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FLEXURE OF THE LITHOSPHERE AND CONTINENTAL MARGIN BASINS *

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ABSTRACT

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The accumulation of sediments at an Atlantic-type continental margin constitutes a load on the lithosphere which simply sags due to its weight. Studies of the geometry of deformation suggests the lithosphere will respond to these loads either by local loading of an Airy-type crust or flexural loading of a strong rigid crust. Sediment loading models of either type cannot, however, explain the substantial thicknesses of shallow-water sediments observed in commercial boreholes from Atlantic-type margins. Other factors such as thermal contraction, gravitational outflow of crustal material or deep crustal metamorphism may contribute to the subsidence. We have used biostratigraphic data from commercial boreholes from the Gulf of Lion and the East Coast, U.S.A. to quantitatively determine the contribution of sediment loading to the subsidence. From these data we determined sea-floor and basement depths for sequential time intervals during margin development. Using the sediment loading models the sediment layers at each margin were progressively "backstripped" and the depth basement would have been without the sediment load calculated. The computed basement depths indicate there is a recognizable component of the subsidence of these margins which is caused by processes other than adjustments to the weight of the sediment. The nature of this subsidence is discussed and comparisons are made with that which would be expected from thermal-contraction models.

INTRODUCTION

Atlantic-type continental margins are dominated during their evolution by uplift and subsidence tectonics. The subsidence history of a margin is recorded in the sediments which accumulate soon after rifting and plate separation. Biostratigraphic data from commercial boreholes indicate continental

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shelves are comprised of substantial thicknesses of shallow-water sediments. This indicates that there has been a significant subsidence at Atlantic-type margins (for example, Sleep, 1971; Keen and Keen, 1973: Rona, 1974).

Several factors may contribute to the subsidence of Atlantic-type margins:

(1) The loading of sediments in continental slope and rise regions which contribute to shelf subsidence due to the strength of the crust (Gunn, 1944; Dietz, 1963; Walcott, 1972; Cochran, 1973).

(2) Thermal cooling of the continental lithosphere following uplift, subaerial erosion and crustal thinning at the time of rifting (Sleep, 1971).

(3) Gravitational spreading of deep crustal layers caused by stress-differences in a newly formed margin (Bott, 1971).

(4) Deep crustal metamorphism following uplift and thermal cooling of the continental lithosphere (Falvey, 1974).

Although it is not certain which of these factors contribute to the subsidence of margins, all hypotheses are in agreement that sediment loading contributes to some part of the subsidence. Gunn (1944), Walcott (1972) and Cochran (1973) have quantitatively shown that substantial thicknesses of shallow- and deep-water sediments may accumulate simply as a result of sediment loading. They used a simple mechanical model in which the strong rigid lithosphere is modelled as a linearly elastic beam overlying a weak fluid substratum. Similar mechanical models have been used to explain the geometry and time response of flexure caused by long-duration ($> 10^6$ years) surface loads in the interiors of plates (for example, Walcott, 1970; Watts and Cochran, 1974).

Flexural models may explain the shape and sediment thicknesses as well as seismic refraction and free-air gravity-anomaly data of wide Atlantic-type margins such as deltas (Walcott, 1972; Cochran, 1973), but they do not explain the characteristics of all margins. There are three main problems with the flexural models:

(1) Atlantic-type margins are generally characterized by narrower shelf widths than produced in the flexural models.

(2) The proportion of shallow- to deep-water sediments in the flexural models is small (about 1 : 5) and does not explain the predominence of shallow-water sediments found in deep boreholes of the coastal plain and shelf regions of the Atlantic.

(3) The rate of basement subsidence is dependent on the sedimentation rate in the flexural models and does not explain subsidence which occurs independently of sediment supply (for example, Blake Plateau during the Tertiary).

The purpose of this paper is to use biostratigraphic data from commercial boreholes from the Gulf of Lion and the East Coast, U.S.A. to quantitatively evaluate the contribution of sediment loading to the subsidence of these margins. These data are used to determine sea-floor and basement depths for sequential time intervals during margin evolution. We will outline a method by which sediment layers at each margin are progressively "backstripped" and the depth at which basement would be without the sediment load is calculated. The computed basement depths indicate that part of the subsidence of these margins which is caused by processes other than adjustments to the weight of the sediment load.

SEDIMENT LOADING AT A CONTINENTAL MARGIN

The accumulation of sediments by the displacement of sea-water constitutes a load on a continental margin which should simply sag due to its weight. The total thickness of sediments which can accumulate depends on the available depth of water and the loading capacity of the underlying basement rocks.

Stratigraphic cross-sections based on commercial seismic reflection and borehole data (for example, off Brazil and south of Australia) provide constraints on the manner the lithosphere responds to sediment loads at Atlantic-type margins. The structure of these margins (Ponte and Asmus, in preparation; Boeuf and Doust, 1975; Falvey, 1974; Deighton et al., 1976) generally comprises a lower sequence of strongly faulted continental sediments overlain unconformably by an upper sequence of gently dipping marine sediments. We interpret this contrast in structural styles as indicating the lithosphere responds to sediment loads at a margin either by: (a) local loading of a faulted Airy-type crust; or (b) flexural loading of a strong rigid crust.

In the classical scheme of Airy isostasy (Heiskanen and Vening Meinesz, 1958), changes in surface or sea-floor elevation are compensated locally by changes in crustal thickness. If a surface load is applied to an Airy-type crust, the crust behaves as would a vertical-sided prism (shear stresses cannot be transmitted to adjacent prisms) which achieves equilibrium by the displacement of the weak fluid substratum. The maximum sediment thickness A which can accumulate on an Airy-type crust is given by (for example, Jeffreys, 1962, p. 336):

$$A = h \cdot \frac{(\rho_m - \rho_w)}{(\rho_m - \rho_s)} \qquad (1)$$

where h is the depth of water available for sedimentation and ρ_s, ρ_w and ρ_m are the average densities of the sediment, water and mantle, respectively. The depression of the basement y caused by the sediment load is:

$$y = A - h$$

which in eq. 1 gives:

$$y = h \cdot \frac{(\rho_s - \rho_w)}{(\rho_m - \rho_s)} \qquad (2)$$

In the scheme of flexural loading (for example, Heiskanen and Vening

TABLE I

Summary of parameters used in sediment loading studies

Density of sediments $\rho_s = 2.4\ \mathrm{g/cm^3}$
Density of sea-water $\rho_w = 1.03\ \mathrm{g/cm^3}$
Density of mantle $\rho_m = 3.4\ \mathrm{g/cm^3}$
Young's modulus $E = 10^{12}\ \mathrm{dyn/cm^2}$
Flexural rigidity $D = 1 \cdot 10^{30}\ \mathrm{dyn\ cm}$
Average gravity $g = 981\ \mathrm{cm/s^2}$

Meinesz, 1958) compensation for a surface load is achieved by downbending of a strong rigid basement. The flexure of a linearly elastic beam or thin-plate y due to a two-dimensional rectangular load of half-width a and height h is given by (Hetényi, 1946):

$$y = h \cdot \frac{(\rho_s - \rho_w)}{(\rho_m - \rho_s)} \cdot (1 - \exp[\lambda a] \cos \lambda a) \tag{3}$$

where:

$$\lambda = \sqrt[4]{\frac{(\rho_m - \rho_w) \cdot g}{4D}} \tag{4}$$

As the beam or thin-plate becomes more rigid $D \to \infty$, $\lambda \to 0$ and in eq. 3 $y \to 0$. Therefore, as the plate increases in rigidity, the depression caused by a surface load becomes small. As the beam becomes weaker $D \to 0$, $\lambda \to \infty$ and eq. 3 $y \to h\ (\rho_s - \rho_w)\ /\ (\rho_m - \rho_s)$. This leads to the case of sediment loading of an Airy-type crust in eq. 2 so that the physical properties of the Airy crust approach those of a very weak beam overlying a weak fluid substratum.

The problem at a continental margin is that sediment loading of either local or flexural type cannot explain the sediment thicknesses or lithologies of Atlantic-type margins. Biostratigraphic analyses of borehole data suggest that a substantial part of the stratigraphic section offshore the East Coast, U.S.A. and Canada were deposited in neritic environments associated with water depths less than about 150 m (Jansa and Wade, 1975). Using the local loading model and the parameters listed in Table I only about 350 m of shallow-water sediments could accumulate in these water depths before all available water was displaced. Using the flexural-loading model more sediments can accumulate since margins can always prograde seaward. Not only does shelf sedimentation contribute to shelf subsidence but also slope and rise sedimentation, because of the strength of the lithosphere. However, flexural loading does not explain the widths of present-day shelves or subsidence rates which decrease exponentially with time.

25 M.Y. GULF OF LION MARGIN

The sediment "backstripping" method has been used to examine the contribution of sediment loading to the subsidence of a young Atlantic-type margin in the western Mediterranean. We used biostratigraphic data obtained from three commercial boreholes in the Gulf of Lion (Cravatte et al., 1974; Ryan, in press: Fig. 1A,B) in which a Miocene through Recent sequence consisting mostly of shales and sandstones unconformably overlies a Paleozoic basement. The crust of the Balearic basin, seaward of the Gulf of Lion, is oceanic in type and probably formed by the rotation of Corsica and Sardinia from southern France during the Late Oligocene/Early Miocene (Alvarez et al., 1974).

Local loading

We first assumed that the sediments in the Gulf of Lion boreholes were deposited on an Airy-type crust and progressively "backstripped" them for 2.5 m.y. time intervals between 25 m.y. B.P..and the present. The computed depth at which Paleozoic basement Z would have been through time if there was no sediment cover and neglecting sea-level changes is given by:

$$Z = W_d + \frac{(\rho_m - \rho_s)}{(\rho_m - \rho_w)} \cdot S \qquad (5)$$

where W_d = water depth of sedimentation, S = total sediment thickness and ρ_m, ρ_s and ρ_w have been previously defined.

Uncertainties in computed basement depths arise from imprecise knowledge of sediment thickness and water depths through time. The main problems in sediment thickness estimates are incorrect age assignments to stratigraphic horizons and compaction effects. Even though most time scales are tied to only the most reliable radiochronological ages, they are still based on a subjective interpolation between stratigraphic horizons dated in cores and outcrops. Biostratigraphic horizons in the Gulf of Lion boreholes were assigned absolute ages following a recent study by Ryan et al. (1974) which attempted a correlation of biostratigraphic horizons with the geomagnetic time scale based on marine magnetic anomalies. This correlation differs from previous studies in that it incorporates evidence from paleomagnetic stratigraphy. Compaction effects are difficult to estimate and depend on the lithology of the sediments as well as their initial porosity. Compaction corrections were applied to the Miocene and Early Pliocene sequences in the Gulf of Lion boreholes using the compaction curves of Hamilton (1959) for sandstones and shales. Corrections were not applied to the lowermost Miocene since it is assumed the pre-Miocene basement was fully compact prior to the initial Early Miocene transgression. The main problem in water-depth estimates arise from uncertainties in the relationship between faunal and lithofacies assemblages and environments. This is particularly true for the bathyl environments (water depths > 150 m: fig. 5, Massiotta et al., in preparation). Water depths in the Gulf of Lion boreholes were estimated by a combination

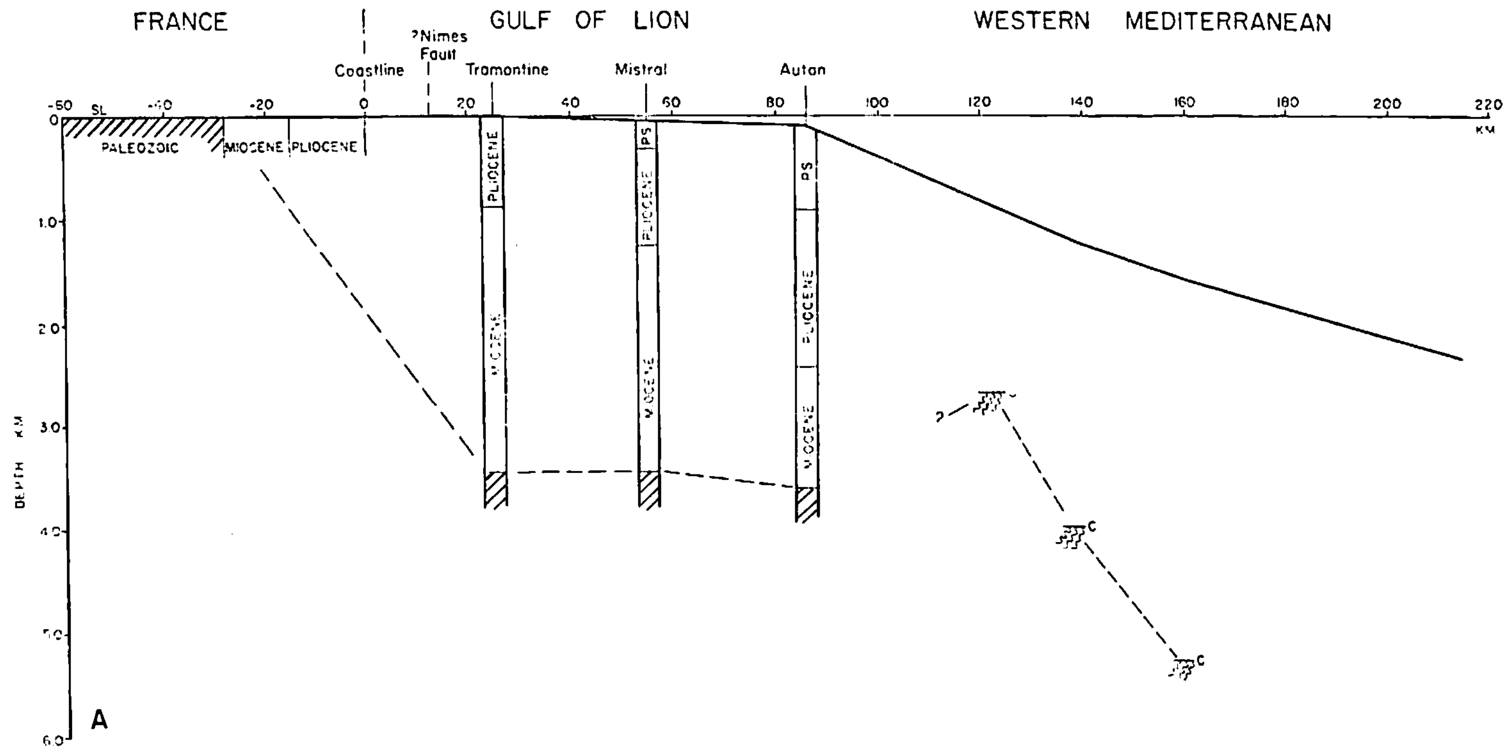

Fig. 1A. Schematic cross-section of the Gulf of Lion with projected boreholes from Cravatte et al. (1974). The Paleozoic basement is indicated by cross-hatching and the acoustic basement beneath the continental slope by wiggly lines as identified on an adjacent seismic reflection profile (Ryan, in press).

TABLE II

Water depths and total sediment accumulation through time for Gulf of Lion boreholes

Age (m.y. B.P.)	Water Depth (m)	Apparent sediment thickness (m)	Apparent basement depth (m)	Corrected basement depth (m)
Tramontine				
22.5	390	150	540	647
20	440	870	1310	1472
17.5	180	1490	1370	1932
15	30	2370	2400	2809
12.5	20	2708	2728	2851
10	20	2950	2970	3047
7.5	10	3100	3110	3142
5	550	2550	3100	3100
2.5	280	3100	3380	3640
0	40	3410	3450	3450
Mistral				
22.5	510	120	630	662
20	700	400	1100	1123
17.5	570	950	1520	1744
15	280	1650	1930	2237
12.5	90	2320	2410	2706
10	60	2900	2960	3200
7.5	40	3200	3240	3341
5	850	2200	3050	3200
2.5	400	2950	3350	3685
0	80	3375	3455	3455
Autan				
22.5	580	40	620	635
20	840	100	940	961
17.5	910	280	1190	1243
15	740	625	1365	1487
12.5	550	1050	1600	1760
10	340	1650	1990	2241
7.5	180	2500	2680	2680
5	1400	1200	2600	2600
2.5	740	2400	3140	3358
0	100	3509	3609	3609

are similar for the first 15 m.y. but diverge markedly after the salinity crisis between 7 and 5 m.y. ago (Hsü et al., 1973).

The computed basement depths in fig. 3 indicate there is a recognizable component of subsidence of the Gulf of Lion margin which is not caused by adjustment of the basement to sediment loading. This component is impor-

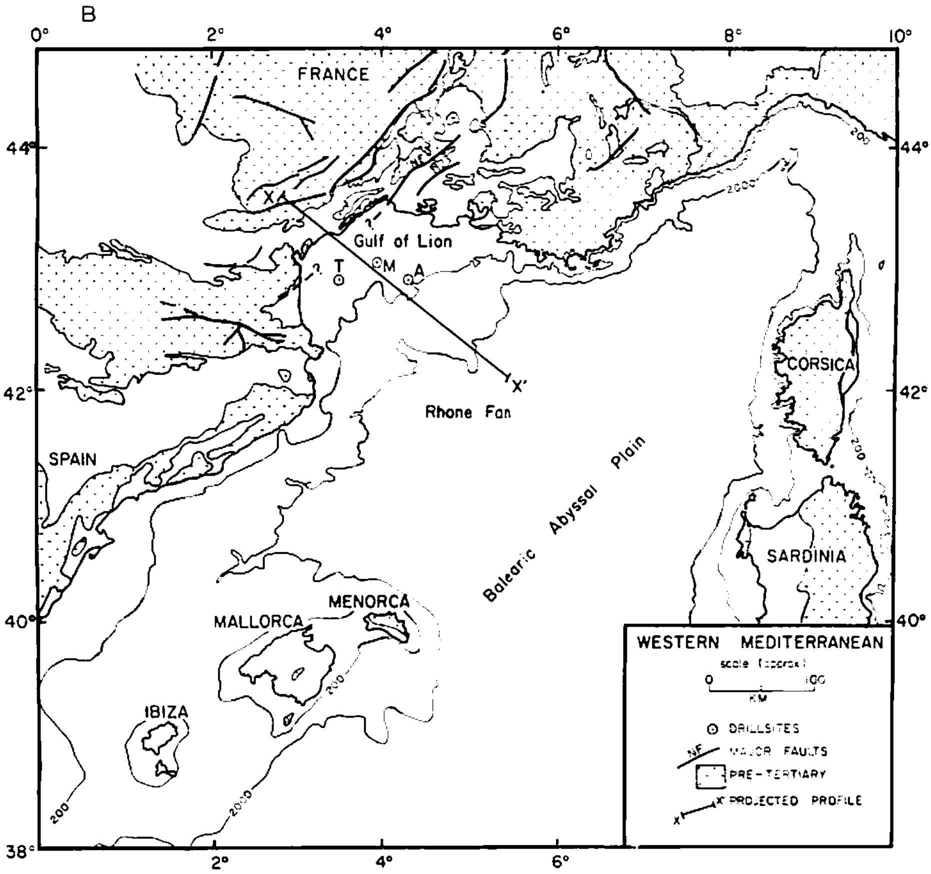

Fig. 1B. Location of the Authan (*A*), Mistral (*M*) and Tramontine (*T*) boreholes in the Gulf of Lion (Cravatte et al., 1974). Major faults are from maps published by the Institut Français de Pétrole. The Nimes Fault (*NF*) has been tentatively extended across the Gulf of Lion following Debelmas and DeMarcq (1974).

of faunal and lithofacies assemblage analyses similar to that carried out by Massiotta et al. (in preparation) in the eastern Mediterranean. Sediment thickness and water depths derived from the biostratigraphic data of Cravatte et al. (1974) and used in this study are tabulated in Table II.

In Fig. 3 computed basement depths through time (Fig. 2) are plotted for each borehole in the Gulf of Lion. Computed basement depths follow closely similar curves for each borehole. The curves show an exponential-like decrease from sea-level at 25 m.y. ago to about 1.5 km at the present. Changes in computed depths are initially rapid (about 20 cm/1000 year) decreasing with time (to about 3 cm/1000 year). The curves for each borehole

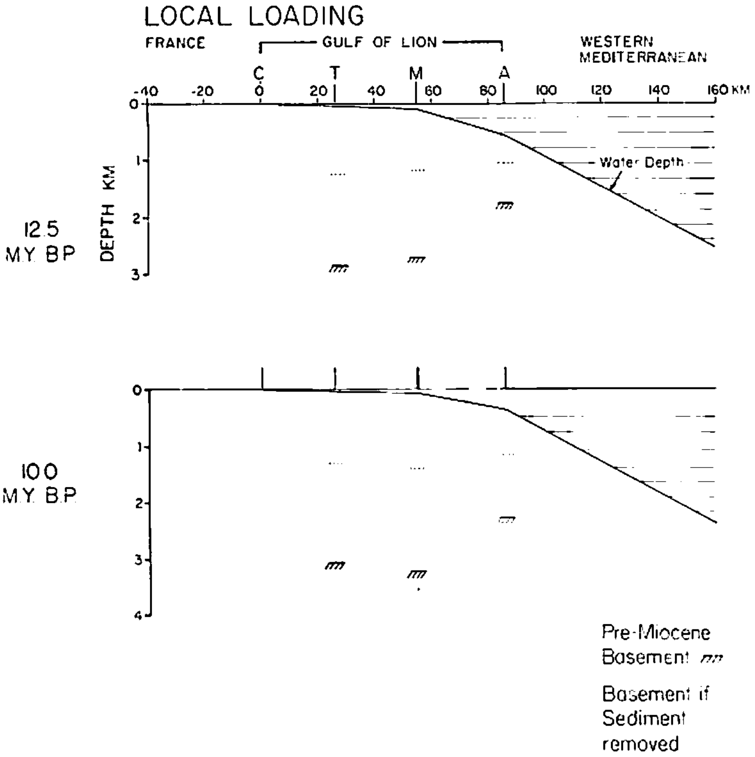

Fig. 2. Simple models for the local unloading of sediments at the Gulf of Lion for 10 and 12.5 m.y. B.P. The slanted shading indicates observed depths of pre-Miocene basement and dotted lines indicate computed apparent depth basement would be if the sediment is removed. The computed depths are based on data in Table I and are derived from eq. 5.

tant since it contributes to nearly half of the total subsidence of the margin (compare Figs. 1 and 3).

Figure 3 also shows the empirical curve for a mid-oceanic ridge (Hays and Pitman, 1973) assuming rifting began 25 m.y. ago, in agreement with the Late Oligocene/Early Miocene age of opening of the Balearic basin (Alvarez et al., 1974). There is good general agreement between computed basement depths for the Gulf of Lion boreholes and the oceanic-ridge curve (Fig. 3). The main difference is that the computed basement depths indicate that the margin initially subsided much faster than adjacent ocean crust.

The computed basement depths in Fig. 3 are referred to present-day sea-level, so sea-level changes since 25 m.y. ago would be reflected by small changes in these depths. If sea-level was higher in the past than at present computed basement depths in Fig. 3 would be too deep. Thus part of the initially rapid change in computed depths could be caused by sea-level changes. However, recent studies (Pitman, in preparation) suggest that since

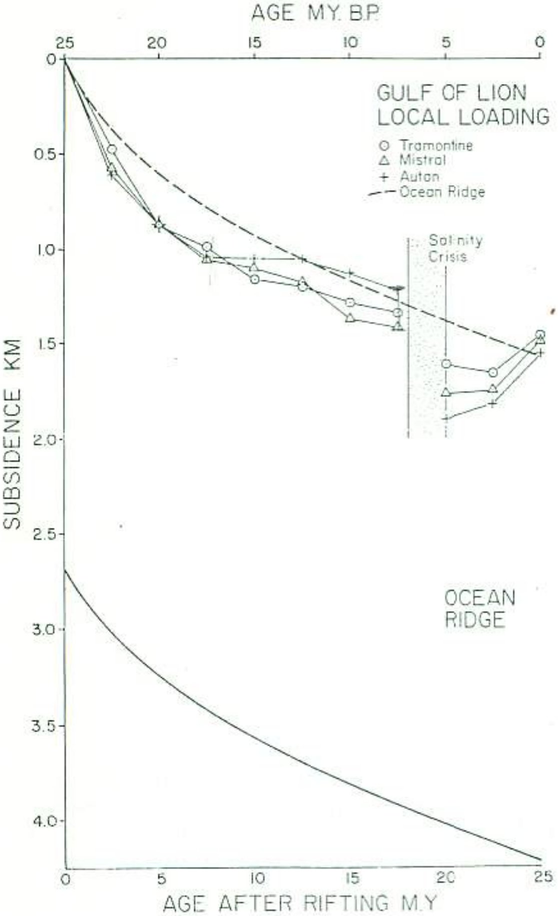

Fig. 3. Plot of computed basement depths through time assuming sediments in the Gulf of Lion boreholes loaded an Airy-type crust. Also shown is the empirical curve for the subsidence of an oceanic ridge (Hays and Pitman, 1973).

25 m.y. ago sea-level has fallen only about 75 meters from causes other than those associated with the building of ice caps. Although it is not known whether sea-level has fallen gradually or suddenly sea-level changes would not have affected computed depths by as much as the 300 meters observed difference between computed depths and the ocean ridge curve.

Flexural loading

We next assumed the sediments in the Gulf of Lion were deposited on a strong rigid basement and progressively "backstripped" them between 25 m.y. ago and the present. In flexural loading, the depth at which basement would be if there was no sediment cover depends not only on the sediment thickness at each borehole but also on the thickness in adjacent regions. Since only three boreholes were available on the shelf we assumed that through time the sediment load extended as far landward as the present coastline and as far seaward as the base of the present continental rise.

Computed basement depths were determined through time by a "trial and error" method in which the flexure of the basement is calculated for different assumed configurations of the sediment load. The sediment load which best explains observed or inferred basement depths is then determined (Fig. 4). In the computations the effective flexural rigidity is assumed to be $1 \cdot 10^{30}$ dyn cm (Table I) which is within a factor of 5 of previously determined values for the continental lithosphere (Walcott, 1970).

In Fig. 5 computed basement depths through time are plotted for each borehole in the Gulf of Lion and compared to the empirical curve for a mid-oceanic ridge. In contrast to local loading (Fig. 3) computed depths differ markedly for each borehole. Changes in computed depths are more rapid for the Tramontine and Mistral boreholes than for the Autan borehole. The curves for the Autan borehole appear to follow the empirical ridge curve but

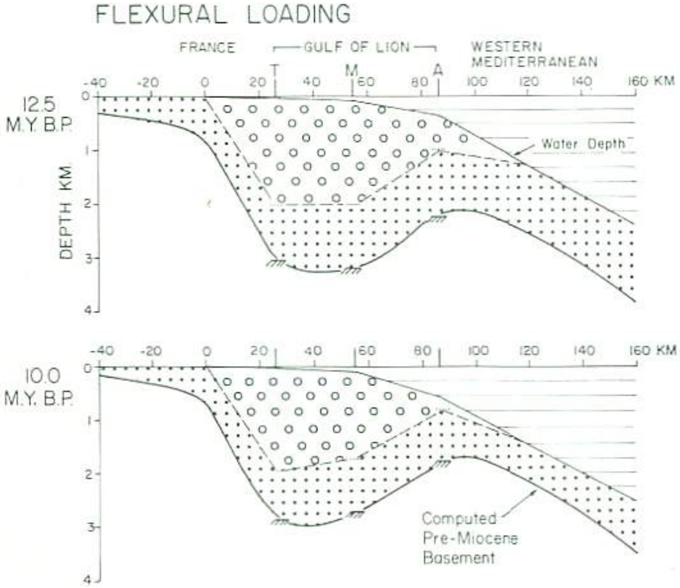

Fig. 4. Simple models for the flexural unloading of sediments at the Gulf of Lion for 10 and 12.5 m.y. B.P. The dashed line indicates the depth the Pre-Miocene basement would be if the sediment cover (coarse and fine stippling) were removed. The sediments above the dashed line (coarse stippling) defines the load used to compute the flexure of the basement (solid line). The sediments below the dashed line (fine stippling) represents the material which infills the flexure and in the computations is assumed to be of similar density to the load. The computations have been carried out for an assumed flexural rigidity $D = 1 \cdot 10^{30}$ dyn cm.

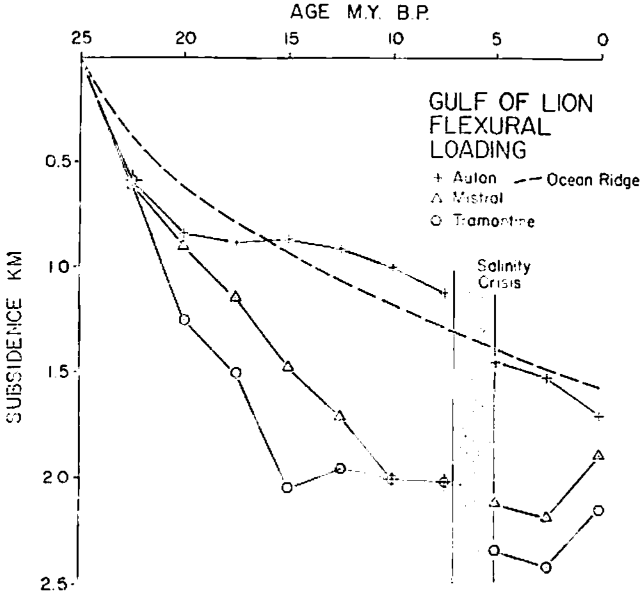

Fig. 5. Plot of computed basement depths through time assuming sediments in the Gulf of Lion loaded a strong rigid basement. Also shown is the empirical ocean-ridge curve (Hays and Pitman, 1973).

curves for the Tramontine and Mistral boreholes differ from this curve by as much as 1200 m.

There are uncertainties in the actual configuration of the sediment load through time but they would not be expected to give rise to significantly different computed depth curves for each borehole. If the sediment load extended further seaward of the coastline than assumed, then flexure at the Tramontine borehole due to this load would be smaller and computed depths greater. Similarly if the load seaward of the Autan borehole is larger than assumed (we have assumed on the basis of a nearby seismic reflection profile that sediments have thinned through time over a basement ridge between the Autan borehole and the base of the rise) the additional flexure caused by this load would reduce the thickness of sediments required at the Autan borehole and computed depths would be shallower. These uncertainties are likely to cause, therefore, even greater discrepancies between the curves for each borehole.

The results of "backstripping" sediments from each of the boreholes in the Gulf of Lion are summarized for both local and flexural loading models in Fig. 6. This figure shows computed depths basement would be at without the sediment load and the total sediment thickness through time for each borehole. The dotted regions in these plots indicates the contribution to the

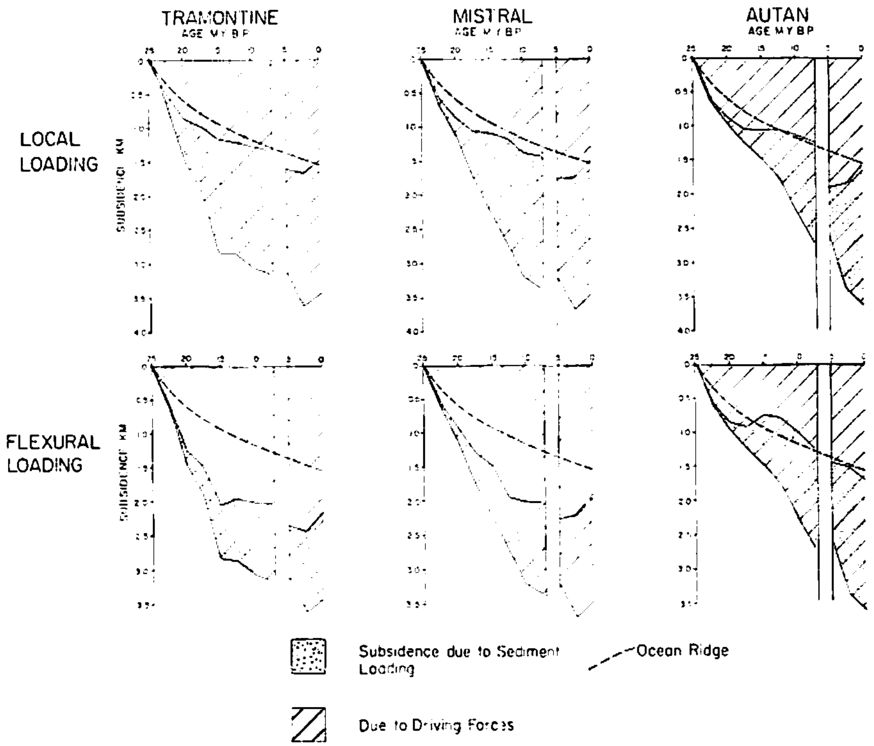

Fig. 6. Summary curves for the subsidence history of boreholes in the Gulf of Lion . The contribution to the subsidence at each borehole of sediment loading is indicated by the dotted region. The capacity of the sediments to load is greater for the local loading scheme than the flexural loading scheme because sediments contribute little to the subsidence if the basement is rigid enough to resist deformation. The shaded region indicates that part of the subsidence are caused by other "driving forces". Small variations in the subsidence curves are probably caused by sea-level changes.

subsidence caused by sediment loading. The contribution to the subsidence of the sediment load is smaller in the Mistral and Tramontine boreholes for flexural loading than for the local loading because sediments have a smaller loading capacity on a strong rigid crust than on an Airy-type crust. The contribution to the subsidence in the Autan borehole is similar for each model. In the flexure model, sediments seaward of the Autan borehole contribute to the subsidence thus increasing the capacity of the sediments to load at this borehole. The shaded region indicates that part of the subsidence which is not caused by sediment loading and can be attributed to other "driving forces".

The sediment "backstripping" method has also been used to examine the contribution of sediment loading to subsidence of the East Coast, U.S.A. margin at Cape Hatteras. Commercial borehole data (Maher, 1965) indicate substantial thicknesses of Middle Jurassic to Recent sediments occur along this margin (Fig. 7). It is generally agreed the central part of the Atlantic Ocean, adjacent to Cape Hatteras, opened 180—190 m.y. ago.

The subsidence of the East Coast, U.S.A. margin has been previously studied in detail by Sleep (1971) who used commercial borehole data from nearly sixty boreholes along the East Coast and Gulf Coast regions. He represented the subsidence as curves of depths to stratigraphic horizons through time, normalized to the base of the Woodbine (~99 m.y. ago.), since basement was reached at only a few of these boreholes.

The subsidence curves of Sleep (1971) are equivalent to normalized curves representing depths basement would be if sediments were "backstripped" from each borehole using the local loading model. The main differences are that the curves of Sleep (1971) are inverted and that they are based on data averaged from more than one borehole.

Sleep (1971) showed that curves representing normalized depths to horizons between the base of the Trinity (~109 m.y. ago) and the present could be explained by an exponential curve of time constant 50 m.y. Small oscillations in these curves were correlated by Sleep (1971) with changes in sea-level.

Local loading

We first assumed the sediments at Cape Hatteras were deposited on an Airy-type crust and progressively "backstripped" them between 109 m.y. ago and the present. The computed depths to basement if there was no sediment cover were determined for each borehole in the Cape Hatteras section (Fig. 7). We assumed the sediments in these boreholes were deposited at or near sea-level in agreement with inferences from lithofacies studies of these sequences (for example, Swift, 1974).

In Fig. 8 (upper curves) computed basement depths using the local loading model are plotted for the Cape Hatteras borehole. Changes in computed basement depths are initially rapid (about 3 cm/1000 year) and decrease with time. There is a close agreement between computed depths and an exponential curve of time constant 50 m.y., constrained to fit the computed depths at 109 m.y. ago and the present. The main difference between the curves occurs between 110 and 65 m.y. ago and are probably the result of sea-level changes associated with the Late Cretaceous transgression.

Flexural loading

We next assumed the sediments at Cape Hatteras were deposited on a strong rigid basement and progressively "backstripped" them between 109

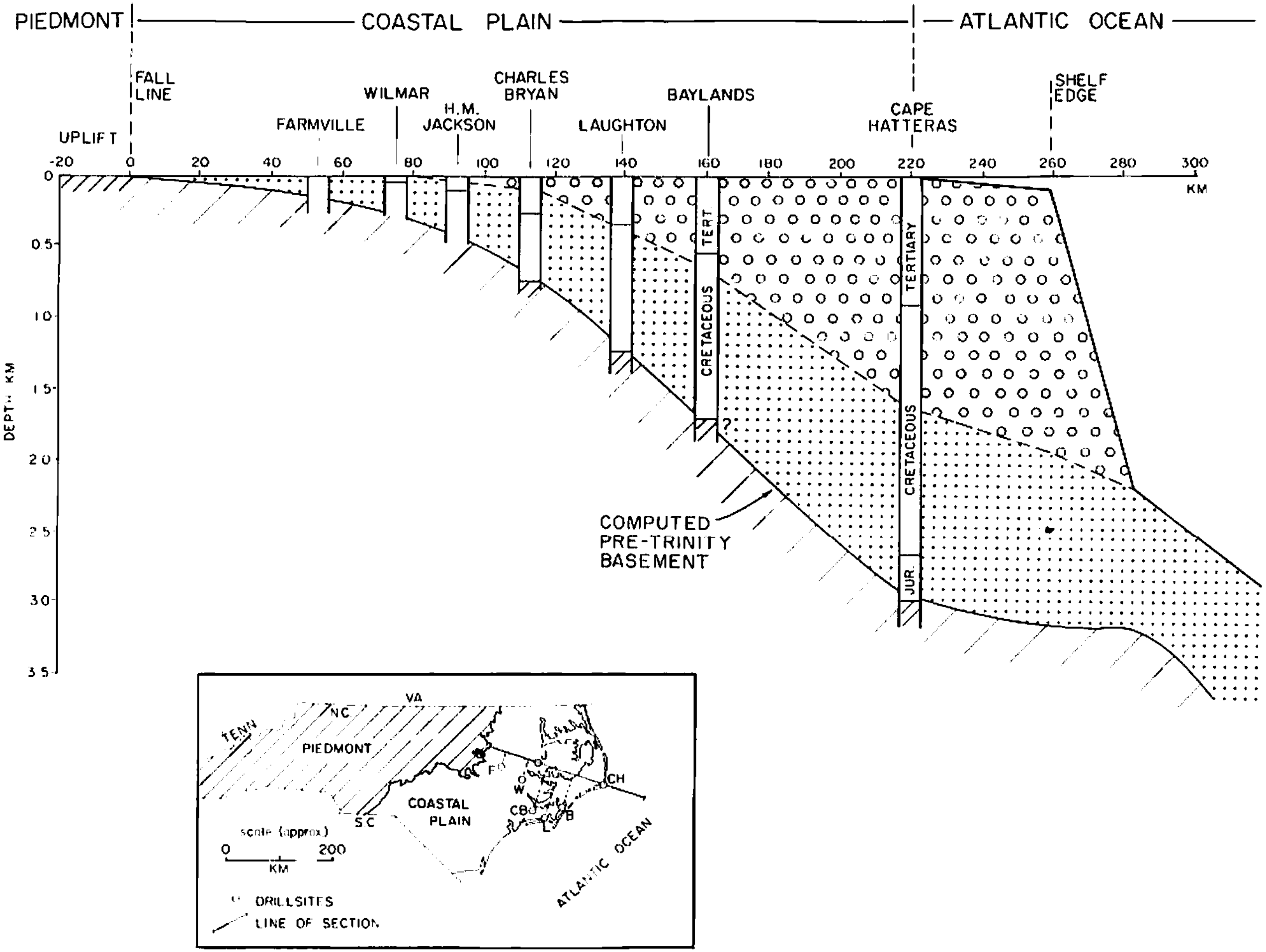

Fig. 7. Schematic cross-section of the coastal plain and continental shelf of the East Coast U.S.A. at Cape Hatteras. The stratigraphy of the boreholes is based on Maher (1965). The dashed line indicates the depth the Pre-Trinity basement would be if the sediment cover (coarse and fine stippling) were removed. The solid line indicates the computed basement for an assumed flexural rigidity $D = 1 \cdot 10^{30}$ dyn cm and a sediment load defined by the coarse stippling above the dashed line. The computed basement agrees closely with basement depths observed at the Charles Bryan, Laughton and Cape Hatteras boreholes and the position of the fall-line.

m.y. ago and the present. In the flexural models it was assumed the load did not extend further inland than the fall-line or further seaward than the base of the continental slope. Although the load may have extended further seaward through time the effect of this at the Cape Hatteras and more landward boreholes would be small. We also assumed that the present shelf edge represented the shelf edge through time. There is no direct evidence from the biostratigraphy of the Cape Hatteras borehole that this was the case. However, J.A. Grow (personal communication, 1975) has suggested on the basis of studies of nearby multi-channel seismic-reflection profiles that the position

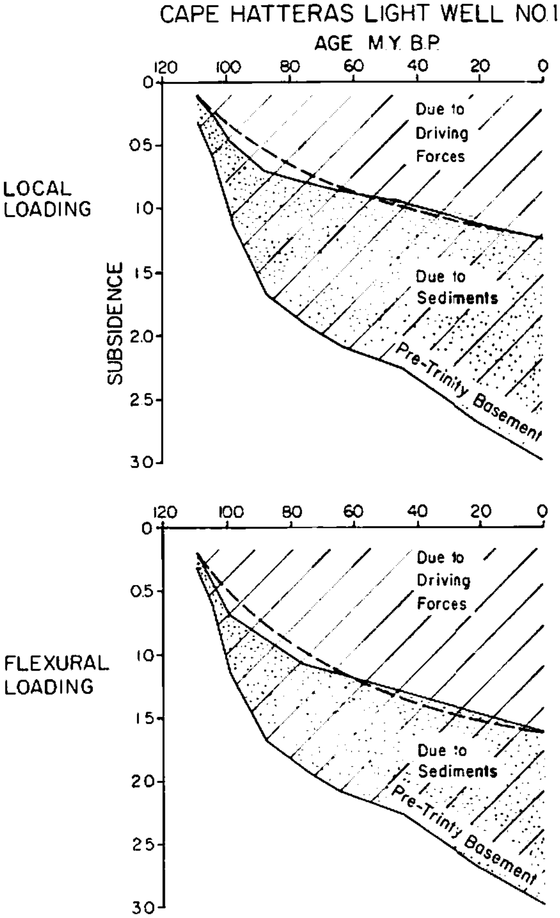

Fig. 8. Summary curves for the subsidence history of the Cape Hatteras borehole. The dotted region indicates that part of the subsidence caused by sediment loading. The remaining is attributed to other forces. The dashed line represents an exponential curve of time constant 50 m.y. constrained to fit the data at 0 and 109 m.y. B.P.

of the shelf edge has been close to the present shelf edge at least since the Late Cretaceous.

Computed basement depths were found through time by a "trial and error" method in which the sediment load which best explains observed basement depths is determined. Assuming the parameters listed in Table I the load configuration was found which best fits basement depths in the Cape Hatteras, Laughton and Baylands boreholes and was in general agreement with inferred depths at the Jackson, Charles Bryan, Wilmar and Farmville boreholes. The computed curve (Fig. 7) predicts closely the position of the fall-line separating the Coastal Plain from the Piedmont. In the flexure models this position separates the region of the depression from a region of uplift. Thus a consequence of the flexure is that sediment loading in the region offshore will cause uplift in the continental interior. In the model (Fig. 7) the maximum uplift is 52 meters and occurs about 60 km landward of the fall-line.

In Fig. 8 (lower curves) the computed depths basement would be through time using the flexural loading model are plotted for the Cape Hatteras borehole. As in the case of the local loading model computed basement depths closely follow an exponential curve with a 50 m.y. time constant. The main difference between this curve and computed depths is between 60 and 110 m.y. ago. The computed depths for the flexural loading model reach a maximum of about 1.6 km which as expected is greater than computed depths for the local loading model.

We also used the method of "backstripping" to determine depths basement would be without the sediment load at other boreholes in the Cape Hatteras section (Fig. 7). The computed depths in these boreholes define the extent of the subsidence which is not caused by sediment loading. Using the flexural model basement has subsided about 1.6 km at the Cape Hatteras borehole and by smaller amounts at the more inland boreholes (Fig. 7). At the Jackson and further landward boreholes there has been little or no subsidence other than that caused by sediment loading. Thus the subsidence not due to sediment loading is limited in horizontal extent to a region between the shelf edge and mid-way between the shelf-edge and the fall-line.

DISCUSSION

The cause of the subsidence of Atlantic-type margins can be considered as partly a consequence of sediment loading and partly due to other "driving forces". Included as possible "driving forces" are thermal contraction (Sleep, 1971), gravitational outflow of crustal material (Bott, 1971) and deep crustal metamorphism (Falvey, 1974). "Backstripping" sediments at these margins allows the effect of sediment loading to be quantitatively determined and the remaining effects of the "driving forces" isolated. Before these effects can be adequately accounted for, however, the correct mechanical model of sediment unloading needs to be used.

At the 25 m.y. Gulf of Lion margin we used mechanical models in which it assumed sediments accumulated either by local or flexural loading in order to explain biostratigraphic data from this margin. Geologic evidence nearby in the south of France suggests the local loading model describes most satisfactorily the manner sediments accumulated in the Gulf of Lion. It is implicit in this model that sediments accumulated independently at each borehole in the same manner as if the basement between these boreholes was divided into one or a number of faults. Evidence from the south of France suggest large NE—SW trending normal faults were in existence during the Miocene/Pliocene, contemporaneous with sediment deposition in the Gulf of Lion. One of the largest of these faults, the Nimes fault, has been tentatively extended offshore across the Gulf of Lion (DeMarcq, 1974). However, no commercial seismic profiler data are currently available to examine the distribution and age of faulting in the Gulf of Lion.

Application of the local loading model to the Gulf of Lion borehole data reveals information on the subsidence of the basement at a young margin which is not caused by sediment loading:

(1) The subsidence is exponential in form and similar for each borehole examined.

(2) The rate of subsidence is initially rapid (up to 20 cm/1000 year) and is significantly greater than inferred from empirical curves which describe the subsidence of mid-ocean ridges.

(3) The magnitude of subsidence (neglecting possible disturbing effects of sea-level changes) 25 m.y. after break-up is about 1.5 km.

At the 180 m.y. East Coast, U.S.A. margin both local and flexural loading models were also used to explain stratigraphic data in commercial boreholes from this margin. Geological evidence suggests the flexural loading model most satisfactorily explains the accumulation of sediments at this margin at least since the Early Cretaceous.

This model is supported by the presence of a fall-line separating the Coast Plain and Piedmont in eastern states of the U.S.A. Although the fall-line is in part faulted (Richards, 1967) it generally represents a "hinge-line" separating a region of subsidence from one of uplift.

In addition, the stratigraphy of the East Coast margin as revealed in commercial boreholes and seismic reflection profiles (for example, Jansa and Wade, 1975) indicates the margin is comprised mainly of unfaulted gently dipping Jurassic and younger sediments.

Application of the flexural model to the East Coast, U.S.A. borehole data reveals information on the subsidence of the basement at an old margin which is not caused by sediment loading:

(1) The subsidence is exponential in form and is adequately described by a time constant of 50 m.y.

(2) The rate of subsidence is smaller than at the young Gulf of Lion margin and does not exceed 3 cm/1000 year.

(3) The magnitude of the subsidence (neglecting effects of sea-level

changes) from 70 to 180 m.y. after the break-up is about 1.7 km (assuming break-up between North America and Africa began 180 to 190 m.y. ago).

(4) The subsidence is a maximum near the shelf edge and decreases to a minimum 150 km inland of the shelf edge.

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