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Thickness of the Plio-Quaternary sediments (IBCM-PQ)

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Abstract. The compilation of the maps of the thickness of the Plio-quaternary sediments, presented in 1 M. and 1/5 M. scale reduction map, was started in 1981 by E.Winnock, a geologist of ELF-Aquitaine. After his death, in 1985, his work was continued with a large contribution from GEMCO, an Unité de Recherche Associée au CNRS (URA 718) at Villefranche sur mer and Paris VI. E. Tzotzolakis, F. Burollet and P. Kouprine are major contributors. Russian geologists provided coverage of the Black Sea and greatly contributed to the compilation of sheet N°10 (Levant Sea). Seismic surveys used in this mapping were mainly carried out by Oil Companies (CFP-Total, ELF Aquitaine, AGIP), a few Institutes (IFP, Ist. di Geof. di Trieste) and some Universities (Villefranche sur mer, Paris VI, Bologna). Because the velocities of Plio-quaternary sediments were not sufficiently known, E. Winnock selected an average velocity of 2 km/s (two way travel), which we have retained. To simplify the numbering of maps, we chose isochron intervals of tenths of a second. So, the values inscribed are approximatively hectometric (see on map the range of colours: white to yellow: 0 to 1 km, orange: 1 to 3 km, red: > 3 km). Generally, the Mio-Pliocene boundary is well defined, on continental slopes by aerial erosional surfaces and in deep parts of basins by high reflectivity of Messinian salt deposits (see their schematic distribution, after Rouchy, in the inset under the Black Sea on sheet 5). As D. J. Stanley underlined previously, the reduction map clearly shows that distribution of Plio-quaternary sediments results from two major factors, alluvial deposits rates near the mouth of a large river and/or in compressive and overthrusting movements. So, the Danube-Dnepr, the Nile, the Rhône and the Ebro submarine deltas are the largest accumulations of terrigeneous sediments, principally turbiditic. Elsewhere, post-miocene compressive tectonics explains Plioquaternary sediment thicknesses, as in southern Sicily and especially in front of the northern appenninic range. On the contrary, in young back-arc basins, (the Tyrrhenian and the

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Aegean Seas), irregular topographic relief induces a very complex and sparce Plio-Quaternary sedimentation. Similary, on a strongly tectonized Mediterranean ridge, isolated from turbiditic terrigeneous supplies, pelagic sediments distribution was not known enough to provide an outline of isochrons. In the same way, owing to the lack of data, the thickness of sediments cannot be estimated along the Cyrenaic margin. The Black Sea is probably a old back-arc basin, where the Plio-quaternary sediment thickness reaches 4 km and whose NE margins are presently affected by strong compressive movements.

1. Introduction

1.1. History and purpose of the project

Following the publication of the first edition of the International Bathymetric Chart of the Mediterranean (Intergovernmental Oceanographic Commission of UNESCO, 1980, on a 1:1 000 000 scale), a multidisciplinary working group was formed to continue this study by publishing geophysical and geological chart series. These compilations, overprinted on the same bathymetric base map, include the following parameters: Gravity Anomalies, Seismicity, Magnetic Anomalies, Thickness of Plio-Quaternary Sediments and Unconsolidated Bottom Surface Sediments.

Compilation of the maps of the Thickness of Plio-Quaternary Sediments, presented here, was started in 1981 by M. Etienne Winnock, a geologist from Elf-Aquitaine (Pau, France), using a large amount of industrial seismic reflection data. After his death, in 1985, his work was continued by the Equipe de Recherche Associée au CNRS 718 (GEMCO, Villefranche sur mer) and carried out at the Departement de Géologie Dynamique of the Université Pierre et Marie Curie (Paris VI). Owing to his important contribution, we honour Etienne Winnock as a joint compiler of this series.

Following the excellent synthesis prepared by Stanley (1977), there was considerable interest in this compilation of the thickness of Plio-Quaternary sediments:

- the Mediterranean Sea consists of a number of sedimentary basins separated from each other by shallow sills; as a result each basin has specific sedimentary characteristics;
- communication with the Atlantic Ocean is restricted to the Strait of Gibraltar. As a consequence, the Mediterranean is subject to short term climatic variations, especially along the latitudinal boundary between temperate and tropical climates;
- its intramontane character results in many regions which have a high rate of terrigenous deposition, alternating it with active pelagic planktonic sedimentation;
- the great depth of these small basins and the steep continental slopes allow the development of large gravity driven processes; these (slumps, mud flows and turbidity currents) are responsible for important accumulations of sediment species.
- The morphological evolution of the basins, and their sedimentary history, are clearly related to active plate tectonics. Some developing basins, such as the Tyrrhenian Sea, are very

recent, and they provide an interesting model of the early stages of sea floor spreading. On the contrary, in the eastern basin, the subduction/collision of the African margin shows sedimentary deformations corresponding to a preorogenic phase (eastern Mediterranean Ridge).

2. Recent geological history of the Mediterranean

2.1. Tectonic evolution

Plio-Quaternary sedimentation in the Mediterranean area is directly related to lithospheric movements resulting from plate tectonics. Since the Jurassic, the widening of the Atlantic Ocean has caused the African and Eurasian plates to move steadily closer to each other, resulting in the progressive disappearance of the Tethys Sea which separated them. During the Jurassic a large fragment of Africa, which today extends from Apulia to the southern Taurides, separated from the African plate and collided with Eurasia, leaving behind a large marginal basin known as the Mesogean Sea, the present remains of which are the eastern Mediterranean basins. These continue to shrink as a result of continental subduction under the Eurasian plate. Around the Mediterranean region, the collision of Africa and Eurasia resulted in the progressive build up of the Alpine orogenesis. Seismic records show that the N-S compression still continues and that the orogenic forces are strongest in the Maghreb Atlas Range, the Apennines and the Dinarides. At the start of the Miocene, 20 million years ago, the Corsica-Sardinia arc and the North Kabilia range separated from Europe, creating the deep western Mediterranean basin (known also as the Algero-Provençal Basin).

In the mid-Miocene, the collision of Africa and Eurasia blocked marine communication between the eastern Mediterranean (the Levant Basin) and the Indian Ocean. From the late Miocene to the Quaternary, a similar process of migration of the Calabro-Sicilian arc to the south-east gave birth to the Tyrrhenian Sea, likewise with oceanic crust. The origin of the Aegean Sea is similar but it is in a less evolved store (without the formation of oceanic crust). So, the Mediterranean sea consists of a very large range of morphotectonic units, of varying age, as for example the north Libyan margin of the Jurassic era, the early Miocene margins (Burdigalian) of the western basin or the Plio-Quaternary margins of the Tyrrhenian Sea. Some active margins, from Miocene to the present day, form the Calabrian and Hellenic Arcs.

2.2. Messinian salinity crisis and birth of Pliocene sea

In the last Miocene, about 6 Ma BP, (Messinian) tectonic movements due to the collision between Africa and Europa and also, at least partially, contemporaneous glacioeustatic falls of sea water level, have probably been the major causes of reduced inflows of atlantic waters into the Mediterranean, through the Strait of Gibraltar or other neighbouring ways.

During this time, (about 1.5 MA between the Tortonian and Pliocene stages) this partial isolation of the Mediterranean basins, subjected also to a dry climate, led to an anomalous wide-ranged process evaporation (named "salinity crisis") and precipitation of thick salts deposits (for example: 3 km in the Western Basin, including 1 km of halite). Obviously, to obtain these salt accumulations in all basins, it follows that the volume of the corresponding evaporated sea water has to be equivalent to forty times the present day sea water mass of the Mediterranean Sea.

Despite there being a lot of articles about the evaporitic process, intense controversies are still not resolved. According to the DSDP team, shallow water conditions prevailed, with intermittent dessiccations and atlantic inundations. Then, after the evaporation of deep tortonian basins waters, these like-sebkhas lay at more than 2 km under the world sea level. An other hypothesis, not as spectacular, suggested the possibility of a shallow (epicontinental) and subsident Messinian Sea and a Plio-Quaternary foundering quickly. For other workers, there is a considerable disproportion between major salt masses deposited during the Messinian (sulphates/chloride) and the equivalent ratio of normal marine water. This anomaly, strongly suggests the necessity of a sub-outflow of Mediterranean residual water to the Atlantic Ocean, e.g. a model of anti-estuarine circulation analogous to the present ones. Unfortunately for all authors, important vertical tectonic movements (Alboran Sea, Tyrrhenian Sea, Sicily-Calabria, Eastern Ridge, Aegean Sea etc.), and the large subsidence of deltaic sedimentary accumulations profoundly modified the morphological characters of Messinian Mediteranean Sea. So, the present distribution of major salt deposits, roughly delimited on insert of sheet 5, is certainly the final result of numerous modifications by new tectonic events, gravity displacements and dissolution processes.

In the first author’s opinion, a hypothesis of pre-existing deep Mediterranean Basins (except for the Tyrrhenian and Aegean Seas) is more in accordance with age (20 MA for the Western Basin) and necessary with the oceanic nature of the crust. Then, after the isostatic rebound following the partial evaporation of Tortonian waters, we can estimate the level of evaporation, in the Western Basin, at about 1300 m under the world sea level. So, we can explain the intense aerial erosion of continental slopes marked by the absence of the Miocene cover, the cutting or deepening of rocky canyons, the deep continental cut of the Rhône River and the slope deposits of red azoic clays covered by lower Pliocene planktonic marls.

The end of the Messinian would be marked by a return of a less arid hydrological balance (probably an increase of rainfall) and a brief flowing of brackish waters into the Eastern Mediterranean from the Paratethis in central Europe (Lago Mare). So, the normal deposits of end Messinian and infra Pliocene is frequently a sequence of interbedded gypsum and marl, with a thickness, in places, of several hundred meters.

The Pliocene transgression is characterised by a rapid and simultaneous filling in of the Mediterranean Basins by Atlantic waters ("Révolution pliocène" by J. Bourcart), through the Strait of Gibraltar, the depth and width of which was clearly greater then than at present. Generally, there is no sign of transgressional erosion of base conglomerates and the presence of abundant planktonic tests in the lower Pliocene deposits emphasizes the rapid filling in of deep basins right up into the deep continental valleys (Pliocene rias).

3. Methods of study

3.1. The heritage

Several partial isopach maps (the Spanish Continental Margin from the Alboran Sea to the Gulf of Valencia, the Po Valley, the Sicilian-Tunisian Shelf) were inherited from E. Winnock; these needed only slight modification. There was also some work in progress (the Levant, Adriatic and Alboran seas).

3.2. Existing isochron maps

Isochron maps of the Plio-Quaternary extracted from research theses (prepared in URA 718 of CNRS) were used without any major modifications: M. El Robrini (Moroccan-Algerian margin), A. Le Cleach (Antalia), D. Lefevre (Gulf of Lyons), P. Le Quellec (Cretan Margin), L. Martin (Aegean Sea), B. Thomas (Sardinian Margin), E. Moussat (Tyrrhenian Sea), L. Viaris de Lesegno (N. Tyrrhenian Basin). Some other isochron maps were used: F. Fanucci and J. P. Rehault (Ligurian Basin), A. Mauffret (Provencal Basin), D. A. Tugolesov et al. (Black Sea), A. F. Limonov and L. Limonova (Levant Sea), N. Zitellini (Tyrrhenian Basin).

3.3. Continuous seismic profiles

A very large number of seismic profiles have been shot in the Mediterranean over the last 20 years, but their definition and penetration vary considerably. Seismic surveys carried out by oil companies usually cover the deep basins and Messinian markers are generally visible. ELF-Aquitaine and CFP-TOTAL, as well as the Institut Français du Pétrole (IFP) have allowed us to consult their archives; also the University of Trieste (I. Finetti, C. Morelli) whose records are of similar quality.

Numerous profiles, shot by Universities, but with lesser penetration, were meanwhile useful for studying margins (Centre de Géodynamique sous-marine of Villefranche s/mer; Laboratoire de Géologie de l'Université Pierre et Marie Curie, Paris VI; Laboratorio di Geologia Marina, Bologna, Italy). Russian geologists provided coverage of the Black Sea and contributed greatly to the compilation of sheet n. 10 (Eastern Mediterranean).

3.4. Establishment of isopachs

Winnock's first objective was the conversion of the data into isopachs. But useful velocities

calculated from industrial seismic profiles were sparse. Several accurate values had been obtained in DSDP-ODP bore holes by in situ velocity surveys or by measurements on core samples, though these were insufficient for the whole of the work carried out.

It was known, on the other hand, that due to the composition of Plio-Quaternary sediments and their compaction by burial, the velocity of P-waves (2 way travel) varies considerably, from 1.65 km/h at the surface to more than 3 km/h at the base of the thickest formations. As these difficulties were virtually insurmountable, Winnock selected an average velocity of 2 km/s (2 way travel) which we have retained. The resulting values are too high in the thin layers and too low in the thick sequences. Such a simplification has the advantage of allowing an immediate estimation of the depth (1 second representing about 1 km of sediment thickness), and a comparison of existing data with those from new profiles. To simplify and clarify the numbering on the maps, the spacing between isochron lines is in tenths of a second (2 way travel time). The inscribed values are thus roughly hectometric.

3.5. Difficulties and limitations

These are of four types:

- upper limit of the evaporites. In the depths of the basins the upper layer of the evaporites is formed of interbedded gypsum and marl, which are strong acoustic reflectors. The exact boundary with the overlying thin bedded lower Pliocene may be difficult to identify on the seismic profiles;
- tectonic deformations. In tectonic areas, whether caused by expansion (Tyrrhenian and Aegean Seas), by halokynesis (Gulf of Lyons, Israëli Margin) or by compression (Mediterranean Ridge and Po Valley), the faults are very short and so numerous that it is impossible to show them all on a 1:1 million scale map. The presentation on the map therefore represents the general geological structure rather than the exact positioning of features. On the Mediterranean Ridge, the very large discontinuities in the thin cover did not permit delineation of isochrons;
- density of data. In certain areas where the Plio-Quaternary cover is thin and seismic profiles are sparse, the approximate contours are drawn in dashed lines. On the Libyan Margin, the absence of seismic data (except those of the Institut Français du Petrole) obliged us to leave the area blank;
- correction of isopach contours. The documents have been compiled using a relatively long period (1980-88). It has been possible to update some of the maps. Other maps contain some omissions and errors which we have been unable to correct. In addition, production delays have meant that the time lapse between the completion of the first maps and their publication, may have been as long as 7 years.

4. General review of Plio-Quaternary sediments

4.1. Palaeogeography of the basins

Throughout the Plio-Quaternary, Africa and Eurasia continued to move closer to each other at an average rate of 1 cm/year, (amounting to about 50 km in the central region since the Messinian. As a consequence, the geography and morphology of the basins have changed considerably over the last 5 Ma. As a result the horsts and basins in the structure of the Alboran Sea have been accentuated, and the north African margin has become steeper. The changes (in the centre of the Mediterranean) are even more obvious. Sicily and Calabria have emerged from the Pliocene Sea, and have been uplifted to more than 2000 m and 3000 m respectively. The uplifting of the Appenines is countered by the opening and subsidence of the adjoining Tyrrhenian Sea which today has a depth of more than 3500 m. The tectonic subsidence and sedimentation of the Po Valley resulting from the North Appenine compression has reached 6000 m today. But it is probably in the Ionian Basin that the morphological changes are most marked. Its structure results from compressional movement under the Aegean Arc where the Mediterranean trenches are the deepest (5010 m depth in the Matapan Trench), together with the extension of the Aegean Sea. Notable also, is the active and continuous uplifting of the whole of the Mediterranean Ridge, which lies between two deep troughs each having independent sedimentation. As a general rule, it can be said that during the Plio-Quaternary, the basins became progressively more isolated due to the uplifting of the sills which separate them.

4.2. Hydrography of the basins currents and water masses

The Strait of Gibraltar has undergone very few changes since its post-Miocene opening, but it is without doubt less deep today. At present, the shallow input of Atlantic waters, which compensates for the evaporation in the Mediterranean, flows along the African coast to the eastern Mediterranean, feeding basins along the way by anticyclonic gyres. Its volume reaches 38 million km^3/y, whereas the outward flow of intermediate waters (in the 100-600 m depth layer) is limited to 36 million km^3/y. Sediments suspended while flowing in from the Atlantic, are deposited mainly in the Alboran Sea, as contourites and pelagites. On the other hand, the inward flow ensures the renewal of the planktonic and microplanktonic biotopes. There are only minor changes as it makes its way eastward to the Levantine Basin.

Renewal of the deep water is necessary to prevent anoxia (see the sapropels, below). Cooling and surface evaporation in winter due to cold strong winds, such as the Mistral and Bora, are essential to create the necessary mixing with depth of the surface and intermediate waters, and resulting in uniform density throughout the water column. Formation zones exist in the southern part of the Gulf of Lyons, also in the Ligurian Sea and above all in the south Adriatic Sea.

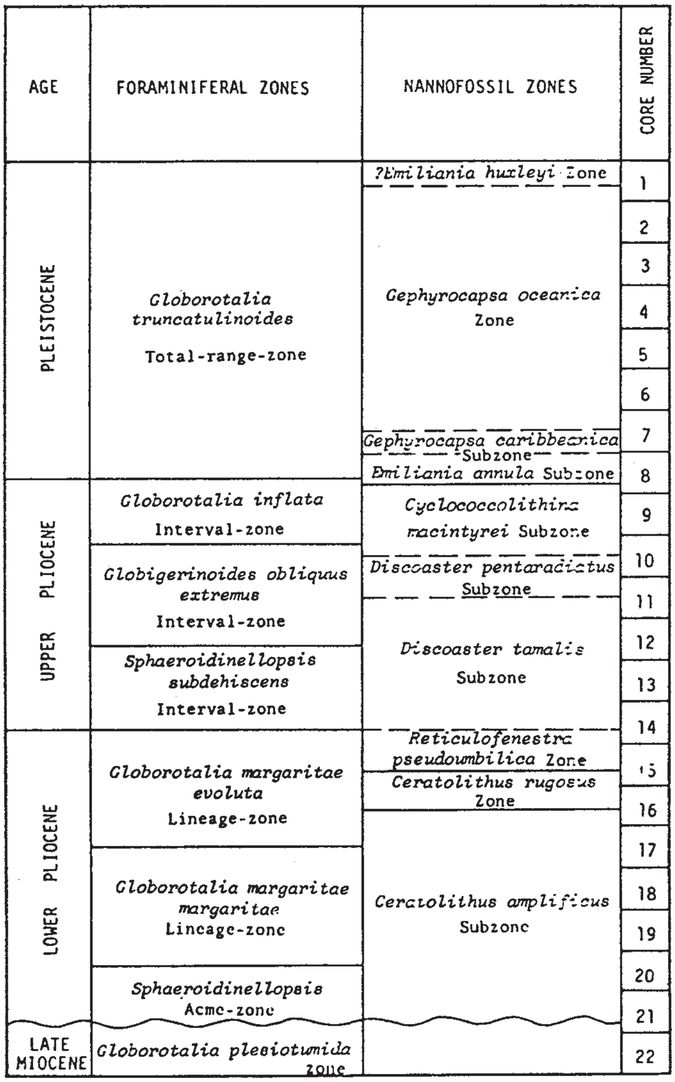

Fig. l - Correlations between foraminiferal zones and calcareous nannoplankton zones, at site 132 (Tyrrhenian Basin), from Cita (1973).

4.3. Variations in sea level and climate

Glacio-eustatic variations in sea level have played an important role in the Mediterranean; these have been accentuated by its intra-continental setting, its fragmentation into several basins and the proximity of high mountain landscapes. We have already mentioned the importance of glacial eustatic variations (-60 m) during the end of the Miocene (Messinian). At the end of the Messinian, global warming, which was more apparent in the eastern zone, resulted in a rise in sea level and an increase in precipitation. To the east, there was a brackish environment due to the influence of waters coming from the Paratethys. In this "Lago Mare" one finds benthic foraminifera and brackish type ostracods.

The restoration of full marine conditions and the infilling of the basins (followed the opening of the Strait of Gibraltar). During the early Pliocene (NN12 and NN13) the abundance of discoasters suggests a warm climate. But the climatic change increased during the late Pliocene, about -2.5 Ma (NN16, Discoaster Surculus zone), associated with temporary inflow of colder Atlantic water - the start of Glacial cooling (Fig. 1). Micropalaeontological and isotopic analyses on Quaternary fossils show that the temperature changes due to Quaternary glaciations seem to have had less influence than the accompanying variations in sea level. The nannoplankton of the eastern Mediterranean had, in general, a somewhat subtropical character. Planktonic foraminifera associations provide excellent correlation with isotopic palaeotemperatures. *G. Pachyderma*, *G. Quinqueloba* and *G. Scitula*, species which are more resistant to cold conditions, are abundant in the deposits of the glaciation period, whereas the large number of *G. Truncatulinoides*, *G. Inflata* and *G. Rubra* indicate a more temperate climate. On the other hand, *G. Triloba* and *G. Sacculifera* are more frequent during the interglacial maxima.

As for all oceans (of which the Mediterranean is a small scale model), the consequences of the lowering of the sea level, on the morphology of the deeper parts of the basin and on the sedimentation, were considerable. The large rivers cut the continental shelves and deposit the alluvium, gravels, sands and clays, which they have transported at the head of the canyons. The instability of these deposits allows them to be swept away by gravity as slumps, mud flows and turbidity currents. By flow to the foot of the continental slope, they build up superimposed lobes where the diameter of the particules generally decrease towards the open sea. These spectacular accumulations have been given the name of 'deep sea fans'.

It seems that most of this type of the world's features were formed during the glacio-eustatic Quaternary lowerings of sea level. In the deeper regions the currents, particularly turbidity currents, are more fluid and have overlain and levelled the abyssal plains where the vertical classification of the granules is more or less apparent with fine sands and clays (turbidites), centimetres to decimetres thick. In periods of high sea level, these turbidic layers are overlain by hemipelagic, sometimes purely pelagic, sediments (20 to 30% of biocarbonates). However, the gravity flows may continue when the absence of a continental shelf allows the rivers to continue to spread their alluvium at the head of canyons or high up on the continental slope. The lowering of the sea level had drastic effects on marine circulation in the straits, in particular, on the Sicilian-Tunisian Plateau and in the Cretan Arc. The possibility that the currents in the Strait of Gibraltar were reversed, for 10 000 years, has been suggested, as the waters of the Mediterranean were less saline than those of the Atlantic Ocean (estuarine circulation).

4.4. Mio-Pliocene and Plio-Quaternary boundaries

ACOUSTIC STRATIGRAPHY. - It has been possible to draw the Mio-Pliocene boundary for nearly all of the Mediterranean basin, thanks to the availability of numerous continuous, high-definition, seismic reflection lines, together with the deep JOIDES and ODP drill holes. Along the continental margin this limit is relatively easy to determine as it corresponds to a continental erosion surface with strong relief, overlain by Plio-Pleistocene unconformity, on-laps, sigmoid foresets

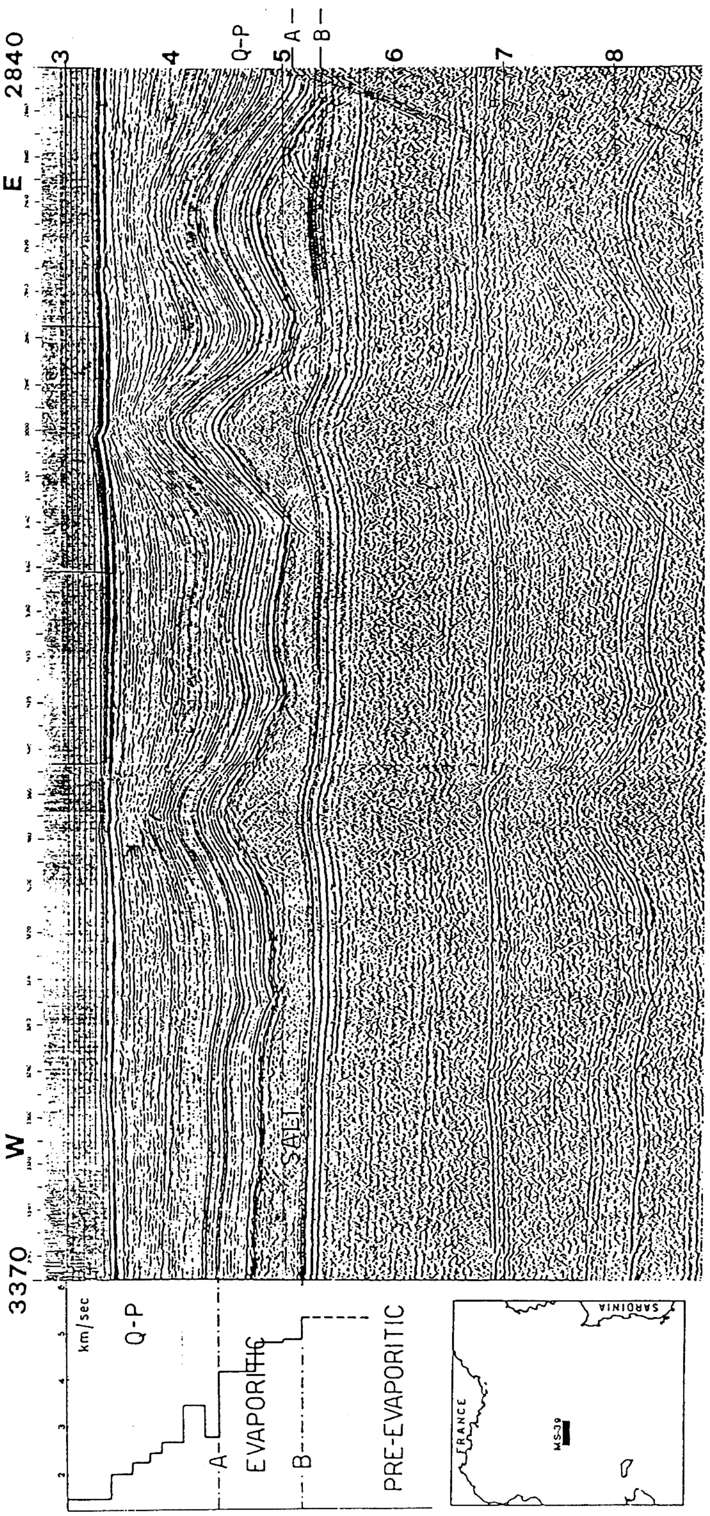

Fig. 2 - An example of halokinesis in the Balearic Basin, after Finetti and Morelli (1973). Q-P = Plio-Quaternary (about l km); evaporitic sequence (2.5 km), clearly divided into upper evaporites (and halite) and infra-evaporites at the base.

etc. However, this boundary is less well defined and lacks continuity in certain tectonic margins (the peri-Tyrrhenian basins for example), or those deformed by salt collapses (such as the Israeli margin). It is frequently indistinct on the hanging walls of the Hellenic subduction (tectonic mélanges).

In the deep parts of the basins, the boundary between the Messinian and the Pliocene shale is marked by a high amplitude seismic reflector, due to acoustic impedance contrast between Pliocene sediments and the evaporites. The contrast is sharper where the infra-Pliocene shales are pelagic and acoustically transparent (Trubi facies). Nevertheless, it is sometimes difficult to separate, by analysing seismic records, the poorly evaporitic Messinian shale from overlying Pliocene turbidites. It should, however, be noted that halokinesis may disrupt normal stratification and the true thickness of the Plio-Quaternary shales (cohesive diapirs from the Ligurian Sea), and that piercing of salt domes also disturbs turbidite flows and their spreading (Fig. 2).

On the Mediterranean Ridge, halokinesis and local compression make isopach mapping of the thickness of the Plio-Quaternary sediments almost impossible. At abyssal depths the Plio-Quaternary boundary is often indistinct in seismic records. Sometimes clear acoustic stratification appears in the Quaternary sediments, due to coarser and thicker turbidites, corresponding to periods of low glacio-eustatic sea level. In the western basin the thickness of the Quaternary sediments is of the order of 300 m.

BIOSTRATIGRAPHY AND HISTORICAL DATING. - The lower Pliocene corresponds to the Zanclian, formerly named Tabianian. It was the tectonic opening of the Strait of Gibraltar that allowed the final return of Atlantic water throughout the Mediterranean basin. The interpretation of Glomar Challenger Leg 42A drill holes shows clearly that the early deposits after the return of the marine conditions are with pelagic limestone (Trubi facies), confirming a depth of 1000 to 1500 m for the evaporites on the Messinian seabed. But it is difficult to understand why on certain margins of the basin, now uplifted to the Messinian, in particular the region of Murcia (Spain), the Mio-Pliocene series is wholly marine, and at Vera the G. Margaritae series or the early Pliocene overlies that of G. Mediterranea from the late Miocene. The beginning of the Pliocene flood is thus dated at -5.2 My, and it is characterised by the general appearance of *Sphaeroidinellopsis* (acme zone N18) and by a new species of nannoplankton, in particular of *Amaurilithus Tricornicutatus* (NN12). Nevertheless, many basal gaps seem to indicate that the transposition was not exactly contemporaneous throughout the region, or that local erosion by the deep currents was particularly active.

The Pliocene-Quaternary dividing line, which was defined in 1948 as the end of the Calabrian, corresponds to the start of the Olduvai palaeomagnetic event (normal polarity), that is today, 1.8 Ma. From a palaeontological point of view, the dividing line is marked by the sudden appearance of the benthic foraminifera *Hyalinea Baltica.* In the deeper sediments, where this species boundary is generally absent, the most frequently used is the disappearance from the nannoplankton of *Discoaster Brouweri* and the appearance among the pelagic forminifera of *Globorotalia Truncatulinoides.* An older dating for this boundary has recently been proposed (See also more recent data presented by Di Stephani et al., 1993).

4.5. Thickness of Plio-Quaternary sediments

RATES OF SEDIMENTATION. - The largest accumulations of sediments are to be found near the mouths of large rivers. The Black Sea is a special case of depocenter where one river, the Danube, is predominant. In the Po Valley and its marine extension into the Adriatic, folding and tectonic overthrusting explain a sedimentary pile of 6 km thick. The maximum thicknesses reached are 4 km in the Nile delta, 2.8 km in the Ebro delta and 2.2 km under the Rhone deep sea fan. Elsewhere, important accumulations exist but with only minor spreading, such as in the Bay of Iskenderun (NE of Cyprus), Antalya Bay (S of Turkey), along the Tirana coast (Adriatic), the intra-slope basins of Gioia (SE Tyrrhenian Sea) which are infilled by 4 km of detritic sediments, the north Aegean troughs or again the Sicilian-Tunisian grabens. All these sedimentary traps are the result of distensive tectonic movements associated with important sedimentary supplies.

Owing to their remarkable individuality, the Mediterranean basins need to be examined separately; this is the result of their isolation by raised sills and by the complexity of the submarine and terrestrial topography, together with the diversity of the climates.

The thinnest sediments (0-200 m) cover the large relatively shallow regions such as the Mediterranean Ridge, the Sicilian-Tunisian shelf or the central Adriatic plateau, where the surfaces are most probabily swept by currents. In places, as confirmed by the JOIDES-ODP drill holes, the Plio-Quaternary series sometimes show important gaps due to contour currents, chiefly at the foot of the continental margins.

Sediment rates have been calculated with high precision, thanks to the Glomar Challenger drillings, principally on Leg 42; these calculated values do not take compaction into account. One finding of great importance is the relatively low rate of sedimentation during the Early Pliocene in all basins; this is in apparent contradiction with its intracontinental character. So, the rate varies from 2 to 4 cm/1000 y, with the exception of the Alboran Sea where the contribution from the Atlantic inflow was already important. Several explanations have been put forward, the most plausible being that the considerable uprising in sea level at the start of the Pliocene resulted in the alluvial sediments being retained in the submerged continental valleys. It may be seen that the same phenomenon, with smaller amplitude it is true, was repeated after each glacial lowering of the sea level. Consequently, the Early Pliocene deep sediments are mainly pelagic, calcareous muds, with coccoliths and planktonic foraminifera (Trubi facies).

During the mid-Pliocene, the rates of sedimentation varied between 4 to 10 cm/1000 y; they were marked by an increase in alluvium and the growing importance of turbidites, as shown by the reduction of sediment thickness on the abyssal highs. The glacial periods of the Quaternary were largely responsible for the feeding of the deep sea fans and deep basins, with material coming from the rivers, deltas and continental shelves. Sedimentation rates reached 20 to 25 cm/1000 y, as found in many places by shallow sampling or from the DSDP drillings. Some local changes are explained by tectonic events.

4.6. The Mediterranean sediments

The Mediterranean Sea is a tectonised micro-ocean where the role of the continental margins is dominant. Due to the young age of many parts of the basins and their recent deformation, continental shelves are generally narrow, the slopes are steep and terrigenous sediments dominate in the abyssal plains.

Except for the large plateau between Tunisia, Sicily and Libya (Pelagian Sea), continental shelves are only well developed near the mouths of large rivers. They are usually narrow and sometimes completely absent (as along the Algerian coast).

The floors of the sheltered bays are covered by Posidonia biotopes, whereas the inner shelf, if mostly rocky, with thin holocene bioclastic deposits. The outer shelf (50 to 100 m deep) is often broken up by old Quaternary coastal sand bars, but more often is covered by relic, mainly würmian, sediments, as can be found in most other oceans. Along the continental slopes, the delta fronts are the only places where the steady and continuous Plio-Quaternary sediments can be easily delineated. Elsewhere, the slopes consist frequently of sharp escarpments in the Hercynian basement (Provence, Corsica and south of the Balearic Isles) or in the sedimentary rocks (the Maltese escarpment, Cyrenaica, etc.). These Plio-Quaternary covers are unstable, discontinuous and often thin. In other places the slopes have suffered tectonic deformation (southern Creta, northern Algeria) resulting in complex relief and very complicated sedimentation. In the Tyrrhenian Sea the continental slopes are strongly structured by normal faults and comprise rocky barriers and basins with retained sediments.

Continental rises are widely developed just in front of the large deltas. They are formed by fan shaped, reworked sedimentary accumulations. Along the other passive margins, near 2000 m, the hemipelagic concordant deposits grade to the onlapping horizontal sediments of the basin floors.

In the deepest areas, leveled plains are formed by a thick layer of turbidites and hemipelagic deposits. This shows the important role played, during the Pleistocene, mainly by continental erosion, but also by the reworking of sediments on the slopes and in the canyons. These horizontal bottom layers are often deeply deformed by salt structures.

The unstable sediments of the Mediterranean continental slopes provide one of the best areas for research into these phenomena. The reworking of the largely clayey sediments is due to several independent or associated causes:

- mobility of the substratum (mainly evaporites);
- sedimentary overweight (under compaction);
- seismic shocks and vibrations;
- faulting or neotectonic movements;
- erosion by loaded currents (down the canyons).

All sorts of reworked sediments have been found on the Mediterranean slopes and bathyal plains. They include features where the original structure has been preserved, though sometimes badly deformed (e.g. the Calabrian arc) or offset by circular faults (e.g. the Gulf of Lion).

The largest amount of reworking, without preservation of stratification, can be found near the feet of the slopes (slumps) and at the lower end of the canyons. However, of greater importance is the fact that, with a higher water contents, these form highly erosive debris flows which cover the plains over several hundred km^2 (Ligurian Sea). More fluid still, are the turbidity currents, whether these have high or low sediment content, they are the major factor in deep sedimentation processes. They are characterized by the presence of coarse or fine grained sandy layers, thinning up, sometimes baren of fossils; but the composition may be entirely marly, devoid of stratification and of coarser sediments. The name Unifite has beeen proposed to distinguish them from the usual hemipelagic deposits.

All the sediments, whether reworked or not, are more or less rich in clayey minerals; illite predominates, but it is accompanied by chlorites and sometimes kaolonite and smectite.

4.7. Sedimentary peculiarities: sapropels

A large amount of attention has been paid to a sedimentary anomaly which occurs frequently in the Quaternary sediments of the eastern Mediterranean and in the Tyrrhenian sea: these are remarkable interbedded layers, 1 cm or more thick, of black mudstone called 'sapropels'. By definition they contain more than 2% of organic matter, sometimes up to 16%, but numerous beds exist containing less than 1% (these are known as episapropels). Their black colour is owed to the presence of iron monosulphide, often associated with pyrite. Vegetal detritus has also been reported. The calcite cames from planktonic organisms (coccoliths, foraminifera); it may form up to 78% of the sediment but bears no relationship to that of the organic content.

Their formation appears to be related to anoxia in the depths of the basins (where there is inadequate replenishment of the deep water), or from an excess of organic matter coming from plankton or from rivers, or again from a combination of these processes. This phenomenon cannot be explained by glaciation, as it exists in the Miocene as well as in the interglacial periods. Today there appears to be a correlation between sapropel deposits and the reduction of surface salinity due to precipitation, with its resulting increase in the supply of alluvial deposits from rivers, especially in the Nile which is fed in summer by the monsoon. Recent Black Sea sapropels confirm this explanation.

Recent research indicates that there is a good correlation between the age of the sapropels and the conjunction of the orbital cycles of the earth (eccentricity and precession), the meteorological consequences of which are amplified by latitudinal effects and the particular geographical characteristics of the eastern Mediterranean. The precision of these calculations is of the order of 1000 years, based on the most recent sapropel layer being from the Holocene. The Tyrrhenian Sea sapropels have resulted from the same climatic oscillations that would have affected the north-west basin, which is the sole source of water for the deep Tyrrhenian Sea. This correlation, if confirmed, constitutes an important discovery.

Other sedimentary anomalies worth noting are:

- tephras: the instantaneous deposit in the Tyrrhenian Sea and throughout the eastern Mediterranean, over a huge area of the seabed (100 000 km^2) of layers of ash (tephras), up to 10 cm thick, thrown out by the Eagean and peri-Tyrrhenian volcanoes;
- homogenites: the reworking or mixing in suspension, in the eastern Mediterrenean, of enor-

mous quantities of peri-continental muds, which have been destabilised by volcanic explosions, such as that of Santorini, 1500 years ago. These deposits are similar to the abyssal accumulations of well mixed muds known as homogenites.

In conclusion, the dominant Plio-Quaternary sediments in the Mediterranean are hemipelagic or pelagic muds, and turbidites of variable sandy contents. Their constitution and, more important, their thickness, result from the intracontinental and intramontane character of the basins, which were built up or smoothed out by Quaternary glaciations. However, tectonic sand gravity reworkings are also important factors in the distribution of deep sediments.

5. The Mediterranean basins and their Plio-Quaternary sediments

5.1. The Western Basin

The Western Basin, often named the Algero-Provençal Basin, is more than 1500 km in length, from Gibraltar to Genova. It may be divided into several geographical units from south-west to nord-east: the Alboran Sea, the Algerian Basin, the Gulf of Valencia (with the Ebro delta and the Balearic isles) and the North-West Basin comprising the Provençal Basin and the Ligurian Sea. However, their names and limits vary with different authors.

It has an oceanic crust from the Tertiary age, as its spreading, from the Burdigalian (about 20 Ma), is a direct consequence of the relative movements of Europe and Africa. In effect, the separation and rotation of the southern edges of Europe (Corsica-Sardinia, Balearic isles, Kabyle mountains chain) caused the opening of this feature wich may be considered to be a back-arc basin.

Steep passive margin surround an abyssal plain which at present has a maximum depth of 2800 m. The sedimentary deposits are very thick, 3000 m of Miocene layered series, 2000 to 3000 m of Messinian evaporites and 1000 to 2000 m of Plio-Quaternary sediments, in the Provençal Basin. There are numerous signs of recent tectonic compression principally along the south margin.

THE ALBORAN SEA. - The Alboran Sea is a narrow basin with a thin continental crust. It comprises a western basin (1500 m deep) and and eastern basin separated by the large Alboran Ridge. It is bordered to the north and south by the orogenic arc of the Betic and Rif mountain ranges and it terminates on the western side with the sill of the Strait of Gibraltar (400 m deep) which is the only natural communication that the Mediterranean Sea has with the world ocean.

It has a very complex structure, consequently its history has been the subject of many controversial discussions. Its basins and ridges appear the result of compresssive and expansive sliding movements between Europe and Africa. One transpressive phase during the Messinian resulted probably in the closure of the Betic and Rif sills. There are some deposition areas where the Plio-Quaternary sediments are about 1000 m thick and the thickness of the Neogene deposits may reach 4000 m.

The western Alboran Basin is older and deeper. On the northern margin, on the Spanish side,

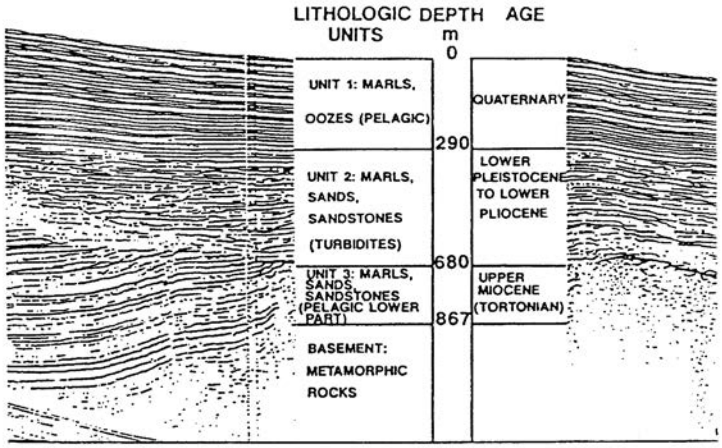

Fig. 3 - Seismic reflexion line and DSDP drilling at site 121 in the western Alboran Basin (Maldonado, 1992).

there is a thick sedimentary prism of a sigmoid type where the reported faults are, according to recent studies, much less active; on the other hand, on the east Moroccan margin there is very little Plio-Quaternary sedimentation. The thickness of the Post-Miocene deposits in the basin (1600 m) shows that there has been a large input of sediments from the Atlantic current (contourites). The sedimentary stratification, such as that in the northern basins, appear to be more irregular in the early Pliocene (due to currents ?) than during the Quaternary (which consists of parallel layers of turbidites and hemipelagites). Many structural horsts, such as the Alboran banks and ridge, have no sedimentary cover.

Drill hole 121 on DSDP Leg 13 (Fig. 3) near a northern basin cored through 290 m of clayey and calcareous mud, having a high sedimentation rate, and then 390 m of sandy and silty turbidites.

ALGERIAN MARGIN. - It is only known from some relatively old scientific surveys, and from several seismic profiles made for oil companies, mainly by Sonatrach and Total. Terrigenous sediments are, due to the former alternating tropical climate, both occasional and abundant. Along the W-Tunisian coast, the continental shelf is narrow or non existent, and the slope is an escarpment which often links the coast directly to the abyssal plain. The sedimentary cover is unstable and its thickness is very irregular. This instability is aggravated by compressive tectonics which affect the whole Maghreb margin and is slowly increasing the steepness of the slope. It is further affected by quasi permanent seismic activity which destabilises the sedimentary deposits causing numerous slumps and turbidity currents; the resulting Plio-Quaternary deposits (1-2 km in thickness) have formed into a series of elongated basins at the foot of the slope.

A progressive deformation of the salt substratum can be observed in the seismic sections under the overlaying deposits. The Algerian abyssal plain, like the whole deep western Mediterranean, is subject to strong salt tectonics.

Gulf of Valencia, the Ebro Delta and the Balearic Islands. - The Gulf of Valencia is another remarkable feature of the western Mediterranean basin. It is 'V' shaped and some 500 km in length, bordered by the South Catalan coastal ranges and the Balearic Archipelago, which is itself a prolongation of the Betic Chain. It is generally believed that this basin is of a back-arc type, and represents an aborted rift of the same age as the western basin, which itself became oceanic during the early Miocene. Its thin basement is pierced by many volcanic extrusions, aged 25 Ma at drill hole 123 of DSDP Leg 13. Volcanic activity during the Pleistocene only affected the area of the Columbretes Islands.

The two opposite margins are very dissimilar. The northern margin of the Balearic Islands, with a small amount of terrigenous detritus, is a rocky scarp which is increasingly covered by sediments as it nears the land. On the other hand, the Spanish margin is a large deltaic shelf built up by the Ebro river sediments and embracing the Columbretes Islands. The thickness of the Plio-Quaternary sediments is reported to reach 2800 m at the foot of the continental slope. From many bore holes it has been found that the base consists of Pliocene clays (Ebro clays) overlain by an accumulation of deltaic sigmoid deposits from the late Pliocene and the Pleistocene. The seaward extension exceeds 100 km, the prodelta being entirely post-Wurmian.

The slope of the delta is cut by numerous small gullies which debouch into the axial valley where the Quaternary turbidites are relatively thin. The absence of a deep sea fan seems to indicate that, during the Quaternary, the Ebro River played a more important role in building up the margin than in feeding the abyssal plain. DSDP drill hole 123 penetrated 268.5 m of Plio-Quaternary sediments, comprising l16 m of graded sands, gravels and turbidites, and 152.5 m of muddy and turbiditic Pliocene deposits.

The eastern margin of Minorca is a rocky scarp, the base of which is covered by Plio-Quaternary sediments, was likewise cored during DSDP leg 42A (drill hole 372). The sediments are mainly nannoplanktonic shales overlying Messinian evaporites (Fig. 4). The Emile Beaudot escarpment forms the southern continental slope of the Balearic Archipelago. It is the most remarkable feature in the western Mediterranean, with a structure recently accentuated by transtensive tectonics.

The North-West Basin Provencal Basin and the Ligurian Sea. - This basin, which is triangular in shape, has an oceanic crust as a result of the rotation, during the lower Miocene, of the Corsica-Sardinia arc. The opposing margins present similar morphotectonic features. The crustal scarp of Provence and that of the west coast of Corsica have been cut into steps by normal faults with a strong throw, and are carved by deep canyons. The longer margins of the Gulf of Lions and west of Sardinia have gentler slopes which are covered by Neogene and Pleistocene sediments.

After the initial Aquitanian rifting, the thickness of sediments near the axis of the basin may exceed 8 km, consisting of 3-4 km of Miocene, 1-2 km of Messinian salts, and 1-2 km of Plio-Quaternary (Fig. 2). But the surface area of the basins on the northern side is very much greater than that on the island side. This produced a sedimentary dissymetry, which resulted, especially during the Plio-Quaternary, in the formation of the large deltaic platform of the Rhône and of an apron which extends to the foot of the island margins. Two rivers were responsible for the buil-

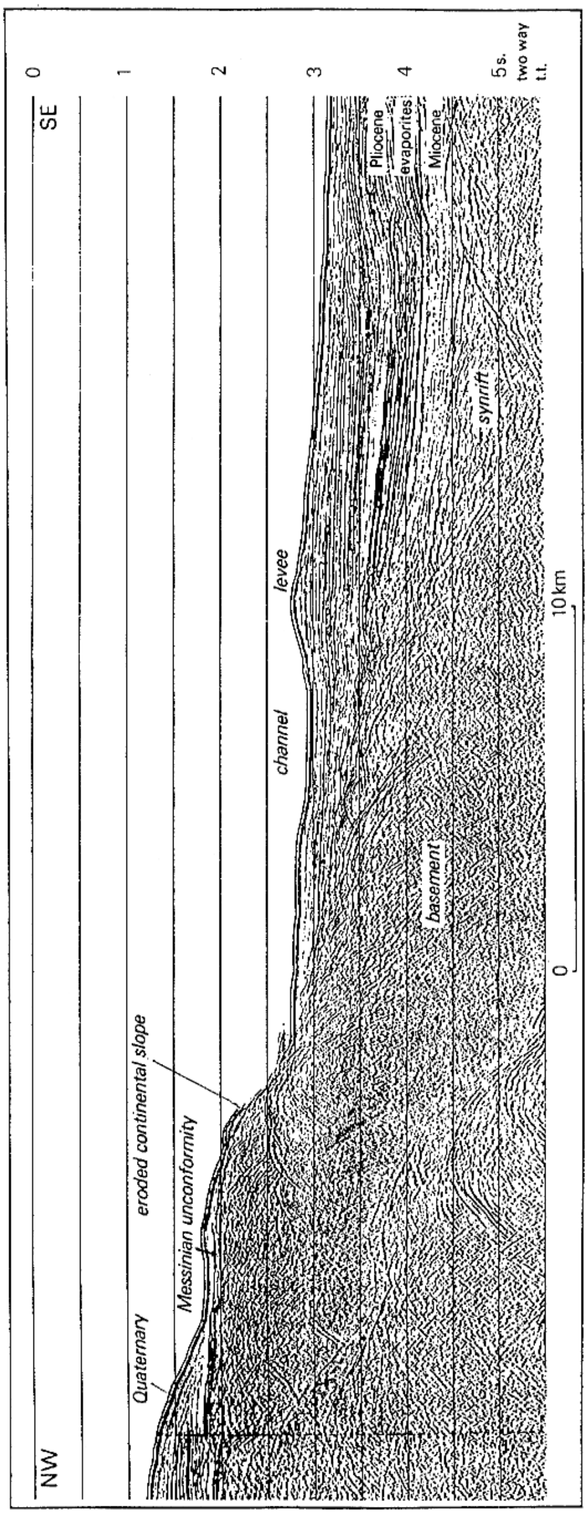

Fig. 4 - Base of eastern Minorca continental slope (near site 372) and abyssal plain (western Mediterranean). Pinch out of Messinian evaporites and Plio-Quaternary sediments (courtesy of A. Mauffret).

ding up of the apron, forming two coalescent deep sea fans: principally the Rhône, but more modestly the Var, in the Ligurian Sea.

Neogene and Quaternary alluvial sediments from the Rhône have built up two associated systems, a shelf delta and a deep sea fan, linked by a canyon. The delta overlies a thick Oligocene-Miocene series, shaped by Messinian continental erosion. The ancient valley of the Rhone appears clearly in the isopach curves of the Plio-Quaternary sediments (as with the Nile). Following the usual upper and frontal deposits of the Pliocene, the Pleistocene sedimentation on the shelf is closely linked to the glacio-eustatic variations in sea level, whereas along the slope, the often unstable sigmoid progradation formations are deep cut by new canyons, with strong regressive erosion during periods of low sea level.

But the most remarkable feature is the deep sea fan which can be clearly seen in the present bathymetry. It covers an area of some 60 000 km^2 and the maximum thickness of the Plio-Quaternary sediments is about 2 km. It may be divided classically into a narrow upper fan, 1.5 km in depth, cut by a deep valley which is an extension of the 'Petit Rhône' canyon, then a mid-fan formed by a sinuous valley bordered by cliffs and levees caused by flooding, having a maximum thickness of 2 km. The spreading distal turbidites form a huge outer fan where the fine sediments are interbedded with those from the Rhône, the Ebro, and the small rivers of Corsica and Sardinia.

Seismic reflection sections show that large recent slumps from the continental slope form the borders of the upper fan, whereas the turbiditic flows of the mid-valley form lateral lobes, as has been observed with the side-scan sonar SEAMARC. Furthermore, the seismic reflection records show, not only the superimposition of the sedimentary lobes, but also the migration towards the west, since the late Pliocene, of the main transportation axis, due to Coriolis force and to the deep currents.

In the Ligurian Basin the deep flow of gravity currents from the Var canyons has been disturbed by tectonic activity and/or by strong salt diapirism. As a result the Var deep sea fan is clearly asymmetric and the thickness of the Plio-Quaternary sediments varies considerably from one place to another. The most recent channel, which is probably Wurmian in origin, reaches as far as the foot of the Corsican margin.

All the Plio-Quaternary sediments of the abyssal plain, in the western basin, are strongly deformed by Messinian salt diapirism under pressure from sedimentary loading and also locally from neotectonic stresses. The pressure exercised by the Rhône deep sea fan, in particular, causes the extrusion of salt diapirs resulting in the formation of plugs up to 300 m in height above the seabed.

5.2. The Tyrrhenian Sea

The Tyrrhenian basin, known as the Tyrrhenian Sea, is probably the most peculiar basin in the whole Mediterranean. In spite of its small size (270 000 km^2), its depth exceeds 3600 m. It is a micro-ocean with a stretched crust, locally oceanic, hemmed in between two active orogenic systems, the Appenines to the north-east and the Calabrian-Sicilian arc to the south. Three impor-

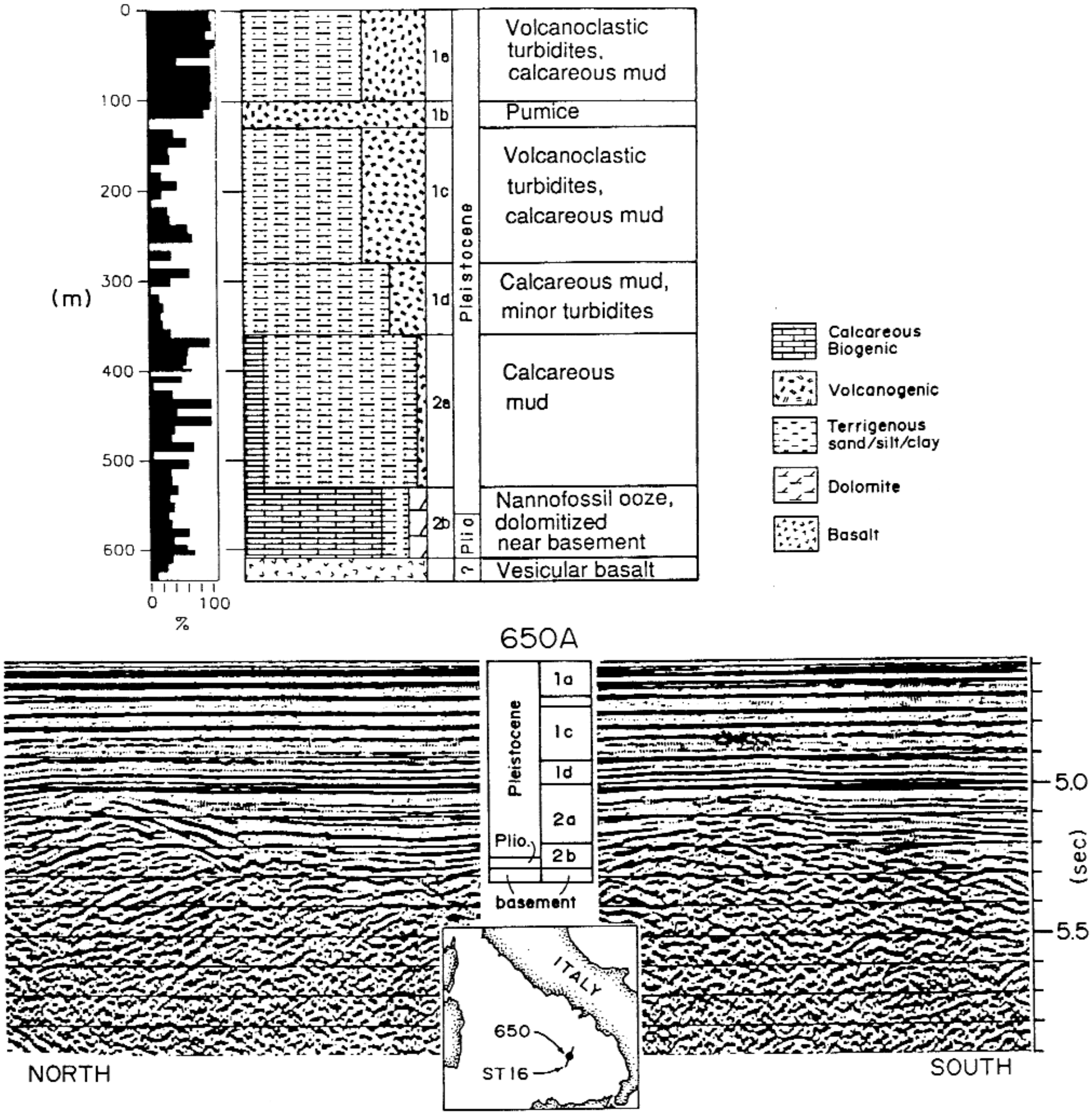

Fig. 5 - Lithostratigraphic units discovered at site 650 (Vavilov Basin), basement and turbiditic filling (after Kastens et al., 1987).

tant isolated volcanic massifs rise more than 2000 m above the deep sea floor and a still active volcanic arc (the Aeolian Islands) cuts across the southern slope. These features result mainly from the very young age of this sea: late Miocene to the present day.

The very dense seismic coverage and the drilling carried out on DSDP leg 107 have provided a good understanding of the Tyrrhenian genesis. The first rifting, during the Mid- to Late Miocene, occurred along the Sardinian margin where some large grabens contain pelagic deposits and Messinian salts. In the central part, continental distension began in Messinian times, with continental detritic discharges and lacustrine deposits. In the east, the Vavilov and Marsili Basins became oceanised during the Pliocene and the Quaternary (Fig. 5), by a mechanism perhaps

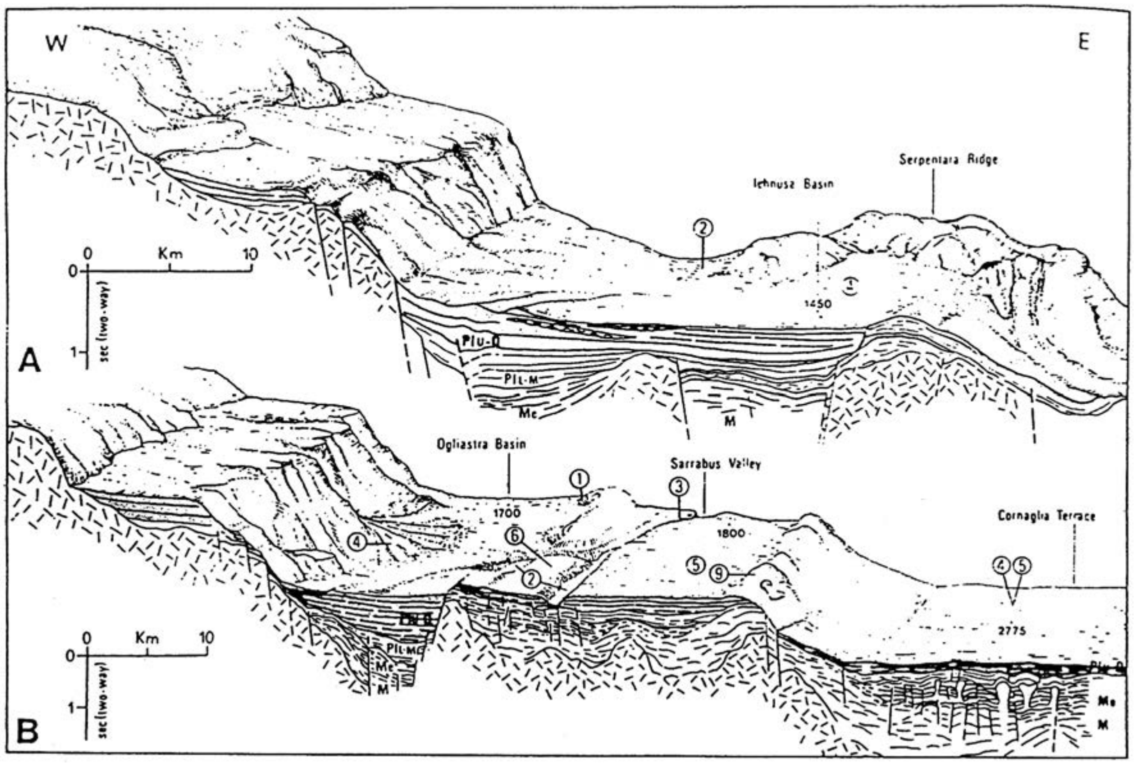

Fig. 6 - Block diagram drawn by Wezel et al. (1979) showing the tilted Sardinia continental margin, and crustal dams keeping back Plio-Quaternary sediments.

more complex than the back-arc model of the basin formerly suggested by several authors. Indeed, the Tyrrhenian Sea is obviously a distensive basin recently created by a compressive environment (the convergence of Africa and Europe). A number of features indicate that this is a back-arc type of process behind the subduction of the Ionian Sea under the Calabrian arc. However, it is important to emphasize here the role of direct crustal motions in the morpho-structural genesis, as, for example, the displacement and present day orogenesis of the Appenine chain.

The sediments are thick along the margins but relatively thin and discontinuous in the abyssal plain. This is due to the barrier formed by slope crustal horsts in relation to the initial rifting and transtensive movements or volcanic eruptions (Fig. 6). Thick terrigeneous Plio-Quaternary sediments are trapped in narrow and deep grabens. Some of these are partially infilled and they show up in the submarine morphology (e. g. north Sardinia and the Sicilian margin). But in others, the terrigenous sediments overflow the barriers and use the canyons to discharge their turbidites into the deeper parts of the basin. This process may be observed on the southern Sardinian margin (1.4 km of Plio-Quaternary sediments), but even more so on the Calabrian internal margin where the Gioia elongated graben, though not visible in the topography, in fact contains nearly 4 km of post-Messinian (partially lacustrine?) sediments. The Corsica Basin which contains 8 km of Miocene to Quaternary well layered deposits, of which 500 m are of Messinian (lacustrine?) origin, has perhaps a tectonic significance.

From west to east in the Basin the marine Pliocene transgression overlays an increasingly recent substratum. To the west, on the stretched Sardinian margin, where the sediment thickness is about 200 m, the Pliocene overlays late Miocene hemipelagic deposits, Messinian evaporites and clastics. To the east, in the Vavilov Basin, drill hole 651 of DSDP Leg 107 found a sediment thickness of 390 m. Here altered tholeiitic basalts, dated 3.5 Ma, are directly overlain by the transgressive late Pliocene beds.

The sediments are turbiditic reworkings of pyroclastic material mixed with Pleistocene coccolith muds. In the Marsili Basin, the most eastern basin, it is the latest Pliocene which overlays the oceanic floor, dated 1.9 Ma.

During the late Pliocene important changes occurred which were probably associated with the start of the estuarine circulation in the Strait of Gibraltar.

Thin sapropel layers formed in the Pleistocene series and the homogeneity of the planktonic fauna decreased some time before the arrival of glacial events. But the increasing importance of tephra deposits should be noted; these indicate the start of new andesitic volcanic activity. Gravity reworkings of volcanoclastics are frequent, such as the 20 metres thick deposit observed at ODP sites 650 and 651, which correlates with a glacial lowering of sea level. In the Marsili Basin, the most recent sediments, found on Leg 107, are 600 m thick. The upper series (350 m of sediments deposited during the last 500 000 years) is particularly rich at its foot in coarse volcanoclastic turbidites. Isotopic analysis of planktonic foraminiferal tests show a high increase, 900 000 years ago, of cold species.

So, in the Tyrrhenian Sea and the western basin, there is a considerable difference in sediment distribution between the margins and adjacent basin floors. This is due to the fact that the Tyrrhenian Sea represents an earlier phase in oceanic evolution and may also have a more complicated tectonic origin.

5.3. The Adriatic Sea

This arm of Mediterranean, open only to the Ionian Sea through the Strait of Otranto, is mainly epicontinental. Most of the sea is less than 200 m in depth, the exceptions being the small Jabuka Trough and the larger South Adriatic Basin, the depth of which reaches 1200 m.

The Adriatic Sea, which is 900 km in length, belongs to the Apulian Plate. Its basement and thick sedimentary cover are caught in the vice caused by the Africa-Europe collision. To the north-east, the Apulian Plate is being forced under the Dinarides by compressive and transpressive mechanisms. On the south-west side, it is the deformation by compression of the Apulian Plate which causes the Appenines to overthrust the Adriatic basin. Furthermore, this basin provides an extension to the Po Plain which sinks under the north thrusting movement of the Appenines and the thick strongly deformed alluvial cover which extends over much of the Adriatic basin. There is a lack of information on the stratigraphy of the Plio-Quaternary deposits in the territorial waters of (former) Yugoslavia and Albania, but, as the isopachs show, the deposits do not exceed 1200 metres along the whole length of the Adriatic. However, two areas of thick sediments have been plotted on the north-west and south-east limits of the Sea. In the north-

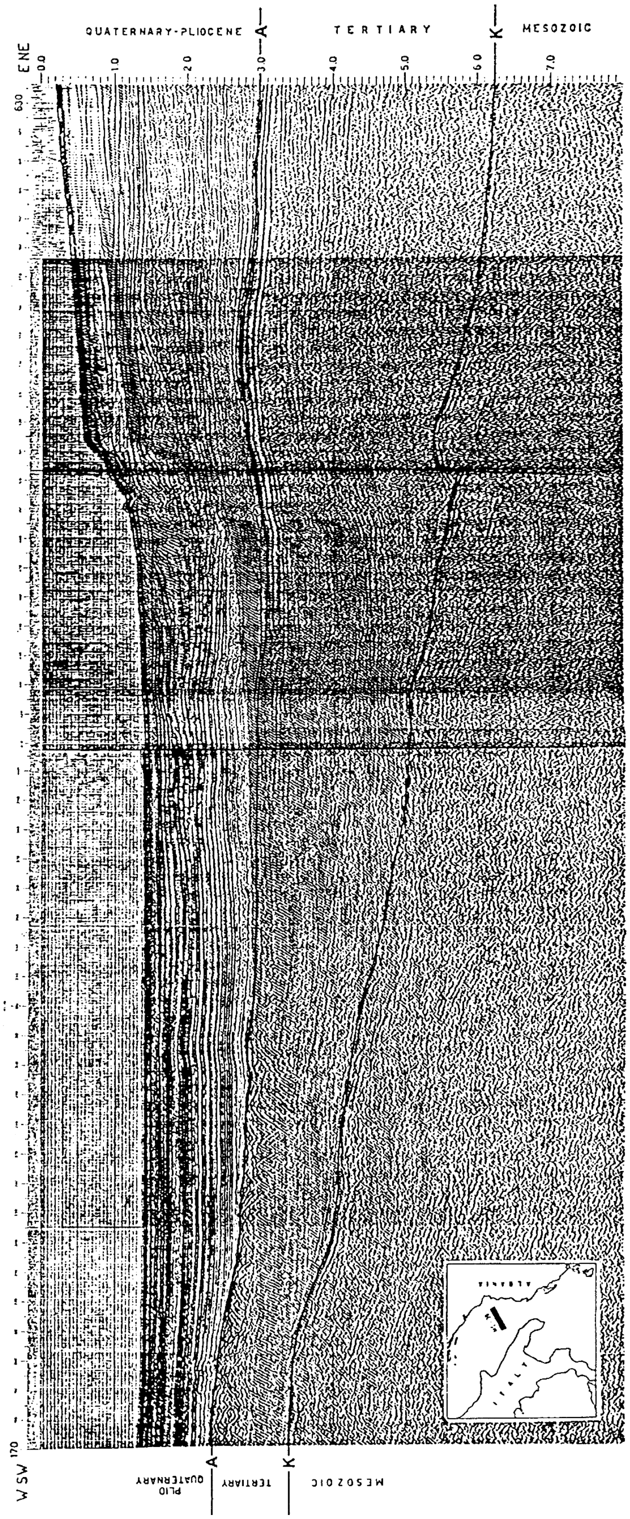

Fig. 7 - Seismic reflection profile on the Albanian continental margin (south Adriatic Sea), after Finetti and Morelli, (1973). Note the thicknesses of Tertiary and Quaternary sediments towards the continent.

west, the Italian coastal zone from the mouth of the River Po to the level of the central trench is formed by a pile of sedimentary layers, from the Miocene to the Pleistocene, overthrusting the deep Adriatic basin. These piles may reach a thickness of 6 km; its limits are however still uncertain. Further south, the thrust front continues on land.

To the south-east, near Tirana, another remarkable accumulation (2.6 km in depth) forms the continental margin of the southern basin. Seismic tracklines do not show any prominent faults here. It seems, therefore, that this active pull-apart-like basin probably results from transtensive movements associated with the Adriatic-Dinarides plates convergence (Fig. 7). After the Messinian dry period, the subhorizontal Pliocene sediments overlaid a strongly faulted substratum, with its thickness sometimes reaching 1500 m. During the late Pliocene, the south-west edge became badly deformed by Appenine orogeny. In the central area of the Italian coast , the Quaternary is made up of three sedimentary formations: the lowest (early Pleistocene), characterised by the presence of Hyalinea baltica, consists of flat and parallel beds of neritic to shallow facies; the intermediate formation is a large pile of sigmoid or oblique deposits built up as a result of glacio-eustatic variations in sea level - these sediments came from the Appenines, the River Po and the (former) Yugoslav coastal ranges; the upper unit constitutes the superficial cover which provides the present morphology of the modern shelf. A study of the Quaternary benthic fauna shows progressive shoaling as a result of the continuous sedimentary infilling of the basin.

5.4. The Pelagian Sea

The Pelagian Sea covers a large faulted and slightly warped shelf which prolongs the African plate. Its basement is covered by more 5 km of Mesozoic and Cenozoic sedimentary series. Its geological limit to the north is the southern shelf of Sicily (Ragusa Plateau, Adventure Bank). This indefinite border with central Sicily is in fact a collision zone well marked by the downthrusting of the African Plate. This downward movement is clearly visible in the Gela Basin where a Plio-Quaternary sedimentary prism more than 5 km thick has been formed. Further south, a remarkable set of long grabens in echelon (South Sicily Troughs) fractures the shelf almost completely from north-west to south-east, forming the Sicily Strait . These are the troughs of Pantelleria (1315 m), of Malta (1715 m) and Linosa (1615 m) which connect with the Tyrrhenian Sea through the Egadi and Pantelleria Valleys and with the Ionian Sea through the Malta Channel.

The rifting of this shelf began during the late Miocene, with little deposit of Messinian salts, and lasted until the Pleistocene. Distension is associated with a important spillitic magmatism (Plio-Quaternary volcanoes of Linosa and Pantelleria). This may be the result of strike-slip movements or of oblique rifting. These troughs then played, and still do, an active role as sediment traps, especially during the Quaternary low sea level period when there was a reduction in the size of the channels, resulting in more active surface and deep water currents. In these very narrow furrows the depth of the main terrigenous sediments, which consist mainly of volcanoclastic deposits, reaches 2 km. However, at the present time, these traps do not receive sufficient sediment to keep them completely infilled, due to the absence of clastic material coming from the Tunisian landmass.

Another group of troughs, that hardly show in the present topography, exists near the Tunisian coast. Their west-east and north-south orientation trends certainly result from basement discontinuities and from recent north Maghrebine tectonics. These terrigenous infilling may reach 5 km in depth.

Separated from the South Sicily Troughs by the central highs of the Tunisian Plateau and of Medina, is the long Gabes-Tripoli Trough which is orientated roughly north-west/south-east along the Tunisian-Libyan coast; it is only slightly faulted and its Plio-Quaternary cover is thin, less than l km. Outside these troughs, the present sedimentation rate is low and recent beds are non-existent on some highs, such as the Adventure Bank. On the internal shelf and on the banks, recent thin bioclastic carbonate deposits predominate, especially on the very shallow banks around the Kerkennah and Djerba islands. In depths of more than 50 m, relic carbonates from periods of low sea level appear as outcrops and, in deeper water (200 m maximum), clayey deposits are found.

Neotectonics are active everywhere and cause irregularities on the present sea floor. In the eastern part of the Gulf of Gabes, some salt domes (Triassic salt) form shallow banks and even today short-lived islands appear, as at Ras Zira, east of Zarzis.

5.5. The Eastern Mediterranean

East of the Malta (Medina) Escarpment and of Calabria, the Mediterranean has a very complicated morphology. According to many authors it represents the remains of a former ocean, named Mesogae, a back-arc basin formed in Jurassic times by the migration of an island arc along the African palaeomargin. The geophysical studies of the Ionian Sea seems to confirm the presence of an oceanic crust in the central and northern parts of the Ionian Sea, with a thick (several thousands of metres) cover of mid-Jurassic to recent carbonate sediments. For other authors, the basement is a stretched and thinned continental crust.

But in the narrow central zone, north of Cyrenaica, and in the Levantine Basin, the subduction of the oceanic mesogean crust has been replaced by a continental collision between the African and European plates. There is also subduction of the African slope and rise (with its thin continental crust) under the Hellenic and Cyprus arcs. Even more remarkable is the large axial chain, or Mediterranean Ridge (see below), bordered on the north by a line of troughs (named the Hellenic Troughs), with a present maximum depth of 1510 m. The Eastern Mediterranean comprises two large basins: the Ionian Sea (see below) and the Eastern Basin (see below).

THE IONIAN SEA . - The Ionian Sea is surrounded by various types of margins. To the west the large Malta (or Medina) Escarpment is a normal fault which terminates near the Libyan margin (Fig. 8). The Mesozoic and tertiary outcrops formed during Messinian times, and the Plio-Quaternary deposits are held together by a calcitic-magnesian and ferromanganesian precipitation which superficially impregnates muds and solidly encrusts rock fragments. These crusts, also present in the Tyrrhenian Sea, do not affect the holocene deposits and could result from a

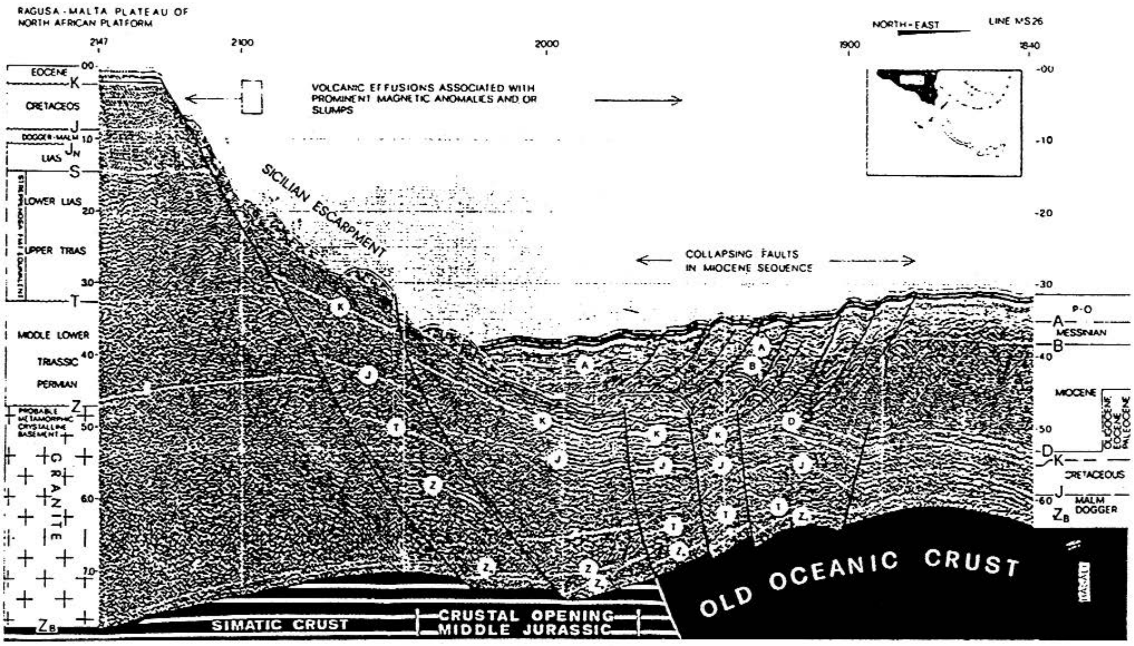

Fig. 8 - Interpreted seismic reflection record across the Malta Escarpment (after Finetti, 1982).

strong circulation of intermediate or deep waters during the interglacial periods, or from microbiological factors.

To the north, the Calabrian margin, from the Strait of Messina as far as the Gulf of Taranto, is also a sedimentary accretion prism which hides the subduction of the Ionian oceanic crust under Calabria. The prism is fed by terrigenous clastic elements from the erosion of the continuously uprising Calabrian arc. The Plio-Quaternary deposits accumulate along the coast, with a thickness of l km in the fore-arc basin. Their distribution in the prism is somewhat irregular.

To the east of the Gulf of Taranto, where the active submarine canyon is roughly the subduction line itself, with at greater depth probably a scarp-like transform fault, the Puglian landform extends into the sea on the Apulian shelf. Curiously, this margin, situated between the Calabrian and Hellenic subductions, is only weakly deformed and devoid of recent sediments, despite the active tectonic environment. Further east is the Hellenic margin which is formed by the internal slope of the Hellenic arc and the subduction trenches. The structures here are exceedingly complex, as a result of their being continuously subject to compressive stresses which deform them. The Plio-Quaternary deposits are thick (1000 m in places) where they are held in small traps, similar to those retained behind tectonic barriers. The turbidites deposits in the trenches are however more conventional. To the north of drill hole 377, there is an unexplained isolated sedimentary accumulation which needs confirmation through further seismic study.

To the south, the Ionian Sea is bordered by the Libyan passive margin. The Sirte Basin (abyssal plain) with its deep sediments is an extension of the Gabes-Tripoli Trough. Along the Cyrenaican coast, the thickness of recent sediments cannot be estimated owing to the lack of data; these sediments are probably supplied mainly by aeolian transport from the southern Libyan desert.

In the centre, the deep part of the basin forms a narrow abyssal plain where the recent sedimentary cover includes 500 to 1000 m of Messinian evaporites with very little diapirism; these are overlain by 300 to 500 m of Plio-Quaternary hemipelagic and turbiditic deposits. Several volcanic massifs from the Miocene emerge from the depths. On the north and north-east periphery the sedimentary cover is progressively incorporated into wedges feeding the external accretion prism of the ridge (Fig. 9). To the south, the Medina and Cyrene seamounts are devoid of sedimentary cover, and in the deep plain, the Plio-Quaternary deposits are thin (200 m on average).

Drill hole 374 (Fig. 10) penetrated 373 m of Plio-Quaternary, 8 m of basal (?) dolomitic Pliocene, and 75 m of dolomite, gypsum and anhydrite. In the Plio-Quaternary series, the deeper part consists of pelagic mud and marl (56% of biocarbonates); it is overlain by planktonic marl and sandy turbidites. Many layers of sapropels have been found with several black or greeny black episapropelic beds. The sedimentation rate reached l5 cm/1000 y during the Pleistocene but fell to 4.7 cm during the Pliocene. The deepest deposits, which are dolomitic and very rich in sapropels, correspond to the basal Pliocene.

THE MEDITERRANEAN RIDGE. - The Mediterranean Ridge, formerly named the Mid-Mediterranean Ridge, bordered to the north by the Hellenic Troughs and to the south and west by abyssal plains, is a large sedimentary feature which extends from the Calabrian Rise to the Anaximander Mountains. It reaches a maximum height of 1300 m below sea level in the central part, which is named the Herodotus Rise. GLORIA images and SEABEAM bathymetric surveys have shown a strong irregular surface (comprised of cobblestones and hummocky structures) and that the features are roughly parallel to the axis of the Hellenic arc, except in the narrowest part where the undulations are without doubt caused by more intense stresses. Seismic reflection records show strongly diffracting reflectors which are both discontinuous and deformed. Most authors consider that the Ridge, including the Mesozoic substratum, is an entirely sedimentary compressive feature. Reverse faults, which would explain the outcropping of deep early Cretaceous shales resulting from mud diapirism, are extremely likely though these are difficult to identify on the seismic records. However, this would result in the prevention of subduction of the surface sediments under the Hellenic arc. It would be necessary in this case to accept that this large ridge is a sedimentary accretionary fore-arc prism and that the subduction suggestion, which has been accepted in the region of the Hellenic Troughs, is not valid.

The proof of intense compression in the ridge is implied by the discovery at several points in the bathymetry (the Prometheus Cone, for example) of a number of mud domes emerging from depressions (2 to 5 km in diameter). It is considered that the brechias containing traces of mud from the lower Cretaceous indicate a diapiric high of more than 2 km. One of us (PFB) interprets this compressive ridge as the equivalent of the Jura ranges in front of the Alpine chain. But recent seismic surveys indicate that the detachment would lie apparent only at the base of the Messinian deposits.

On this high feature, isolated from the continents by deep furrows and troughs, the Plio-Quaternary sedimentation is thin and mainly hemipelagic or pelagic. In relatively quiet zones,

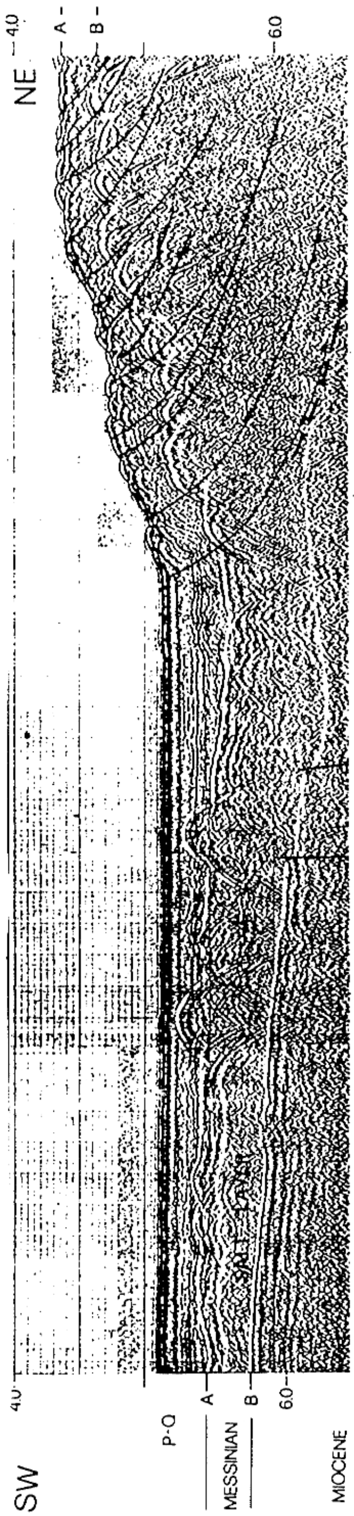

Fig. 9 - Seismic Reflection Line on the south-western edge of the Mediterranean Ridg. interpreted by Finetti (1982). Subhorizontal Plio-Quaternary deposits on the abyssal plain, contrasting with the more deformed features towards the ridge.

the sedimentary layer seldom exceeds 100 to 200 m above a strong reflector of unknown origin (probably evaporitic Messinian); In other places, more tectonized and diffracting layers are difficult to identified. Elsewhere, the Plio-Quaternary sediments are sometimes absent or difficult to detect in the very deformed deposits.

DSDP drill holes 125 and 125A are particularly good examples of the laying down of sedimentary deposits. The Pleistocene series (identified by *Globorotalia Truncatulinoides*) consists of 35 m of nannofossil muds, containing in its upper layers, beds of both sapropels and also of tephras. The rate of sedimentation is low (2.3 cm/1000 y). The Pliocene nannofossil mud, which is about 40 m thick (sedimentation rate 2.6 cm/1000 y), has at least 2 biozones out of the 6 recognised (*G. Margaritae* and *Sphaeroidinellopsis* acme zones); this may be due to slippage.

The Messinian is represented by a thin dolomitic sapropel bed with gypsum crystals overlying dolomitic marl with brackish diatoms. So it is surmised that the ridge was folded and emerged before the Pliocene. On the other hand, in the Hellenic Troughs (site 127-128), the Pleistocene sandy turbidites are more than 400 m thick. Near this site drill hole 377, situated in a fracture of the ridge, penetrated 100 m of Pleistocene overlying with discontinuity, the Early or Middle Pliocene shales. The Pleistocene is made up of foraminifera mud, interbedded with harder layers containing volcanic ashes, or bioclastic accumulation of calcareous tests.

THE EASTERN (OR LEVANTINE) BASIN. - It may for convenience be divided into two geodynamically different parts at the latitude of the Eratosthenes Seamount. The northern part is a tectonized zone, at the edge of the plate where the sedimentation is of local importance. The southern part is the African plate border, dominated by the Nile sediments from the Herodotus Abyssal Plain on the western side to the Israeli margin on the eastern one.

The northern zone includes the Anaximander submarine mountains which are linked to Cyprus by the Florence Ridge. This feature separates the northern basins (Rhodes, Antalya, Adana, or Cilicia Trough) from the southern Herodotus-Eratosthenes basins. The subduction line between the African and European plates, identified by the Hellenic Troughs, disappears near the Bay of Rhodes, and cannot really be identified again to the east before the north-east extremity of the basin.

In the central area, there may be a transpressive transform zone on the Florence Ridge with low activity subduction along the southern margin of Cyprus and a strike-slip link to the north-eastern coast. In this region, which is not well known, some recent Russian studies have shown that the Bay of Iskenderun (Gulf of Alexandretta) may be bounded to the north and south by two strike-slip faults. The northern basins and especially the Adana (Cilicia) Trough, may be identified as Miocene back-arc basins, and the Island of Cyprus may be a fragment of the arc made up from the uplifted oceanic basement, which emerged during the Pleistocene. The Plio-Quaternary sediments are no more than l km thick in the Rhodes Basin, where the fragmentation of the deposits by diapirism can be clearly seen on the very dense network of seismic sections. But the formation of deep deposit centres, due to salt collapse, is more evident in the Antalya Basin where acoustic bedded structures indicate the predominance of turbidites. There is insufficient seismic data for the Adana (Cilicia) Trough to prove the presence of diapirism, but it certainly exists, as some recent publications report that the Messinian salt is strongly present towards the north-east,

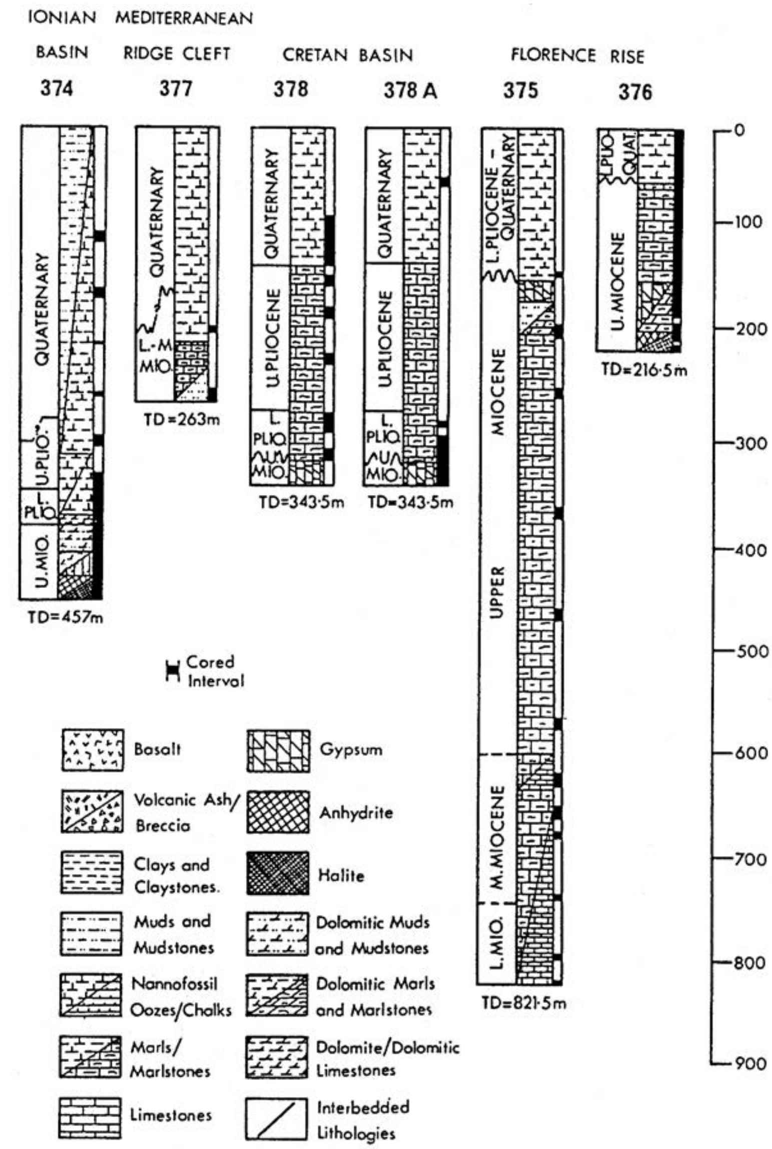

Fig. 10 - Generalized lithologic facies drilled at Leg 42A, site 374 (Kidd et al., 1987).

in association with graben fracturing. In the coastal region, the thickness of the Plio-Quaternary sediments is not known at the present time, but it is understood that near the alluvial and deltaic coastal plains there is active subsidence and that the Plio-Quaternary sediments are probably more than 2 km thick.

The southern part of the basin is totally dominated by the alluvial sediments of the Nile, but the great Nile delta consists of several morphosedimentary units:

- first, a deltaic shelf surrounded by continental slopes, tectonised in places by several normal faults. The isopachs illustrate clearly the Messinian aerial surface and the palaeo-course of the Nile. The thickness of the post-Messinian sediments increases rapidly towards the shelf-break to reach 4 km in the axis of the valley;

- the western rise forms the Nile Cone (Rosetta Fan). It does not possess the distinctive character and classical subdivisions of a deep sea fan. In fact, the canyons on the continental slope are shallow and the seismic profiles do not show any superimposed lobes but only some channels with low levees. Sedimentary instability engenders a few displacements but chiefly of deformations which are shown on the chart as faults. The rise extends as far as the Herodotus Abyssal Plain. In the south, the sedimentary cover is deeply bedded and regular, whereas the other parts of the abyssal plain are deformed by salt domes every 20 to 30 km. The outer part of the Mediterranean Ridge, which borders this abyssal plain, was drilled during DSDP Leg 13 (drill hole 131). 0nly Pleistocene sediments were drilled to a depth of 272 m. Most of the upper deposits are turbiditic, with interbedded thin calcareous pelagic layers.

The sedimentation rate reaches 30 cm/1000 y. Some of these turbidites may be 2.5 cm thick, ill sorted and made up of sands and silts originating from the Nile. Below 140 m, the sediments are more diversified (black clays, beds of clean sand, etc.). They get harder with depth. From this, it has been reckoned that the whole of the Herodotus Abyssal Plain and the base of the rise are infilled by coarser terrigenous material.

The northern area has the aspect of a huge landslide of unconsolidated sediments on fluid softs. The seismic profiles show piercing diapirs penetrating through nearly 3 km of Plio-Quaternary sediments. Near the foot of the rise, the diapirs are surrounded by rim synclines and a large wall of transverse dissymmetric salt which forms a sedimentary barrier and step in the topography. Beyond the wall, which is linked to the Eratosthenes Seamount, the Nile sediments overflow the abyssal plain to a depth of perhaps 2 km.

To the east, the rise, which is named the Levantine Plateau, extends as far as the foot of the Israeli margin. Even with their large thickness (up to 2 km), the sediments seem to be little affected by sliding, and salt domes are rare, except in the south where a number of piercing diapirs and some rim synclines can be observed. The chart shows that the Israeli margin is well fed by Nile sediments as far north as Haifa, transported probably by longshore drift and other marine currents. A thick accumulation of clayey sedimentation, a steep continental slope and a fluid salt substratum provide the ideal conditions for intense deformations and gravity induced reworking of the sediments. This is certainly the best example of a margin cut by listric faults, flattened on the salt substratum and offsetting the stratifications (Fig. 11). Also observable are large sedimentary slumps, triggered off perhaps, according to some authors, by seismic events. Only a few examples of these deformations created by numerous thick sedimentary deposits at the feet of the listric faults could be shown on the isopach chart (IBCM-PQ sheet 10).

The complicated history of the Nile explains the important variations in sedimentary flux during the Plio-Quaternary, from the Messinian dry period and the Pliocene transgression up to the building of the Aswan High Dam. The Pliocene Palaeo-Nile constructed the delta and created the greater part of the submarine cone up until the Pleistocene. After a long arid period, the Pre-Nile became a more important river than it is today. However, recent papers have discussed the time when the tropical tributaries were captured by the Egyptian Nile. The lifting of the eastern desert in relation to the uplifting of the Red Sea shoulders has also been taken into account.

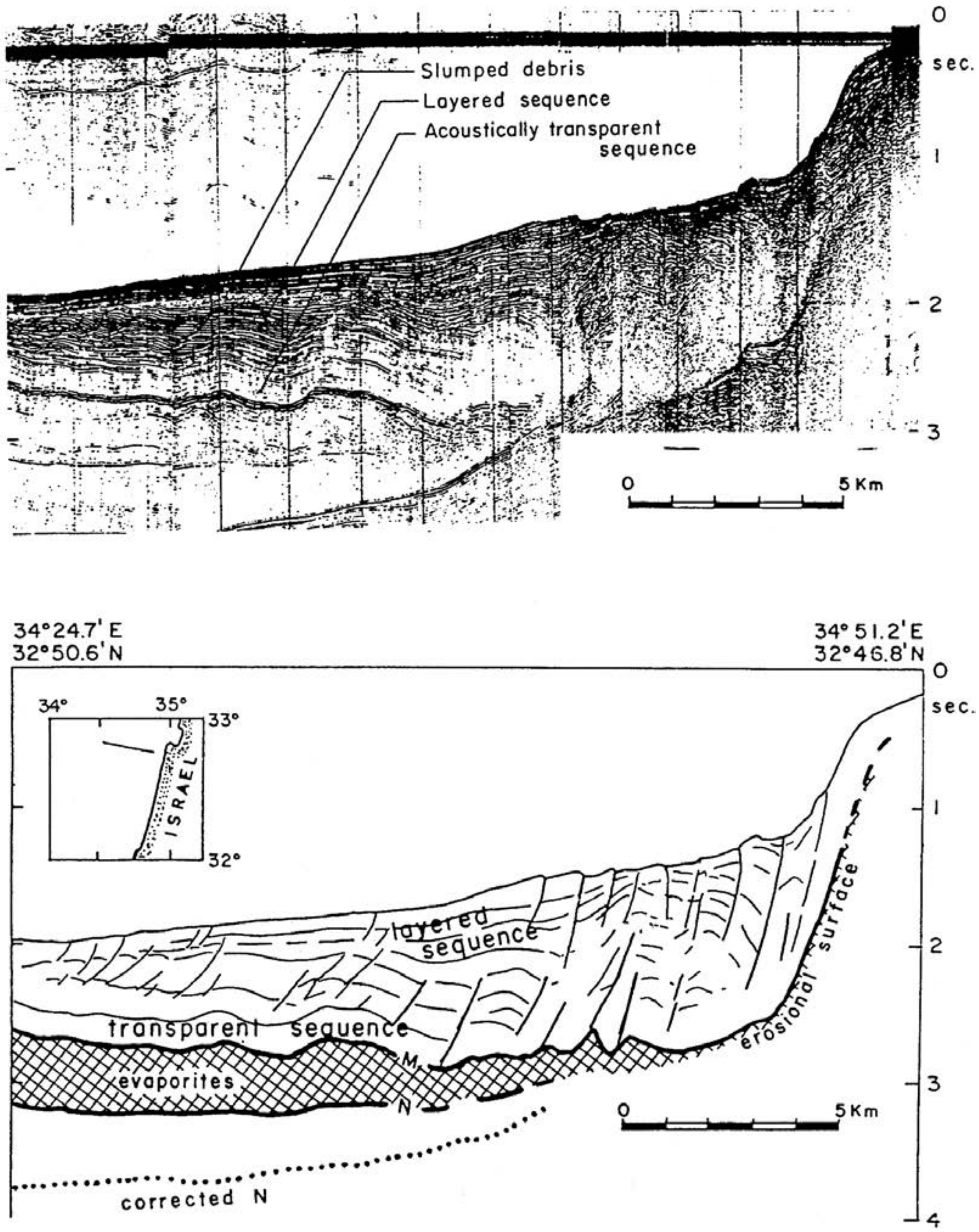

Fig. 11 - An example of continental margin sedimentary instability (central Israel), due to salt mobility and active sedimentation: rotational slidings, reworking sediments and induced topographic modifications on the sea floor (after Almagor, 1980).

The Nile deposits represent 200 m of sedimentary thickness on the shelf and its sediments have been recovered from DSDP drill hole 130, well outside the main cone. The very wet post Tyrrhenian period produced enormous quantities of very coarse detritic material, which consolidated into unconformable deposits. The prodelta of the Nile, created 30 000 years ago, is actually in regression at the present time, due, in part, to the retention of alluvial sediments by the Aswan High Dam.

5.6. The Aegean Sea

The Aegean Sea (including the Cretan Trough) is a link between the Mediterranean Sea proper and the Black Sea, through the Dardanelles and the straits of the Hellenic arc. It is a distensive zone, on a thin continental crust. Generally speaking this is an epeiric sea strewn with local throughs, all shallow, except the Karpathos Basins where the depth reaches 2500 m. The major distension is thought to have begun in the middle Miocene, at the same time as the start of the subduction of the African margin under the Aegean massif. This global north-south tectonic movement, resulting here in the formation of a back-arc basin, has continued up to the present time. The mechanism is complicated by the western movement of Anatolia due to pressure from the Arabian plate; the effects of this migration are particularly obvious in the North Aegean area.

It is customary to divide this large fractured region into three parts: the North Aegean Basin, a region of elongated troughs, the Central Aegean, fragmented into vertically displaced blocks and the Cretan Trough, a true back-arc basin.

The North Aegean Basin is characterised by a succession of deep grabens which are an extension of the Anatolian (north Turkish) strike-slip fault towards the south-west as far as the Greek coast (Saros Trench and Sporades Basin). The first distension is from the late Miocene (N. 140); the second extension (N. 50) dates from the early Pliocene, the start of the slippage of the Anatolian fault; and the last phase (north-south) started in the Pleistocene and is still seismically active today. The Sporades Basin is very much larger than the Saros Trench; both are dissymmetric with steep southern slopes and gentle northern ones. They are associated orthogonally with deep and distensive northern basins, edged by active faults. The Thasos Basin, for example, is limited on its north-eastern side by a fault with 8 km of throw; it is infilled by 6 km of sediments, 3 km of which are Plio-Quaternary. To the north-west, in the Gulf of Thermaïkos, a drill hole has penetrated through 3.5 km of, often coarse, clastic sediments, including 1.8 km of Plio-Quaternary deposits. The depth reached in the Sporades Basin was 5 km, of which 2 km were Plio-Quaternary of the same origin.

In the central part of the North Aegean troughs, many short and discontinuous faults make drafting of the isopachs difficult. The small grabens, which receive less sediments, are lozenge shaped; this shows up the anti-clockwise movement of the fault, producing flower type structures.

The central plateau consists of a mosaic of high and small basins (up to 1000 m depth) resulting from alternating compression and distension phases since the Middle Miocene. N. 40 and N. 120 faults predominate, accompanied by several north-south grabens. The Plio-Quaternary sedimentary basins are situated mainly in the east, in the extension of the Anatolian valleys. Deposits, more than 1 km thick, are cut by many secondary faults. The chief characteristics of this zone are its north-west/south-east extension and the considerable irregularity in sedimentary cover from the Neogene to the Quaternary.

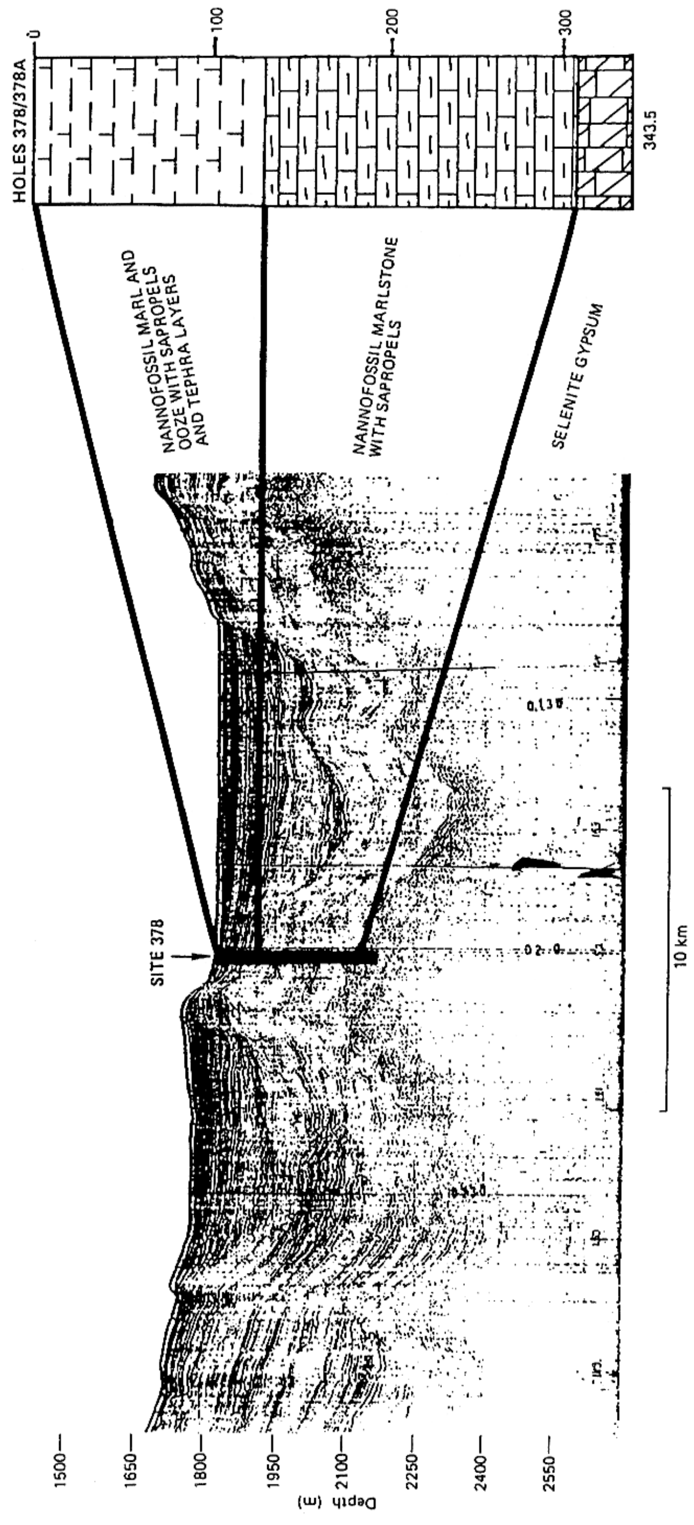

Fig. 12 - Seismic Reflection Line in the Cretan Basin and projected DSDP drill site 378, showing the more stratified upper sequence of the Quaternary infilling.

The Cretan Trough is bordered on the south by the Cretan (or Hellenic) Arc, and on the north by the southern border of the Kikladhes (Cyclades) and Dodecanese Archipelagoes, with the volcanoes of Milos, Santorin (Thira) and Astipalaia. The morphostructural features and the network of faults suggest a radial extension. In general, this extension is clearly of a back-arc type, as is proved by the presence of live and recently active volcanoes. The sea floor has not been oceanised, as in the Tyrrenian sea, but the Karpathos Basin, for example, reaches a depth of 2560 m, (due to the south-eastward movement of the isle), or nearly 3500 m if the sediments are added.

The large Iraklion basin forms an essential part of the distension (Fig. 12). It is limited on its eastern side by two grabens, parallel to the arc, and infilled by 1200 m of Plio-Quaternary sediments. In the central part, the network of faults and their orientation are disorganized and distribution of the sediments is irregular. Drill hole 378 of DSDP Leg 42A, located in a 1835 m deep basin, penetrated 343 m of sediments overlying Messinian carbonates and gypsum. The Pleistocene, with a sedimentation rate sometimes reaching 20 cm/1000 y, is represented by 131 m of nannoplankton marl, with a few sapropel layers. Volcanic debris are sparse which is perhaps surprising when one recalls the nearby historic explosion of Santorin.

The Pliocene series is made up of marl hardened by nannofossils and numerous sapropel beds, some of which are up to 43 m thick. In general, the dividing line between the sapropels and the marl is sharp whereas the change to the overlying sediments is gradual. The composition is extremely variable: 30 to 40% clay, 10 to 20% carbonates, 30 to 50% nannoplankton and 20 to 40% diatoms. The base of the deposit is rich in serpentines.

It is noticeable that there is a curious absence of any Infra-Pliocene layer, with Cyprideis, as with the Lago Mare. This might suggest an invasion from the Parathetis into the Mediterranean by way of the northern Adriatic.

6. The Black Sea

Black Sea Plio-Quaternary isopachs map, inserted in Sheet 5, was enterely outlined by Russian geologists, following a resolution of the IBCM Editorial board. Unfortunately, recent faults network has not been reported on them. Fig. 13, reprinted from the article by Finetti et al. (1988), presents a good aspect of active tectonics in the NE coast.

The Black Sea is a deep intracontinental basin, connected to the open ocean only via the Bosphore Strait. It is a semi-stagnant basin with entirely anoxic conditions below 200 m water-depth. Its total area is approximately 420 000 km^2, the water volume is 540 000 m^3 and the inner-outer flow through the Bosphore Strait, about 485 km^3/y.

Except the very shallow Azov Sea (40 000 km^2) and the NW-W well developed shelf (Moesian platform) which has a 20 to 200 km width, the other shelves are narrow and their contiguous slopes are very steep. The deepest parts of the basins are remarkably flat, like an abyssal plain, weakly tilted southward, from 1800 to 2200 m deep.

The Black Sea is an intramountainous basin, partially surrounded by active overthrusting belts, e.g. northward, the Drobogea, Crimea, Great Caucasus and Shatsky and southward, the Balkans, and W and E Pontides. The Black Sea Mid-Ridge is an inactive high structure which

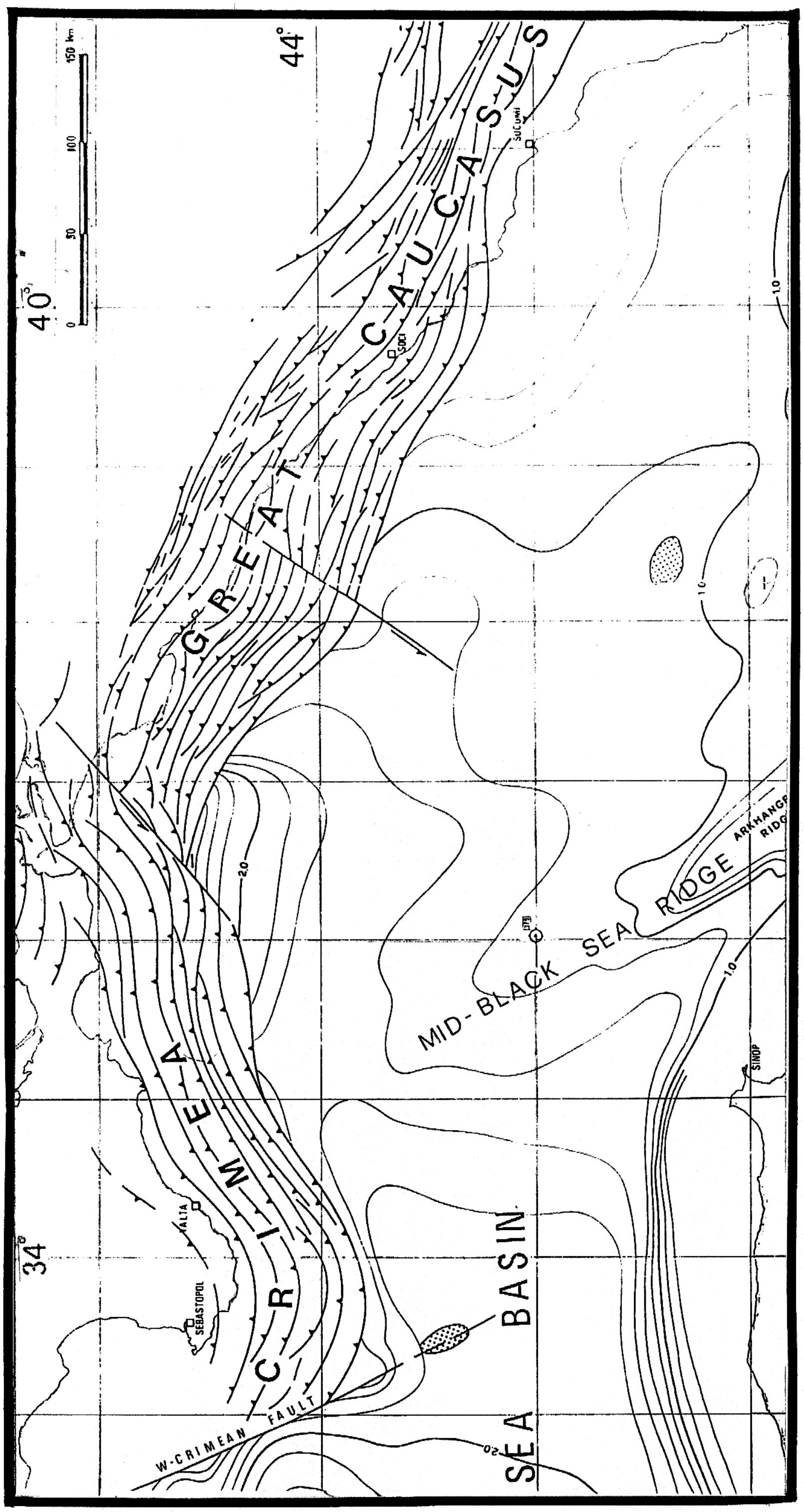

Fig. 13 - Plio-Quaternary isochrons and tectonic map showing the active overthrusting on land and continental margin of the N-NE Black Sea. Reprinted from Plate 11, in Finetti et al. (1988).

divides the deep parts into west and east basins.

Numerous hypotheses have been proposed to explain the origine of this deep basin enclosed in a continental crust, as a E-W large transtensive strike-slip fault running up to the Caspian Sea. But, today, it seems more probable that the origin of the Black Sea was similar to back arc (marginal sea) ones, as attested by the oceanic crustal type of basement lying under the 14 km thick sediments of abyssal plain. So, the Black Sea would have been created by crustal rifting, behind the subduction of Thetys under the Eurasian plate.

Dense multichannel seismic network carried out by Italian and Russian Universities showed this region has been affected by two main rifting phases. The first one, in Middle-Jurassic, was reduced to a stretching of the continental crust. But the second, from lower Cretaceous to Paleocene, created a narrow oceanic floor in the western basin. A compressive activity is still particulary active in the Great Caucase belt where the dense reverse faulting extends far into the NE continental slope. As seismic reflection records clearly show, the Plio-Quaternary deposits of margins are strongly disrupted and large included reverse faulting. In front of Crimea, the lesser active overthrusting is still apparent in topographic relief of margins, as on the other side, along the Pontides belt. On the opposite, westward side, on the Moesian platform and its slope, where the Pliocene, and also some Neogene series are frequently absent, the distending movements prevail, characterised by normal faulting or listric faults resulting from gravity and sedimentary subsidence.

In deep flat bottoms, seismic profiles show a remarkable pile up of very well layered deposits, beginning in the lower Tertiary, when the distending tectonics ceased. The Plio-Quaternary sequence has a thickness of about 2000 m but reaches 4000 m in the west part of the western basin, in the Danube deep delta region. Layers are also less regular, due probably to turbiditic processes. In places, near the foot of the Moesian slope, sonar soundings discovered numerous piercings of mud volcanoes and associated cones, resulting from undercompacted clay masses and led up by sedimentary-like faults.

History of recent sedimentary facies in the Black Sea show they are closely related to glacio-eustatic sea level variations and continental water supplies, which also explain the alternate deposits of sapropels and normal oxydized sediments. During the last Würm, the isolated Black Sea was supplied by well-oxygenated fresh waters and oxided sedimentary particules. But, during the rise of the post glacial sea level, the Mediterranean sea water began to spill over the Bosphorus Strait and invade the bottom of the basin. Vertical circulation was reduced, and anerobic conditions and formation of sapropel took place. But for 3000 y, the high level of sea water induces a two-way circulation into the Bosphorus Strait. At present, deep deposits are coccolites oozes and rich organic clayey sediments.

Acknowledgments. We dedicate this mapping work to the memory of Ekenna Winnock, who started and forwarded this IBCM project despite a long illness. Many thanks are due to John Hall, Geological Survey of Israel, for providing color separation of the Mediterranean Plio-Quaternary sediments map. Under the auspices of the IOC-FAO-CIESM and with data contributions from research institutions and private societies, after 20 years collaboration of an ad-hoc international group, the International Bathymetric Chart of the Mediterranean (scale 1:1000000; 10 sheets) was published in 1981. The importance of the physiographic results suggested their completion with the most pertinent geophysical and geological data. At the same scale maps of the Bouguer gravity anomalies (IBCM-G; 1989), of the seismicity (IBCM-S; 1991), of the Plio-Quternary thickness (IBCM-P/Q; 1993) were also published, and maps of the unconsolidate sediments (IBCM-Sed.; 1997) and the magnetic anomalies (IBCM-M; 1998) are being printed. Each map is illustrated by an explanatory brochure (IBCM-S also by catalogue) and can be obtained (when available, also in digital form) from: Ocean Mapping, IOC-UNE-SCO, 75732 Paris, Fax +33.1.4568.5812.

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Plate 1 - The Mediterranean Plio-Quternary sediments map.