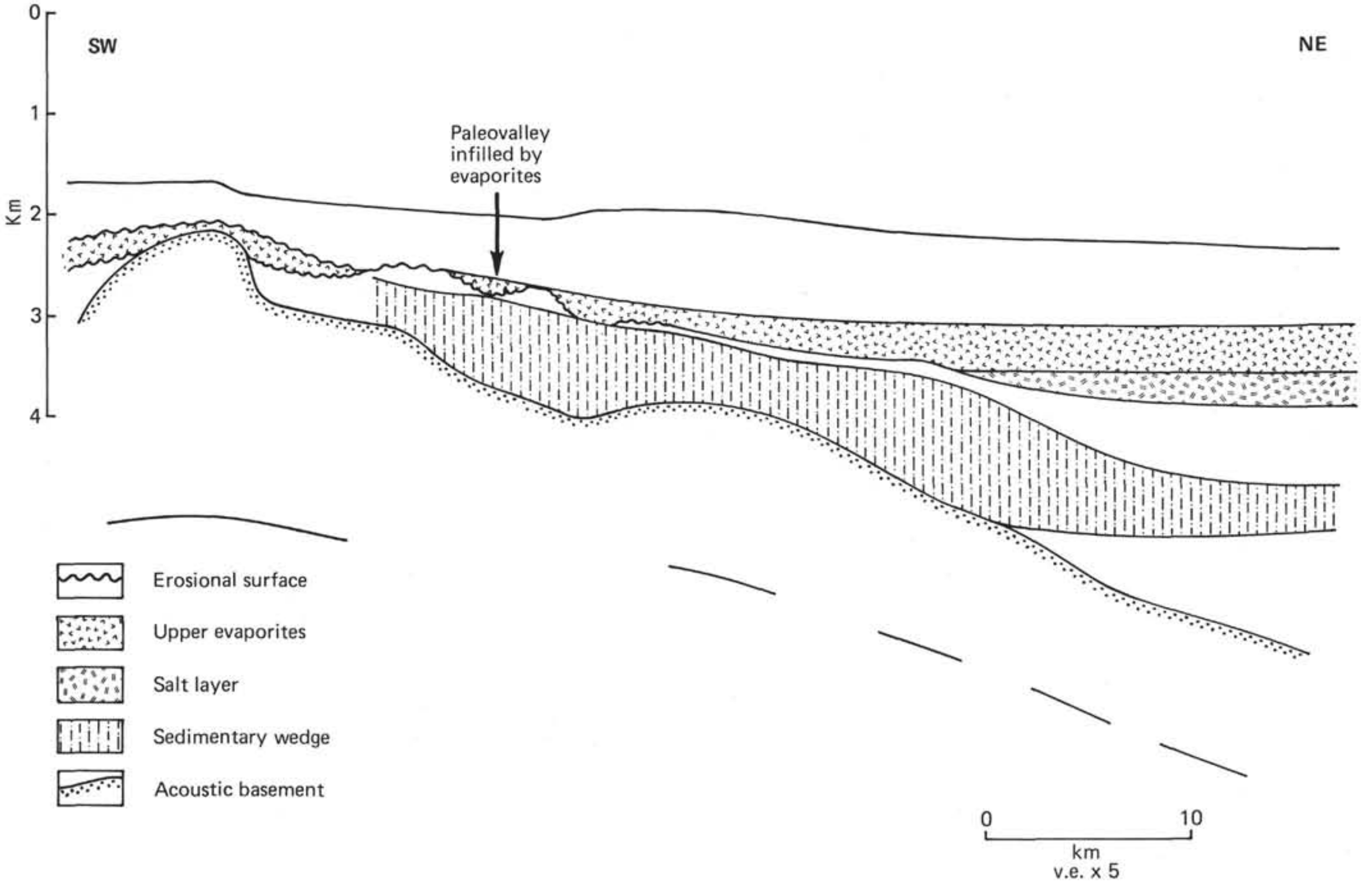

Figure 5. *Seismic profile at the eastern mouth of the Gulf of Valencia showing a sedimentary wedge within the Miocene and the "upper evaporites" infilling the intra Messinian erosion surface (depths in km).*

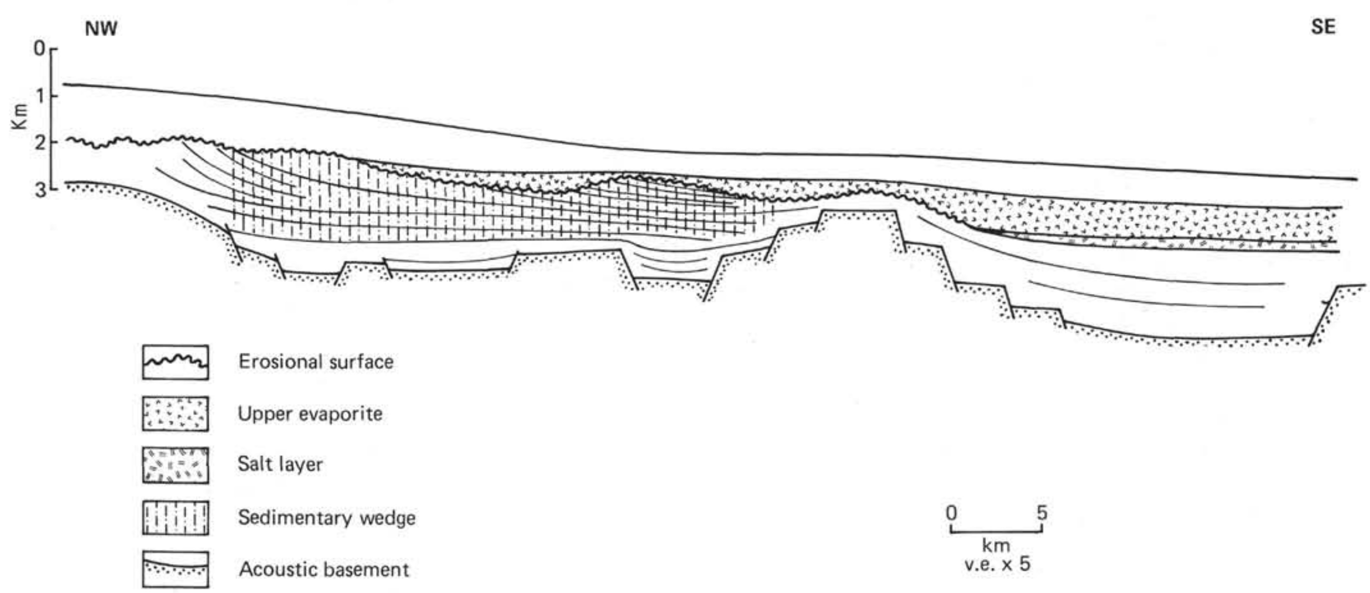

Figure 6. *Typical section off the Catalonia margin showing prograding deposits in the Miocene, and the "upper evaporites" infilling the intra Messinian erosion surface (depth in km).*

2) An overlying "upper evaporitic layer" with a maximum thickness of 500 to 600 meters.

This upper unit, in contrast to the underlying one, is generally flat in the deep basin, the irregularities of the basin having been previously filled by the salt layer.

Seismic profiles show clearly that these "upper evaporites" onlap the salt layer and extend much farther onto the marginal areas (Figure 8).

Two interesting features are observed on the seismic profiles:

1) The existence, in some areas, of a sedimentary wedge on the margin, more recent than the Miocene wedges described above. These wedges seem to be directly linked to the Messinian event (Figure 9).

2) The existence of a very well-defined erosion surface which can be followed on the margins towards the basin until the pinched out salt layer is encountered. This erosion surface may be unconformably overlaid by the "upper evaporites" which filled the irregularities of this surface (Figure 6). Because of the geometric relationship, it seems possible that the sedimentary wedge might be a product of this erosional process. Thus this erosion surface is clearly a major feature in the interpretation of the Messinian evaporite deposition.

As occurs on the Menorca Rise (Mauffret et al., this volume), this erosional event created major unconformities and the evaporites or Pliocene sediments rest directly on any older formations: basement, sediments related to rifting, marine Miocene sediments, etc. In this area the erosion surface is exposed because of cutting by contour currents active during Pliocene-Pleistocene time. This important erosional event is clearly recognized at Site 372 where the Messinian section attributed to the "upper evaporites" rests directly on Serravallian (Cita et al., this volume; Müller, this volume) or lowermost part of Tortonian (Bizon, Site 372 Report, this volume), and thus confirms the seismic reflection interpretation.

The unconformity also extends throughout the Gulf of Valencia (Mauffret, 1976; Stoeckinger, 1976), along the Catalonia margin (Figure 10), to the Gulf of Lion (Figure 7), and everywhere along the western Mediterranean margins (along Corsica and Sardinia as shown by Hole 134 drilling where the Pliocene rests directly on continental deposits of the rifting phase, following our interpretation, in the Alboran Sea).

The maximum extension of this erosion surface toward the basin was at the end of the time the salt layer was deposited, but since the "upper evaporites" are shallow to subaerial deposits (Garrison et al., this volume), several erosional episodes could have occurred during their deposition. This could explain why, in a few cases, the upper evaporites are also eroded, and the depression is filled by Pliocene sediments. This is the case in the Gulf of Valencia near Hole 122 (Ryan, Hsü, et al., 1973; Mauffret, 1976).

Other spectacular features linked to this erosional event are the canyons of the Catalonia margin (Figure 8) which cut into the granitic basement. On this map, it appears that the "upper evaporites" filled the base of these canyons. This suggests that the erosion predated deposition of the "upper evaporites." Nevertheless, seismic data clearly demonstrate that several other canyons are Pliocene-Pleistocene submarine features (Stanley et al., 1974).

We arrived at the following conclusions from these observations:

1) The erosional surface and the formation of some of the canyons was a result of subaerial erosion linked to a major regression along the margins at the

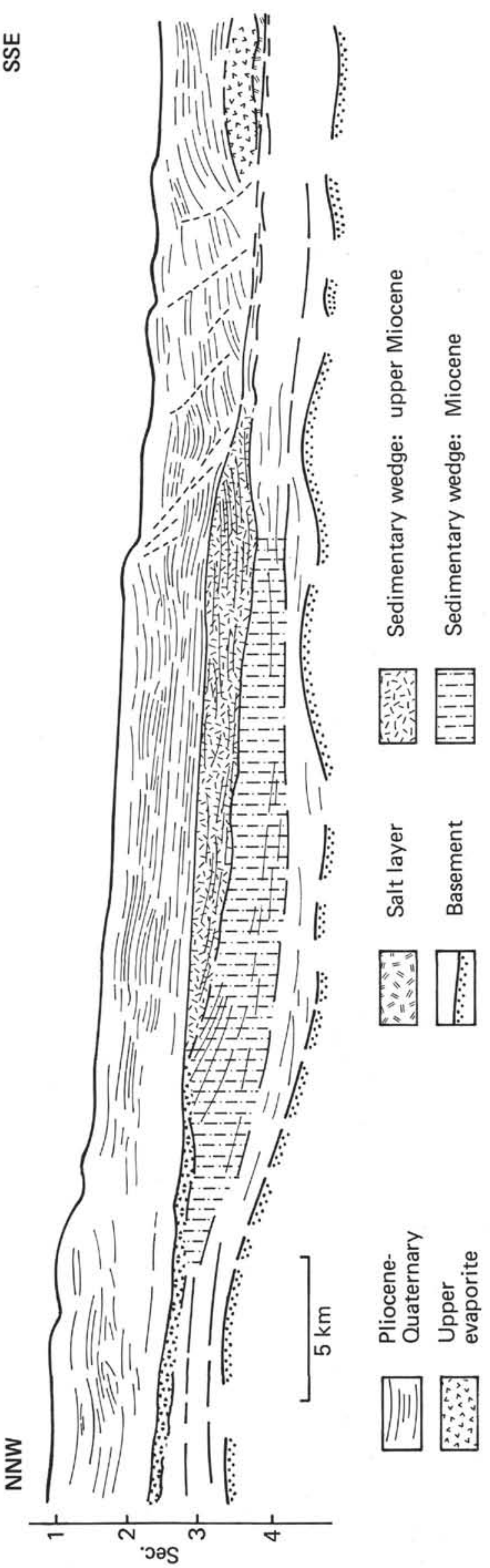

Figure 7. *Typical section off the Gulf of Lion margin showing sedimentary wedges in the Miocene and late Miocene and the intra-Messinian erosion surface.*

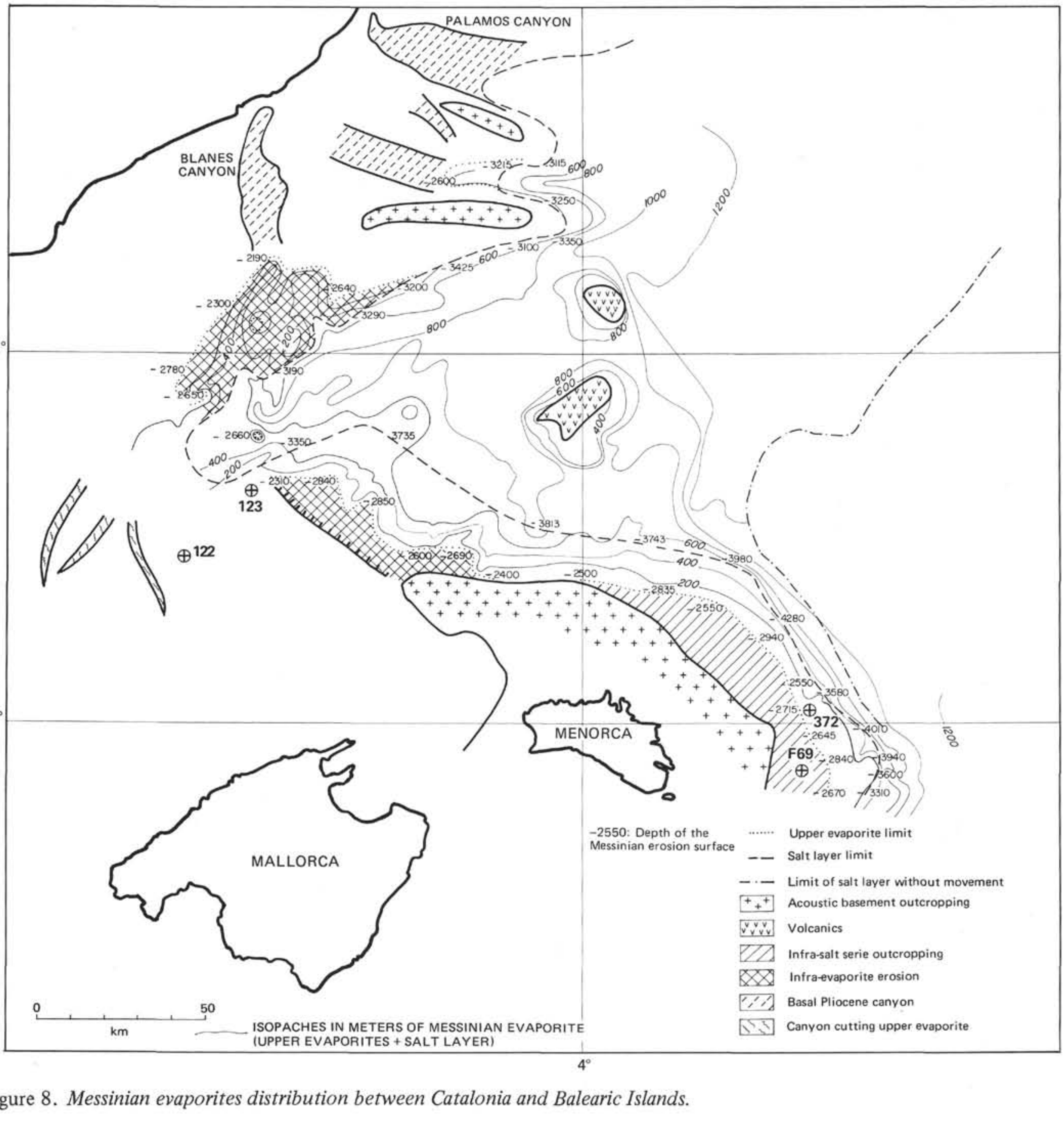

Figure 8. *Messinian evaporites distribution between Catalonia and Balearic Islands.*

same time the salt layer was being deposited in the deep basin.

2) This period of erosion was a short event within the Messinian age. Thus a continuous transition from the Messinian to Pliocene, or Tortonian to Messinian, does not preclude the existence of a break in the Messinian.

Subsidence During the Pliocene-Pleistocene

The subsidence of the western Mediterranean during the Pliocene-Pleistocene has been one of the most controversial problems among geologists. Bourcart (1962) first suggested that a major subsidence of the Mediterranean occurred during the Pliocene—the "Pliocene Revolution"—which gave the present shape of the Mediterranean Sea. Since then, two opposing views, mainly in relation to deposition of the Messinian evaporites in the Mediterranean, have been proposed and vigorously contested. Some authors (Burollet and Byramjee, 1974; Stanley et al., 1974) follow the proposal by Bourcart and explain the present position of the evaporites by foundering, during the Pliocene, of a previously shallow (not much below sea level) basin. Other authors (Ryan, Hsü, et al., 1973; Hsü et al., 1973; Hsü, 1972) have denied the occurrence of this Pliocene foundering and explain the present position and the formation of the evaporites by desiccation in a deep basin, followed by a catastrophic flooding during the early Pliocene.

In order to interpret the geophysical evidence of this Pliocene-Pleistocene subsidence, we must take into account the geodynamic evolution of the basin.

There is no absolute evidence of the age of the drifting phase in the North Balearic Provencal Basin, but it appears that opening occurred during a short period during Aquitanian or early Burdigalian time with creation of oceanic crust. This opening was followed by subsidence of the basin by several processes:

1) **Cooling of the oceanic lithosphere after drifting of Corsica-Sardinia.** Generally in oceanic areas, a subsidence-versus-time curve is applied (Sclater and Francheteau, 1970). It is perhaps inappropriate to strictly apply such a curve here because this basin is more similar to a back arc basin than a normal oceanic one, and also because the oceanic area is very narrow compared with other oceans (about 100 km). Likewise "normal" cooling may not have taken place inasmuch as there is much evidence (boreholes on shelves) to indicate that heat-flow values are much higher than is normal for a 20-25 million year old oceanic basin.

2) **Loading by sediments.** Clearly this must be an important factor in the western Mediterranean where about 7 to 9 km of sediments have been deposited in 20-25 million years.

Nevertheless, it is certain that subsidence began during the earlier Miocene, continued throughout the Messinian into Pliocene-Pleistocene times, and is still active today. Therefore, the Pliocene-Pleistocene vertical movements must be considered as only a part of the subsidence history of the basin. Consequently, we will not use a theoretical approach, but will merely evaluate the degree of subsidence from geophysical data.

Evidence from Pliocene-Quaternary Prograding Deposits on the Margins

If the prograding deposits consist of several prograding subunits, then the margin has subsided (Falvey, 1972). Prograding Pliocene-Pleistocene deposits on the shelves, investigated by means of boreholes vary in thickness depending upon their distance from the shelf break.

The nature of the Miocene sediments below the prograding shelves is also significant. If platform deposits are recognized in the upper Miocene (Tortonian) the amount of subsidence can be grossly determined. A good example is given by Cravatte et al. (1974) from the Gulf of Lion, where the thickness of Pliocene-Pleistocene sediments varies from 875 to 1250 to 2425 meters from the Tramontane to the Autan, through the Mistral holes, respectively, near the shelf break. Tortonian sediments were deposited in a shelf environment; the maximum value of subsidence at the shelf break was about 2400 meters without any relationship to what may have happened during the Messinian regression. Similar figures are recorded from the Gulf of Valencia. From prograding features, Mul-

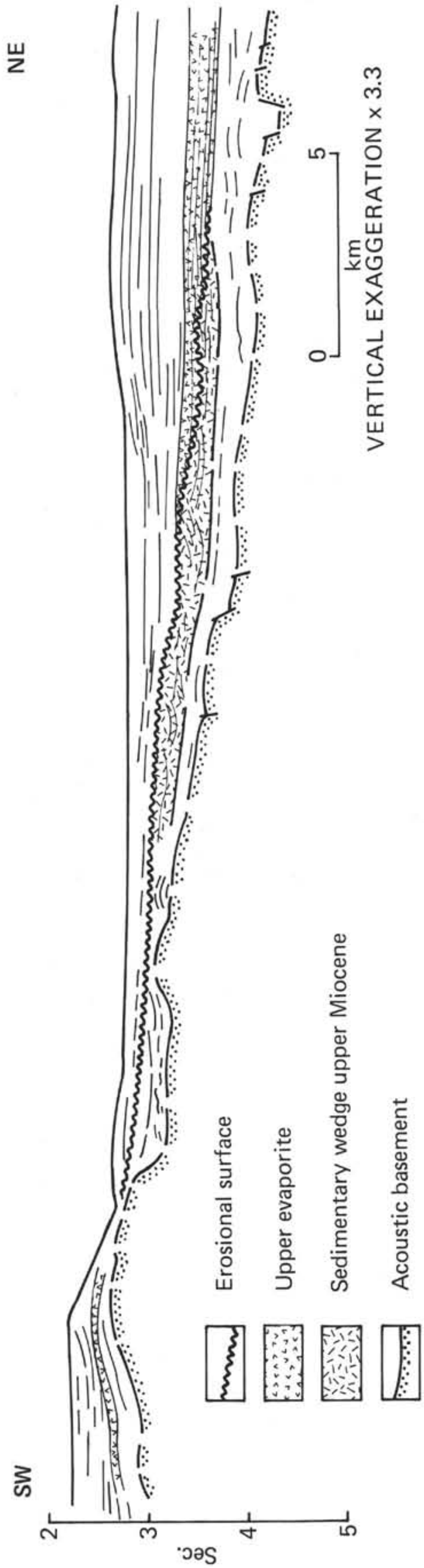

Figure 9. *Seismic profiles (IFP J 207) North of Mallorca showing an upper Miocene sedimentary wedge and the "upper evaporites" infilling the intra-Messinian erosion surface.*

der (1973) estimated at least 1500 meters of subsidence. The Tortonian shelf-facies sediments are recognized from below the prograding shelf on paleo-reliefs (Stoeckinger, 1976), and thus the subsidence can be estimated at about 2500 meters.

Evidence from Fault Escarpments and Throw of Messinian Evaporites or Messinian Erosion Surface

Some of these observations, which seem significant to us, may be refuted by proponents of the deep-basin desiccation model who may claim that in such cases the evaporites were deposited at different levels on a pre-existing topography. Figure 10 shows an example of a fault throw of about 1350 meters of the Messinian erosion surface. East of Menorca, a similar feature can be seen with a 500-meter throw. South of the Balearic Islands, on the Emile Baudot escarpment, evaporites are shifted 1800 meters (Figure 11).

Depending upon the area, subsidence is marked either by a regular tilting of the margin (Gulf of Lion) or by tilting and faulting. Of course, such faults give only an indication and a minimum value of subsidence. It is clear from seismic prospecting that these faults were active before, during, and after the Messinian event.

CONCLUSIONS

The contribution of seismic reflection data to the establishment of a depositional model for the Messinian evaporites in the North Balearic Provencal Basin is summarized as follows:

1) A deep Miocene basin existed prior to evaporite deposition.

2) A thick homogeneous "salt layer" filled major depressions of the basin and pinches out of the margin of this Miocene basin.

3) During upper Miocene time, deposition of the "salt layer" corresponds to a significant regression marked by an erosion surface on the margins. This erosion surface was shaped by shallow water to subaerial processes. The erosional event occurred within the Messinian stage and not at the Messinian/Pliocene boundary.

4) An "upper evaporite" unit with various facies extended farther than the salt layer onto the margin and rests in places on the erosion surface.

5) Messinian-Pliocene-Pleistocene subsidence is the continuation of the Miocene subsidence of the basin. Subsidence may be as much as 1500-2500 meters at the shelf break.

Although each Messinian evaporitic basin has its own geodynamic evolution, we suggest that the Messinian events of the North Balearic Provencal Basin can be extended to the other evaporitic basins of the Mediterranean area, where similar features are observed from the seismic data.

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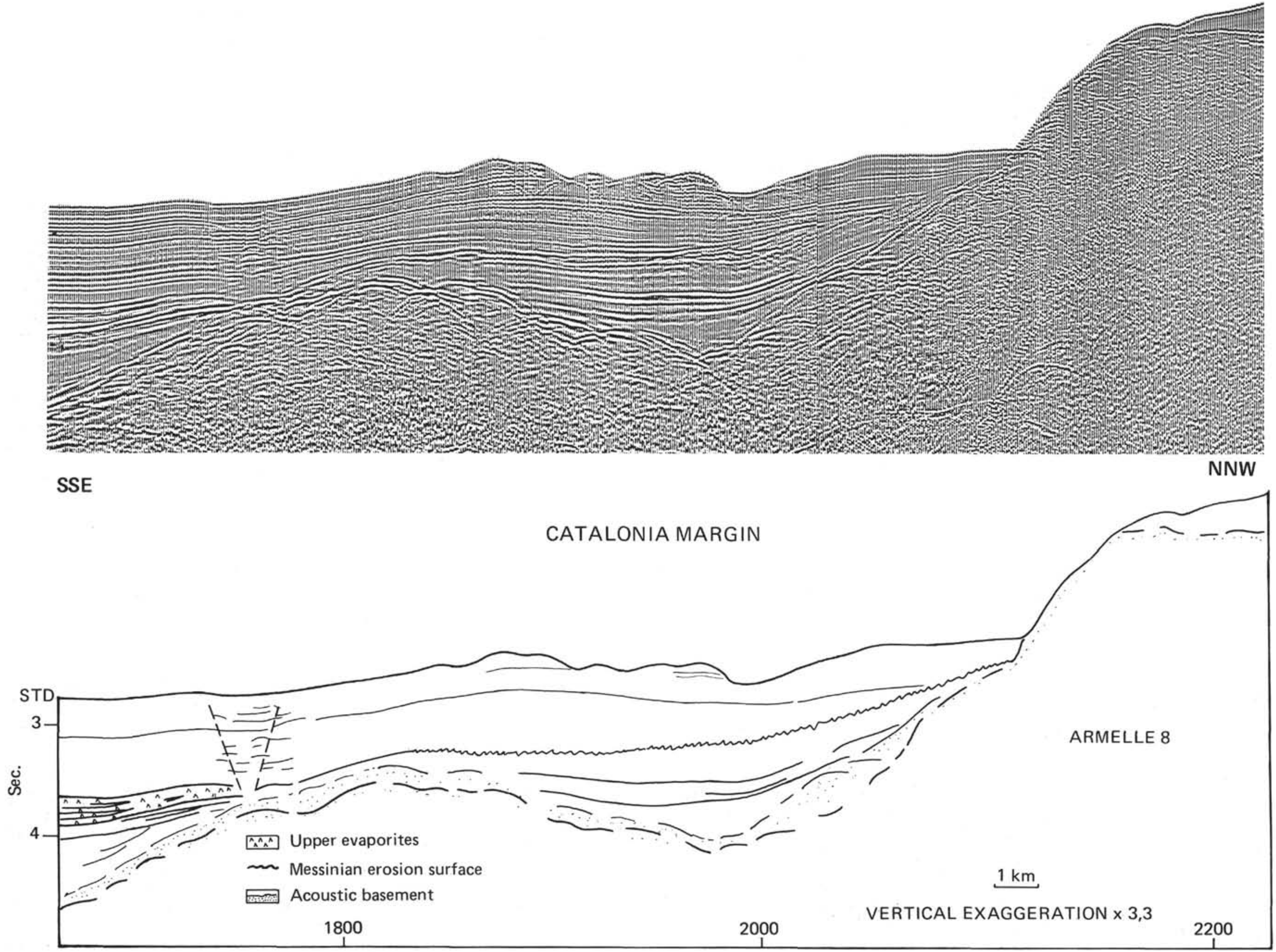

Figure 10. *Seismic profile through the Catalonia margin showing the pinch-out of evaporites and the Messinian erosion surface.*

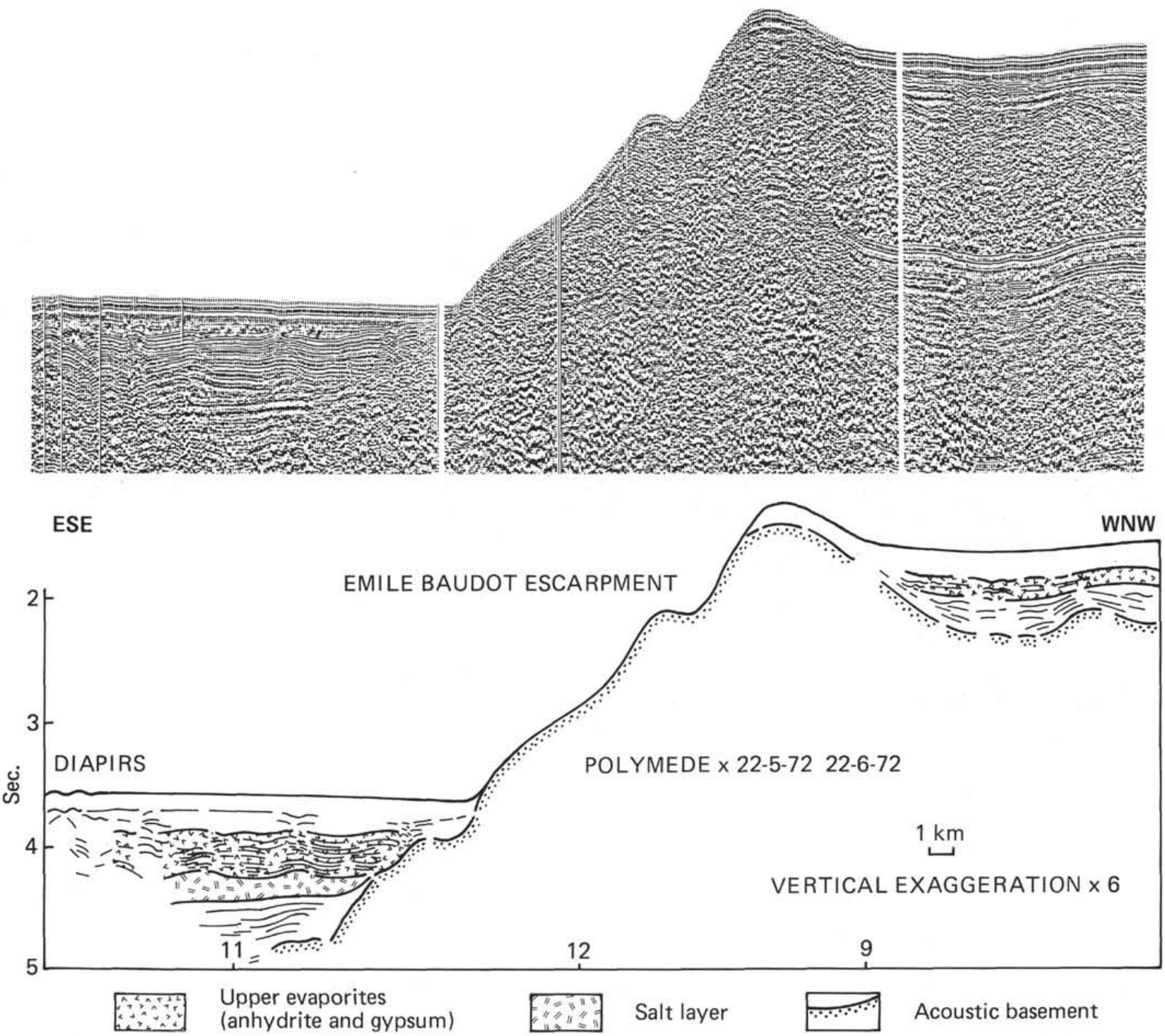

Figure 11. *Seismic profiles showing difference in altitude of the Messinian evaporites in the Emile Baudot escarpment area (south of Balearic Islands).*

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