

Quaternary Transgressive/Regressive Cycles in the Gulf of Argos, Greece

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Borings in the Argive Plain reveal cycles of marine incursions, each ending with a Mediterranean soil profile and followed by a prograded fluvial and coastal wedge. The sediment prism of the Gulf of Argos shelf, visible in high-resolution seismic reflection profiles, also consists of transgressive and regressive depositional sequences identified by onlap, downlap, and truncation of deposits. At least four major reflectors, recognizable by their high acoustic impedance and erosional features, can be correlated across the shelf. The sediments between each pair of reflectors represent the seaward part of a set of transgressive and regressive marine deposits. They can be matched to the stratigraphic sequence on land where each marine unit is topped by a soil. Corrected for subsidence, the terminations of the overlapping and downlapping units define a local sea-level history; its time scale can be derived from a comparison with the eustatic sea-level history deduced from ocean cores. Thus, marine seismic reflection data can be used for the correlation of Quaternary oceanic and terrestrial chronologies. © 1990 University of Washington.

INTRODUCTION

Coastal stratigraphic sequences have the potential to link directly Quaternary land and marine stratigraphies. In subsiding coastal plains and shallow seas, the complex intercalations of terrestrial and marine sediments produced by Quaternary sea-level fluctuations are often preserved. However, because methods used on land to establish the stratigraphic record differ greatly from those applicable at sea, the stratigraphies on either side of the present coastline have rarely been integrated. In this study, we examine the Middle and Late Quaternary history of the coastal plain and continental shelf of the Gulf of Argos, using boreholes on land and high-resolution seismic reflection surveys at sea. From the combined results we develop a model for the identification of glacial/interglacial cycles on Mediterranean continental margins. If found to be of wide applicability, this model may be useful in the difficult problem of correlating the continental Quaternary history with that of the oceans. Our

results correspond to Butzer's (1975) model based on Majorcan data.

METHODS

For the stratigraphic study of the coastal plain we have mainly relied on boreholes drilled for hydrological purposes to 60- to 150-m depth by the Greek Service of Land Improvement and the Polytechnic University of Athens (Fig. 1). The logs of those holes list standard sediment properties, the calcite/dolomite ratio, and some diagnostic marine fossils (e.g., *Miliolidae*, *Elphidium* sp., corals). We have used 51 of those holes to establish the late Quaternary stratigraphy of the Argive Plain. In addition, in order for us to examine a range of sediment samples, 13 bailer holes up to 30 m deep were drilled by a local drilling company (Fig. 1). In the field, large samples taken every meter down-hole were split into gravel (>2 mm), sand (2.0-0.063 mm), and mud (<0.063 mm) fractions. Gravel and sand composition, fossil assemblages, color, field texture, and soil properties

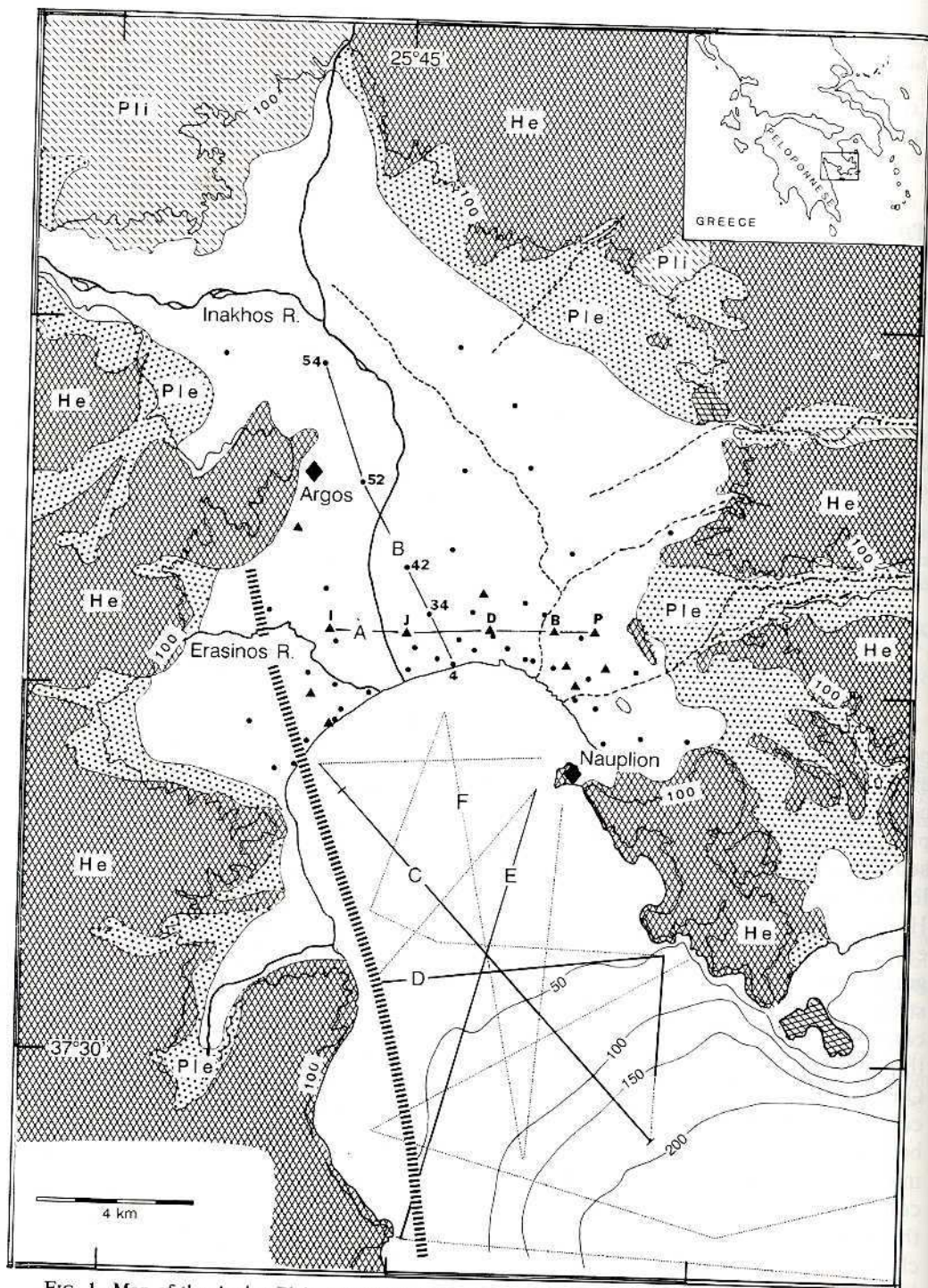


FIG. 1. Map of the Argive Plain and Gulf of Argos, with locations of boreholes (triangles: Greek agencies; dots: bailer holes), sections A and B (Figs. 2 and 3), and marine seismic reflection lines. Bathymetry (in m) based on our survey combined with data from Greek charts. He: Mesozoic-Paleogene Hellenic nappes; Pli: Pliocene; Ple: Pleistocene fans; blank: Holocene alluvium and colluvium.

were recorded (Finke [a.k.a. Zangger], 1988; Zangger and Malz, 1989).

The single-channel marine seismic reflection survey (Fig. 1) was carried out with an SIG sparker operating at 250 to 380 joules of power. The returns, received by an eight-unit EG&G-265 hydrophone streamer, were recorded on an EPC-3200 recorder. A Raytheon 200-kHz echosounder was used for precise water-depth control and a Motorola Miniranger system with portable shore stations provided positions at approximately 10-min intervals and at all course changes; the precision of these positions is estimated at better than ± 50 m. Penetration of the shelf prism was achieved to a maximum depth of 0.20 sec (two-way travel time), but a strong first multiple limits interpretation at depth. The interpreted records were converted into line drawings of key reflectors, plotted against two-way travel time in seconds without correction for small variations in survey speed (about 6 knots). To compute true reflector depths and sediment thicknesses, we have used 1.6 km/sec as a reasonable approximation of late Quaternary sediment velocities; the uncertainty involved is about $\pm 10\%$.

TOPOGRAPHY AND GEOLOGY OF THE REGION

The Argive Plain and Gulf of Argos form an elongate trough open at its southeastern end to the Aegean Sea, but land-bound on both sides as far south as $37^{\circ} 30' N$ (Fig. 1). Along the western shore, high mountains drop steeply into deep water, whereas on the east side narrow shelves and gentler slopes make the transition to deep water. A ca. 8- to 10-km-wide shelf occupies the northern Gulf, ending in a shelf break between 95 and 100 m from where the bottom descends steeply to a more gentle lower slope at 150 m. The maximum depth of the basin, ca. 700 m, occurs in the south where the Gulf opens into the Aegean.

The Argive Plain-Gulf of Argos basin, 75 km long from the apex of the plain to the open Aegean and 30 km wide, is of tectonic

origin. Situated at the boundary between the Pelagonian and Pindos zones of the central Hellenide nappe, it is bordered by mountain ranges that consist mainly of flysch, limestones, and ophiolites of Mesozoic through Eocene age. After major orogenesis ended in the middle Cenozoic (Jacobshagen, 1986), most or all of the Peloponnese emerged and was leveled by erosion. A new phase of tectonic extension and subsidence related to the present geodynamics of the Aegean region began in the eastern Peloponnese in the Pliocene (Schröder, 1986).

Compared to other areas of Greece, such as the Gulf of Corinth (Makropoulos and Burton, 1984), the Argive region of the Peloponnese is not very active seismically at present. However, the deep borings in the Argive Plain penetrated more than several hundred meters of Pleistocene deposits indicating considerable subsidence. Raised Tyrrhenian beaches (Kelletat *et al.*, 1976; Schröder and Kelletat, 1976) imply Late Quaternary uplift of the margins of the trough (and/or subsidence of its center). Flemming (1978; Flemming and Webb, 1986), on the other hand, used coastal archaeological sites to place the Argive Plain and nearshore zone inside the 0 m/1000 yr subsidence contour. His estimated Holocene subsidence rate increases southward from 0-1 m/1000 yr in the northern Gulf of Argos to more than 1 m/1000 yr along the Southern Argolid Peninsula at the far southeastern end of the Gulf (Flemming, 1968; 1978).

COASTAL PLAIN STRATIGRAPHY

The Late Quaternary depositional sequence of the Argive Plain has been described in detail by Finke (1988). The central and southern parts of the plain are covered with Holocene floodplain alluvium which is slowly accumulating during occasional floods of the low-discharge streams (Therianos, 1974, Fig. 9), mainly the Inakhos River; a maximum thickness of 8 m occurs near the present coast. Marine de-

posits intercalated within the Holocene sequence extend up to 1.5 km inland from the coast, recording the maximum reach of the postglacial transgression. The subsequent (and continuing) regression is caused by coastal accretion.

The base of the Holocene (Fig. 2) is in sharp contact with Pleistocene floodplain deposits and overbank loams that have accumulated over many thousands of years and are topped with paleosols characteristic of the semiarid Mediterranean (e.g., Barbaroux and Bousquet, 1976; Brunacker, 1974, 1979; Macleod, 1980; Pope and van Anandel, 1984). These mature Middle to Late Pleistocene soils crop out on the fringes of the Argive Plain and cover the alluvial fans. Their colors range from yellowish brown (10YR5/4) to dark brown (10YR4/3) or dark reddish brown (5YR3/4). Pedogenic calcite nodules 2–6 mm in diameter create a gravelly texture (Bk horizon with stage 2 carbonate of Gile *et al.*, 1966).

Marine fossils are found in the boreholes from 20 m downward (Zangger and Malz, 1989), proving that most deeper sediments were originally deposited in a shallow sea (Figs. 2 and 3). These marine sediments have been altered extensively by pedogen-

esis and/or diagenesis and now resemble the soils of the overlying fluvial deposits, except that below 20 m the calcareous nodules increase in diameter to 5 cm or even form calcrete layers (K horizons). The fossil fauna of this marine Pleistocene is very distinctive in appearance. Corals and thick-shelled oysters are common and the shells of gastropods, cockles (*Cerastoderma*), and other bivalves are much bigger and thicker than the Holocene fossil and living fauna, as has been commonly noted for Tyrrhenian and earlier faunas in the Mediterranean (e.g., Butzer, 1975; Kelletat and Gassert, 1975; Kelletat *et al.*, 1976; Keradren, 1970, 1971). The middle Holocene and at least five transgressive marine units can be identified in the deep Greek borings (Fig. 3).

The 30-m-deep bailer holes permit us to recognize soil horizons as well (Fig. 2). Each of the three Pleistocene marine units observed in these borings can be subdivided into as many as four subunits with distinct sedimentary and pedological characteristics, although erosion and advanced soil formation have locally obliterated some of those. The lowest subunit in each has retained its original dark bluish-gray color

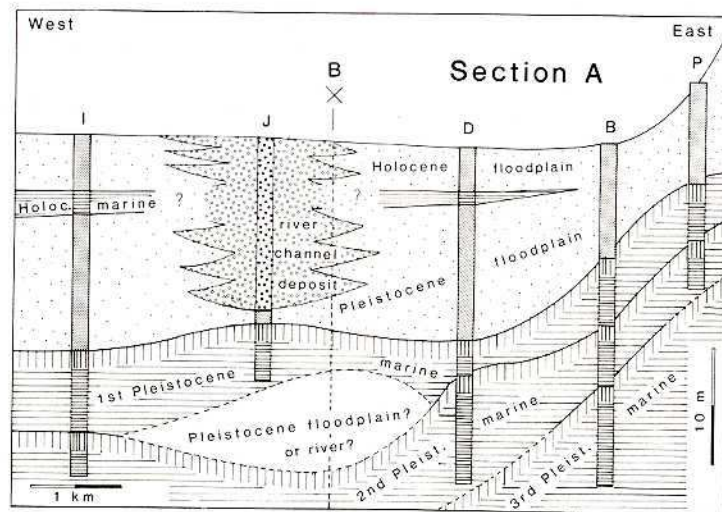


FIG. 2. Coastal section A (Fig. 1) of the late Quaternary, based on bailer borings. Three marine Pleistocene deposits, altered by soil formation can be recognized. Presence of Pleistocene floodplain deposits between first and second marine units inferred from intersection (large cross) with section B.

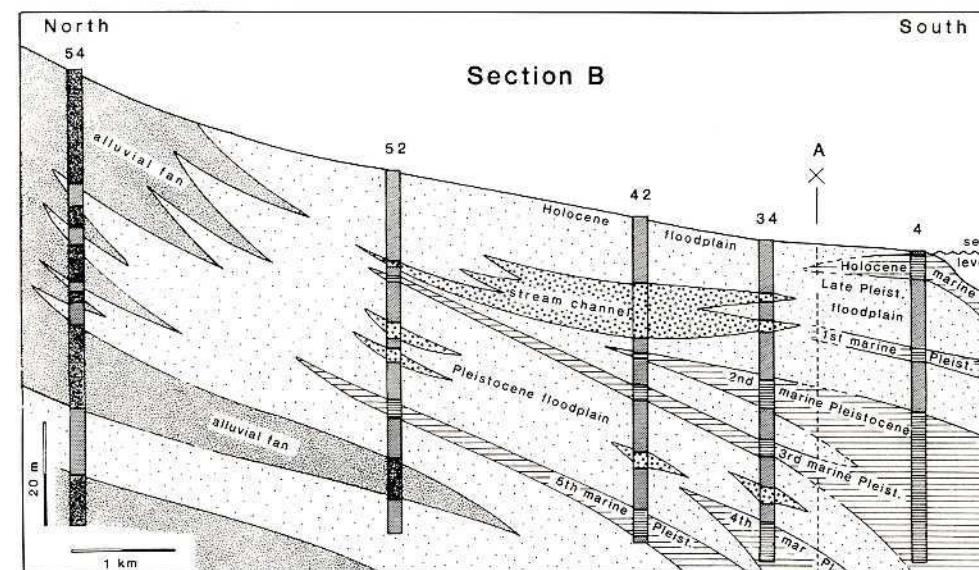


FIG. 3. Axial section B (Fig. 1) of the late Quaternary, based on Greek borings. Below Holocene marine and floodplain deposits five Pleistocene marine units formed at interglacial sea levels can be seen, each overlain by a regressive fluvial member. The stream channel deposits are from the Inachos River.

and still closely resembles a marine mud; large shells are abundant and together with limestone pebbles, imply a transgressing shore. The second subunit is an oxidized, yellowish, well-sorted marine silt with small, unaltered shells. The next-higher subunit represents the consolidated, reddish-brown Bt horizon of a paleosol formed on the marine deposit during long subaerial exposure. Marine fossils are preserved only inside pedogenic calcareous nodules. The uppermost subunit is a hard, diagenetically consolidated calcareous layer (K horizon; stage 5 carbonate of Gile *et al.*, 1966) containing traces of marine organisms only within the calcrete; these nodular layers are well known to Greek geologists and drillers under the name of "pouri."

In section B (Fig. 3), which extends far inland, fluvial units overlie the marine beds and landward replace the marine units altogether. The coastal section A (Fig. 2) has only one such continental intercalation between the Holocene marine bed and the first Pleistocene marine unit, but the crossing with section B indicates that another

fluvial bed between the first and second marine units should occur between holes D and J or below the latter.

These episodes of alternating marine and fluvial deposition accompanied by soil formation are analogous to the Pleistocene littoral sedimentary cycles described by Butzer (1975) for the western Mediterranean. They may reflect variations in the rate of subsidence, but must be related mainly to the much greater range of Pleistocene eustatic sea-level changes, measured in many meters/1000 yr (e.g., Fairbanks, 1989).

SHELF STRATIGRAPHY

The seafloor of the northern Gulf of Argos slopes gently to a depth of about 40 m, then gradually steepens to a shelf break at about 100 m (Figs. 1 and 4). The seafloor is marked by broad, low ridges and small, channel-like depressions that are surface expressions of a now-buried landscape of streams, lagoons, inlets, and bars like those of the postglacial transgressive deposits of the shelf of Southern Argolid (van Anandel

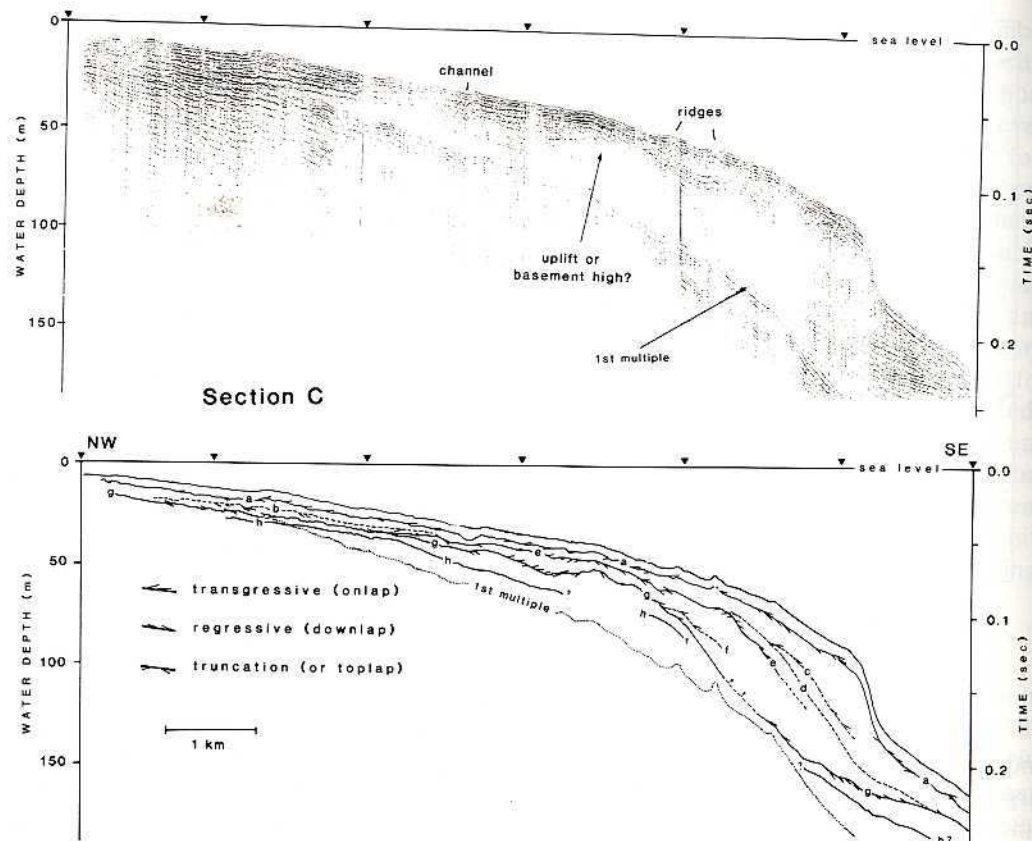


FIG. 4. Top: Seismic reflection section C (Fig. 1). Depth within sediments in seconds of two-way travel time. Vertical exaggeration 31 \times . Black triangles mark position fixes. Bottom: Tracing of main features of this section. Lines labeled a-h are the boundary reflectors of transgressive and regressive sequences. Symbols indicate types of bed contacts (terminology after Mitchum *et al.*, 1977). Interpretation at greater depth limited by first multiple echo.

and Lianos, 1984). In the inner Gulf, the recordings (e.g., Fig. 4, top left) show the chaotic reflections known to be characteristic of the paralic (coastal and very shallow marine) realm (e.g., Curry and Moore, 1964; Vail *et al.*, 1977).

Except for areas where basement highs pierce the seafloor, thinly stratified sediments are ubiquitous on the shelf and in the deeper basin. Many individual reflectors can often be traced over considerable distances (Fig. 4); a few are quite prominent because of their larger-than-average acoustic impedance and their locally rough, seemingly eroded surface. On close examination (Fig. 5), onlap and downlap, as well as toplap and erosional truncation of minor

reflectors as defined by Mitchum *et al.* (1977) can be seen in many places. Using these features, we have been able to identify some major reflectors, labeled a through h (Fig. 4), which represent useful stratigraphic boundaries. Some of them, e.g., a and g, can be traced from the near-shore zone to the upper slope and even beyond, whereas others have a more limited extent and terminate either by landward onlap or seaward downlap. Below we refer to the reflectors themselves with letters (a, b, etc.), and to the depositional sequences in the sense of Mitchum *et al.* (1977) and van Aniel and Calvert (1971), defined by them as (seafloor/a), (b/g + e/g), (g/h) and so forth.

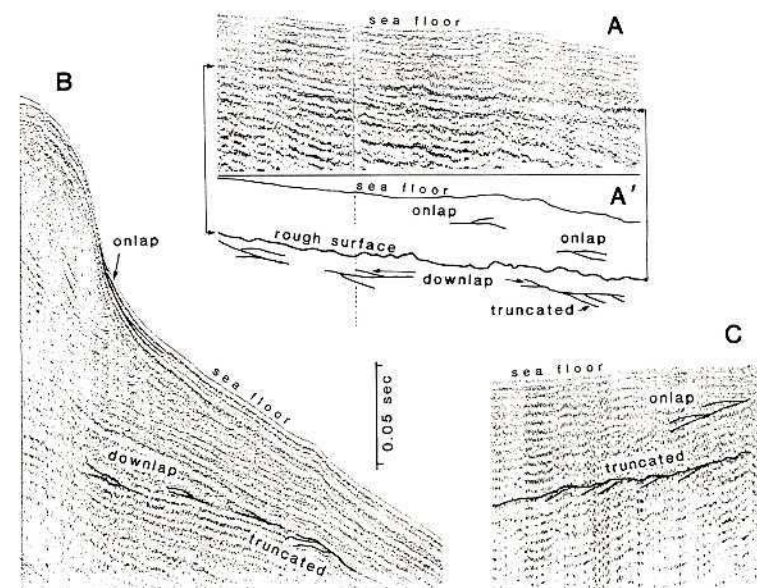


FIG. 5. Seismic reflection records illustrating types of reflecting surfaces and bed contacts; terminology from Mitchum *et al.* (1977). Depth scale in seconds two-way travel time, vertical exaggeration ca. 30 \times .

Of the seven depositional units defined in section C (Fig. 4) by their major boundaries, only one (b/g + e/g), contained between reflectors b and g + e, ends by downlap onto surface e and is thus entirely regressive. All others begin with a transgressive (onlapping) set of strata, although their upper parts are usually regressive and in many places marked by erosional features. Three of those (seafloor/a, a/g, and g/h), extend from the continental slope into the present nearshore zone. The presence of chaotic (paralic) reflections at their shoreward ends indicates that they were deposited at high sea levels, although they have subsided well below present sea level since then. The other transgressive units, such as c/d, d/e, and e/g + f/g, end on the middle or outer shelf implying less-extensive transgressions.

The major depositional sequences bound by reflectors a, e, g, and h can be identified on most survey lines by correlation at track crossings. The other labeled reflectors recognizable in section C (Fig. 4) occur mainly on the outer shelf, are less prominent, and

hence cannot be identified as consistently in other sections.

Onlap onto the continental slope, erosion, and downlap on the less-steep basin floor are evident (Fig. 4, top right; Fig. 5, left). Some disturbed, chaotic bedding there suggests mass downslope movement. Major episodic outbuilding of the slope onto the rise, alternating with times of little deposition or even erosion, is demonstrated by reflectors c, d, and f (Fig. 4).

Our type section C shows little evidence of deformation, although a small basement high (Fig. 4, top) disturbs some sequences, but this may be due to draping and/or onlap rather than to uplift or subsidence. Elsewhere in the northern Gulf, however, ample evidence exists for neotectonic activity (Fig. 6). Normal faults are common, their presence often betrayed by small steps in the seafloor that indicate continuing movement. Basement highs border several subsiding troughs, revealing an unexpectedly complex Late Neogene structure of the Gulf of Argos graben. The rate of subsidence appears to vary considerably from

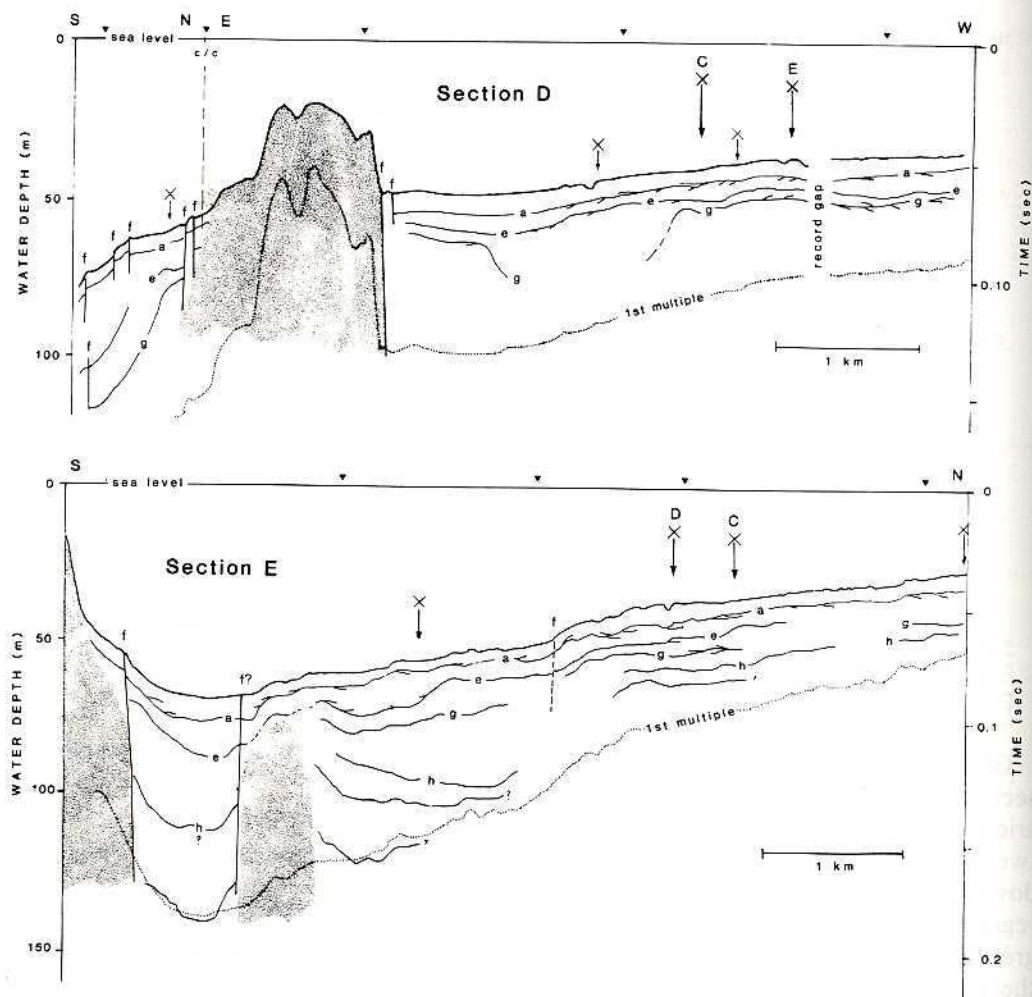


FIG. 6. Top: Section D; bottom: section E (Fig. 1). Left: water depth in meters. Right: sediment depth in seconds of two-way travel time. Vertical exaggeration 22 \times . Black triangles mark position fixes. Large crosses mark intersections with other seismic reflection profiles. Basement high shaded; "f" labels faults. Selected bedding contacts are shown.

basin to basin, as noted on land by Finke (1988). It varies temporally as well: the deep basin defined by reflector g in section D (Fig. 6) and the trough in h in section E north of the smaller of the two basement highs (Fig. 6), are no longer active. The basin between the two basement highs in that same section E, on the other hand, is sinking rapidly.

A MODEL OF QUATERNARY MEDITERRANEAN SHELF STRATIGRAPHY

What are the major reflectors that define

the depositional sequences of the Gulf of Argos? In the Southern Argolid, the post-glacial transgressive surface separating Holocene from Pleistocene shelf deposits can be traced to a late Pleistocene soil surface on land (van Anandel and Lianos, 1984). In the Gulf of Kavalla (northern Aegean), a core penetrating the Pleistocene-Holocene unconformity contained a calcareous Bk soil horizon on marine clay similar to soils found in our Argive Plain borings (Perissoratis and van Anandel, 1988).

These observations suggest that the reflectors defining the main depositional se-

quences in the northern Gulf of Argos may represent former land surfaces on which transgressive, or more rarely (given the low sediment supply), regressive deposition took place during the many sea-level changes of the Quaternary. At low glacial sea levels, subaerial exposure extended the hard, clay-rich B and calcareous Bk to K horizons of the eastern Mediterranean soils (Barbaroux and Bousquet, 1976; Brunacker, 1979; Dudal *et al.*, 1966) onto the shelf where they greatly enhanced the acoustic impedance of the surface. Furthermore, the calcareous Bk and K horizons are very resistant to erosion. Such soils require several thousand years to form (Birkeland, 1984, pp. 194-224; Harden, 1982), but time was available because exposure of the shelf during glacial intervals ranged from thousands of years near the shelf edge to tens of thousands on the present plain.

Our own bailer borings show that such soils did indeed form on the transgressive marine deposits (Fig. 2) as a result of subaerial exposure during low glacial sea lev-

els. Now these sequences have subsided below the levels at which they were formed, but because they extend varying distances inland from the present shore they must have originated during transgressions to levels close to or somewhat above the present one.

How does the marine stratigraphy based on seismic reflection data compare with that of the late Quaternary on land? The best marine section for comparison would have been axial section F (Fig. 1) because it directly extends section B seaward, but due to bad weather it is of poor quality. Consequently, the diagram of the plain-shelf stratigraphy of Fig. 7 is based on correlation of section C with bailer borehole I from section A (Fig. 2), supplemented with an inferred reconstruction for the inner plain and bordering fans based loosely on section B. For this diagram, the marine data were converted to a depth scale in meters using a sediment velocity of 1.6 km/sec. If one assumes that regressive sequence b/a is the correlate of the Late Pleistocene floodplain

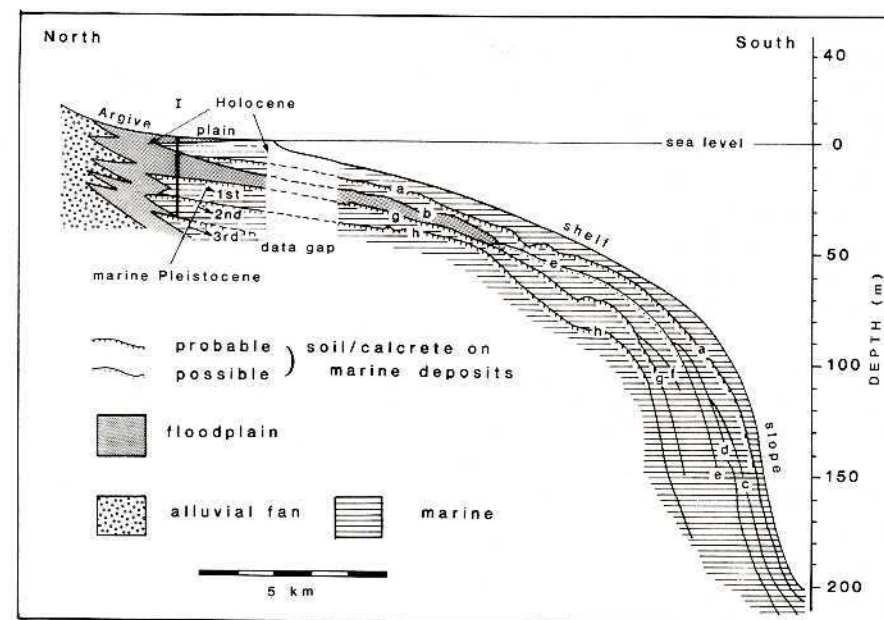


FIG. 7. Diagrammatic representation of the Middle and Late Quaternary depositional cycles of the Argive Plain and shelf. Based on correlating section C (Fig. 4), corrected to show depths of principal reflectors in meters, with bailer hole I at the western end of section A (Fig. 2). Diagram ends on alluvial fan near Argos. Note that the youngest marine transgressive unit at sea (a/b + a/e) must pinch out seaward of borehole I.

unit on land, reasonable depth correspondences are obtained between marine reflectors g and h and the first and second Pleistocene marine units of section A. If, on the other hand, one were to correlate a/b with the first Pleistocene marine unit on land, ca. 15 m subsidence of borehole I relative to the adjacent marine area would be implied; neither the marine data nor the borings on land support this. Therefore, we accept as plausible that the first Pleistocene marine unit on land actually is not the marine transgression of the last interglaciation. The third through fifth cycles encountered on land (Fig. 3) may exist at sea as well, but the strong first multiple prevents us from identifying them in the reflection records.

Figure 7 is clearly hypothetical but it is the best that can be done until sufficiently long cores are obtained at sea to date the reflectors and compare them to soil horizons on land. Until then, we can only speculate where the correlations of the diagram in Fig. 7 might lead us.

Assuming then that the strong regional reflectors a, g, e, and h correspond to soils capping marine sequences correlated with those found in boreholes on land, the marine sequences themselves must have formed at high, and hence interglacial, sea levels. The soils, on the other hand, were superimposed during exposure at the low sea levels of glacial maxima and so should extend to depths of 100 m or more. Although on the steep upper slope the record is not as clear as on the shelf, the distinct acoustic character of a, g, and h indeed extends to at least that depth. The other, less-extensive regressive and transgressive sequences should record stadial and interstadial events.

Subsidence has increased the depths of all shelf reflectors, but we can correct for this approximately by assuming that the landward terminations of the interglacial sequences formed at sea levels near the present one. Adjusting also for a sound velocity in the sediments of 1.6 km/sec, we can obtain lowest sea-level stands from the

maximum depths of high acoustic impedance, sea levels intermediate between glacial maxima and interglaciations from landward terminations of onlapping units and seaward terminations of regressive ones, and interglacial levels from the innermost terminations of major marine units (Table 1). What we lack is a time scale for these local Pleistocene sea-level events.

How does the information in Table 1 compare with our present knowledge of Middle and Late Pleistocene sea-level history? The best estimate of global sea levels during the last 250,000 years (Fig. 8, top) comes from Chappell and Shackleton (1986); Pleistocene sea levels deduced by Keraudren and Sorel (1987) from uplifted terraces near Corinth correspond reasonably with it. While fully aware of the speculative nature of the correlation, we point to reasonable parallels between our sea-level history (Fig. 8, bottom) and the Chappell and Shackleton curve. The soil responsible for reflector a would have formed during the low sea level of the last glacial maximum, while reflectors e and g would date to low stands about 135,000 and 180,000 yr B.P. Reflector h predates the Chappell and Shackleton curve unless it belongs to a minor low stand at 220,000 yr B.P. The landward terminations of the marine deposits capped by a, g, and h correspond to interglaciations at 120,000, 200,000, and 235,000 yr B.P. It is also possible that h is older and corresponds to an

TABLE 1. DEPTHS BELOW PRESENT SEA LEVEL OF TERMINATIONS OF LATE AND MIDDLE PLEISTOCENE TRANSGRESSIVE AND REGRESSIVE SEQUENCES OF THE ARGIVE PLAIN AND GULF OF ARGOS CORRECTED FOR SUBSIDENCE

Correction ^a for (reflector)	Lowest soil	Termination	
		Seaward	Landward
-10 m (a)	> -100 m		
-19 m (g)	> -65 m	b: -16 m	c: -44 m; d: -50 m
-27 m (h)	> -75 m		e: -17 m; f: -44 m

^a When subtracted from current depths of terminations, this factor yields depths corrected for subsidence shown in the two right-hand columns.

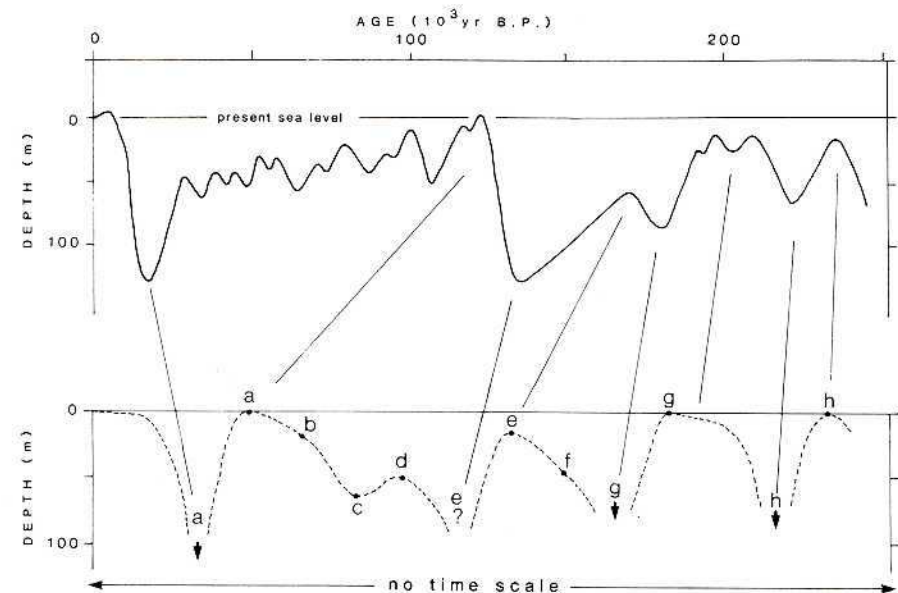


FIG. 8. Sea-level changes and shelf sedimentation. Top: Middle and Late Quaternary eustatic sea-level changes (Chappell and Shackleton, 1986). Bottom: depths below sea level at time of deposition of the seaward and landward terminations of main reflectors of Fig. 4 (no time scale). Small arrows indicate lowest observed positions of soils formed on reflectors during maximum low stands of the sea.

uplifted terrace in the Gulf of Corinth with a suggested age of about 300,000 yr B.P. (Keraudren and Sorel, 1987).

These approximate ages permit us to estimate approximate long-term rates of subsidence. Numerous measurements on all available profiles show that for the more stable areas the spacing between the principal sequence boundaries a, g, and h is about 8–9 m on the inner shelf and 10–12 m on the middle shelf. In the more rapidly subsiding basins of sections D and E (Fig. 6), the spacing is two to four times as large. The interval between the glacial maxima represented by a and g is about 110,000 years; that between g and h is either 40,000 or somewhat more than 100,000 years. This yields a regional minimum subsidence rate of ca. 10 cm/1000 yr, increasing to 20–40 cm/1000 yr in rapidly subsiding shelf basins.

Finke (1988) has shown that the Holocene subsidence rate varied locally in the coastal Argive Plain. Along the eastern mountain front near Nauplion the plain

seems to have been stable, but the center has subsided at an average rate of 10–15 cm/1000 yr and the western margin south of Argos at 50 cm/1000 yr. The Holocene rates are thus of the same order of magnitude as the long-term rates estimated above. Schröder and Kelletat (1976) cite 25 cm/1000 yr as a long-term subsidence rate, in reasonable accord with our numbers.

Shelf depositional sequences similar to those described above have been reported from elsewhere in the northeastern Mediterranean as well (Colantoni and Gallignani, 1978; Aksu *et al.*, 1987; Perissoratis and Mitropoulos, 1989; Lykousis and Chronis, 1989; Aksu and Piper, 1984). Some of those have been seen as Holocene deltaic sequences rather than as products of marine transgressions and regressions, but deserve reexamination in terms of the model presented here.

In conclusion, if our correlations should be confirmed by future core data, mature soil surfaces might be recognized in the Quaternary prism of other Mediterranean

continental margins as reflectors of high acoustic impedance. In that case, a useful tool would be available for the correlation of sea-level changes deduced from the ocean record with Quaternary surfaces on land.

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