Quantitative subsidence analysis of the Mesozoic evolution of the Lusitanian basin (western Iberian margin)

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Abstract

Quantitative subsidence analysis of 26 wells in the Lusitanian basin provides new constraints on the western Iberian Mesozoic passive margin development. Backstripped tectonic subsidence curves show a three-fold subdivision of vertical motions from Late Triassic onward. Continental rifting was initiated during the Late Triassic and Early Jurassic. From Middle Jurassic onward a distinct different behaviour is expressed in the subsidence curves for the North and the South Lusitanian basin. During the Middle Jurassic the South Lusitanian basin records a stretching episode with stretching factors of about 1.08, while the North Lusitanian basin typically has a Middle Jurassic hiatus. This different development is also expressed in the Late Jurassic and Early Cretaceous sedimentary sequence when both the North and South Lusitanian basin are subjected to another stretching episode, with a more pronounced development of the southern than of the northern part of the basin. The stretching factors for this last phase are about 1.03 for the northern part and 1.08 for the southern part of the area. This north–south difference during the Middle Jurassic to Early Cretaceous, for which the transition roughly coincides with the location of the Nazaré fault zone, is probably a result of differences in pre-rift crustal composition or thickness. Late Cretaceous sediments are mostly absent in the analysed wells. In the southern part of the basin the absence of the Cretaceous record is a consequence of erosion due to Cenozoic inversion of the basin. The generally low estimates for stretching factors suggest that the analysed eastern part of the Lusitanian basin forms the distal part of the mid-Cretaceous continental breakup. A comparison with subsidence curves of neighbouring basins of Iberia reflects general patterns in Mesozoic basin development and confirms the generally held view that the extension leading to continental breakup migrated from south to north during the Middle Jurassic to Early Cretaceous in West Iberia.

Keywords: Basin subsidence; Passive margins; Mesozoic; Iberia; Tectonophysics

1. Introduction

The Lusitanian basin, situated in the western part of the Iberian Peninsula, records the opening of the North Atlantic Ocean during the Mesozoic. Fig. 1 shows the pre-drift configuration of the con-

tinents bordering the North Atlantic. This part of the North Atlantic was defined during the Mesozoic by two major fracture zones: the Charlie Gibbs and the Newfoundland–Gibraltar fracture zones (Verhoef and Srivastava, 1989). For the western Iberian margin and its conjugate, the Grand Banks of Newfoundland, the first indications of Mesozoic continental rifting are of Late Triassic age. During the Paleozoic
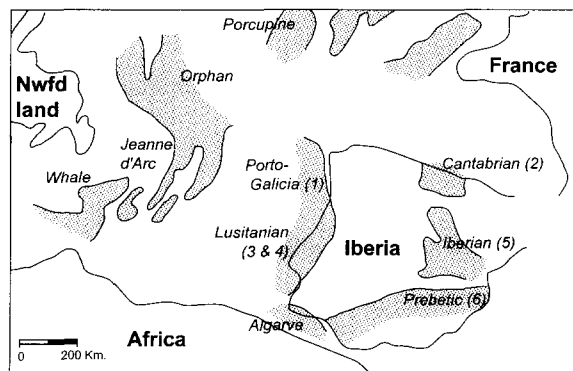
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Fig. 1. Schematic overview of the rift basins of the Iberian continent and its conjugate margin in pre-drift situation. The directly neighbouring basins of the Lusitanian basin discussed in this paper are indicated by numbers that correspond with Fig. 9. (Modified from Tankard and Balkwill, 1989.)

the Variscan fold belt had developed in the North Atlantic region and during the Late Paleozoic the development of wrench faults marked a pronounced change in stress system (Ziegler, 1989). In the Middle Jurassic, breakup was established by separation of Africa and North America. From then on the Central Atlantic seafloor spreading axis was propagating to the north. During the Late Jurassic this probably resulted in the separation of South Iberia and North America (Srivastava et al., 1990), followed by the Aptian separation of Galicia Bank and North America (Boillot et al., 1989) and the mid-Cretaceous separation of Europe and North America. The crustal separation during the Aptian led the western Iberian margin into a phase of relative tectonic quiescence, while tensional stresses that had been active since the Late Triassic were relaxed. During the Late Cretaceous and Early Tertiary, a change of stress patterns occurred associated with the collision of Europe and Iberia during the Early Tertiary and the collision of Africa and Iberia in the mid-Tertiary. On the Iberian continent this stress regime resulted in the inversion of Mesozoic grabens. In the Lusitanian basin compression resulted in an inversion of a part of the basin and the associated development of two small-scale basins to the WNW and ESE of the inverted area (Ribeiro et al., 1979). The present-day stress field documented by Cabral (1989) shows curved trajectories for the maximum compressive principal stress axis that turn from NNW–SSE in the extreme south

of the Iberian Peninsula towards WNW–ESE for the western Iberian margin.

Fig. 2 shows a detailed overview of the geology of the Lusitanian basin and Fig. 3 shows a cross-section through the basin, combining onshore and offshore seismic sections. The basin is one of the few basins around the North Atlantic with synrift sediments exposed onshore. Mesozoic sediments are outcropping in the NNE–SSW-oriented inverted zone and in a small zone along the Variscan basement at the eastern border of the basin. The onshore geology of the Lusitanian basin has been extensively studied (Ribeiro et al., 1979; Guéry et al., 1986; and references therein). In their study Wilson et al. (1989) emphasize the importance of the Nazaré fault zone (Fig. 2). It is evident from the stratigraphic well reports that the Lusitanian basin can from Middle Jurassic onward best be separated in two distinct areas, separated by this Nazaré fault zone. In the following they will be called the North and the South Lusitanian basin. So far, only Wilson et al. (1989) supplemented their studies with limited subsurface data. We present the results of a comparison of an extensive set of well data together with stretching estimates as well as a comparison of Mesozoic subsidence for the different basins on the Iberian Peninsula.

2. Stratigraphy

For this study 26 wells were analysed for which the locations are given in Fig. 2. The wells were drilled in the period 1949–1990 and 13 of the wells are situated onshore and 13 offshore. Fig. 4 summarizes the stratigraphic history of the study area together with mean thicknesses derived from a comparison of the 26 wells. Five of the analysed wells reached basement. Four of these wells have Triassic sandstones lying unconformably on Paleozoic and Precambrian rocks. In the following a brief summary of the Mesozoic lithologies of the wells will be given. The summary is based on GPEP (1986), extended with new observations.

Mesozoic sedimentation started in an extensional regime that came into existence during the Late Triassic. The oldest dated sediments are of Carnian to Norian age (Palain, 1977) and consist mainly of red continental sandstones and mudstones, deposited in
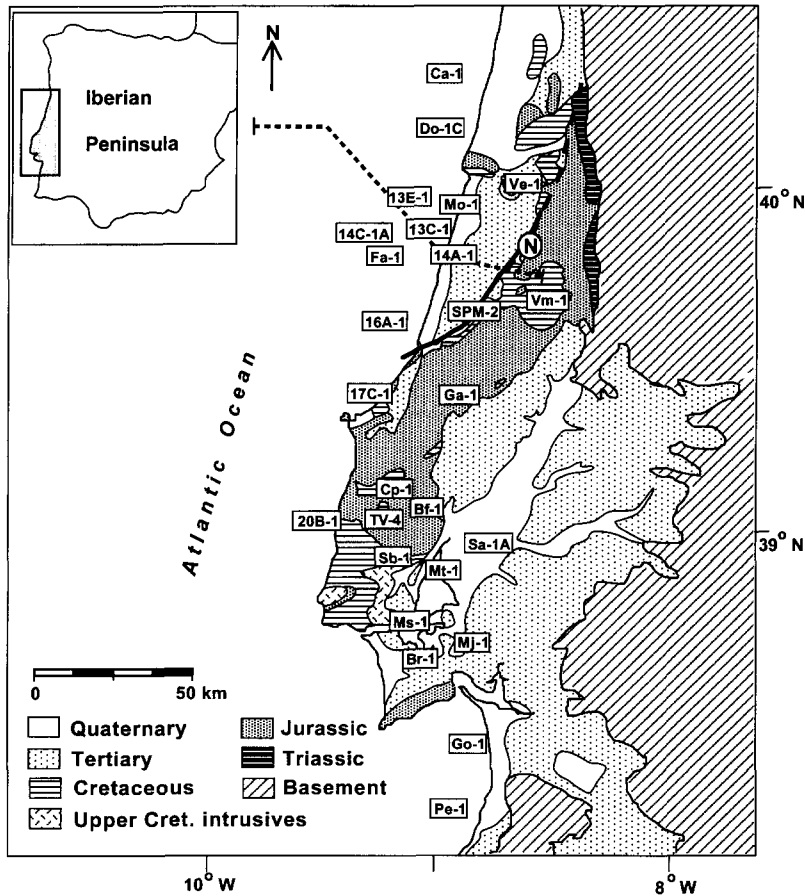
Fig. 2. Geological setting of the Lusitanian basin and location of the 26 wells analysed in this study. The upper left corners of the boxes give the exact locations of the wells. N = Nazaré fault zone. The dotted line gives the location of the cross-section shown in Fig. 3.

small basins. The thicknesses in the three wells that reach basement containing this unit range from 160 to 388 m. The exact upper age of the continental red beds and the starting point of the subsequent salt accumulations are badly constrained (see Sopeña et al. (1988) for a discussion). The analysed wells show that sedimentation of clastics proceeded on the margins while evaporites were deposited in the central areas of the locally developing basins. As in none of the wells the evaporites are dated, we assume for the subsidence analysis that evaporites were deposited during the Hettangian and that continental sandstones represent the Upper Triassic. Thus, the first homogeneous occurrences of evaporites are given an age of 208 Ma, and represent in a number of wells the oldest stratigraphic marker in the analysis.

The evaporites, consisting to a large extent of halite and gypsum alternated with shales, have considerable changes in thickness. The thicknesses are much more homogeneous in the southern than in the northern wells, where the evaporites are clearly associated with the presence of younger fault structures.

The Hettangian typically ends with a thin limestone member in the northern part of the area deposited under tidal flat conditions. During the Sinemurian shallow shelf carbonates were deposited in the north that to the central part of the basin laterally were exchanged for deeper shelf shales. From Pliensbachian to Aalenian laminated shales and lime/mudstones locally alternating with small amounts of marl were deposited in a large part of the area. To the extreme south and southeast of the basin
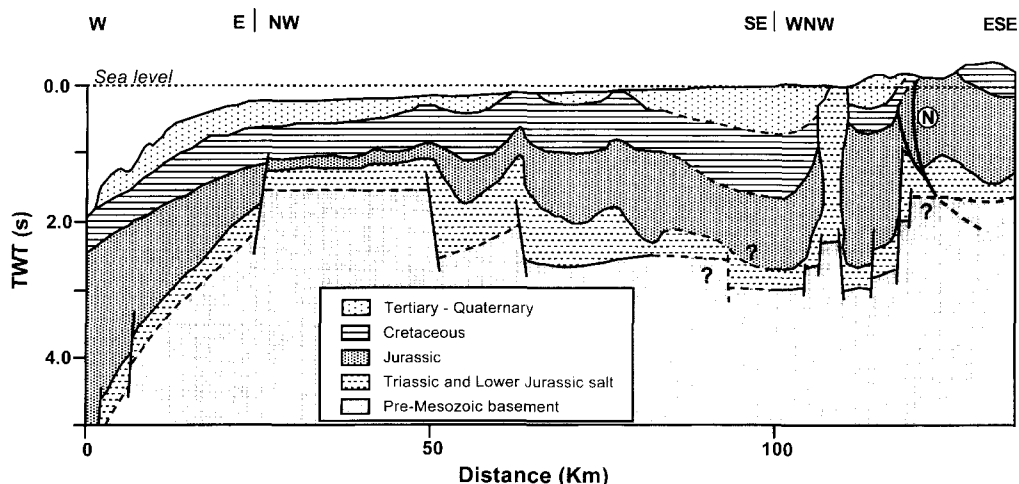
Fig. 3. A cross-section through the western Iberian margin obtained from a combination of seismic lines. Seismic interpretation was done by the Geological Survey of Denmark and Greenland (GEUS). N = Nazaré fault zone. For the coastline area, where no data are available, and for the area underneath the Nazaré fault zone the probable location of the basement is indicated with question-marks. Uncertain horizons are dashed. Location of the seismic sections in Fig. 2.

these deeper shelf deposits graded into shallow shelf carbonates.

During the Bajocian and Bathonian shallow marine conditions resulting in carbonate platforms became present in the region. These platforms extended into the basin from the eastern and western basin margins. In the central part of the basin deeper shelf limestones and marls were deposited during the Bajocian followed by shallow marine carbonate sediments during the Bathonian. During the Upper Callovian overall non-deposition conditions were established and part of the limestones and marls deposited during the early Callovian were removed. This resulted in an overall absence of Callovian sediments in the northern part of the basin and about 150 m thickness of the unit in the southern part. The non-deposition conditions extended into the Oxfordian resulting in locally developed karst surfaces.

The late Oxfordian begins with the deposition of lacustrine carbonates in the central part of the basin which grade into open marine and deeper marine conditions towards the south. The distinction between north and south becomes remarkably clear during this time span. Mean thicknesses for late Oxfordian sediments are about 300 m in the south while the northern part was almost sediment-starved. During the Late Jurassic an important phase of salt diapirism took place, resulting locally in erosion

of Middle Jurassic deposits and leading to differentiated sediment accumulation rates in the basin. In the analysed wells large accumulations of salt are accompanied by small sedimentation rates during the Late Jurassic and vice versa, indicating a strong control of salt movement on sediment accumulation rates. During the Kimmeridgian sediment accumulation rates considerably increased especially in the South Lusitanian basin. The northern part of the basin was subjected to terrestrial (fluvial) conditions during this time and marine influence increased towards the south. Shallow marine and coastal conditions were present in the central part of the basin and outer shelf sandstones and marls were deposited in the southeast. During the Portlandian these environments persisted, although the shallow shelf carbonates were predominant then in the southern part.

From the Portlandian onward sediment accumulation rates decrease, and during the Early Cretaceous there is almost no deposition on the margin. For the first time since the Early Jurassic sedimentation rates are quite homogeneous for the complete basin. During the Early Cretaceous continental and shallow marine conditions prevail in the area, associated with a number of unconformities that are, however, badly constrained in time. During the Cenomanian and Turonian an influx of shallow marine limestones

North Lusitanian Basin:

Water depth (m):

Marine influx

Terrestrial, shallow marine

Terrestrial

Terrestrial, fluviatile
Restricted marine

Shallow marine

Deeper marine

Tidal flat

Terrestrial, fluviatile

Limestones &
Dolomites

Shales &
Siltstones

Sandstones

Halite &
Anhydrite

Basement

South Lusitanian Basin:

Water depth (m):

Terrestrial, shallow marine

Shallow shelf

Outer shelf

Brackish lagoonal

Shallow marine
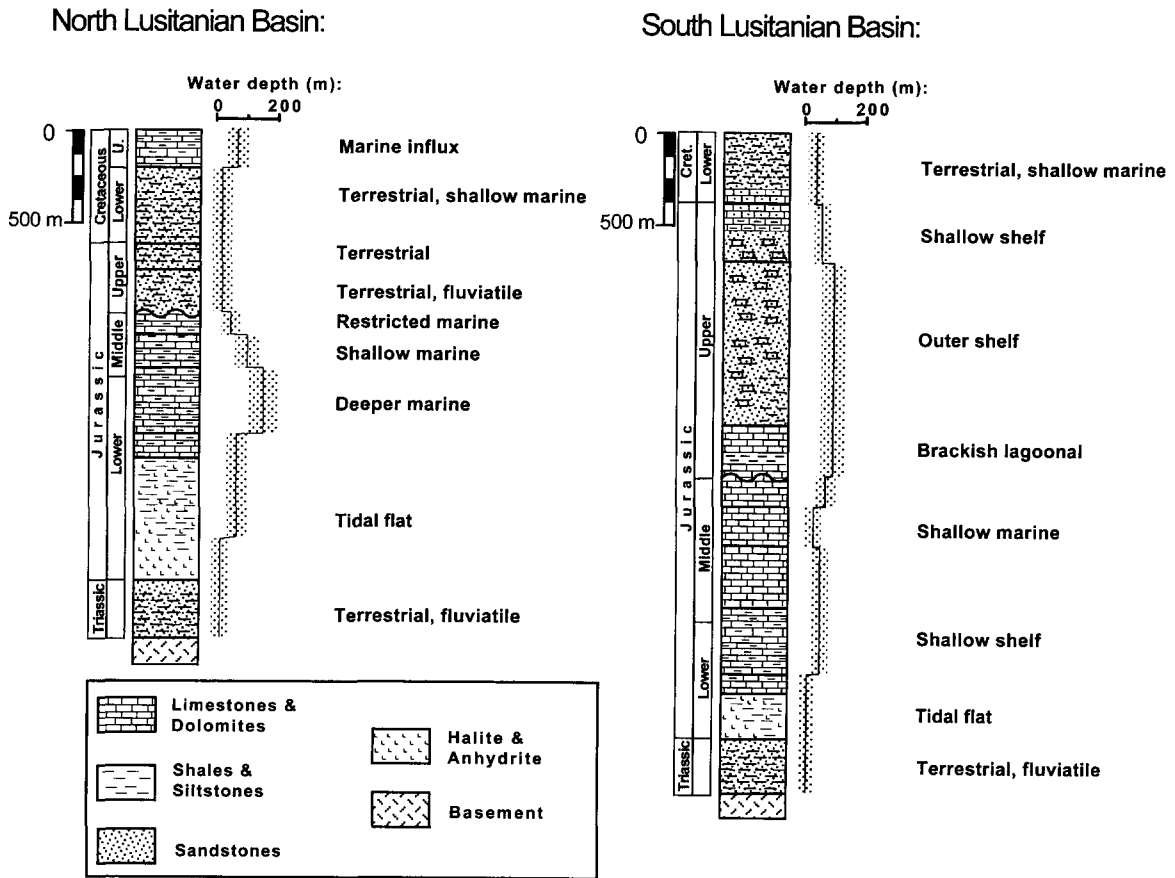
Shallow shelf

Tidal flat

Terrestrial, fluviatile

Fig. 4. Stratigraphic columns compiled from the well reports. Mean thicknesses were taken for the north and south part separately in order to show the different accumulation rates and depositional environments. The transition between these two areas is discussed in the text. Water depths estimated from paleo-environment maps (GPEP, 1986) together with uncertainty ranges are also indicated.

is recorded in a number of the wells. In most of the wells, however, the Cretaceous is not represented.

3. Subsidence analysis

The wells from the Lusitanian basin have been backstripped (Watts and Ryan, 1976; Steckler and Watts, 1978) adopting local isostasy to correct for the effect of sediment loading. Compaction corrected sedimentary records of the wells were used with application of the porosity–depth relationships according to Bond and Kominz (1984), constrained by sonic logs. Difference has been made for two depths, including a depth where the low-depth relationship takes over from the high-depth relationship. Furthermore, the timescale of Harland et al. (1990) was used.

Fig. 4 shows the minimum and maximum interpreted palaeobathymetry for the North and South Lusitanian basin during the Mesozoic. It also indicates the mean values that we adopted for our analysis. The depths are to a large extent constrained by wells 13C-1, 16A-1, 20B-1 and Bf-1. For these wells biostratigraphical well sheets exist indicating that depositional depths were never extremely deep for the basin. Water depths were interpreted for the whole study area with the aid of a compilation of palaeo-environments (GPEP, 1986). The depth estimations for the different environments are according to Ingle (1980). The palaeobathymetry curves show that after the continental environments of Late Triassic and Hettangian water depth is increasing during the Early Jurassic. This is followed by decreased water depths

during the Middle Jurassic, during which carbonate platforms developed in the South Lusitanian basin. The Late Jurassic shows considerable local changes in water depth which are, however, never exceeding 150 m. From Early Cretaceous onward the water depths are in general quite shallow.

Fig. 2 shows that the analysed wells are all situated in a zone 80 km wide, parallel to the coastline. The results that will be discussed are representative for this eastern (largely onshore situated) part of the basin only. The ocean–continent transition is situated at about 200 km offshore (Whitmarsh et al., 1993). Fig. 5 illustrates the effect of uncertainties in palaeobathymetry and porosity assumptions. The uncertainties in water depths are obviously negligible compared to the porosity uncertainties. Although not all the wells reach the Triassic sandstones or underlying basement, most of the wells reach the Upper Triassic–Hettangian salt deposits. Our analysis, therefore, is restricted to the subsidence of the basin since the beginning of the Jurassic. Another restriction of the data set is that a number of wells are located on local basement highs. Within these limitations, however, the analysed wells offer clear constraints on the development of the Lusitanian basin. Fig. 6 gives an overview of the tectonic subsidence curves for all the analysed wells. The tectonic

subsidence curves are displayed in the proper geographical context. This means that the left side of the figure indicates the westernmost wells and the right side displays the easternmost wells. Within each column the wells are arranged from north at the top to south at the bottom. The chronostratigraphic horizons for each well are indicated by crosses.

Almost all the wells record the Early Jurassic continental rifting phase. The wells that contain the Hettangian evaporites show that their initial tectonic subsidence is to a large extent controlled by the large variations in thickness of this unit. However, while most of the wells have the evaporites as their lowermost unit, the top of these deposits is the lowermost chronostratigraphic horizon in the analysis and thickness variations are not taken into account in the tectonic subsidence. The better defined wells (for example 17C-1 and 13C-1) indicate stretching during the Sinemurian and Pliensbachian, with a subsequent thermal subsidence of the basin. A remarkable deviation is present in the southernmost wells, where a hiatus represents the uppermost Early Jurassic. While only 50 km to the north the sediments indicate deep marine environments, a local uplift and associated erosion must have taken place before the earliest Middle Jurassic.

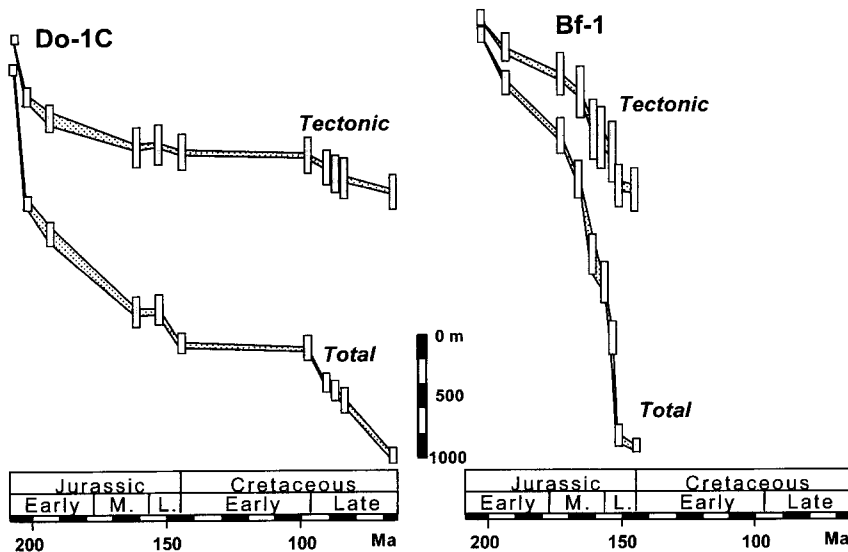During the Middle Jurassic differentiated vertical

Fig. 5. Tectonic and total subsidence curves for two wells indicating the uncertainty in paleobathymetry (grey area) and in porosity estimates (error bars).

motions take place in the Lusitanian basin, and distinct differences between the northern and southern part of the basin become evident. In the North Lusitanian basin wells only record small tectonic subsidence rates, or are represented by hiatuses during this time. This is in contrast to the South Lusitanian basin where considerable tectonic subsidence is recorded. The boundary between these two different subsidence domains coincides with the Nazaré fault zone, and our analysis suggests that from Middle Jurassic onward this Nazaré zone had a strong control on the Lusitanian basin development.

Overall rifting of the area was established during the Late Jurassic and Early Cretaceous, with vertical motions again being more pronounced to the south of the Nazaré zone. The tectonic subsidence curves of Fig. 6 show basin subsidence in the northern- and southernmost wells during this time span. In the middle part of the basin, to the south of the Nazaré zone, the wells do not contain the complete subsidence record of this Late Jurassic–Early Cretaceous phase. During the latest Cretaceous and Tertiary the basin became subjected to compressive forces and as a consequence the basin became uplifted with the pronounced development of an inverted zone. The Nazaré zone was reactivated as a major reverse fault during this deformation phase (Ribeiro et al., 1990a). The erosion associated with this uplift has removed for a large number of well locations the Cretaceous and part of the Late Jurassic record. A complicating factor for the Early Cretaceous is that the deposits during this time slice consist of terrestrial sandstones that are extremely difficult to date. Most of the wells that contain Early Cretaceous sands are constrained only by the stratigraphic markers at the top and the bottom of this unit, and as a consequence the information is very incomplete. The overall vertical motions, however, appear to be quite homogeneous for the Early Cretaceous, suggesting that somewhere during this time span the transition from synrift to postrift takes place. This observation is in close agreement with the generally held view that separation of Galicia and the Grand Banks of Newfoundland was established at 118 Ma (Boillot et al., 1989).

The Late Cretaceous is only documented in the wells to the north of the Nazaré zone and one well (Ms-1) in the south. The wells indicate a third phase of tectonically induced vertical motions. The movements during this time are obviously small compared to the two preceding phases that recorded the rifting and thermal development of the western Iberian margin.

4. Stretching factors

Stretching factors have been estimated for the 26 wells where possible. To this aim, we have examined constraints on the thermo-mechanical structure of the pre-stretched lithosphere. The Iberian Massif outcropping to the east of the Lusitanian basin is generally subdivided into a number of tectonometamorphic zones (Julivert et al., 1972) of which the Central Iberian Zone and the Ossa-Morena Zone are of primary interest to this study (Fig. 8). The contact between these two zones consists of a major fault zone (the Coimbra–Cordóba shear zone (Burg et al., 1981)) which may represent either a Cadomian or a Variscan suture (see Azor et al., 1994, for a discussion). When Mesozoic extension started, the Variscan basement consisted of differently structured lithospheric blocks within which the Variscan fault zones were subsequently reactivated. The present-day Iberian crust seems to have a thickness similar to mean European Variscan crust as described in Cloetingh and Burov (1996). The ILIHA DSS Group (1993) report crustal thicknesses of 28 km directly to the north of the Lusitanian basin and 30 km near Lisbon. Crustal thicknesses for the Iberian plate decrease to values below 10 km towards the ocean–continent transition to the west (Whitmarsh et al., 1993) and increase to values of about 32 km beneath the Iberian Massif to the east (ILIHA DSS Group, 1993). The pre-rift crustal thickness is assumed by us to correspond roughly to the present-day value of the crustal thickness of Variscan Iberia and is taken to be 32 km here (following assumptions in Salas and Casas (1993) and Van Wees and Stephenson (1995)). The pre-stretched Variscan lithosphere has a thermo-tectonic age of about 170 Ma at the onset of Lusitanian basin formation during the Late Triassic (Ribeiro et al., 1990b; Beetsma, 1995). For this thermo-tectonic age an estimate of about 125 km thickness for the pre-rift lithosphere is obtained.

Fig. 7 displays for three wells the fitting of stretching factors to the subsidence curves. A num-
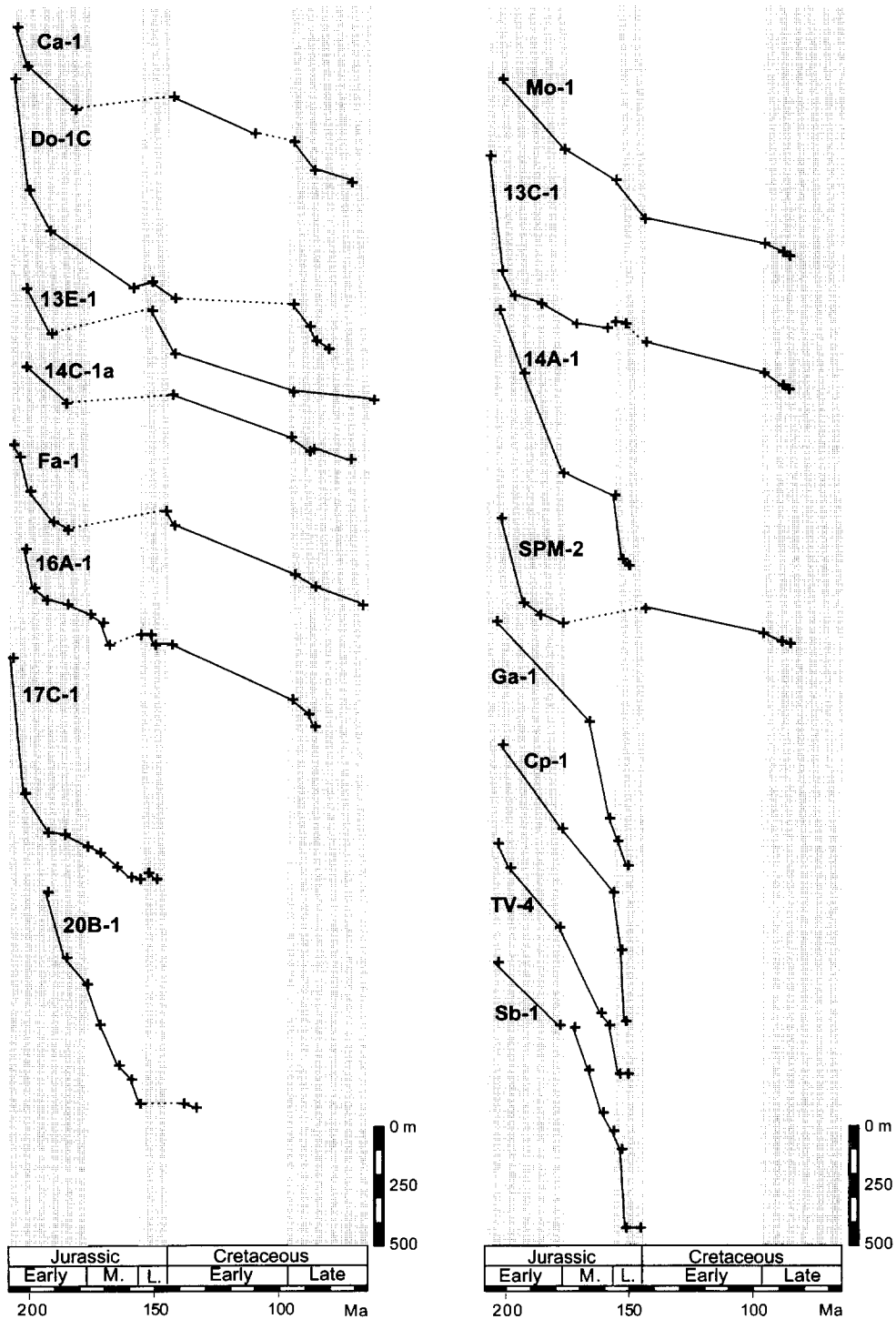
Fig. 6. Tectonic subsidence curves for the 26 analysed wells in the eastern part of the Lusitanian basin. The curves are arranged horizontally from west to east and vertically from north to south. The chronostratigraphic horizons are indicated by crosses and different time units are shaded to simplify comparison of the curves.
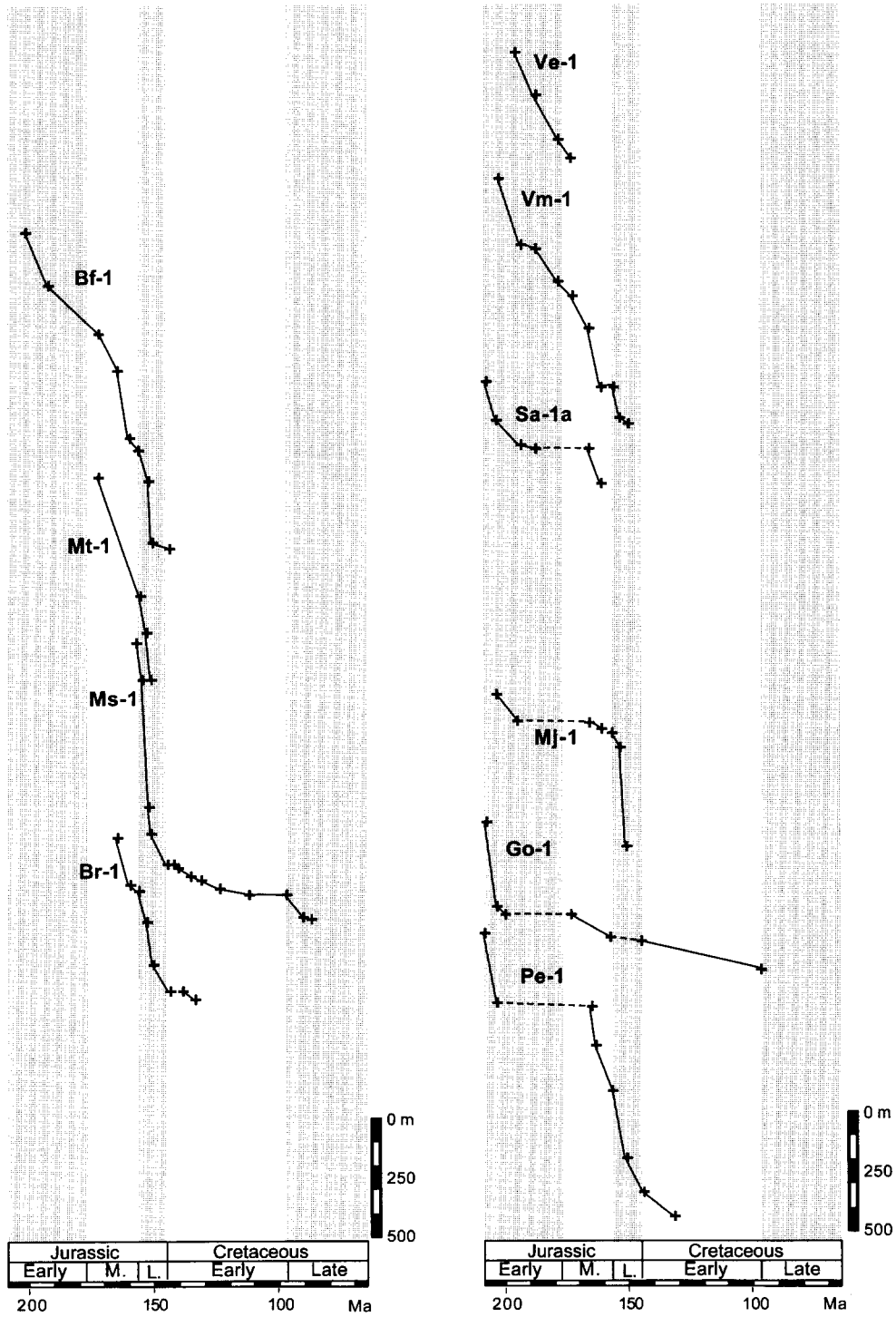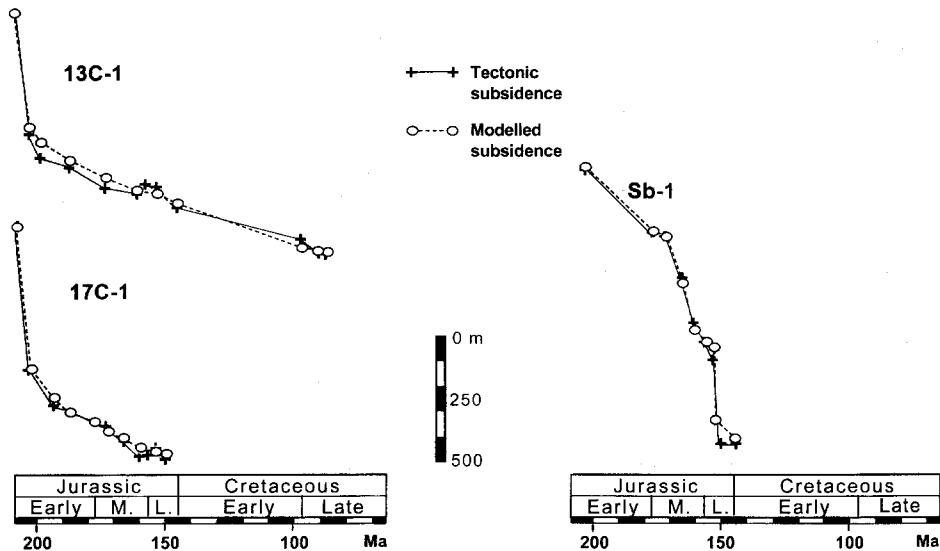
Fig. 6. Continued.

Fig. 7. Three examples of the fitting of stretching estimates to the tectonic subsidence curves (see text for discussion).

ber of wells, especially in the North Lusitanian basin, can be fitted by two stretching events, similar to well 13C-1. The first stretching phase, which has a stretching factor of 1.17 for well 13C-1, has a period of rapid stretching during the Early Jurassic followed by thermal subsidence until the beginning of the Late Jurassic. During the Late Jurassic and Early Cretaceous a second stretching phase of 1.02 was fitted to the data. Well 17C-1 and Sb-1 in Fig. 7 are indicative for a number of wells that deviate from this general pattern. Well 17C-1 is situated in the zone that became inverted during the Late Cretaceous and Tertiary. Erosion removed the uppermost Jurassic and Cretaceous sedimentary record, and the subsidence curve can be explained by a single Early Jurassic event with a stretching factor of 1.22 and subsequent thermal subsidence. Well Sb-1 is representative for most wells in the South Lusitanian basin that cannot be explained reasonably with only two stretching phases. After the Early Jurassic event with a stretching factor 1.06, well Sb-1 records a second stretching event during the Middle Jurassic with a factor 1.10 followed by a third event also of 1.10 during the Late Jurassic. Inspection of Fig. 6 demonstrates that almost all the wells to the south of the Nazaré zone record this Middle Jurassic stretching phase, while northern wells (like 13C-1, for example) can reasonably be explained by ther-

mal subsidence or are represented by unconformities during the Middle Jurassic. Well Sb-1 is situated in the inverted zone and had probably, like 17C-1, its Cretaceous stratigraphic record removed by erosion.

Fig. 8 summarizes the estimated stretching factors for the analysed part of the basin for the Early Jurassic and the Late Jurassic to Early Cretaceous stretching events. The continental rifting phase during the Early Jurassic (Fig. 8) is characterized by the same order of stretching factors for the whole area, although some large local deviations do exist. However, not all the wells reached basement and the different lowermost chronostratigraphic horizons have to be taken into account for this. Furthermore, the stretching estimates are influenced by the Late Jurassic salt movement, which scatters the Early Jurassic picture. The stretching factors during the Middle Jurassic are quite homogeneous for the South Lusitanian basin with a small deviation around 1.08. The North Lusitanian basin did hardly experience tectonic subsidence during the Middle Jurassic phase. For the Late Jurassic to Early Cretaceous phase, which is recorded on a basinwide scale again, a difference in estimated stretching factors is visible for the northern and the southern part of the area (Fig. 8, right). The northern part of the basin has stretching factors of about 1.03 and the southern part of the area has stretching factors of about 1.08. For wells
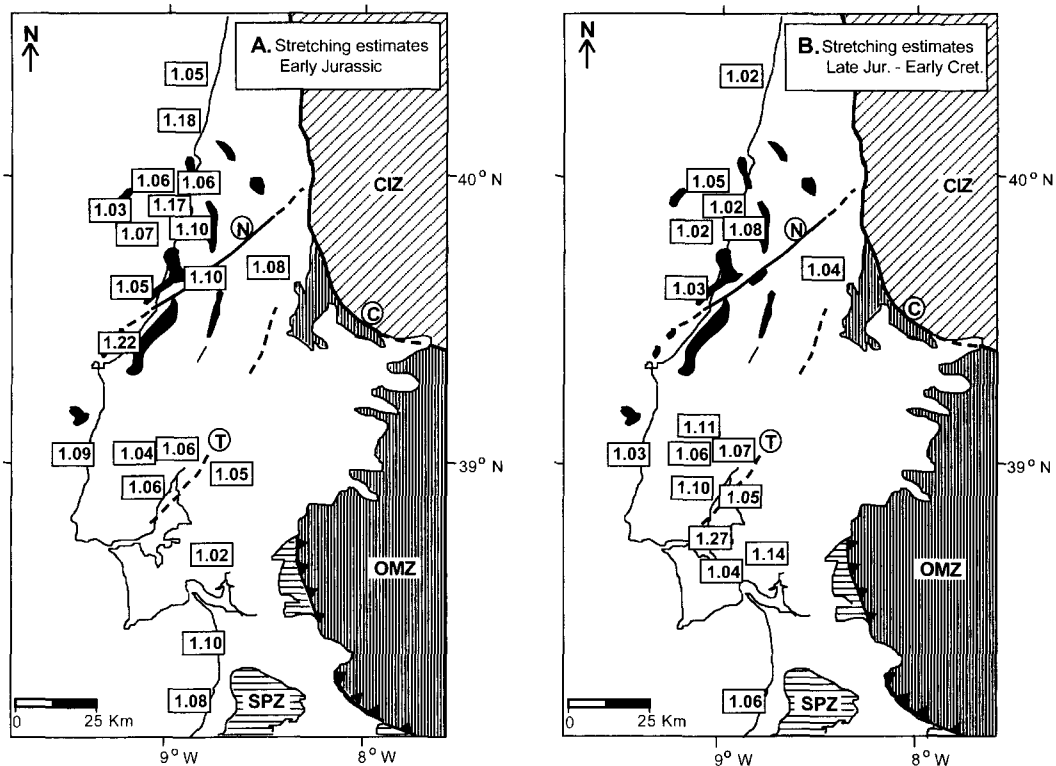
Fig. 8. Estimated stretching factors for two of the three distinguished phases together with main aspects of the Lusitanian basin tectonic setting. CIZ = Central Iberian Zone; OMZ = Ossa-Morena Zone; SPZ = South Portuguese Zone; C = Coimbra–Cordóba shear zone; N = Nazaré zone; T = Tagus fault. Major diapiric structures are indicated in black. Left: Early Jurassic continental rifting phase. Right: Late Jurassic–Early Cretaceous synrift phase.

that are situated in the zone that was inverted during the Cenozoic the factors only represent minimum estimates, while erosion has removed part of the sedimentary record. As mentioned above, the difference between the north and south part of the basin roughly coincides with the Nazaré zone. The north–south differences during the Middle Jurassic to Early Cretaceous could be explained by differences in thickness or density structures of the underlying crust, with thinner continental crust or a higher crustal density for the area to the south of the transition zone. In this context the Nazaré zone could very well represent an inherited Variscan weakness zone.

The inferred stretching factors are generally low. However, in the framework of the opening of the North Atlantic the estimates are quite reasonable. Srivastava and Verhoef (1992) estimate from their studies of the restoration of plates a 30% space reduction for the Lusitanian basin. Furthermore, it is

generally assumed that the basement directly to the east of the study area did not experience significant extensional basin development. While the area under discussion is situated quite near these basement outcrops and relatively far from the present-day ocean–continent transition, the estimates will probably approximate the real stretching factors reasonably well. The low stretching estimates thus support the notion that the eastern part of the Lusitanian basin forms the distal part from the area where the continental breakup with Grand Banks was established.

5. Comparison with subsidence characteristics of other Mesozoic basins of Iberia

The subsidence history of the Lusitanian basin clearly is controlled by the opening of the Atlantic Ocean. In Fig. 9 our results are summarized by backstripping curves for the synthetic stratigraphic
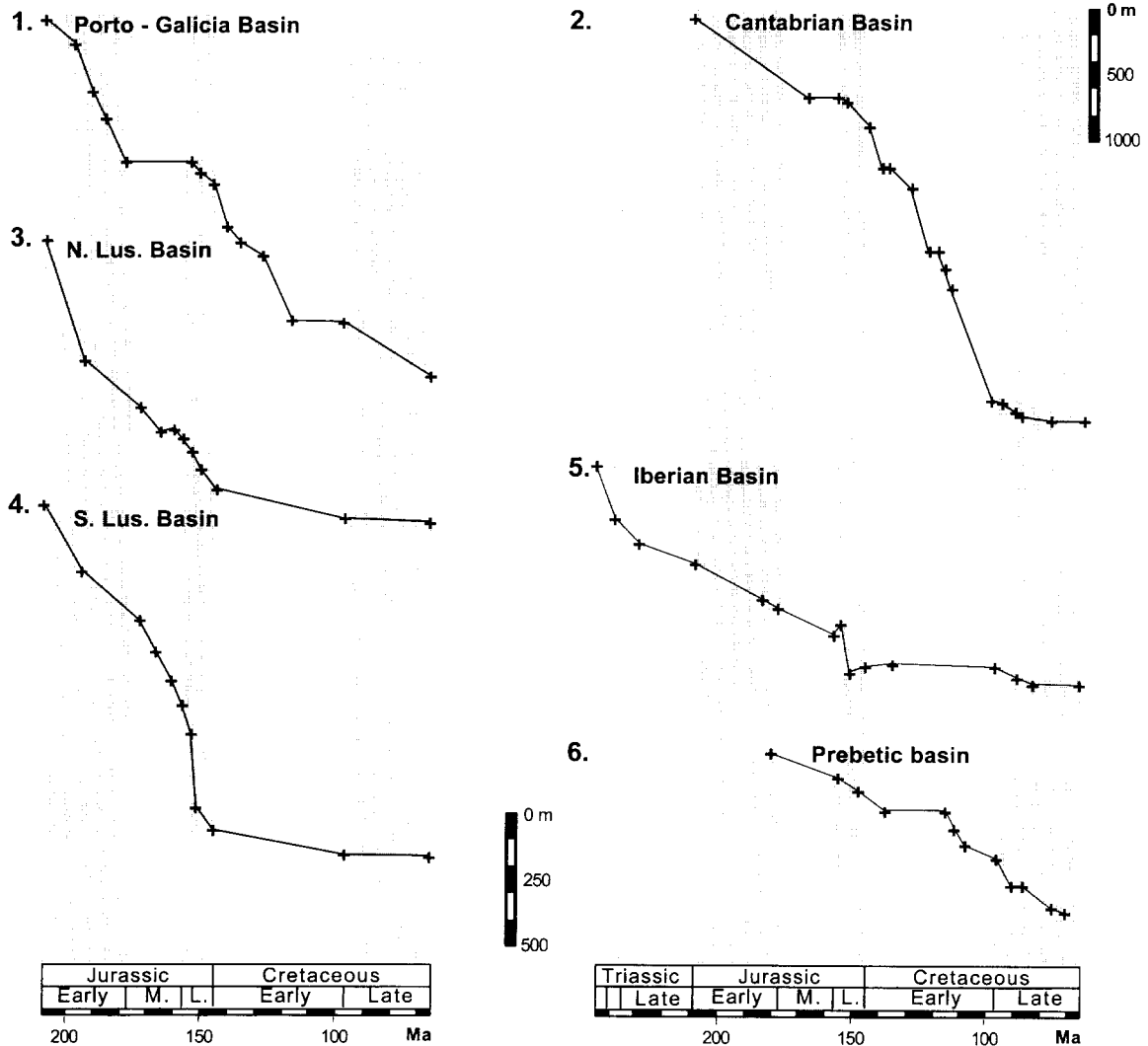
Fig. 9. Comparison of two subsidence curves based on the synthetic columns of Fig. 4 (curves 3 and 4) with subsidence curves from neighbouring basins of Iberia. The curve for the Cantabrian basin (2) is taken from Hiscott et al. (1990), the Iberian basin curve (5) is from Van Wees and Stephenson (1995) and the Prebetic basin (6) is from De Ruig (1992). The vertical scale is as indicated in the middle of the figure except for the Cantabrian basin which has the scale displayed to the right of the curve. Different time units are shaded to simplify comparison of the curves.

columns of Fig. 4, which visualize the subsidence history of the area under discussion quite well. These curves can be placed in a more regional context by correlating the Mesozoic tectonic pulses with the neighbouring basins of the Iberian Peninsula (Fig. 1). Inspection of Fig. 9 suggests that regional subsidence pulses do not directly stand out with respect to deviations due to local factors. However, from studies of

the different basins of Iberia it is clear that the curves do reflect the regional tectonic setting. In the following, the timing of the Triassic phase of continental rifting, the overall present Callovian to Oxfordian hiatus, the south to north shift of synrift motions and the response to the opening of the Bay of Biscay will be discussed.

The timing of the Triassic continental rifting

phase is badly constrained in all the Mesozoic basins of Iberia. Sopeña et al. (1988) describe a system of pull-apart basins that originated in Late Permian and Early Triassic with the Iberian and Cantabrian basins containing the oldest sediments unconformable on Variscan basement. In the Prebetic the basin development started probably a little later during the Early or Middle Triassic (Sopeña et al., 1988). In the western part of the Iberian Peninsula the oldest sediments lying unconformably on Variscan basement are of Late Triassic or even Early Jurassic age, but were never dated in detail. The same starting point for sedimentation is also described by Jansa et al. (1980) for the Grand Banks. The lack of information on this first phase of extensional motions, that lasted more or less until the Sinemurian, hampers any regional interpretation that goes farther than the probable shift in time of the Triassic initial motions from east to west. In general the motions during this time span are thought to be related to the progression of the Tethys rift system (Ziegler, 1989). The timing and kind of subsidence from Sinemurian to Bathonian also differs from basin to basin. In the foregoing it has been pointed out that vertical motions in the South Lusitanian basin indicate a stretching phase during the Middle Jurassic. Salas and Casas (1993) describe a Middle Jurassic postrift stage for the Iberian basin and De Ruig (1992) describes a phase of rifting during the Pliensbachian for the Prebetic basin. From Fig. 9 it appears that the Porto-Galicia basin has a hiatus during the Middle Jurassic, similar to the non-deposition conditions that were described for the northernmost Lusitanian wells.

Homogeneous vertical motions begin to take place from Callovian onward on the Iberian continent. During the Callovian and earliest Oxfordian a hiatus is present in all the Mesozoic basins of Iberia that is associated with karstified surfaces. This hiatus represents an overall change in depositional environments (Hiscott et al., 1990). During the Middle Jurassic carbonate deposition was established in all the basins of the Iberian continent. The sedimentation during the Late Jurassic involves a substantial supply in clastic sediments on the western and eastern side of the Iberian Massif (Ziegler, 1989; Salas and Casas, 1993). Ziegler (1989) relates this to an important uplift and eastward tilting of Iberia during this time span. In general subsidence took place

rapidly compared to the previous motions and was associated with fast changing depositional environments and a number of unconformities (Hiscott et al., 1990).

From Fig. 9 a shift in time of the synrift motions can be deduced for the western Iberian margin from Middle Jurassic to Early Cretaceous. The Porto-Galicia basin is subjected to extensional stresses more or less at the Jurassic–Cretaceous boundary in contrast with the Lusitanian basin which is subsiding already during the Kimmeridgian and has to the south of the Nazaré zone also considerable subsidence during the Middle Jurassic. The Cantabrian basin shows a timing similar to the Porto-Galicia basin and in the Prebetic basin Late Jurassic subsidence represents the main rift phase (Peper and Cloetingh, 1992). In general it seems that the synrift motions were recorded earlier in the south of the Iberian continent than in the north. For the Iberian basin this synrift phase is difficult to trace while vertical motions increased more slowly.

During the Early Cretaceous, the Porto-Galicia and Cantabrian basins are under influence of the opening of the Bay of Biscay. This opening resulted especially for the Cantabrian basin in fast subsidence rates. The other basins on the Iberian continent are subjected to the thermal component of the Middle and Late Jurassic stretching, except for the Prebetic basin, which also records a phase of subsidence from Aptian onward which is probably related to motions in the Mediterranean (De Ruig, 1992).

6. Discussion and conclusions

Subsidence analysis of the Lusitanian basin shows that Mesozoic sedimentation is to a large extent influenced by a three-fold subdivision of vertical motions. The first episode resulted in continental rifting of the Variscan basement from Late Triassic until the Hettangian. The sediments were deposited in locally developing grabens of which the exact orientation is difficult to trace. Several authors (e.g., Wilson et al., 1989; Ribeiro et al., 1990a) have stated that Variscan weakness zones exerted a major control on the location of the continental basins. The conditions of the pre-rift crust are important controls on the location of the basin development that are however extremely difficult to qualify. On the regional scale

of the Iberian continent the continental rifting started earlier and is more pronounced to the east than to the west.

The second and third episodes of rifting would ultimately lead to crustal separation between Iberia and Grand Banks. These motions are expressed in a well pronounced different behaviour of the South and North Lusitanian basin from Middle Jurassic to Early Cretaceous. During the Middle Jurassic tectonic subsidence took place in the South Lusitanian basin, while the northern part was uplifted and was probably subjected to erosion. During the Late Jurassic and Early Cretaceous this north–south difference is expressed by larger stretching factors to the south. On a regional scale, subsidence of the different Iberian basins supports a south to north migration of the synrift extensional phase, that would be followed during the Cretaceous by a south to north migration of the final breakup. Wilson et al. (1989) relate the existence of the Nazaré weak zone to both the different timing and different subsidence histories of the North and South Lusitanian basin. Our analysis suggests that the control of the weak zone on differences in vertical motions is much more important than its control on the timing of breakup.

The exact behaviour of the Nazaré zone during the Mesozoic in association with the observed differences in subsidence rates is of special interest. Wilson et al. (1989) suggest that the zone behaved as a major transfer fault during the Mesozoic and relate the difference in subsidence rates to different fault configurations of the two sections. J.C. Kullberg (pers. commun., 1995) concluded from detailed tectonic studies on the Nazaré fault zone that the sense of movement during the opening of the Lusitanian basin had an oblique slip direction with both a left-lateral and an extensional component. This is in agreement with the general reconstruction picture presented by Srivastava and Verhoef (1992) in which they observe that at North Atlantic closure time the Nazaré zone was co-linear with the northeastern edge of the Bonavista platform that behaved as a major extensional fault during the Mesozoic. In the foregoing we have suggested a different composition or thickness of crustal blocks as an alternative hypothesis to explain the different subsidence rates. According to this new explanation, the crust to the south of the fault zone probably would be thinner

than the crust to the north of it. Thinner crust to the south also offers a reasonable explanation for the Late Cretaceous–Early Tertiary volcanism and emplacement of granites that only occurs to the south of the Nazaré zone. This alternative explanation implies that the Nazaré zone was not necessarily reactivated as a zone with left-lateral displacement only, but could have accommodated significant extensional movement during the Mesozoic as well.

Acknowledgements

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