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Folding of lithosphere in the Piemonte-Ligurian ocean

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Abstract

Basin development in the Jurassic-Cretaceous Piemonte-Ligurian ocean as inferred from geological data is compared with a model for folding of oceanic lithosphere and subsequent flexuring due to sediment loading. According to the model, basins with a width between 130 and 160 kilometres and a relative depth ranging from 2000 to 2500 metres will develop on oceanic lithosphere with a cooling age between 35 and 55 My. These results are in good agreement with the dimensions of the Internal and External Ligurian basins, calculated from geological reconstructions. Furthermore, the model provides an explanation for the occurrence of slumps and olistostromes observed in the sedimentary record from the Aptian onwards, and for the extensive erosion on the 'Bracco Ridge', a submarine high which separated the Internal from the External Ligurian basin.

Introduction

Based on the results of a detailed structural mapping (Van Wamel et al., 1985; Van Zutphen et al., 1985; Hoogerduijn Strating & Van Wamel, in press), Van Wamel (1987) presented a possible outline of the tectonic evolution of the Ligurian Apennines. This evolution involved the formation of oceanic lithosphere from the Middle Jurassic to the Late Cretaceous in the Piemonte-Ligurian basin. The oceanic lithosphere was covered by radiolarian chert, pelagic limestone and black shales.

Prior to or simultaneous with subduction, the oceanic lithosphere with its thin sedimentary cover was folded. Buckling resulted in the formation of longitudinal culminations, and differentiated the Ligurian basin in an Internal and an External basin separated by a submarine high, referred to as the 'Bracco Ridge' (Fig. 1 A; see also Elter, 1972). During and after buckling the basins were filled with sediments, whereas the longitudinal ridges suffered submarine erosion (Fig. 1 B). Due to this erosion basalt, serpentinite and gabbro were exposed on the ocean floor and incorporated as olistoliths and breccias in the bordering sedimentary sequences (Galbiati, 1985; Van Wamel et al., 1985). The originally east directed subduction (Boccaletti et al., 1980; Marini, 1982; Van Wamel, 1987) of young oceanic lithosphere started at the onset of the Late Cretaceous, in an area situated to the west of the Ligurian basins. Deformation in the Ligurian basins, presumably related to the subduction and resulting in the development of initially large, west-facing isoclinal folds, occurred during the Late Cretaceous to Middle Paleocene.

The deformation of the lithosphere of the Piemonte-Ligurian ocean is the result of large intraplate stresses, associated with the change of move-

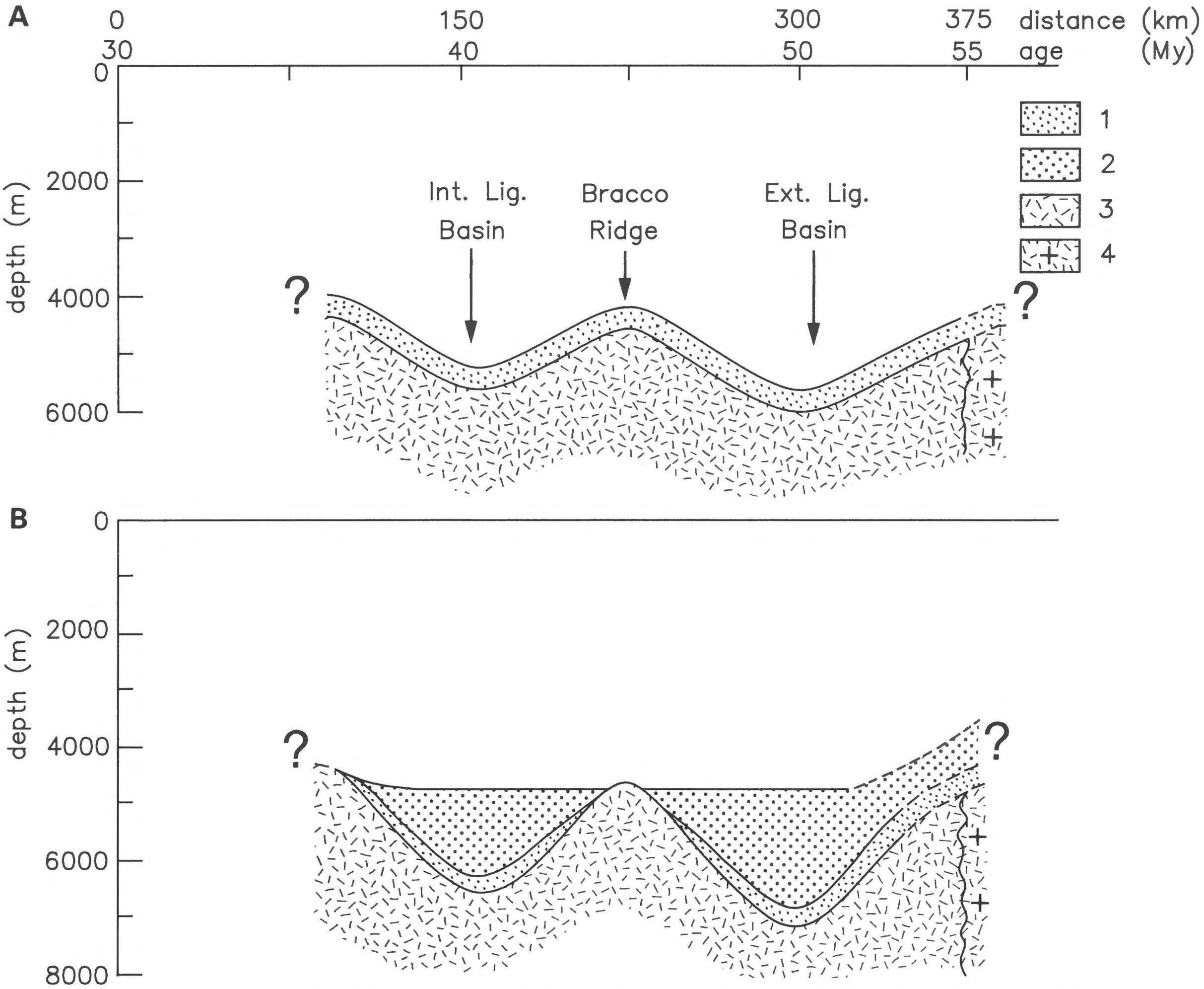

Fig. 1. Schematic representation of buckling and sediment infill as proposed by Van Wamel (1987). A (top) – Buckling of oceanic lithosphere with a thin cover of pre-Aptian pelagic sediments. B (bottom) – Infill of post-Aptian sediments and flexuring of the basin centres due to loading, whereas the ridges are eroded. 1-pre-Aptian sediments, 2-post-Aptian sediments, 3-oceanic lithosphere, 4-thinned continental lithosphere. Supposed distance from the spreading center and cooling age of the oceanic lithosphere are indicated.

ment of the African plate relative to Europe. During the Jurassic (from the Bathonian/Callovian onward) this movement was sinistral, which gave rise to the formation of oceanic lithosphere in the Piemonte-Ligurian basin and the central Atlantic ocean (Fig. 2; Dercourt et al., 1986). While extension in the latter continued throughout the Cretaceous, ocean floor generation in the Piemonte-Ligurian ocean ceased after the Tithonian. From the Aptian onward oceanic spreading started in the north Atlantic region, which resulted in a change to a compressional regime in the Piemonte-Ligurian basin.

The aim of this paper is to compare the development of sedimentary basins in the Jurassic-Cretaceous Piemonte-Ligurian ocean as suggested by Van Wamel (1987) on geologic grounds, with a model for folding and flexuring of oceanic lithosphere. The present model is based on earlier model studies of folded oceanic lithosphere in the northeastern Indian ocean (e.g. McAdoo & Sandwell, 1985; Cloetingh & Wortel, 1985, 1986) and of flexuring of oceanic lithosphere beneath passive continental margins (e.g. Cloetingh et al., 1982; Cloetingh, 1988). The following section discusses the adopted model for the rheology of the oceanic lithosphere and presents the calculations for lithospheric folding and flexuring.

Mechanical model

Model of the oceanic lithosphere

In Fig. 3 a hypothetical section is presented through the eastern half of the Piemonte-Ligurian ocean and the adjacent margin during the Aptian. Generation of oceanic lithosphere lasted from the Bathonian/Callovian (170 Ma) till the Early Cretaceous (145 Ma; data from Dercourt et al., 1986; timescale according to Harland et al., 1982). During this period of 25 My, a maximum half-spreading rate of 1.5 cm.y is assumed (Perry et al., 1981). Until the Aptian (115 Ma) the oceanic lithosphere cooled, resulting in a maximum cooling age of 55 My at the onset of compression.

An elastic-plastic olivine rheology of the oceanic lithosphere is adopted, in which the upper part behaves brittle, the central part is in the elastic regime and the lower part deforms by ductile flow (Goetze & Evans, 1979; see also Cloetingh, 1982 and Cloetingh et al., 1982).

The lower boundary of the mechanically strong upper part of the oceanic lithosphere is defined by a threshold temperature below which the creep strength of olivine exceeds 100 MPa. McAdoo & Sandwell (1985) (cf. Goetze & Evans, 1979) calculated that the base of the mechanically strong upper part of the oceanic lithosphere follows the 740° C isotherm. The thickness S is related to the cooling age t of the lithosphere and can be expressed as,

$$S = 6.2 \sqrt{t} \text{ km} \qquad \text{for } t < 80 \text{ My} \tag{1}$$

The lower boundary of the thermal oceanic lithosphere is defined by the 1200° C isotherm (see also Wortel, 1980).

From a number of independent geophysical approaches Cloetingh (1982) inferred a thickness of 60 kilometres for the mechanically strong upper part of the continental lithosphere and a thickness of 150 kilometres for the thermal continental lithosphere.

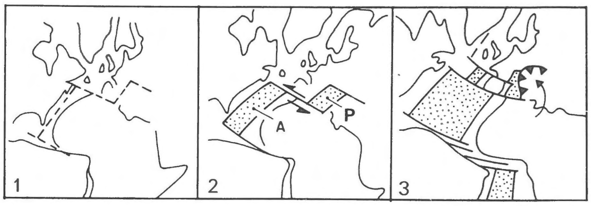

Fig. 2. Mesozoic evolution of the Tethys (after Lemoine et al. 1987)
1: Triassic to Mid Jurassic: pre-rift, then rifting.
2: Mid Jurassic to Late Cretaceous: ocean opening and collapse of passive margins, followed by oceanic spreading in the Central Atlantic (A) and Piemonte-Ligurian (P) domain. Oceanic spreading in the Piemonte-Ligurian ocean ceased towards the end of the Late Jurassic.
3: Late Cretaceous: opening of the North Atlantic ocean and continued spreading in the Central Atlantic ocean. Beginning of closure of the Piemonte-Ligurian ocean.

The depth profile of the ocean floor is adopted from Parsons and Sclater (1977).

Buckling of oceanic lithosphere

Based on SEASAT observations and marine geophysical data in the Indian ocean just south of the Bay of Bengal, McAdoo & Sandwell (1985) presented a model for the folding of oceanic lithosphere. Using Goetze & Evans' (1979) rheological model they concluded that intraplate stress levels of 0.5 to 0.6 GPa (5–6 kbar) are required to induce buckling in oceanic lithosphere with a cooling age of about 55 MY. Stress levels of this magnitude have also been calculated for the northeastern Indian ocean by Cloetingh & Wortel (1986), using finite element techniques (see Fig. 8).

Cloetingh & Wortel (1986) demonstrated that the extreme high intraplate stresses in that area are the result of the focusing of the compressive resistance associated with the Himalayan collision to the north and the subduction of young oceanic lithosphere in the northern part of the Sunda arc to the east.

McAdoo & Sandwell (1985) used the elastic-plastic olivine rheology of Goetze & Evans (1979) and computed the age dependence for the buckling wavelength λ,

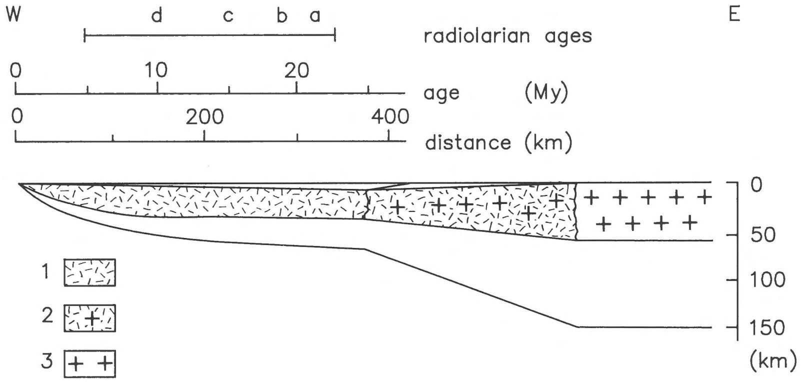

Fig. 3. Hypothetical section through the eastern half of the Piemonte-Ligurian ocean and the adjacent continental margin at the onset of the Early Cretaceous. Spreading is assumed to have taken place over a period of 25 Ma with a half-spreading rate of 1.5 cm/year. This corresponds with a distance from the spreading centre of 375 kilometres. The range of radiolarian ages (V. Bortolotti, 1986, pers. comm.) and their inferred positions are indicated (a-External Ligurian basin, b-Internal Ligurian basin, c-Elba, d-Tuscany). The mechanically strong parts of the lithosphere are hatched: 1- oceanic lithosphere, 2- thinned continental lithosphere, 3- continental lithosphere.

$$\lambda = 2\pi \left[\frac{D}{g\Delta\varrho_1}\right]^{1/4} \cdot (1 - F_c/F_s)^{3/8} \qquad (2)$$

in which g is the acceleration of gravity and $\Delta\varrho_1$ the density difference between the undepleted mantle (ϱ_m) and water (ϱ_w). F_c is the horizontal load needed to induce buckling and F_s the saturation load for which the lithosphere fails. Just prior to complete failure, however, the lithosphere buckles. Using constants appropriate to the oceanic lithosphere (see Table 1) and the lithospheric thicknesses given in equation (1) and equation (14) from McAdoo & Sandwell (1985), the buckling load appears to be slightly less than the saturation load (i.e. $F_c/F_s = 0.94$).

D in equation (2) is the flexural rigidity, which is related to the thickness of the mechanically strong part of the lithosphere by $D = ES^3/12(1 - \gamma^2)$, where E is Young's modulus and γ is Poisson's ratio.

The calculations presented here for the deflection of the oceanic lithosphere are based on an elastic rheology. This provides a first order description only, but makes it possible to solve most problems with the use of analytical methods instead of the more complex numerical techniques, needed to solve the same problems for an elastic-plastic rheology. To bridge the gap between the analytical calculations for an elastic rheology and the results of numerical analysis of an elastic-plastic rheology magnification factors are used.

The vertical deflection of the folded lithosphere can be calculated using the ratio Z, the ratio of curvature of the sinusoid per kilometre (in μrad/km) of an elastic lithosphere (Weissel & Haxby, 1982; McAdoo & Sandwell, 1985). The amplitude A is given by

$$A = {}^{1}\!/_{4}\lambda \left[\frac{1 - \cos\omega}{\sin\omega}\right], \ \omega = {}^{1}\!/_{4}\,\lambda\, Z \qquad (3)$$

with

$$Z = \frac{2\pi\, G\, \Delta\varrho_1}{g} \exp\left(- \frac{2\,\pi\, d}{\lambda}\right) \qquad (4)$$

where G is the gravitational constant. The depth of the ocean floor d is related to the cooling age of the oceanic lithosphere by $d = d_0 + 0.35\sqrt{t}$, where D_0 is the depth of 2500 metres of the crest of the spreading ridge (Parsons & Sclater, 1977).

Flexure due to sediment loading

To calculate the flexure of the oceanic lithosphere due to sediment infill in the basins, the equations of Hetényi (1946; see also Cloetingh, 1982) are used for the bending of an infinite uniform elastic plate

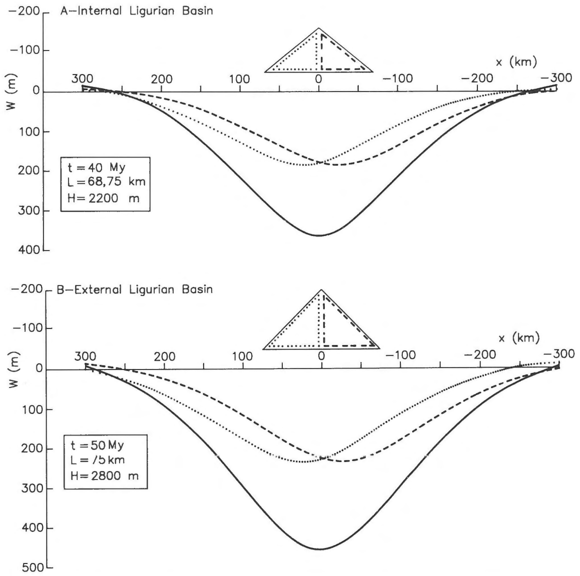

Fig. 4. Deflection W (in metres) of an elastic oceanic lithosphere due to an instantaneously applied sediment load for the Internal (A) and External (B) Ligurian basin. Sediment infill is represented by two triangular wedges (dashed and dotted). The resulting flexure due to loading of each wedge (curves with same signature as the wedges) and loading of the total sediment infill (solid triangle and curve) are shown (see text and Appendix for explanation). Sign convention: downward displacements are positive, upward displacements are negative. Distance is taken from the point directly underlying the top of the triangle (x = 0). Left is taken as the positive direction. Loading specifications are given in the figure.

due to a distributed load in the form of an triangular wedge (see Appendix and Fig. A1).

The sediment infill in the basins is represented by two identical triangular wedges (Fig. 4). The width L of each wedge is based on the calculated wavelength (equation (2)) and the height H on stratigraphic data (Van Wamel et al., 1985; Van Zutphen et al., 1985).

Comparison with the basin development in the Piemonte-Ligurian ocean

Wavelength and amplitude

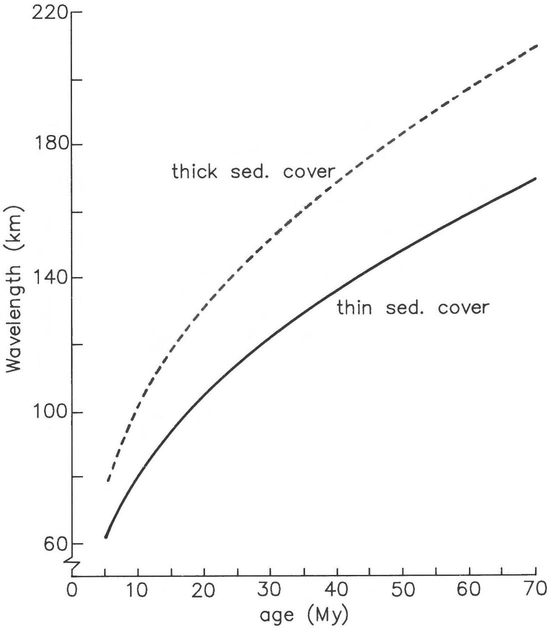

Fig. 5. Buckling wavelength versus cooling age for elastic-plastic oceanic lithosphere with a thin (solid curve) or thick (dashed curve) sedimentary cover (see text for explanation). Figure modified after McAdoo & Sandwell (1985).

Both the wavelength (Fig. 5) and the amplitude (Fig. 6) are calculated and plotted versus the cooling age of the oceanic lithosphere. The curves without sediment loading are calculated using $\varrho_m - \varrho_w$ (= $\Delta\varrho$ 1) in equations (2) and (4) and represent the values for an oceanic lithosphere without a sedimentary cover. The curves with sediment loading are calculated using the density difference between undepleted mantle and sediment ($\varrho_m - \varrho_s$) in equations (2) and (4) and represent the situation for buckled oceanic lithosphere covered by a sedimentary sequence with a thickness of a few kilometres. In general these two situations represent the conditions for oceanic lithosphere underlying respectively the abyssal plane (without sediment loading) and the continental margin (with sediment loading). The thickness of the pre-Aptian sedimentary sequence in the Internal Ligurian basin is estimated at about 350 metres (Van Zutphen et al., 1985). Therefore the curves without sediment loading will be used.

According to Van Wamel (1987), the width of the External Ligurian basin can be estimated at about 150 kilometres. Galbiati (1985) made a de-

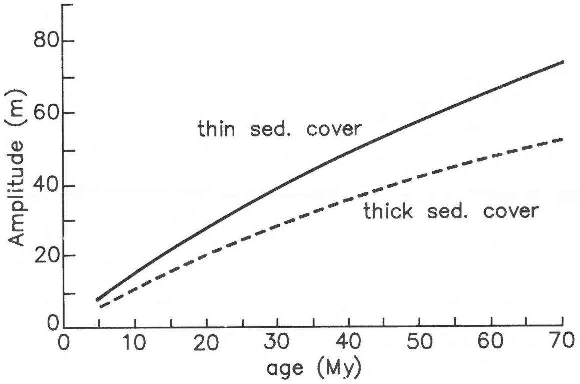

Fig. 6. Amplitude versus cooling age for elastic oceanic lithosphere with a thin (solid curve) or thick (dashed curve) sedimentary cover (see text for explanation).

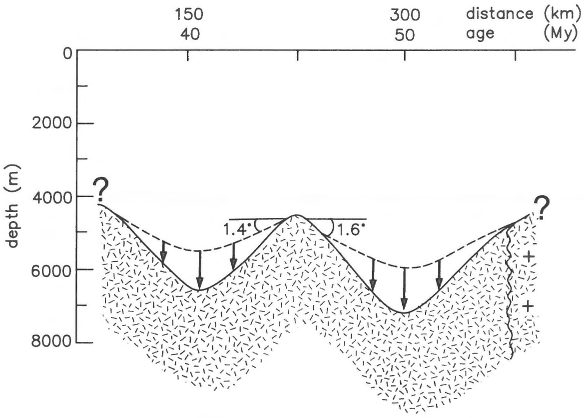

Fig. 7. Compilation (solid curve) of effects of buckling (dashed curve), time-dependent sediment loading and an intraplate stress of about 0.4 GPa (arrows) for an elastic-plastic oceanic lithosphere with an age ranging from 35 to 55 My.

tailed reconstruction of the eastern half of the Internal Ligurian basin during the Upper Cretaceous. Assuming a symmetric sediment infill, the postulated width of the total basin will be about 140 kilometres. These values are in good agreement with the wavelength of 130 to 160 kilometres for oceanic lithosphere with a thin sedimentary cover and a cooling age between 35 and 55 My (Fig. 5). These cooling ages are considered to represent the youngest and oldest oceanic lithosphere underlying the Ligurian basins. Throughout the rest of the paper cooling ages of 40 and 50 My are taken as representative for respectively the Internal and External Ligurian basin.

Equation (4) for the amplitude is based on an elastic instead of an elastic-plastic rheology. Therefore, the calculated values are much too low to be compatible with present day observations (McAdoo & Sandwell, 1985). In the Bay of Bengal the amplitude of the folds range from 500 to 1500 metres (Weissel et al., 1980; Geller et al., 1983) for oceanic lithosphere with an age of 50–60 My. To approach these observed amplitudes, the calculated values have to be magnified with a factor 12.5.

Based on the amplitude calculations (Fig. 6) and the magnification factor of 12.5 the relative depth of the Internal and External Ligurian basin due to buckling have been determined to be about 1200 and 1450 metres respectively (Fig. 7). It should be noted that the depth mentioned here represents the difference in height between the top of the ridges and the floor of the basins and does not indicate the absolute water depth.

Sediment infill and sediment loading

As a first approximation we may consider the deflection of an elastic lithosphere due to an instantaneously applied sediment load (see Appendix). This results in a subsidence of approximately 360 metres for the Internal, and 460 metres for the External Ligurian basin (see Fig. 4).

In contrast to the calculations based on a static model involving instantaneous sediment loading, a more realistic approach takes into account that the flexure is time-dependent, as the basins are gradually filled with sediments while subsiding at the same time. Furthermore, the thickness of the mechanically strong part of the oceanic lithosphere increases as a result of cooling during sediment infill (Cloetingh, 1982). To obtain an estimate of the resulting flexure, the ratio is calculated of the deflection of an elastic lithosphere due to instantaneous sediment loading (see Appendix) to the deflection through time of lithosphere with an age dependent equivalent elastic thickness loaded by sedimentary wedges with an age-dependent height (finite element model from Cloetingh et al., 1985). The results of Cloetingh et al. (1985) show that the deflection is concentrated in the basin centres whereas the width of the subsiding area is much smaller.

The ratios thus obtained for the deflection in the basin centres are approximately 1.8 for the Internal ($t = 40$ My) and 1.9 for the External Ligurian basin ($t = 50$ My). It follows that the subsidence of the basin centres due to time-dependent sediment loading will be of the order of about 650 metres for the Internal, and 900 metres for the External Ligurian basin.

The effect of intraplate stress

Comparing the Piemonte-Ligurian ocean with the Bay of Bengal, a difference in cooling ages of the lithosphere is obvious. As the cooling age of the lithosphere in the model under consideration (35–55 My) is slightly less than the age of the lithosphere in the Bay of Bengal (50–60 My; McAdoo & Sandwell, 1985), the stresses needed to induce buckling are by necessity somewhat smaller. Based on the relationship between buckling load and cooling age for an elastic-plastic lithosphere (Fig. 8; McAdoo & Sandwell, 1985) the stresses in the Piemonte-Ligurian ocean can be estimated to have been of the order of 0.35 to 0.45 GPa (3.5–4.5 kbar).

If a compressive intraplate stress during sediment infill is incorporated in the model, an additional uplift at the basin edges and subsidence in the basin centres will occur (Cloetingh et al., 1985; Cloetingh, 1986). For an intraplate stress of 0.4 GPa and an elastic rheology these differential movements will result in an additional subsidence of the basin centres of about 150 metres, whereas the basin edges are uplifted about 100 metres. These estimates include effects of the adjacent basins. The combined flexure due to sediment loading and an intraplate stress of 0.4 GPa is shown in Fig. 7.

Slope processes on the intra-oceanic ridges

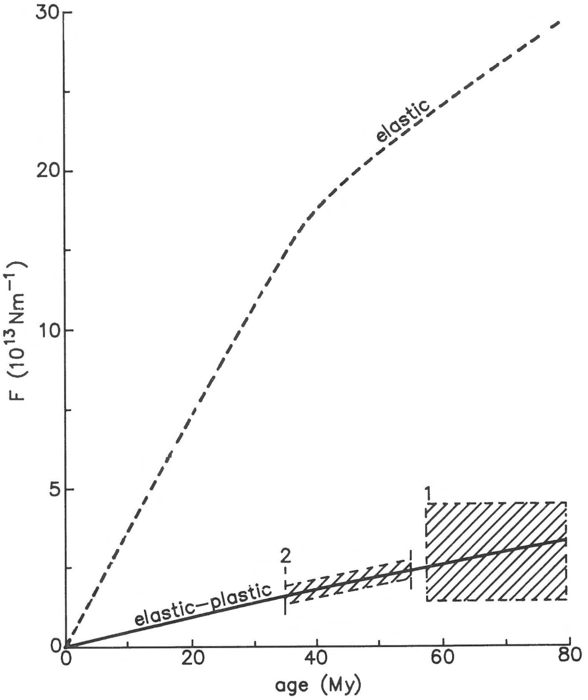

Fig. 8. Buckling load versus cooling age for lithosphere with an elastic-plastic rheology inferred from rock-mechanics studies (Goetze & Evans, 1979) given by the solid line and for fully elastic oceanic lithosphere given by the dashed line (after McAdoo & Sandwell, 1985). Box 1 indicates calculated stress levels in the Bay of Bengal by Cloetingh & Wortel (1986). Box 2 indicates inferred stress levels for the Piemonte-Ligurian ocean during the Middle to Late Cretaceous. After Cloetingh (1988) with modifications.

From the Aptian onward in the Apennines (e.g. Elter, 1972; Galbiati, 1985; Van Wamel et al., 1985) and Alps (e.g. Matter et al., 1980) the sedimentary sequences covering the oceanic lithosphere are characterised by numerous olistostromes, slumps and breccias. These slope deposits were concentrated in the areas bordering the intra-oceanic ridges and contain both pelagic and ophiolitic material. The intra-oceanic ridges acted also as intra-basinal source areas for ophiolitic debris (chromite in the Simme and Gets Flysch) and lime-mud (common among Senonian Flysch) in the Flysch deposits in the Alps (e.g. Homewood & Caron, 1982).

From the wavelength and amplitude calculations it appears that the slopes bordering the 'Bracco Ridge' had an average inclination of about 1.5° (Fig. 7). The pre-Aptian sedimentary cover on the slopes dominantly consisted of a well layered sequence of pelagic shale and limestone (the Palombini formation). This type of deposits has a low permeability. With continued sediment loading (see Fig. 1) the pore pressure within the shale may well have risen above the hydrostatic pressure, which made these deposits highly susceptible to gravitational sliding (e.g. Mandle & Crans, 1981).

In view of the seismic activity, observed at present in deforming oceanic lithosphere such as in the Bay of Bengal (Sykes, 1970; Stein & Okal, 1978; Cloetingh & Wortel, 1985, 1986; Wiens et al., 1986), it may be assumed that the Piemonte-Ligurian ocean was also an area with high intraplate seismicity. The occurrence of presumably overpressured sediments on a slope with an inclination of about 1.5° in an area of high intraplate-seismicity provides a good explanation for the development of olistostromes and slumps in sedimentary sequences bordering the intra-oceanic ridges. Under these conditions ophiolitic material from the ridges could become incorporated in slope deposits as ophiolitic sands and olistolites. The deposition of ophiolitic breccias, however, was probably restricted to scarps on the ridges.

Discussion

Slight differences between the tectonic interpretation of Van Wamel (1987) and the present model are twofold. Van Wamel (1987) used the Jurassic time-scale of Van Hinte (1976), in which the Bathonian-Callovian (i.e. onset of ocean floor generation) stage boundary age was estimated at 155 Ma. However, in most recent geological time-scales, the age of this stage boundary is estimated at 169 Ma (Harland et al., 1982; see also Kent & Gradstein, 1985). Furthermore Van Wamel assumed that ocean floor was generated until the Aptian, whereas data from Winterer & Boselini (1981) and Dercourt et al. (1986) indicate that it ceased towards the end of the Tithonian. Therefore the time during which ocean floor is generated is limited from 40 My, as suggested by Van Wamel (1987), to 25 My used in the present study.

The present model aims to give a first order approximation of basin development in the Piemonte-Ligurian ocean. Therefore an ideal oceanic lithosphere is used. Note, however, that the ophiolites in the Alps and Apennines represent pieces of an 'atypical' ocean floor (e.g., Abbate et al., 1980; Weissert & Bernoulli, 1985; Lemoine et al., 1987). In addition, the influence of faults on the folding and flexuring of the lithosphere and the time-dependent unloading of the ridges due to erosion are neglected. Moreover, the change from oceanic to thinned continental lithosphere has been supposed to have no influence on the rheology of the lithosphere underlying the Internal and External Ligurian basins which, in view of the different rock types involved, necessarily leads to a considerable simplification. As the flexuring due to sediment loading and intraplate stress is calculated for an elastic rheology, these will be absolute minimum values.

In the model presented here, basin geometries are assumed to be symmetric. In contrast, intraoceanic ridges in the Alpine part of the Piemonte-Ligurian ocean appear to have been strongly asymmetric. Homewood & Caron (1982) for example argued that the ridges were underlain by asymmetric basement folds and a series of blind thrusts. However, given the present understanding of the geology of the Apennines, it is not yet possible to decide between a symmetric or more asymmetric geometry of the Internal and External Ligurian basins. More work needs to be done on the facies distributions of the Late Cretaceous sediments in the basins and on the tectonics related to the formation of the ridges.

Notwithstanding these shortcomings, the present study may provide a basis for understanding the type and dimensions of structures (e.g. basins and ridges) that may be expected in young oceanic lithosphere during compression.

Conclusions

Based on the tectonic evolution of the Ligurian Apennines and the stratigraphy in the Internal and External Ligurian basin (Van Wamel, 1987), basins have been inferred with a width of about 150 kilometres and a relative depth of 2500 to 3000 metres developed on oceanic lithosphere with a cooling age ranging from 35 to 55 My. The basins were separated by ridges which suffered from submarine erosion.

For an elastic-plastic oceanic lithosphere with a cooling age of 35 to 55 My the combined effects of buckling, time-dependent sediment loading and an intraplate stress of about 0.4 GPa resulted in the development of basins with a width ranging from 135 to 160 kilometres and a relative depth ranging from 2000 to 2500 metres. These basins were separated by ridges which did not subside or even showed slight uplifts (Fig. 7). The calculated values for the width and the relative depth of such sedimentary basins are in good agreement with the geological observations and fit well with the dimensions of the Internal and External Ligurian basins as proposed by Van Wamel (1987).

From the present study it can be concluded that folding and flexuring of oceanic lithosphere due to compression and sediment loading may have been a dominant mechanism in basin development in the Piemonte-Ligurian ocean, prior to and simultaneously with subduction.

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Appendix

Flexuring of an infinite uniform elastic thin plate due to an instantaneously applied load in the form of a triangular sediment wedge

The deflection of a thin water-covered elastic plate due to instantaneous sediment loading is considered. The load is represented by a triangular sediment wedge with a density difference of water to sediments $\Delta\varrho_2$, height H and width L (Fig. A1). The top of the wedge is located directly above $x = 0$, whereas the toe of the wedge is located at $x = L$. Note that the right is taken as the negative direction.

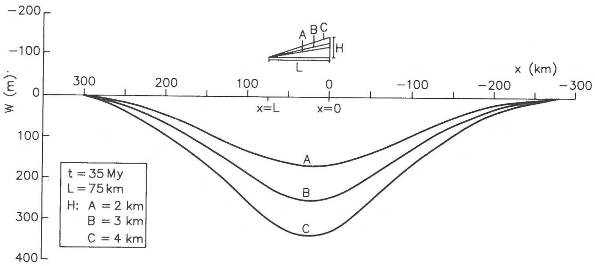

Fig. A1. Deflection of a thin elastic plate induced by a distributed triangular load. Load specifications in figure.

Here I follow Cloetingh (1982) in using the formulas given by Hetényi (1946) for the bending of an infinite uniform elastic plate due to a distributed load in the form of a triangular wedge. The deflections w under the load ($L > x > 0$) are given by

$$w = \frac{\Delta\varrho_2 H \alpha}{4\Delta\varrho_1 L}\{\exp(-L/\alpha)\exp(x/\alpha)$$
$$[(\cos x/\alpha)(\cos L/\alpha - \sin L/\alpha) +$$
$$(\sin x/\alpha)(\cos L/\alpha + \sin L/\alpha)] + \exp(-x/\alpha)$$
$$[\sin x/\alpha - (\cos x/\alpha)(1 + 2L/\alpha)] + 4(L - x)/\alpha\} \tag{A1}$$

where $\Delta\varrho_1$ is the density difference between undepleted mantle and water ($\varrho_m - \varrho_w$) and α the flexural parameter.

$$\alpha = \left[\frac{4D}{\Delta\varrho_1 g}\right]^{1/4} \tag{A2}$$

D is the flexural rigidity and g the acceleration of gravity. Similar expressions apply for the displacement to the left of the load ($x \geqslant L$), where

$$w = \frac{\Delta\varrho_2 H\alpha}{4\Delta\varrho_1 L}\{\exp(-x/\alpha)\exp(L/\alpha)$$
$$[(\cos x/\alpha)(\cos L/\alpha + \sin L/\alpha) -$$
$$(\sin x/\alpha)(\cos L/\alpha - \sin L/\alpha)] - \exp(-x/\alpha)$$
$$[(\cos x/\alpha)(1 + 2L/\alpha) - \sin x/\alpha]\} \tag{A3}$$

and to the right of the load ($x \leqslant 0$), where

$$w = \frac{\Delta\varrho_2 H\alpha}{4\Delta\varrho_1 L}\{\exp(-L/\alpha)\exp(x/\alpha)$$
$$[(\cos x/\alpha)(\cos L/\alpha - \sin L/\alpha) +$$
$$(\sin x/\alpha)(\cos L/\alpha + \sin L/\alpha)] - \exp(x/\alpha)$$
$$[(\cos x/\alpha)(1 - 2L/\alpha) + \sin x/\alpha]\} \tag{A4}$$

These calculations apply for a situation in which there is no intraplate stress.

Table 1. Parameters

Parameter	Definition	Value/units
E	Youngs modulus	6.5×10^{10} Pa
g	acceleration of gravity	$9.8\,m/s^2$
G	gravitational constant	6.67×10^{-11} Nm^2/kg^2
λ	Poisson's ratio	0.25
ϱ_m	undepleted mantle density	$3360\,kg/m^3$
ϱ_s	sediment density	$2300\,kg/m^3$
ϱ_w	seawater density	$1000\,kg/m^3$
d_0	depth of spreading ridge	2500 m
Thickness pre-Aptian sedimentary sequence:		
	Int. Ligurian basin	350 m
	Ext. Ligurian basin	400 m
Thickness mechanically strong part of oceanic lithosphere at the onset of compression (Aptian):		
	Int. Ligurian basin (t = 40 Ma)	39 km
	Ext. Ligurian basin (t = 50 Ma)	44 km

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