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Geological Evolution of the Mediterranean Basin

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CHAPTER 9

Recent Geological Evolution of the Adriatic Sea

Luciano Dondi,[1] Antonio Rizzini,[2] and Pietro Rossi[3]

Analysis of the recent geological development of the Adriatic, from the Po Delta to the Gargano promontory, is based on Quaternary sections that can be correlated with those on land. For example, the Sabbie di Asti Formation extends offshore from the Po Valley into the Adriatic Basin to the region immediately east of Ancona. Southward, the equivalent unit is the Sabbie di Carassai Formation, composed of basinal turbidites. In the southwestern part of the Adriatic, the Argille del Santerno Formation is widespread; this formation accumulated in platform to slope and basinal environments. Pleistocene biostratigraphy is based on both planktonic and benthonic foraminifera, and we chose *Hyalinea balthica* to identify the Neogene–Quaternary boundary.

Three seismic-stratigraphic units are identified, namely a lower unit with even parallel reflectors, an intermediate with oblique reflectors, and an upper with even parallel reflectors. The characteristics of the intermediate unit are associated with glacially controlled eustatism. Apennine, Yugoslavian, and probable Po Plain supplying areas are recognized, based on the main progradational trends. The sediments of the lower unit and the most distal parts of the intermediate foreset unit consist of turbidites that tend to fill the basin by a combination of out- and up-building processes. The final filling phase in the deepest parts of the basin occurred mainly by up-building. As a result, turbidites are in contact with sandy-clayey shelf sediments without evidence of slope deposits.

The structure of Quaternary sections reflects the effects of the underlying strata. This is partly due to draping of deposits over preexisting structures, but also records the continuation of orogenic phases during sedimentation.

Introduction

This chapter surveys the recent geological evolution of the Adriatic, emphasizing primarily the Quaternary stratigraphy and tectonics. Data were obtained during the course of petroleum exploration carried out by AGIP in the Adriatic during the last 20 years. Herein we focus on the Italian offshore area extending from the Po Delta in the north to the Gargano promontory in the south (Fig. 9.1). The survey is based on the paleontological data obtained mainly from cuttings, on electric log correlations, on seismic interpretation, and on sedimentological studies. The latter involves interpretation of electric logs and seismic sections calibrated from cores. Stratigraphy was carried out by the study of foraminifera.

Given the limited economic importance of the Quaternary successions, available information is sparse and of poorer quality than that available for pre-Quaternary formations. Few bottomhole cores were taken in these unconsolidated formations, and sampling of cuttings is not yet really sufficient for a detailed biostrati-

[1] Paleontological Department, Nuovi Laboratori AGIP, 20097 San Donato Milanese, Italy.
[2] Sedimentological Department, Nuovi Laboratori AGIP, 20097 San Donato Milanese, Italy.
[3] Geological Planning Department, AGIP, 20097 San Donato Milanese, Italy.

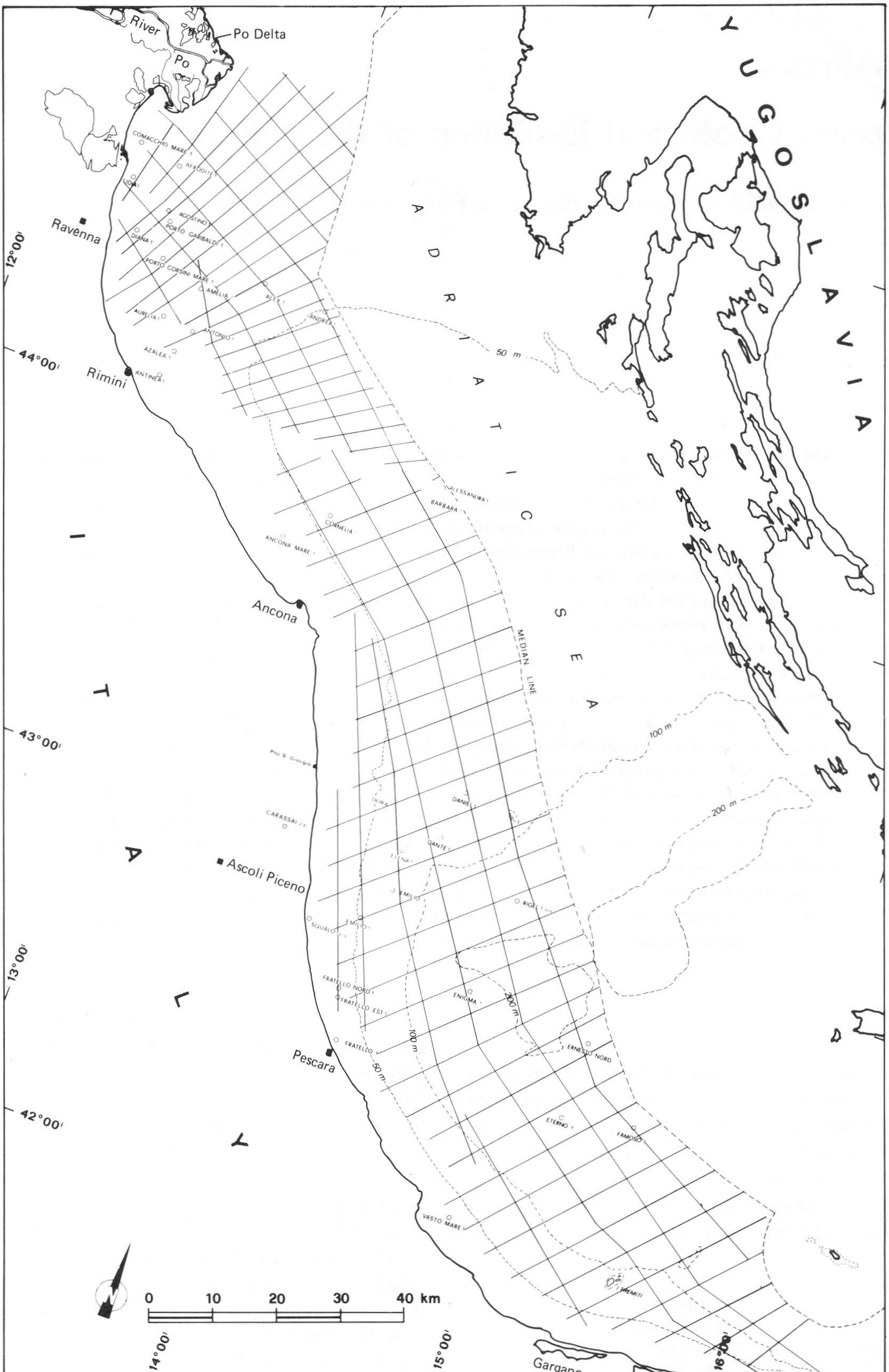

Fig. 9.1. Index map showing seismic lines and control wells in the Adriatic Sea. (Depth in meters.)

graphic study; this is due in part to the high penetration rate during drilling. Good correlation between seismic data and well data in the middle and lower parts of the Quaternary have, nevertheless, furnished a sufficiently accurate picture for this interval, particularly in the northern and central sectors of the Adriatic Sea where a larger number of wells have been drilled.

In the less explored southern Adriatic sector, correlation between seismic and paleontological data is much poorer and made more difficult by the lack of reliable electric log correlations. Information concerning the upper part of the Quaternary is sparse because of the poor seismic response and fewer cuttings from shallower sections.

Geologic reconstruction and basin analysis is based in large part on over 5000 km of seismic sections from the extensive survey carried out in 1967–1968 (under the ruling of Italian law No. 613, 1967, which governs hydrocarbon exploration on continental shelves).

The subbottom maps presented in this chapter are accurate to approximately 100 m. They were plotted from reflection seismic surveys of various origins and by using recorded well velocities and an average velocity applicable to the entire Adriatic offshore area. The latter does not take the factor of seafloor depth into account.

Biostratigraphic Framework

Stratigraphic definition of Quaternary marine sequences presents more difficulties than that of older marine successions mainly because of its short duration and its particular pattern of sedimentation in the Adriatic, as will be described in the following sections. The faunal assemblages do not show a particularly marked evolutionary change during such a short geological time span. Moreover, because organisms are strongly affected by paleoenvironmental factors, thanatocoenosis effects that obliterate chronostratigraphic meaning are often recorded and thus confuse interpretation of the sequences. It is important to note, therefore, that biostratigraphic sequences used to define the Pleistocene involve faunal assemblages that are usually affected by environmental factors. Only in the lowermost part of the Pleistocene, usually deposited at greater depths, is it possible to use the appearance and disappearance of some planktonic and benthonic forms in addition to the occurrence of high-latitude fauna. In this context, some authors currently favor the use of a suitable type-section to identify a group of biostratigraphic events that occur in an interval close to the appearance of the first high-latitude fauna. Thus, it will be possible to select a Neogene–Quaternary (N/Q) boundary based only on climate factors, so that it can be used for wide-range correlations, even outside the Mediterranean.

The studies carried out to date (Colalongo et al., 1981) have shown that, between the first appearance (FAD) of *Arctica islandica* and that of *Hyalinea balthica,* there is a restricted interval in which a few planktonic foraminifera (*Globorotalia acostaensis, Globigerinoides ex. gr. obliquus, G. obliquus extremus, Globigerinoides bollii*) disappear, and others appear (*Globigerina cariacoensis, Globorotalia hessi, Globigerinoides tenellus*). Moreover some ostracods and calcareous nannoplankton (*Cytheropteron testudo, Gephyrocapsa oceanica*) also appear (Fig. 9.2).

In the thicker sequences, such as the Santerno section (located in the Santerno Valley, northern Apennines, near Bologna), the appearance of *Arctica islandica* precedes that of *Hyalinea balthica* by about 400 m (Colalongo, 1968).

The detailed stratigraphic distribution of some index species, both planktonic and benthonic, near the Pliocene–Pleistocene boundary is shown in Figure 9.2. In the study of wells in the Adriatic Sea, available sampling consists almost entirely of cuttings. In actual practice, therefore, we have not been able to apply strictly the biostratigraphic criteria that define the Pliocene–Pleistocene boundary illustrated in Figure 9.2. We have found it more convenient to record the appearance of *Hyalinea balthica* as the faunal marker closest to the Pliocene–Pleistocene boundary; this provides uniformity to our data interpretation without introducing a marked difference from the above-listed criteria.

In the same diagram the FADs of *Arctica islandica* and *Globorotalia truncatulinoides excelsa* are also shown. Ruggieri and others (1975)

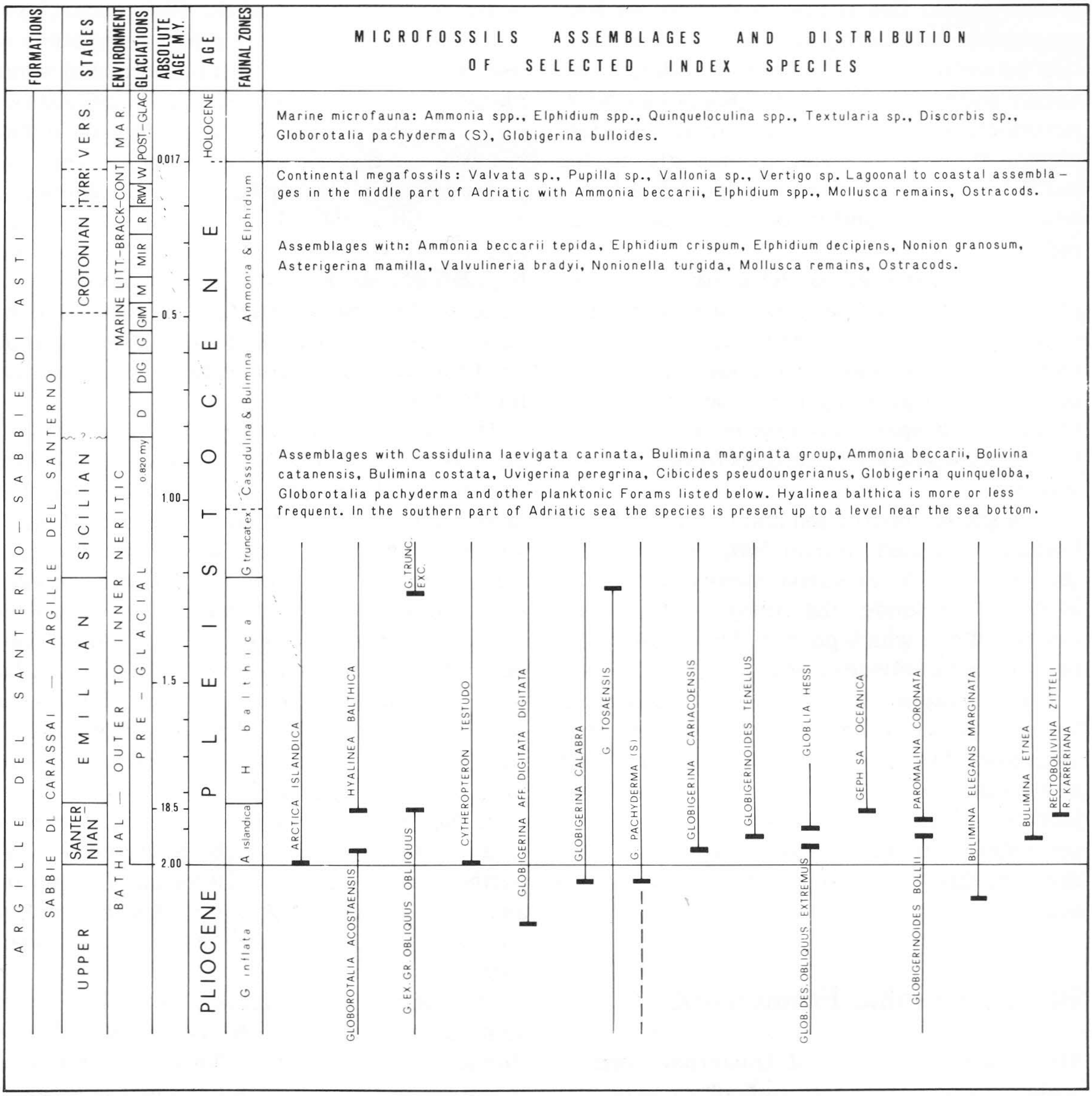

Fig. 9.2. Stratigraphy and microfossil assemblages and distribution in the Quaternary section of the Italian basins. Data gathered from unpublished AGIP reports, Ruggieri and others (1975), Ruggieri and Sprovieri (1977), Ruggieri (1979), and Colalongo and others (1981).

tentatively suggest equating the base of the Pleistocene with the appearance of *Arctica islandica*—which might also equate with that of the Santernian (formerly part of the Calabrian), the base of the Emilian with the FAD of *Hyalinea balthica,* and, finally, the base of the Sicilian with the FAD of *Globorotalia truncatulinoides excelsa*. In this manner, the three biostratigraphic zones coincide with the three Pleistocene stages. However, we are unable, for reasons already stated, to identify the suggested stages by means of microfaunal assemblages. Hence, by using the *Hyalinea balthica* marker, we can map the base of the Emilian.

Not far above the N/Q boundary, where the Adriatic sequences are continuous, the faunal assemblages become poorer in planktonic forms and it is progressively more difficult to use the above-mentioned index species. They are followed by assemblages that are increasingly controlled by ecological factors. From bottom to top, the recorded assemblages consist of *Cassidulina carinata, Bulimina ovula, Bulimina marginata* group, *Ammonia beccarii, Bolivina catanensis, Bulimina costata, Uvigerina peregrina, Cibicides pseudoungerianus, Globigerina quinqueloba, Globorotalia pachyderma,* and other, less indicative, planktonic forms. In this thanatocoenosis *Hyalinea balthica* is almost always present with varying frequency.

It is not even possible to determine whether part of the sedimentary section drilled belongs to the Sicilian, because *Globorotalia truncatulinoides excelsa* is found only south of the latitude of Ancona. The latter taxon is absent owing to unfavorable environment, and the recorded assemblages consisting of *Cassidulina* and *Bulimina* or *Ammonia* and *Elphidium* have no chronostratigraphic significance but are strongly facies dependent.

In the uppermost part of the Pleistocene, we find assemblages increasingly poorer in number of species. These are represented by *Ammonia beccarii, Ammonia beccarii tepida, Elphidium crispum, Elphidium decipiens, Nonion granosum, Asterigerina mamilla, Valvulineria bradyana, Nonionella turgida,* ostracods, and remains of molluscs. These assemblages reveal a marked bathymetric shallowing. We note that in this uppermost part of the Pleistocene peat strata or lenses are often found, and it is inferred that these deposits were deposited in coastal and lagoonal environments.

Some detailed studies of the uppermost part of the Quaternary have been made by examination of cores collected from the seafloor to 40–70 m. These were collected for the selection of drilling and production platform sites (Veggiani and De Francesco, 1972). It has been determined that overlying the Pleistocene, which became continental after the Würmian regression, transgressive Holocene marine deposits were laid down along a 30 km wide section that extends along the present coastline. The Holocene shows a markedly reduced thickness toward the median part of the Adriatic where only the Pleistocene crops out. The latter consists of continental and coastal lagoonal sediments of the last glaciation (Van Straaten, 1965; Brambati and Venzo, 1967; Colantoni and Gallignani, 1980). From these studies, it appears that Holocene deposits attain their maximum thickness from the Po Delta toward the Ravenna area (25–35 m); they thin toward the Venice Lagoon and toward the south.

Attention is called to those sectors (adequate well-control) where the Pleistocene transgressively overlies more ancient deposits of the late Pliocene. This is predominantly an area in the upper Adriatic east of Venice and a belt along the Marche coastline between Rimini and Ancona. Here it seems that Pleistocene sedimentation began with deposition of an upper littoral–neritic environment, characterized by a *Cassidulina* spp. and *Elphidium* spp. assemblage. This is followed by an interval with microfauna of a deeper, outer neritic environment, characterized by a *Globorotalia pachyderma–Hyalinea balthica* assemblage. This, in turn, is followed by a sequence of sediment that records a shallowing. Paleontologically, it is represented by the well-known *Cassidulina, Bulimina,* and *Hyalinea balthica* assemblages and finally, toward the top, by the thanatocoenosis with *Ammonia beccarii, Elphidium* spp., and molluscs, indicative of a littoral environment with lagoonal settings.

Lithostratigraphy

The Quaternary series of the Adriatic area comprise clastic sediments that, from a lithostratigraphic standpoint, can be grouped into the following formations: Argille (clay) del Santerno, Sabbie (sand) di Asti, and Sabbie (sand) di Carassai (Fig. 9.3). The first consists predominantly of clayey sediment and the other two of sandy sediments with some gravel and clay intercalations. To clarify the lithofacies relationship and paleogeography we provide a short summary of these formations. We recall that they have been used to classify the Po Valley (Rizzini and Dondi, 1978, 1979; Dondi et al., 1982) and Adriatic sediments.

Argille del Santerno

The Argille del Santerno Formation is varied and widespread in most Adriatic and Po Valley areas. This unit also comprises Pliocene and Pleistocene clay sequences that crop out along the northern edge of the Apennines (Piacenzian and Tabianian clays, etc.) and the isolated out-

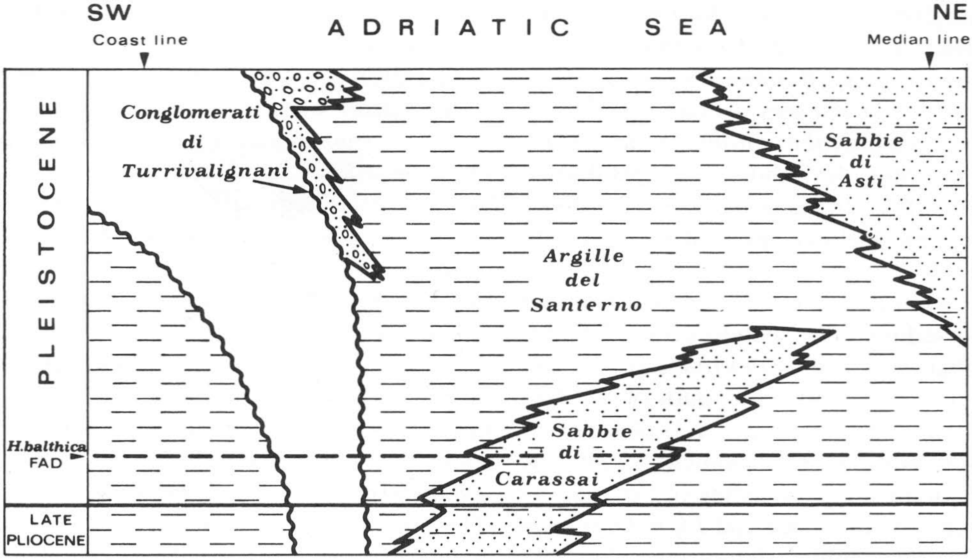

Fig. 9.3. Tentative stratigraphic relationship of the major Quaternary formations identified in the subsurface of the Italian Adriatic Sea.

crops on the Alpine edge of the Po Valley (Cornuda clays, etc.). The formation consists of gray-green or gray–light-blue clay, sometimes intercalated with sand beds a few meters thick; sometimes the clays contain abundant silt. The clays have a slightly variable composition but are always predominantly illitic. This dominantly clayey unit contains some sizeable sandy intercalations that are identified as members. These sandy intercalations are more frequent at the basin edge and appear to have a local source.

The type section of this formation is the Santerno Valley (Bologna region) from Tossignano to Imola; according to Ruggieri and others (1975), the Pleistocene part should correspond to the Emilian, including the Imola Sands. The paratype for the Adriatic Sea occurs in the Vasto Mare 1 well, from the seafloor (−40 m) to a subbottom depth of 660 m (Fig. 9.4). From a paleontological viewpoint, the Santerno clays belonging to the Quaternary contain characteristic foraminiferal assemblages with *Hyalinea balthica, Cassidulina,* and *Bulimina, Ammonia* and *Elphidium*.

The environment of deposition in the lower part of the Pleistocene sequence, as determined from the microfaunal associations, is generally rather deep, i.e., outer neritic to bathyal. Upwards, this sequence grades to shallower marine deposits, from outer neritic to littoral. As will be seen, these sediments represent basin, slope, and shelf deposits according to their physiographic position in the basin. The areal distribution of the Argille del Santerno (Fig. 9.5) is controlled by basin morphology and passes laterally to the Asti and Carassai formations of the same age.

Sabbie di Asti

The Sabbie di Asti Formation extends from Piedmont basins to the Po Valley Basin, and then to the Adriatic area. It consists of a fairly uniform sequence of clayey sands, sandy clays, and silts, which gradually pass from one lithotype to another. In the Adriatic area, the sands are clayey, mostly medium-fine or fine-grained. On electric logs it can be seen that the Sabbie di Asti consist of poorly defined strata, separated by thin sandy clay intercalations. The sand beds are very thick; they consist of poorly sorted sands deposited in low-energy environments. The textural gradation from this formation to the underlying clayey formation (Argille del Santerno) is, for the most part, gradual, and the sands in the lower part of the formation are fairly fine-grained. Sands consist of quartz of various types, feldspars, micas, lithic frag-

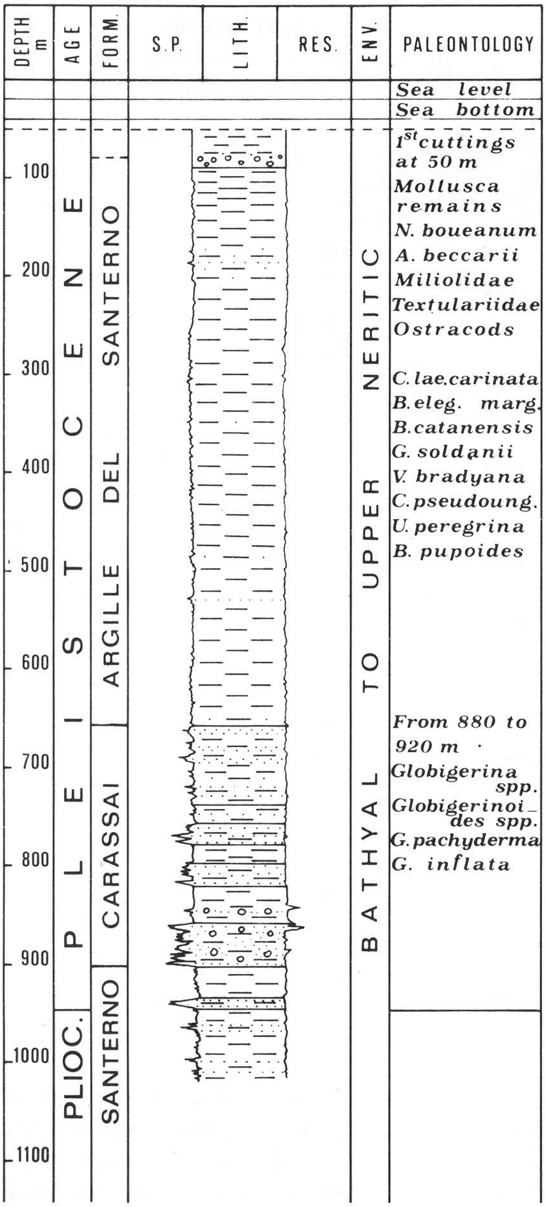

Fig. 9.4. Paratype sections in the Vasto Mare well (southeast of Pescara). Argille del Santerno: from the seafloor (−40 m) to −660 m. Sabbie di Carassai: from −660 to −900 m.

ments, and subordinate amphiboles; the sands are mostly lithic, sometimes passing to feldspathic.

The type section of the formation is in the Asti area (Piedmont); the paratype for the Adriatic Sea is recovered in the Alessandra 1 well, from the seafloor (−103 m) to 1525 m (Fig. 9.6).

On the basis of the areal and vertical distribution of the sediments forming this formation, we can demonstrate some events of a regional nature. Relatively coarse-grained sediments are found only in the upper part of the formation and limited to the northwestern part of the formation where they become alluvial deposits overlying the Asti Formation. In the Adriatic area, near the top of the formation, there are peat-rich deposits indicating a shallow-marine, possibly littoral, environment.

The thickness of the Asti Formation is fairly uniform, averaging 1000 m. Its maximum is in the central part of the northern Adriatic; seaward off the Po Delta it can attain 2000 m. This formation, associated genetically with the Po Basin, becomes thinner southwards: off Ancona, for example, it occupies only the central part of the Adriatic Sea, coinciding with the median line, and pinches out rapidly to the south and southwest (Fig. 9.7).

Sabbie di Carassai

Off Pescara the Quaternary stratigraphic sequence is slightly different from that found to the north. Here, sand and conglomerate bodies form very irregular beds, different from those in the Sabbie di Asti Formation. These rather discontinuous bodies can be grouped as the Sabbie di Carassai Formation (named after the well drilled onshore in the Ascoli Piceno region) and the Conglomerati di Turrivalignani (about 26 km southwest of Pescara) Formation. The latter formation is not well represented in the Adriatic Sea and is only locally significant. For this reason, we do not describe it and refer the reader to the description of outcrops from the type area (Crescenti, 1971).

The Sabbie di Carassai Formation may occur as a single body or divided into units separated by clay-rich facies, whose thickness can reach several hundred meters. The Carassai Formation grades upwards into the Santerno clays. Laterally, the formation may be in contact with the Santerno Formation, and northward, off Porto San Giorgio, it also may interfinger with the Porto Garibaldi Formation. The Porto Garibaldi Formation is a turbidite unit of Pliocene age, which only locally reaches the early Quaternary; its maximum development is in the Po Plain and offshore in the adjacent Adriatic.

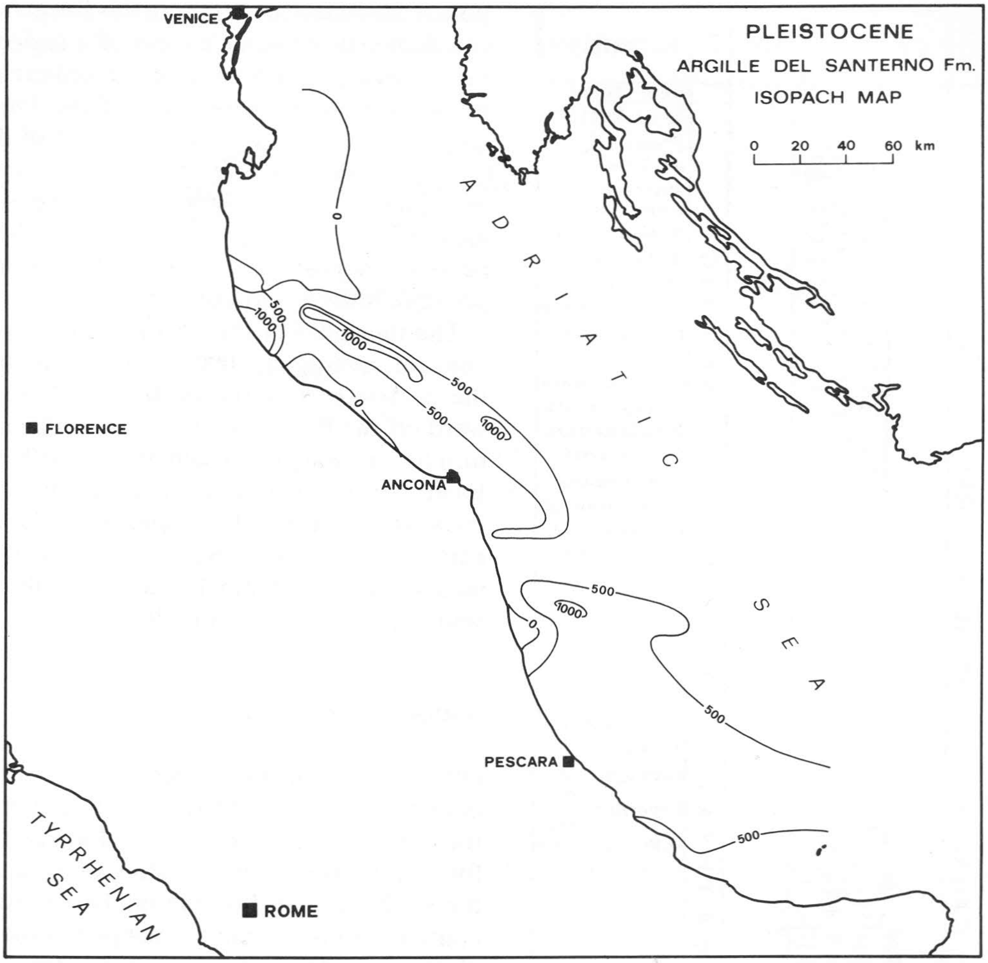

Fig. 9.5. Isopach map of the Argille del Santerno Formation of Pleistocene age.

The Sabbie di Carassai Formation consists of sand beds, several tens of meters thick, intercalated with clay beds of almost the same thickness. The sands are generally fine to medium grained and slightly clayey. Their mineralogical composition is similar to that of the Sabbie di Asti Formation. The sand beds are interbedded by thin clay beds, which are seldom distinguishable on the logs owing to their thinness. The best defined sand beds show complete Bouma sequences (cf. Bouma, 1962). The type section of the formation is the Carassai 2b well, from 440 to 813 m and from 1932 to 3263 m; the paratype section in the Adriatic is the Vasto Mare 1 well, from −660 m to −900 m (Fig. 9.4).

The areal distribution of the Carassai Formation is irregular because this formation is formed by sedimentary bodies in different depositional basins of different age. At the time of their deposition, the Adriatic Basin was already divided into various subbasins separated by active ridges. Sediments over ridges are predominantly clayey, whereas the Sabbie di Carassai sequences were deposited in the depressions. The whole formation tends to thin out in the southern Adriatic, but it is thicker along the shore and in inland basins. It is noted that microfaunas are generally scarce; benthonic forms that dominate the faunas are probably reworked. Sediment distribution and petrological analyses of cores show that these deposits are turbidites organized as negative sequences which we interpret as progradational lobes. Nevertheless, our data base is incomplete. It cannot be excluded that other equivalent sediment types can occur, especially in onshore ar-

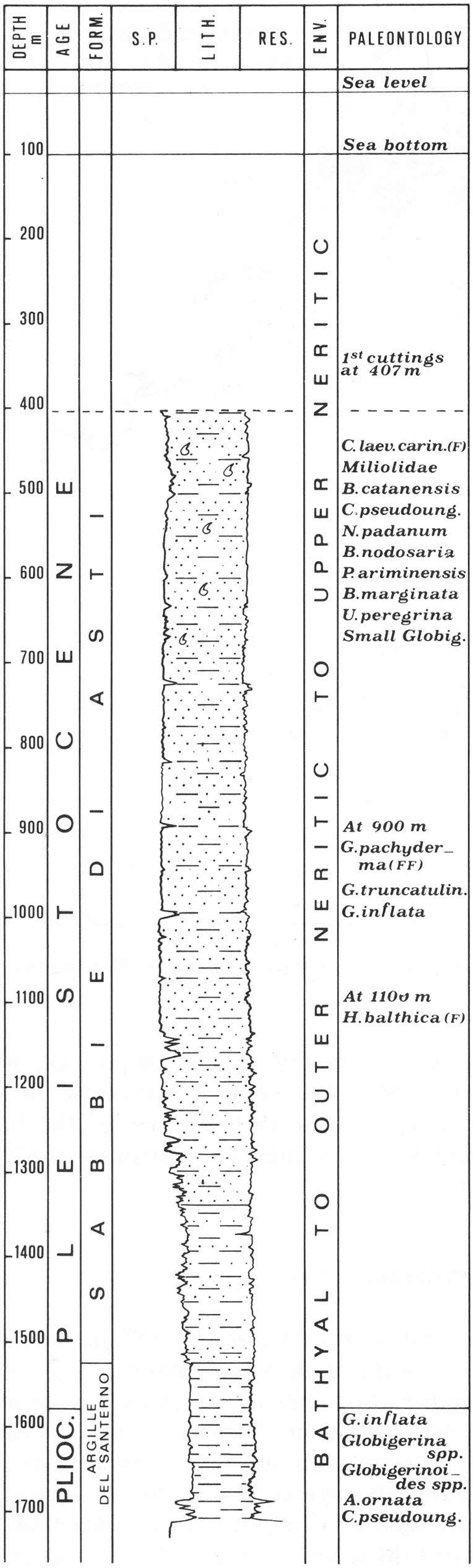

Fig. 9.6. Paratype section for the Sabbie di Asti Formation in the Adriatic Sea area. Alessandra well 1 (due east of Rimini), from the seafloor (−103 m) to −1525 m.

eas because of the highly varied morphology of the basins in which these deposits accumulated.

Seismic Stratigraphy

The first indications relative to depositional processes of the Quaternary sequence in this region date back about 30 years (Rocco, 1955). Examination of seismic data in the adjacent Po Valley, supplemented by well data, has resulted in the identification of three units in the Quaternary:

1. lower, characterized by subparallel reflectors, corresponding to marine sediments;
2. intermediate, characterized by highly and variously oblique reflectors, corresponding to littoral sediments; the particular attributes of this interval are correlated with sea-level changes triggered by glaciations; and
3. upper, characterized by subparallel reflectors, corresponding to alluvial sediments, perhaps Holocene.

The seismic data subsequently acquired offshore in the Adriatic indicate that this division as three Quaternary units extends to this area as well. The main difference is that the upper unit of the sequence shows marine characteristics. Furthermore, the intermediate unit appears quite well developed and shows a geometry typically indicative of progradation (Figs. 9.8, 9.9).

The main characteristics of these seismic units provide a basis for a reasonable interpretation of their depositional origin.

Lower Unit

This unit is characterized by even parallel reflectors; it displays horizons with a high reflector factor and good areal continuity. With regard to the identification of the lower limit of this unit, it should be remembered that seismic and deep drilling data acquired in the Adriatic area indicate a strong orogenic phase during the late Pliocene; the intensity decreased from west

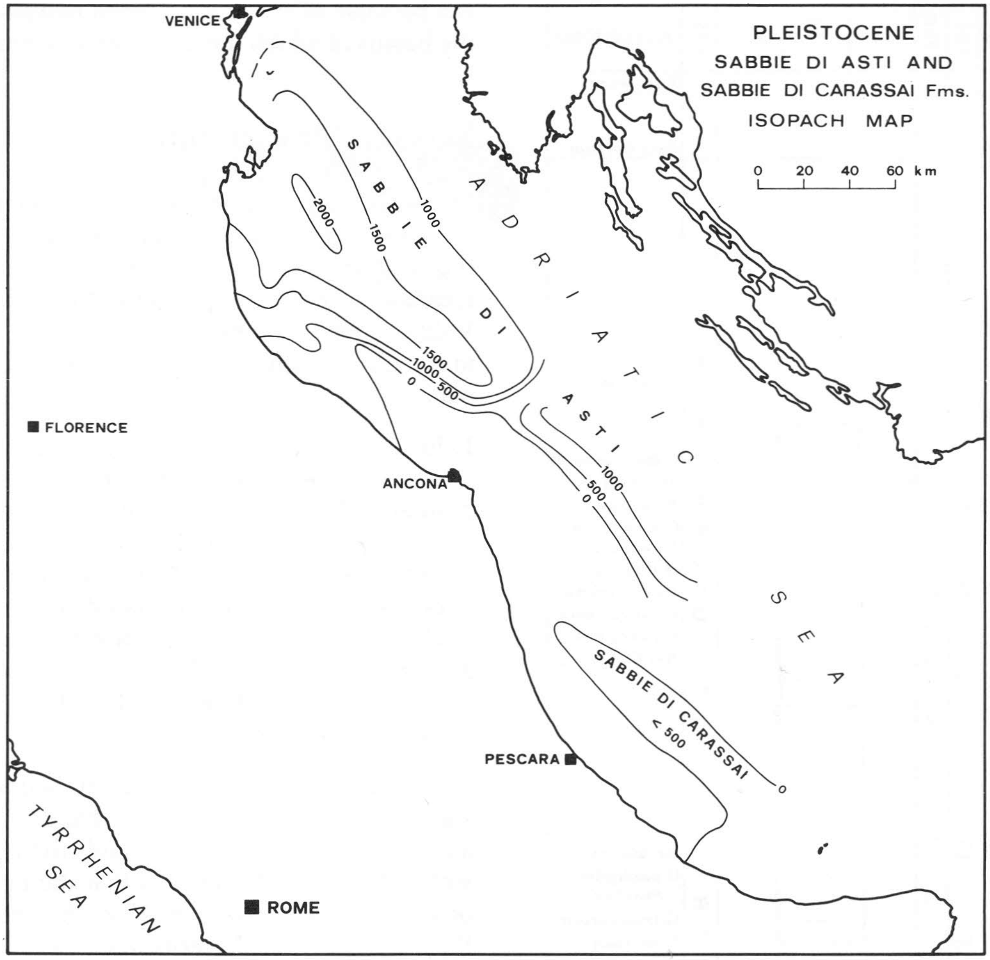

Fig. 9.7. Isopach map of the Sabbie di Asti and of the Sabbie di Carassai formations, of Pleistocene age.

to east, verging east or northeast. This tectonic phase gave rise to unconformities in the topmost Pliocene sequence and resulted in a lack of deposition and erosion on the more prominent structural highs. Later, this relief was covered by Early Quaternary deposits, characteristically marine sediments substantially similar to those of the Pliocene. As a result, the lower boundary of the Quaternary appears conformable in the deeper basin but largely transgressive in shallower areas. The thickness of the "lower unit" ranges from several hundred meters in the north-central sector to zero meters in most of the south-central sector. On the more prominent pre-Quaternary highs, seismic data show that the whole interval may be missing altogether. In the northern sector, correlation from electric logs is good over several tens of kilometers. The lithological composition of this interval generally shows an increase in sand percentage in the deeper parts of the basin, whereas clay sediments prevail in the shallower parts.

Intermediate Unit

This unit is characterized by oblique reflectors. The seismic data show sedimentary foreset structures that appear irregularly distributed in the Adriatic Basin. A more accurate examination of significant seismic sections (Figs. 9.8, 9.9) reveals typical prograding clinoform patterns, such as sigmoid, oblique tangential, and parallel (Mitchum et al., 1977). The tangential and sigmoid types appear to alternate rather

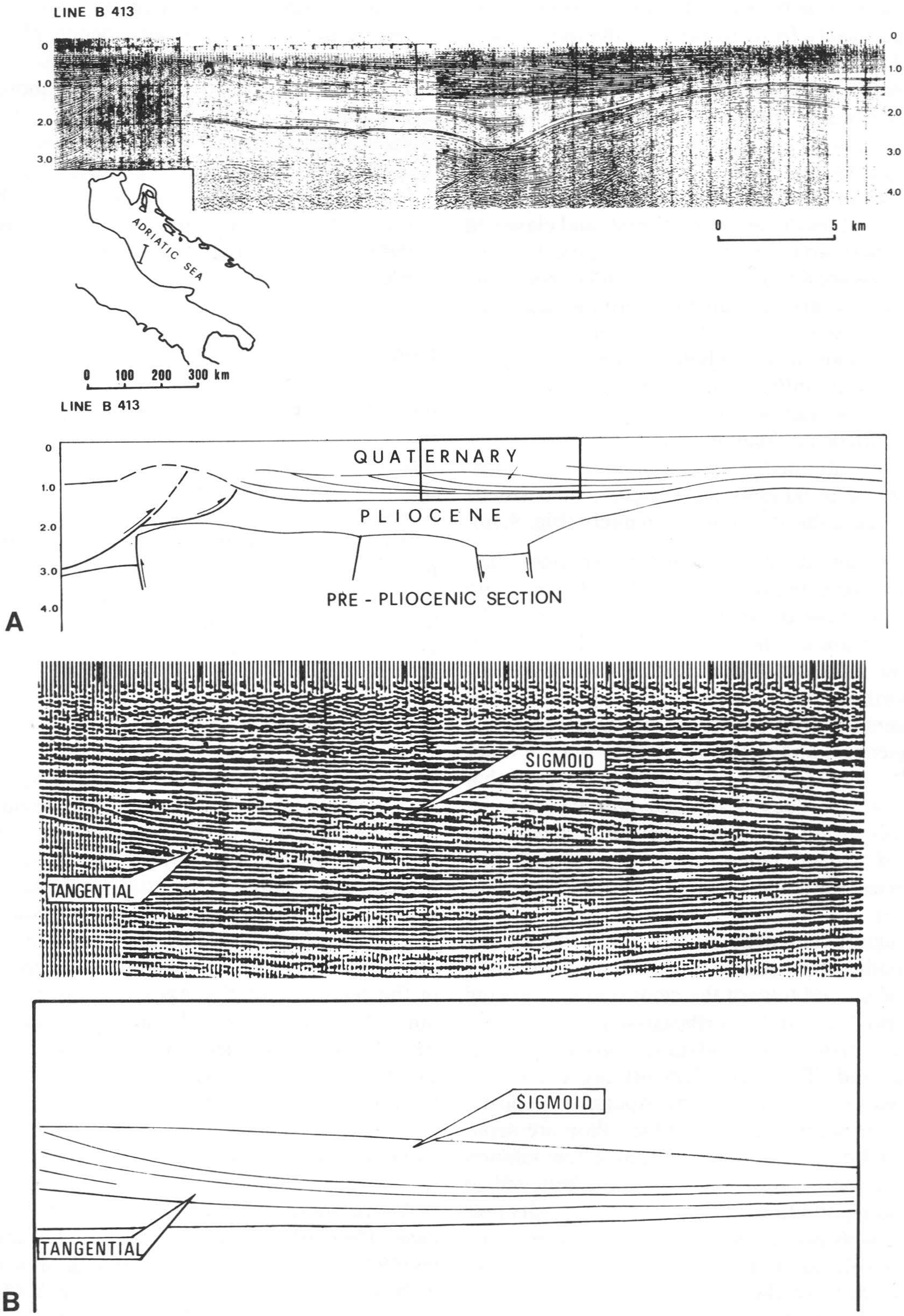

Fig. 9.8. Seismic line B 413, showing stratigraphic configuration (A), and sigmoid and tangential progradational stratification (B).

regularly. It is believed that this alternation resulted mainly from eustatic oscillations in sea-level produced by the major glaciations that affected the northern hemisphere. The tangential foresets would appear to correspond to the periods of glacial low-stands, the sigmoid ones to interglacial high-stands. The lithological composition of this interval is generally sandy in the northwest, marly in the southeast, and clayey in the other parts; unfortunately, electric log correlations are limited. The lower and upper limits of this unit are difficult to determine, but seismic data suggest that the phenomenon started concurrently in the whole Adriatic area. It is particularly difficult to determine the upper limit of the unit because of the scarcity of seismic horizons at shallow depth.

In the intermediate unit it is possible to identify three progradational systems, their trends and geographic distribution, namely (Fig. 9.10):

1. Apennine deposits, clearly of Apennine origin, accumulated over a wide belt stretching along most of the coastline and extend offshore toward the central part of the Adriatic. The advance of the coast is predominantly northeastward. In the north, Apennine sediments overlie mainly marine Quaternary sequences, and in the south they overlie older deposits. Seismic correlations indicate that their age does not reach late Pleistocene. This group comprises the better developed and typical clinoform progradational patterns, particularly in the south (Figs. 9.8, 9.9).
2. Yugoslavian deposits are identified in the southeastern sector of the area under study and extend toward the central area, showing a predominantly northeast-southwest trend. Two distinct progradational phases are recognized. The older deposits are much less well developed than the Apennine deposits of the same age, from which they are separated by a strip no more than a few kilometers wide. These sediments are believed to correspond to the distal part of deposits presumably present in a more typical form in the Yugoslavia offshore region. Much more developed are the late Yugoslavian deposits, which sometimes extend southwestward so as to overlie the Apennine deposits (Fig. 9.11). The Yugoslavian deposits, particularly in the southeastern part of the study area, appear to be affected by an orogenic phase of late Pleistocene age which, in places, caused the erosion (at least in part) of the more recent deposits.
3. Po Plain deposits extend southeastward from the Po Delta parallel to the Adriatic median line toward the area of Barbara 1 well. These facies are poorly represented by seismic data, and their origin thus remains to be defined.

Upper Unit

As stated earlier, this unit remains poorly defined. The seismic responses are often disturbed by seafloor multiples. In sectors where this unit is thicker, seismic data show characteristics of even parallel stratification.

It is to be noted that the area south of the Barbara 1 well is difficult to interpret because the above-mentioned depositional series coalesce. This sector is interpreted as the central part of the basin before its infilling.

Tectonics

Recently a description of the Pliocene–Quaternary tectonic evolution in Italy was reviewed by Pieri and Groppi (1975) in a regional study that also covered the Adriatic Basin (see also Morelli et al., 1969). That study indicated that we are dealing with an asymmetrical basin. The inner flank of the basin, on the west side of the area, is steeper and has been directly involved in the tectonics of the Apennine margin. The outer flank, which is wider and relatively gentle, rises to the northeast. On the inner margin, overthrust phenomena have been identified, with repetitions of Pliocene units and, less commonly, pre-Pliocene sequences, which sometimes complicates the structural interpretation.

A structural map (scale 1 : 1,000,000) of the basal Pliocene was enclosed with the above-mentioned study. When comparing this map with that of the basal Quaternary (Fig. 9.12) we find good agreement in the eastern and central parts of the area. However, there is considerable disparity to the west.

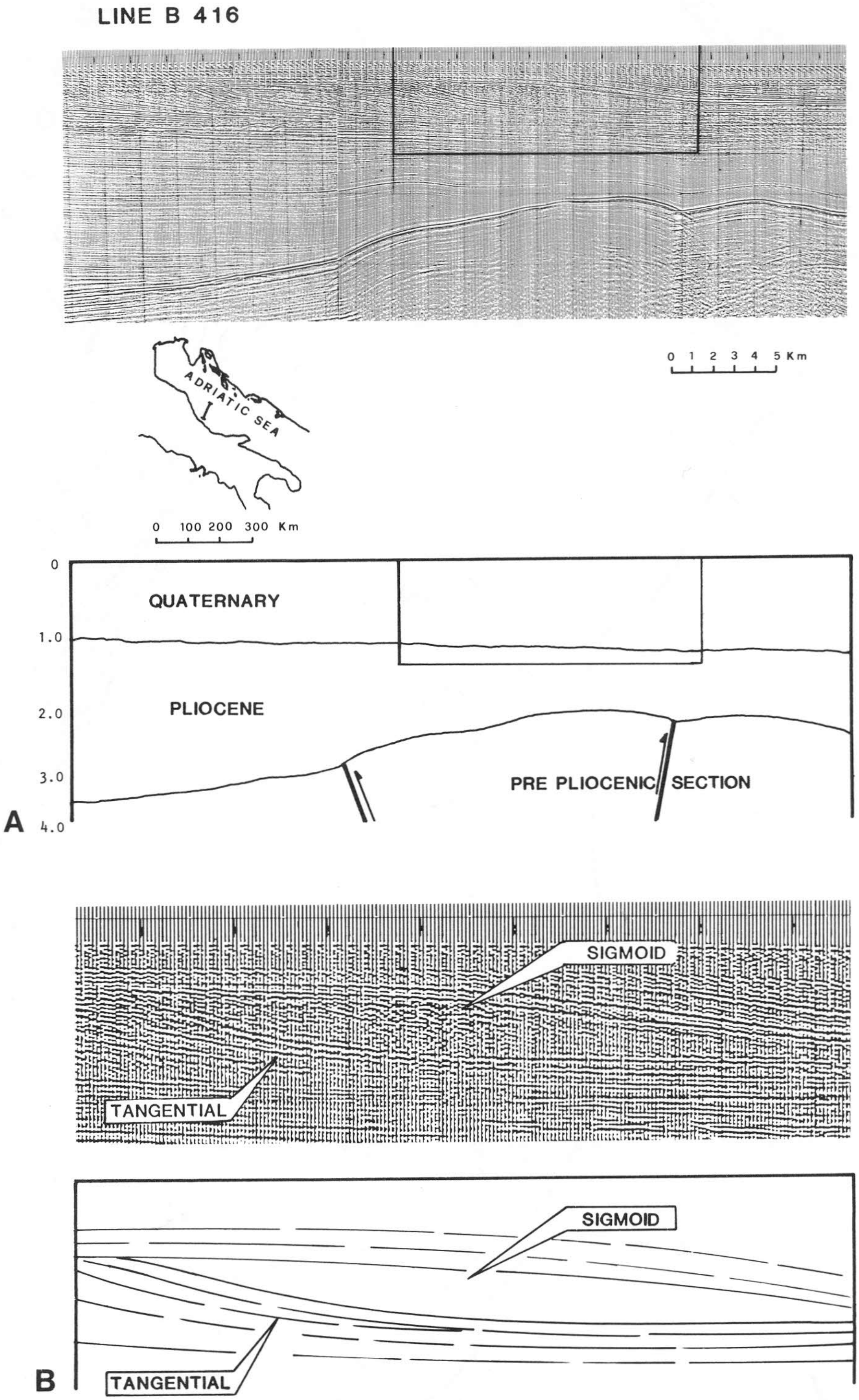

Fig. 9.9. Seismic line B 416, showing stratigraphic configuration (A), and sigmoid and tangential progradational stratification (B).

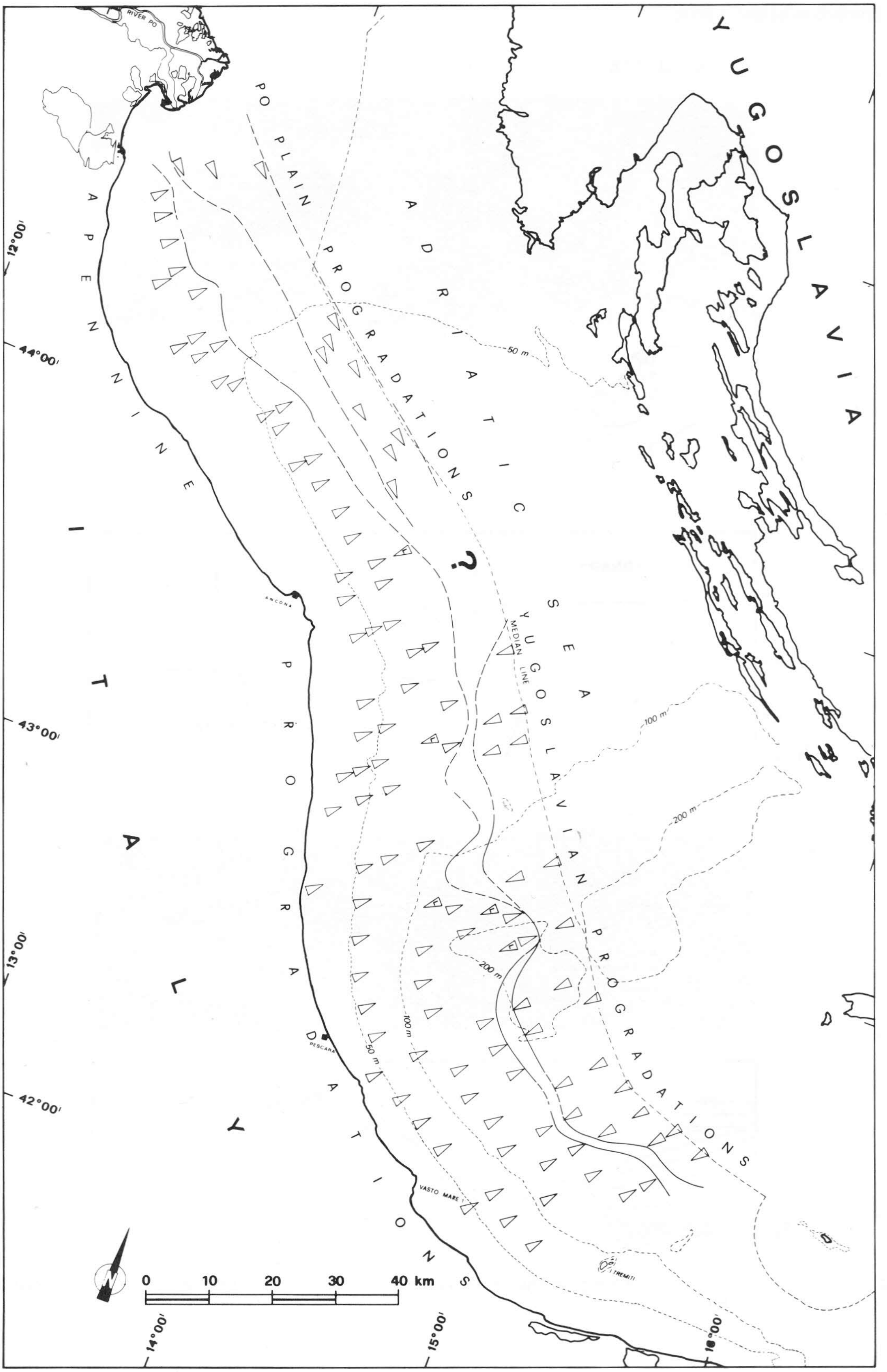

Fig. 9.10. Areal distribution of progradational trends in the Adriatic. Triangles indicate the azimuth of the prograding maximum dip. Symbol L (inside some triangles) indicates late Pleistocene Yugoslavian progradations.

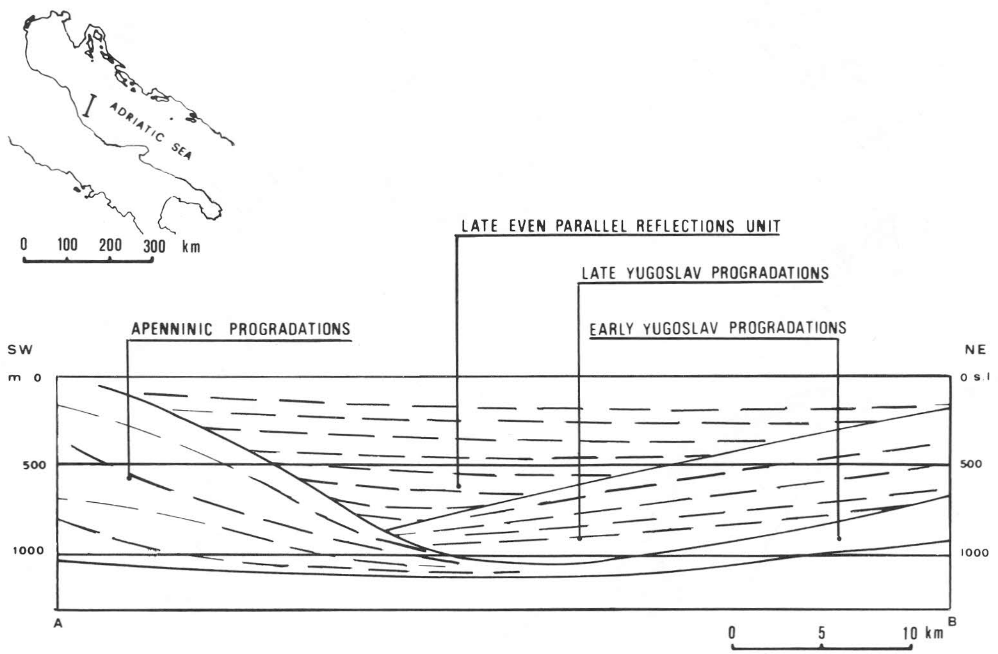

Fig. 9.11. Composite sketch, from different seismic lines, indicating the complex onlapping situation of different progradational units present in the west-central part of the Adriatic Basin.

The present structural setting of the Quaternary sequence is a result of three factors: deposition over the previous basin morphology; this sequence was subject to late Pleistocene folding of the outer margin of the Apennines; the sequence was also subject to recent uplift in the central eastern area.

The basal Quaternary map also allows us to recognize the following structural elements:

1. an area with several structural highs developed along the coast, linked to Apennine overthrust folds;
2. a large structural low in the northern-central part of the Adriatic, trending northwest-southeast, an extension of the Po Plain;
3. an uplifted area, in the central part of the Adriatic Sea, consisting of foreland structures; and
4. a south-central structural low area bounded to the north and east by foreland structures and linked to the south with the Tertiary trough of the Bradano Basin.

Basin Evolution and Conclusions

The interpretation of events that controlled Quaternary deposition is based on information from the sedimentological study of cores, paleo-ecological data, electric logs, and, chiefly, the characteristics of seismic reflectors revealed by these sequences.

From the base up, the first Quaternary series are generally fine-grained (Santerno Formation). The Carassai Formation is also present at the Pliocene–Quaternary boundary; in the Adriatic area it appears to be composed entirely of turbidites that are restricted to the main synclines. It can thus be assumed that, at the beginning of the Quaternary, sedimentation occurred in a fairly deep basin with a rather complex morphology owing to the presence of numerous ridges. The general shape of the basin cannot have been very different from that of the present except that the coastline appears to have been more irregular and located further inland, and that the basin must have been much deeper. A very marked ridge lay along the Adriatic median line.

The Quaternary sea clearly records transgressive stages at the beginning, but this trend reversed fairly quickly and a phase of gradual basin filling began. This lasted, with alternating events associated with glaciation, throughout the Quaternary and became reversed only recently with the Holocene transgression. The

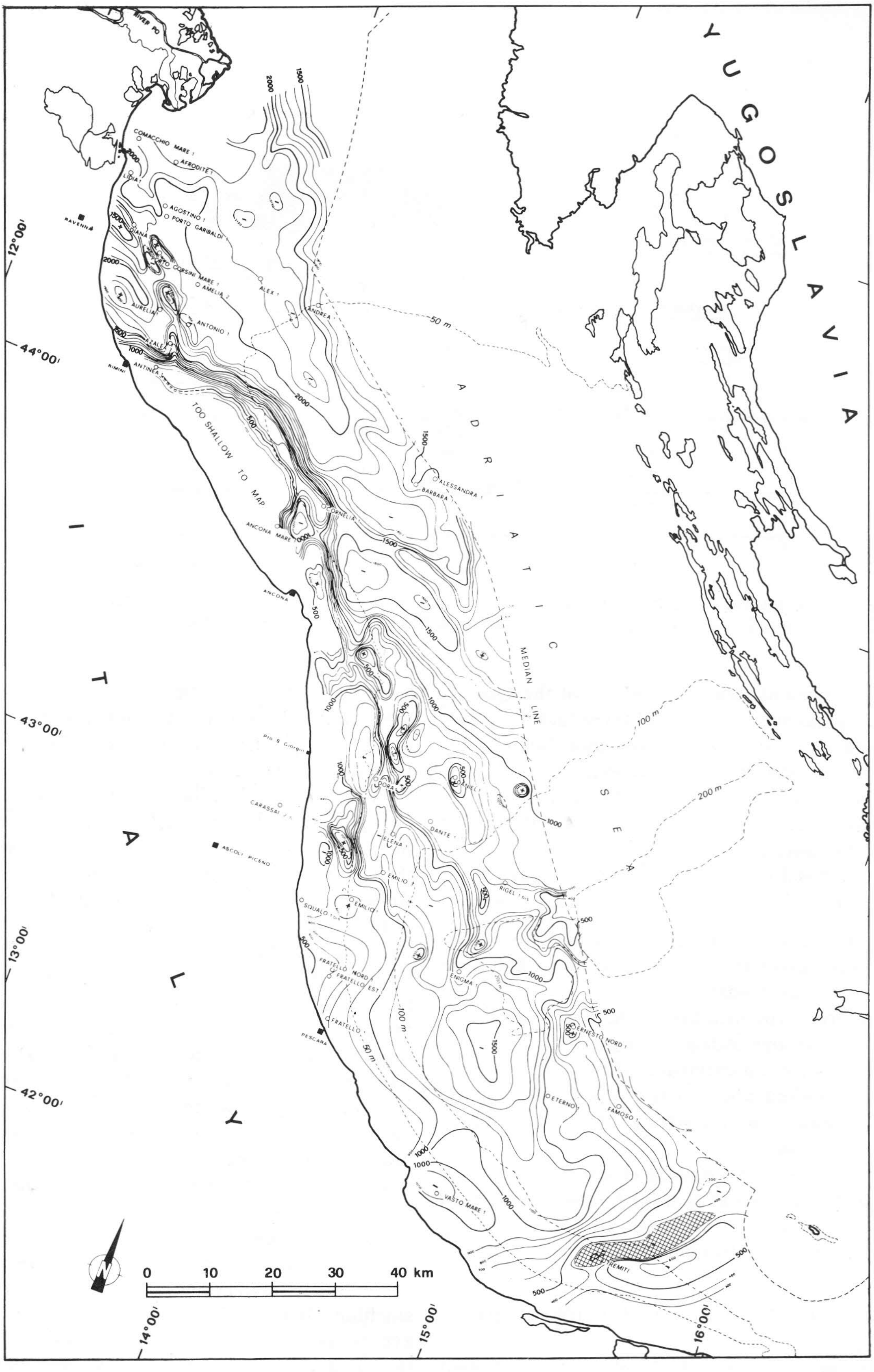

Fig. 9.12. Structural contour map of the base of the Adriatic Quaternary section (contours in meters). The grid pattern depicts the area where Quaternary sediments are practically absent.

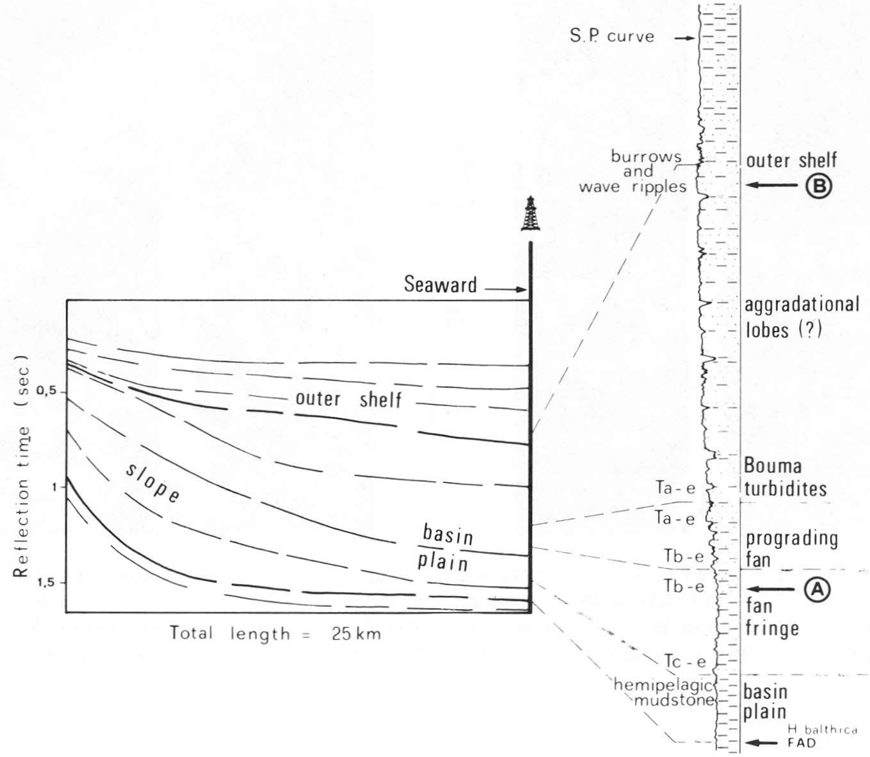

Fig. 9.13. Environment of deposition and sedimentological pattern of the Quaternary sequence in the central part of the Adriatic Sea. The structural sketch is a line drawing interpreted from seismic lines. Sedimentary structures are reported as they were logged on slabbed cores. Examples of core structures (A, B) are shown in Figure 9.14.

initial Pleistocene transgression is clearly evident on the basin edges, especially in the Istrian–Venetian platform area along the Romagna–Marche coastline and on the better developed ridges. The sediments comprising the infill were either clayey (Santerno Formation), sandy (Asti Formation), or admixtures of both (Carassai Formation). The sequence of events may be interpreted by analyzing the seismic data calibrated with well data.

At the base of the section and particularly in the center of the basin, we find deposits classified seismically as the lower unit with even-parallel reflectors. These are interpreted as resulting from basin sedimentation, both clayey (Santerno Formation) and turbiditic (Carassai Formation). The turbidite strata give the strongest seismic reflectors. Overlying these sediments is the intermediate unit, with oblique reflectors, interpreted as progradations of the slope deposits over the basin strata. The deposition of these two units, which developed extensively over a long period, led to the gradual fill of the deep basin where deposits with parallel stratification could be deposited.

The upper unit with even parallel stratification represents the final phase of basin infill by shelf and continental deposits.

Details of this regional evolution can be expanded in those areas where a reasonable number of cores have been taken. For example, in the central area of the north Adriatic Sea (Fig. 9.13), deposits that form the base of the Quaternary section consist of clays interlayered with a few thin beds of fine sand and silt. This unit is 100 to 200 m thick; seismically it is correlated with the lower unit, and stratigraphically it is associated with the Santerno Formation. The sand or silt interbeds seldom exceed 10 cm in thickness and consist almost only of the Bouma T_c and/or T_b intervals. The sequence is considered to be a very distal segment of deep-sea fan, i.e., a fan-fringe (Fig. 9.14A) according to the position of this facies in the basin (cf. Mutti, 1977).

Overlying sediments become more sandy

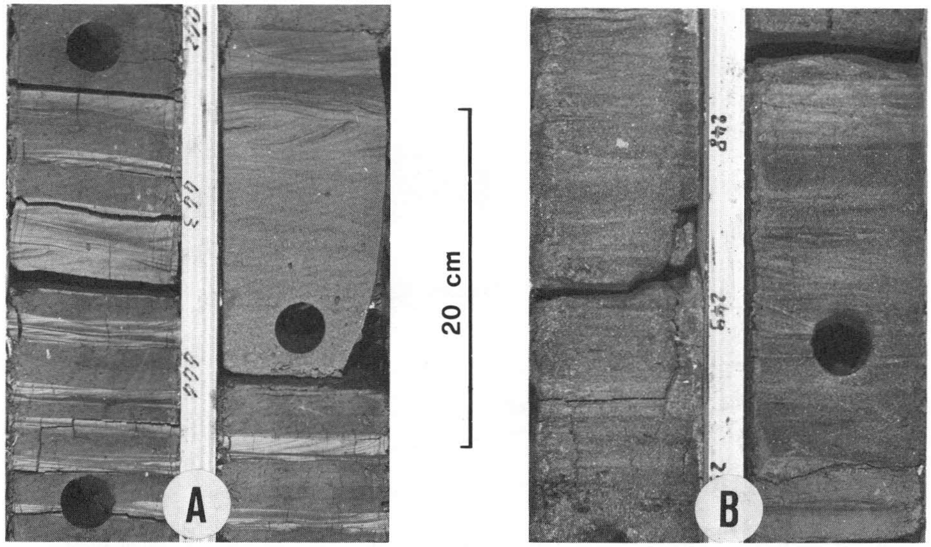

Fig. 9.14. Slabbed cores taken in the well core log shown in Figure 9.13. A, fan-fringe deposits: sandy levels show mainly T_c Bouma intervals. The core slab on the right shows one of the few layers with a complete $T_{a–c}$ Bouma sequence. B, shelf deposits: small-scale wave and cross-bedding in finely laminated shaly sand; also faint and small burrows. Location of the cores is shown in Figure 9.13.

and, from a seismic viewpoint, belong to the basal parallel stratified unit, but they are located in a section in the westernmost parts of the basin in which the first foreset sequences are already present. These deposits are identified as Sabbie di Asti. They consist of sand beds a few meters thick, with well-developed and almost complete Bouma sequences. These sequences are clearly recognizable even though the sands are unconsolidated. Clay beds are as thick as the sand beds, or thinner. These deposits appear organized as a single negative sequence, i.e., a thickening upwards sequence that can be interpreted as a prograding subsea fan (cf. Mutti and Ricci Lucchi, 1972). This unit is approximately 100 m thick. A rather uniform section of clayey sand beds lies above these alternations. Each sand bed is several tens of meters thick and is interbedded with clay beds not more than a few meters thick. These deposits also belong to the Sabbie di Asti and are several hundreds of meters thick.

Structures in split cores cut from the lower part of the latter interval clearly indicate that these sands represent classic turbidite deposits with complete Bouma sequences. These sequences are either amalgamated or poorly separated from each other by a few centimeters of clay. These sediments are very fine grained, show a conspicuous clayey matrix, and have almost completely filled the synclines; it is concluded that they were deposited by a highly efficient transport mechanism (cf. Mutti, 1979). From the seismic viewpoint these deposits appear to be characterized by parallel reflectors (lower unit) but are completely surrounded by the foreset bedded sequence (intermediate unit), especially in a direction towards the Italian coastline.

The cores cut from 500 m higher in the previously mentioned core, in the upper part of the Sabbie di Asti (attributed to the upper unit with parallel stratification), provide a different environmental picture. These are not clayey sand beds, generally amalgamated, but a highly irregular sand-clay sequence with clay-rich sands characterized by ripple marks and bioturbation (Fig. 9.14B). These are interpreted as shelf deposits subject to wave action and thus may represent storm layer deposits (Gadow and Reineck, 1969) or transitional deposits between coastal shelf sands and outer shelf clays. Thus we have ascertained that, in the central part of the Adriatic Basin, the lower part of the Sabbie di Asti consists of turbiditic deposits while the upper part is represented by shelf deposits.

What happens in the 500 m of section lying between the two cored intervals remains unknown, and we cannot pinpoint where and how this facies change occurs. In fact, no significant lithologic variations are detected in this section on the electric logs. The clay interbeds are few, irregularly distributed, and never thicker than 5 to 10 m; it is unlikely that some of these are slope deposits. It would appear probable that the turbidite sedimentation of the basin floor is directly interbedded with the outer shelf and coastal deposits. This may be due to the almost vertical infill of the basin, without interposition of classic clay-rich slope sediments. It is also assumed that, though thin and not evident from seismic data, the slope deposits are represented by part of the recovered clayey sands located between cored turbidites and the shelf deposits. In either case, slope sediments do not appear well developed.

This, in turn, would indicate that the turbidites may have accumulated at relatively shallow depths, since slope sediments (even if locally present) are poorly developed. A similar situation is recorded by C.N.R. geotechnical well VE-1, located on the western outskirts of Venice: Here Quaternary turbidite sediments underlie coastal sediments, from approximately 300 m down (Favero and Passega, 1980). However, in this well silts and marls, more than 130 m thick, occur between the sandy turbidites and the shelf sediments; these silts and marls are interpreted as low-density turbidite deposits. This lithologic sequence, however, was not evident in our studied wells. This different sequence, even in deposits that represent the final infilling of the Adriatic Quaternary Basin, may be due to the different physiographic position of the two well sites within the basin; i.e., our well (Fig. 9.13) likely represents a depocenter near the center of the Quaternary basin, while the VE-1 well penetrated a more peripheral position.

In summary, it appears that infill of the central part of the north Adriatic Sea occurred mainly by depositional up-building, whereas infill of the outermost parts of the basin occurred mainly by out-building processes. Deposition and structural modification have continued almost concurrently to the present. Moreover, this setting has been considerably modified periodically by eustatic factors.

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