AMMONITES FROM LUMPY LIMESTONES IN THE LOWER PLIENSBACHIAN OF PORTUGAL: TAPHONOMIC ANALYSIS AND PALAEOENVIRONMENTAL IMPLICATIONS

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Abstract: Preservational features of ammonites recorded in the Lower Pliensbachian lumpy limestones of the Lusitanian Basin confirm the deep marine origin previously established for this facies. These deposits can be subdivided into three main taphofacies which are distinguished by preservational ammonite features: 1) lumpy limestones and marly intervals with reelaborated ammonites, 2) laminated marls and bituminous shales with accumulated ammonites, and 3) homogeneous limestones with resedimented ammonites. The background sedimentation of suboxic (dysaerobic, bioturbated lumpy muds; taphofacies 1) to anoxic conditions (anaerobic, laminated muds; taphofacies 2) on deep zone was interrupted by depositional events related to distal gravity flows (taphofacies 3). Lumpy limestones containing reelaborated ammonites, and showing gradational boundaries and inverse grading developed in deep environments due to sedimentary starving. The stratigraphic intervals of taphofacies 1 represent the lowest values of sedimentation and accumulation rates. Taphofacies of type 1 alternate with taphofacies of type 2 composing stratigraphic cycles of metric order. Such cycles resulted from cyclical environmental changes of hundreds of thousands of years. Deepening episodes of 4^{th}-order led to the development of dysaerobic to anaerobic environments, whilst subsequent shallowing episodes increased the levels of bottom oxygenation.

Key words: applied taphonomy, sequence stratigraphy, ammonites, taphofacies, carbonate platforms, environmental cycles, palaeobathymetry, Lower Jurassic, Lusitanian Basin, Iberia.

Resumen: Las características tafonómicas de los ammonites registrados en las calizas grumosas del Pliensbachiense inferior de la Cuenca Lusitana confirman el origen marino profundo previamente establecido para esta facies. Estos depósitos pueden ser subdivididos en tres tafofacies principales que se distinguen por las características tafonómicas de los ammonites: 1) calizas grumosas e intervalos margosos con ammonites reelaborados, 2) margas con laminación paralela y margas bituminosas con ammonites resedimentados, y 3) calizas homogéneas con ammonites resedimentados. La sedimentación de fondo en ambientes marinos profundos, que lateralmente pasaba de condiciones subóxicas (en los de lodos grumosos, bioturbados y disaeróbicos; tafofacies 1) a anóxicas (en los lodos laminados y anaeróbicos; tafofacies 2), estuvo interrumpida por eventos deposicionales debidos a flujos distales de gravedad (tafofacies 3). Las calizas grumosas con ammonites reelaborados, que presentan límites gradacionales y granoclasificación inversa, se formaron en ambientes marinos profundos, debido al déficit de aporte de sedimentos. Los intervalos estratigráficos de esta tafofacies 1 representan los menores valores de tasa de sedimentación y de velocidad de sedimentación. Las tafofacies de tipo 1 alternan con las tafofacies de tipo 2 constituyendo ciclos estratigráficos, de escala métrica, que son el resultado de modificaciones ambientales cíclicas de cientos de miles de años. Durante los episodios de profundización de 4° orden se desarrollaron ambientes disaeróbicos a anaeróbicos, en tanto que durante los subsecuentes episodios de somerización aumentaron los niveles de oxígeno en los sedimentos del fondo.

Palabras clave: tafonomía aplicada, estratigrafía secuencial, ammonites, tafofacies, plataformas carbonáticas, ciclos ambientales, paleobatimetría, Jurásico Inferior, Cuenca Lusitánica, Iberia.

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Lumpy limestones and bituminous shales occur within the Lower Jurassic deposits of the Lusitanian Basin, especially in some localities along the present day coastline from Peniche to Brenha, North of the river Tagus. The lithofacies of lumpy limestones is very common in the Lower Pliensbachian of the Lusitanian Basin, having been studied at Peniche, S. Pedro de Moel, Coimbra, Rabaçal and Brenha (Fig. 1A). Deposits of this lithology are known as "Vale das Fontes marls and marly limestones" at the lower portion of the Quiaios Formation (Soares *et al.* 1993). The term Brenha Formation (Fig. 2) was first used in lithostratigraphic schemes developed during petroleum exploration in the 1970s, and then employed in some papers (Wright & Wilson, 1984; Wilson *et al.*, 1989; Watkinson, 1989). The Brenha Formation is a distinctive stratigraphic unit of Early and Middle Jurassic age, showing a strongly diachronous (Sinemurian-Pliensbachian) lower boundary. Previous studies on these lumpy limestones were predominantly focussed on biostratigraphy (cf. Mouterde, 1955, 1967; Mouterde, Dommergues & Rocha, 1983; Phelps, 1985; Dommergues, 1987), though sedimentological aspects have also been discussed (Hallam, 1971, 1986; Dommergues *et al.*, 1981; Wright & Wilson, 1984; Dromart & Elmi, 1986; Elmi *et al.*, 1988; Watkinson, 1989; Soares *et al.*, 1993; Parkinson, 1996). In the present study attention has mainly been focussed on the section of Peniche, although some of the figured specimens come from the outcrop of Brenha. The purpose of this study is to carry out a taphonomic analysis of the ammonites preserved in this limestones, in order to assess the palaeoenvironmental implications.

Ammonite taphonomy

The stratigraphical succession analysed consists of over 20 m of limestones and shales, exposed along the cliffs of the northern side of the Peniche peninsula (Fig. 1B). This succession is of Early Pliensbachian age (Mouterde, 1955; Dommergues, 1987; Elmi *et al.*, 1988). The succession is formed by thin, heavily bioturbated limestones, alternating with thicker and weaker bioturbated, marly intervals (Fig. 3). Limestone intervals comprise mudstone to wackestone with recrystallized bioclasts (ammonoids, brachiopods, belemnites, thin shelled gastropods, spicules of sponges, bivalves, radiolaria, ostracods, fragments of echinoderms and algae). Carbonized wood fragments of centimetric size are also present. *Chondrites* and other bioturbation structures are common. Marly intervals include lump levels, alternating with laminated mudstones and shales.

The lumps included in the limestone beds and marly intervals are micritic, calcareous concretions, subspherical and angular in shape, millimetric or centimetric in size. Sometimes several lumps are clumped together to form larger concretions up to 3 cm diameter. Contacts between lumps and matrix are sharp and well defined in marly intercalations, but may be gradational in some limestone levels. These concretions may be aligned on certain sedimentary surfaces. Some lumps are covered by micritic laminae as cryptalgal oncolite structures (Elmi *et al.*, 1988). These concretions are not represented in the bituminous shales.

Ammonite fossils are recorded throughout the studied sections, and they locally show little size. The degree of ammonite packing (estimated by the difference between the number of specimens and the number of fossiliferous levels divided by the number of fossiliferous levels) and

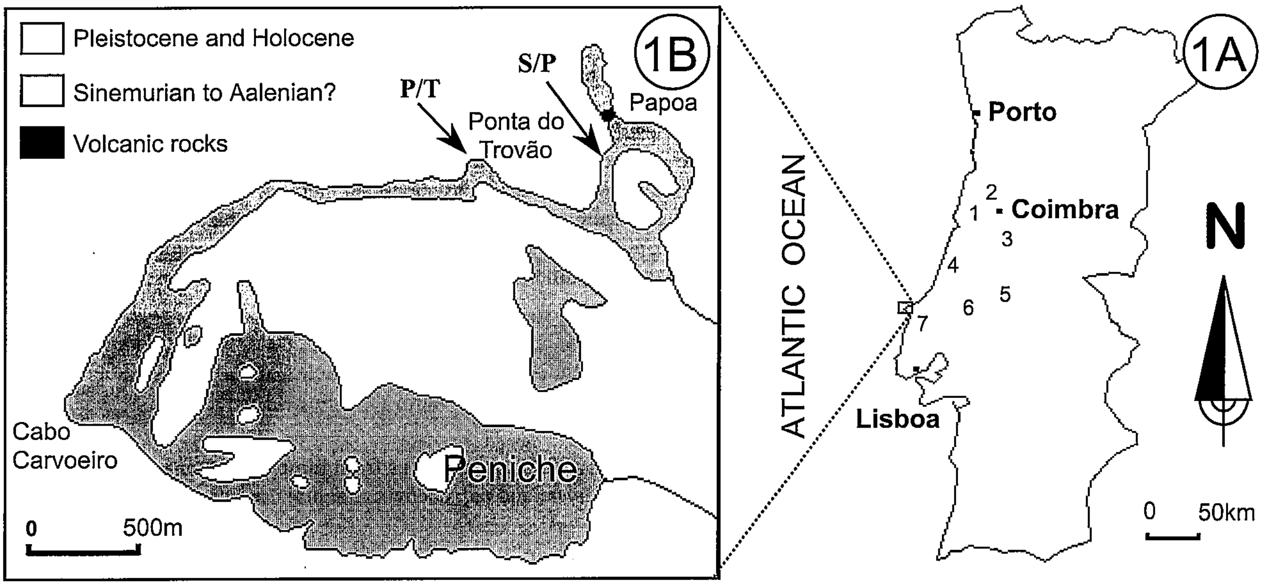

Figure 1.- A) Location map of the main sections of Vale das Fontes marls and marly limestones (Quiaios Fm.) in the Lusitanian Basin (1 - Brenha, 2 - Coimbra, 3 - Rabaçal, 4 - S. Pedro de Moel, 5 - Tomar, 6 - Porto de Mós, 7 - Peniche). B) Geological map of the Lower Jurassic in the Peniche Peninsula (S/P - Sinemurian/Pliensbachian boundary; P/T - Pliensbachian/Toarcian boundary).

the ammonite stratigraphical persistence (proportion of fossiliferous levels) display high values. Ammonite shells and internal moulds normally appear scattered in the sediment, showing no pattern of imbricated or encased regrouping. The aragonitic shells have been dissolved. Moldic porosity is completely filled by spar cement.

The studied Pliensbachian deposits can be subdivided into three main taphofacies, distinguished by the preservational features of the ammonites: 1) lumpy limestones and marly intervals with reelaborated ammonites, 2) laminated marls and bituminous shales with accumulated ammonites, and 3) homogeneous limestones with resedimented ammonites.

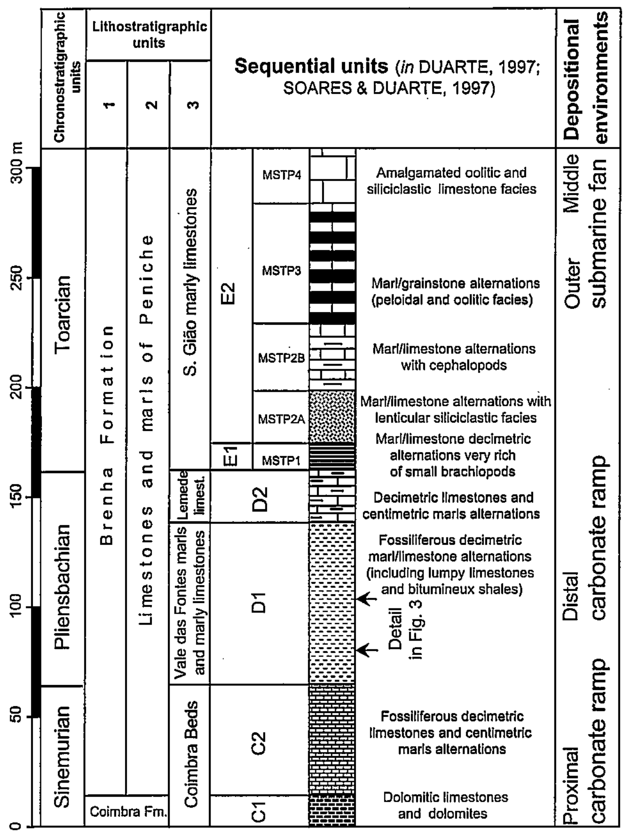

Figure 2.- Diagrammatic section of the Lower Jurassic in the Peniche Peninsula: lithostratigraphic units (1 and 3 for all the Lusitanian Basin; 2 - sector of Peniche in Carta Geológica de Portugal, 1992), facies and depositional environments.

Taphofacies 1: Lumpy limestones and marly intervals with reelaborated ammonites

Deposits of this taphofacies are composed by mudstone to wackestone beds ranging in thickness from 5 to 40 cm, and marly intervals from 10 to 50 cm. Dominant colours are yellowish or greyish. Lump size ranges from 2 to 40 mm (Fig. 4). Structures of bioturbation of centimetric size are abundant. Tubular and narrow (1-3 mm diameter), pyrite-filled burrows with various orientations are common. The boundaries of lumpy limestones are commonly gradational, but the base in some beds is sharper than the top. Lumpy limestones may grade laterally into marly intervals containing concretions. The concretions are scattered fairly uniformly through

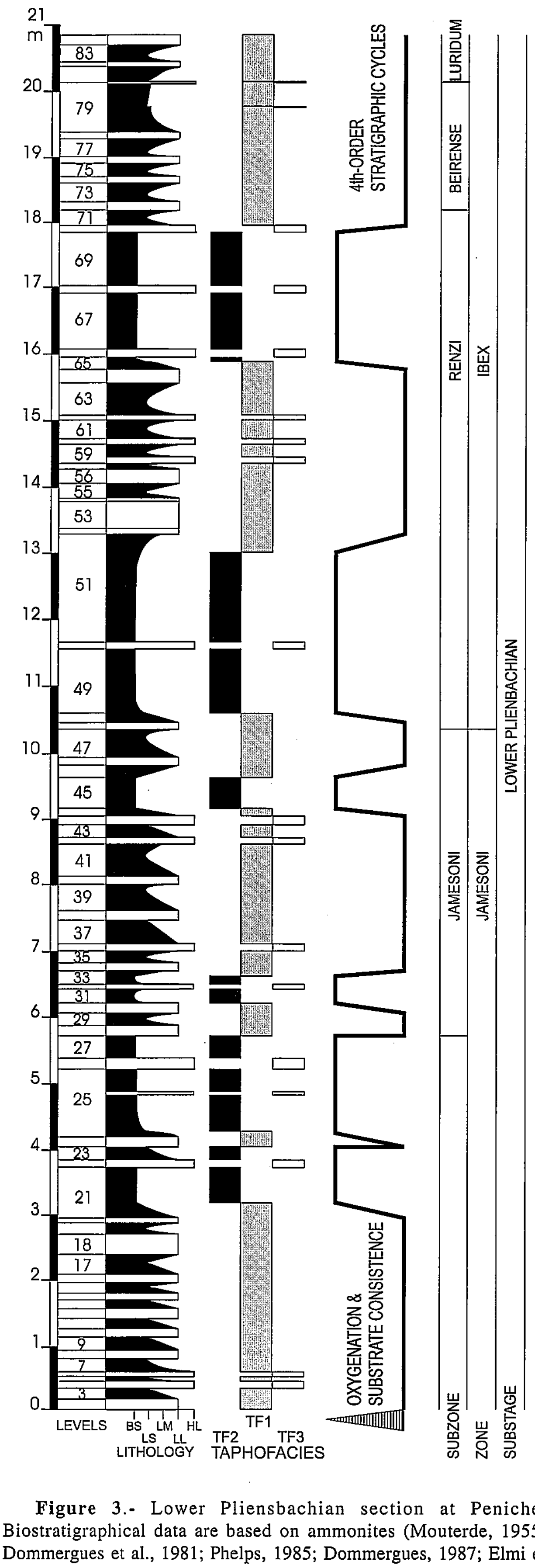

Figure 3.- Lower Pliensbachian section at Peniche. Biostratigraphical data are based on ammonites (Mouterde, 1955; Dommergues et al., 1981; Phelps, 1985; Dommergues, 1987; Elmi et al., 1988). BS = Bituminous shales; HL = Homogeneous limestones; LL = Lumpy limestones; LM = Lumpy, marly intervals; LS = Laminated marls; TF1 = Taphofacies of type 1; TF2 = Taphofacies of type 2; TF3 = Taphofacies of type 3.

limestone intervals. However, they can be sorted in marly intervals. Concretions of marly intervals show distribution grading, also (*i.e.*, gradual variation, in a progressively upward direction within a marly interval, of the upper concretion-size limit; Fig. 5). Gradual size-reduction or normal grading of concretions is more common than gradual size-increase or inverse grading, in these marly intervals.

Recorded associations of ammonites in this taphofacies are dominated by reworked elements (*i.e.*, reelaborated and resedimented elements *sensu* Fernández-López, 1991). Accumulated elements, showing no evidence of removal after laying on the sea-bottom, are very scarce or absent. Reelaborated internal moulds (*i.e.*, exhumed and displaced before their final burial) may be dominant (Fig. 6). Resedimented shells, displaced on the sea-bottom before their initial burial, are locally common. The degree of removal (*i.e.*, the ratio of reelaborated and resedimented elements to the whole of recorded elements) and the degree of taphonomic heritage (*i.e.*, the ratio of reelaborated elements to the whole of recorded elements) can reach 100%. However, the degree of taphonomic condensation (*i.e.*, mixture of fossils of different age or different chronostratigraphic units) reaches very low to zero values in all cases. Ammonite mixed assemblages composed of specimens representing several biozones or biohorizons in a single bed have not been identified and the biostratigraphical completeness can reach 100%.

Taphonic populations of type 1 and 2 are dominant. Taphonic populations of type 1 are composed of monospecific shells showing unimodal and asymmetric distribution of size-frequencies, with positive skew (Fernández-López, 1991, 1995, 1997). These populations have a high proportion of microconchs and the shells of juvenile individuals are predominant, whilst adults are scarce. Taphonic populations of type 2 are composed of mono- or polyspecific shells showing unimodal and normal distribution of size-frequencies, with high kurtosis. Populations of this second type have a low proportion of microconchs and the shells of juvenile individuals are scarce, whilst the shells of adult individuals are common. Taphonic populations of type 3 are composed of polyspecific shells showing uni- or polymodal and asymmetric distribution of size-frequencies, with negative skew. Shells of juvenile individuals are absent, microconchs are very scarce and shells of adult individuals are predominant in taphonic populations of this last type.Taphonic populations of type 1 are indicative of autochthonous biogenic production of shells, showing no signs of sorting by necroplanktic drift (Fernández-López, 1991, 1995, 1997).

Biostratinomic processes of biodegradation-decomposition are generally intense in this taphofacies (Fig. 7). Before burial, ammonite shells commonly lose the soft-parts and the aptychi, as well as periostracum and connecting rings.

Reworked concretions, shell fragments and concretionary internal moulds can be encrusted, developing oncolitic cryptalgal structures (cf. Elmi *et al.*, 1988). Shells and internal moulds can present microbial laminae, developed during removal processes. Reelaborated, internal moulds commonly show calcareous microbial or stromatolitic laminae, that mainly developed on the exposed side during exhumation and displacement processes (Figs. 6.1B , 6.3B and 8). However, skeletal remains of encrusting organisms (such as serpulids, bryozoans or oysters) and biogenic borings are very scarce. Remains of intrathalamous or extrathalamous serpulids were only developed on some resedimented shells.

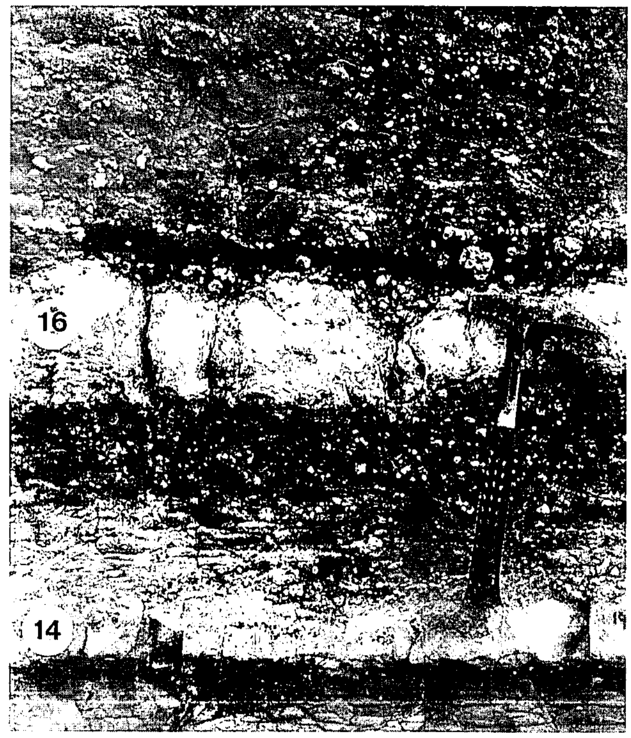

Figure 4.- Close-up view of Lower Pliensbachian deposits, Peniche (Portugal), showing some details of the taphofacies 1 (lumpy limestones and marly intervals with reelaborated ammonites). Numbers of calcareous levels are indicated as in the log represented in text-figure 3. Hammer for scale is 33 cm long.

Complete concretionary internal moulds of the body chamber and phragmocone, indicative of low rates of sedimentation and accumulation, are abundant. In contrast, compressed, partial internal moulds of body chambers (*i.e.*, hollow ammonites), indicative of very rapid sedimentary infill and high rate of sedimentation, are scarce. Body chambers and phragmocones are normally filled by homogeneous sediment, although the lower portions are more calcareous and the upper portions are more argillaceous than the sedimentary matrix (Fig. 8).

Processes of early mineralization are intense. Concretionary internal moulds are calcareous. In the most lumpy intervals, pyritic internal moulds may be locally common, as reelaborated elements (Figs. 6.5 and 6.6).

Signs of abrasion and bioerosion on shells and internal moulds are very scarce. Reelaborated internal moulds can show disarticulation surfaces and fractures (Figs. 6.6-6.9); more seldom and associated with erosional sedimentary surfaces, they may show truncational abrasion facets.

Concretionary internal moulds showing the septa of the phragmocone are the dominant fossils. Hollow phragmocones (*i.e.*, shells without septa) are scarce, and they are usually compressed by increasing sedimentary loading during diagenesis. The septa can disappear by early dissolution, whilst the wall of the shell may still stand, giving rise to compressed elements showing discontinuous deformation by gravitational diagenetic compaction.

Fragmentary shells are common. Shells usually show closed and opened fractures on the wall. Reelaborated internal moulds commonly show disarticulation surfaces with sharp margins (Fig. 6.8). Fragmentary internal moulds also occur, bearing no signs of rounding by abrasion or bioerosion, due to low turbulence at the water/sediment surface, and they usually display no traces of gravitational deformation by diagenetic compaction.

Shells and concretionary internal moulds are usually reorientated. Ammonites with their long axes parallel to bedding surface are dominant.

Siphuncular tubes are usually disarticulated due to intense and lasting biostratinomic processes of biodegradation-decomposition and dissolution.

Sediments of this facies are interpreted as having been deposited in an open sea, below wave base, taking into account the absence of sedimentary structures indicating either shallow water (such as wave reworking) or storm deposition (such as hummocky bedding). However, the presence of reelaborated ammonites implies that some form of current flow or winnowing affected the burial of concretionary internal moulds. Currents were slight, but concretionary internal moulds of ammonites were disarticulated and azimuthally reorientated on softgrounds through reelaboration (*i.e.*, exhumation and displacement on the sea-bottom, before their final burial). The formation of such calcareous concretions must have taken place either on the sea-floor contemporaneously with the sedimentary process or else within the sediment during the early diagenesis. In this hemipelagic environment, episodes of lower rates of sedimentation and accumulation favoured a higher degree of bioturbation and reworking of ammonite shells. Reelaboration processes and the activity of burrowing organisms are the main factors that induced the development of ammonite associations showing a high degree of taphonomic heritage, but the degree of stratigraphic and taphonomic condensation is negligible over geochronological time-scale. Selectively increased porosity was induced by draught filling in ammonite shells (intra-cameral draught stream created by external turbulence through constricted siphuncular openings; Seilacher, 1971) and bioturbation of the sedimentary matrix, both of these processes favouring a relatively fast lithification. Concretionary internal moulds of ammonites and lumpy structures were developed on the sea-bottom, under oxic to suboxic conditions. Although the calcareous benthos is very scarce, the presence of abundant burrowing structures suggests aerobic to dysaerobic biofacies. The absence of pyritic ammonites other than reelaborated internal moulds suggests that anaerobic conditions did not develop near the sedimentary surface. However, reelaborated ammonites and reworked concretions included in some beds, showing the base sharper than the top, could be mobilised by massive sliding.

Taphofacies 2: Laminated marls and bituminous shales with accumulated ammonites

A second taphofacies is composed by dark, organic rich, marly mudstones and bituminous shales, commonly showing millimetric scale, bedding-parallel lamination (Fig. 9). Laminated intervals are normally 20-30 cm thick, although they may range from few centimetres to 1 m thick. Large structures of bioturbation of centimetric size are sparse but some marly intervals contain abundant, small *Chondrites*. Tubular and narrow (1-3 mm diameter), pyrite-filled burrows with various orientations are abundant. Finely disseminated pyrite occurs locally. The boundaries of the laminated intervals are commonly gradational (*e.g.*, 21 base, 25 base, 31 base, 33 top, 45 base, 45 top, 49 base, 49 top, 51 base, 51 top and 65 base). However, some erosional surfaces have been identified (in levels 21 top, 23 top, 25 top, 27 base, 27 top, joint 31/33,

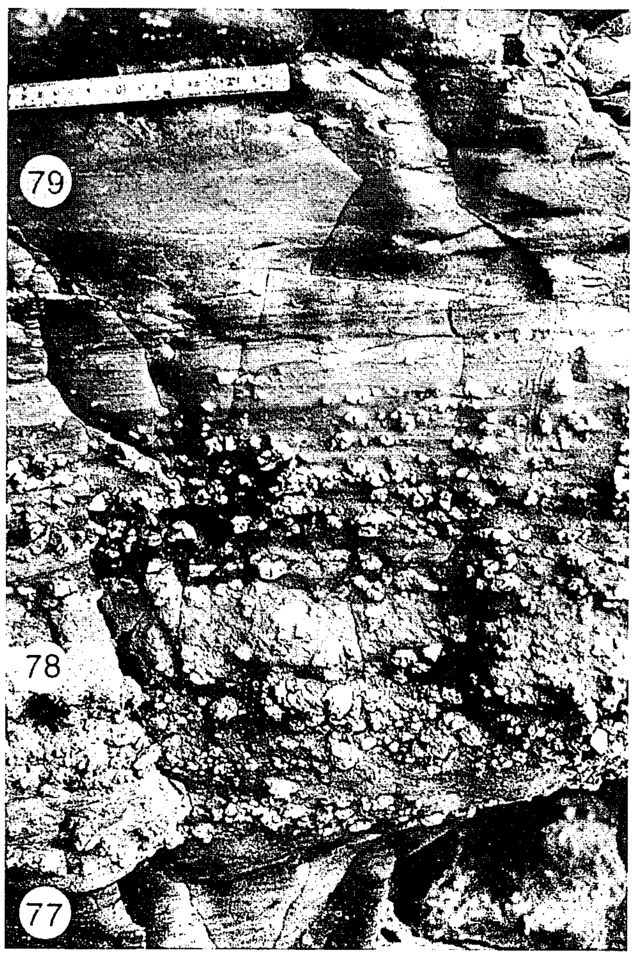

Figure 5.- Close-up view of the level 78 (taphofacies 1, lumpy limestones and marly intervals with reelaborated ammonites), showing gradational boundaries. Bar for scale is 17 cm long.

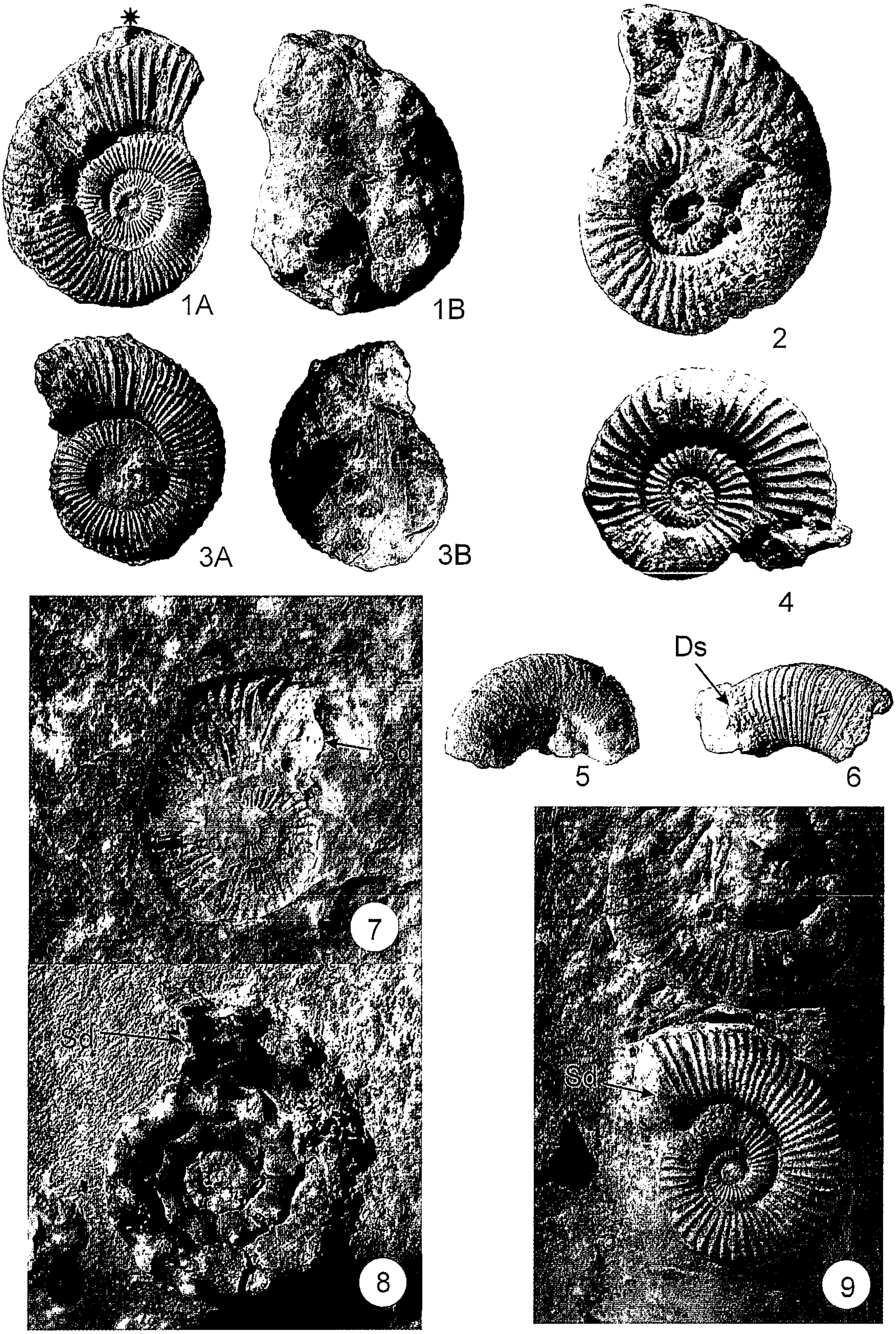

Figure 6.- Reelaborated ammonites showing petrographic differences and structural discontinuity (Sd) between the sedimentary infilling and the enclosing sedimentary rock, or disarticulation surfaces (Ds), and maintaining their original volume and form as a result of rapid early cementation. All the specimens are calcareous concretionary internal mould, except figures 5 and 6 which correspond to pyritic moulds. Specimens represented in figures 1B and 3B are preferentially encrusted by calcareous microbial or stromatolitic laminae on the upper side. The asterisk indicates the end of the phragmocone. Lower Pliensbachian. 1.- *Dayiceras* sp., specimen BR2, x2, Brenha. 2.- *Dayiceras* sp., specimen BR6, x2, Brenha. 3.- *Dayiceras* sp., specimen BR1, x1, Brenha. 4.- *Dayiceras* sp., specimen PE55/1, x2, Peniche. 5.- *Dayiceras* sp., specimen BR5, x1, Brenha. 6.- *Dayiceras* sp., specimen PE67/1, x1, Peniche. 7.- *Dayiceras* sp., specimen BR3, x2, Brenha. 8.- *Dayiceras* sp., specimen PE78/1, x2, Peniche. 9.- *Metaderoceras* sp., specimen PE63/1, x2, Peniche.

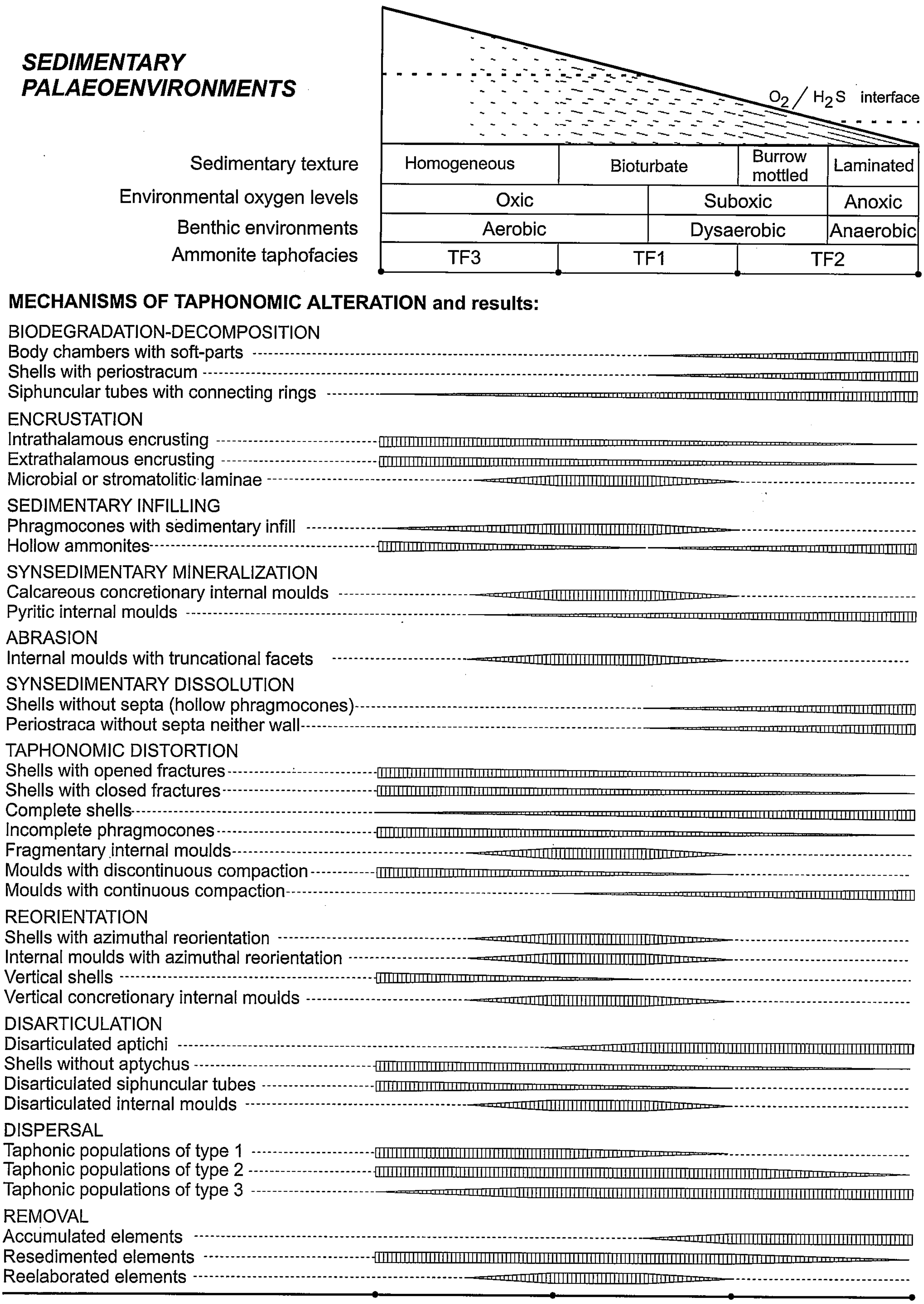

Figure 7.- Taphonomic gradients observed on ammonites from the three taphofacies recognized in the Lower Pliensbachian deposits of the Lusitanian Basin (TF1 = Taphofacies of type 1; TF2 = Taphofacies of type 2; TF3 = Taphofacies of type 3).

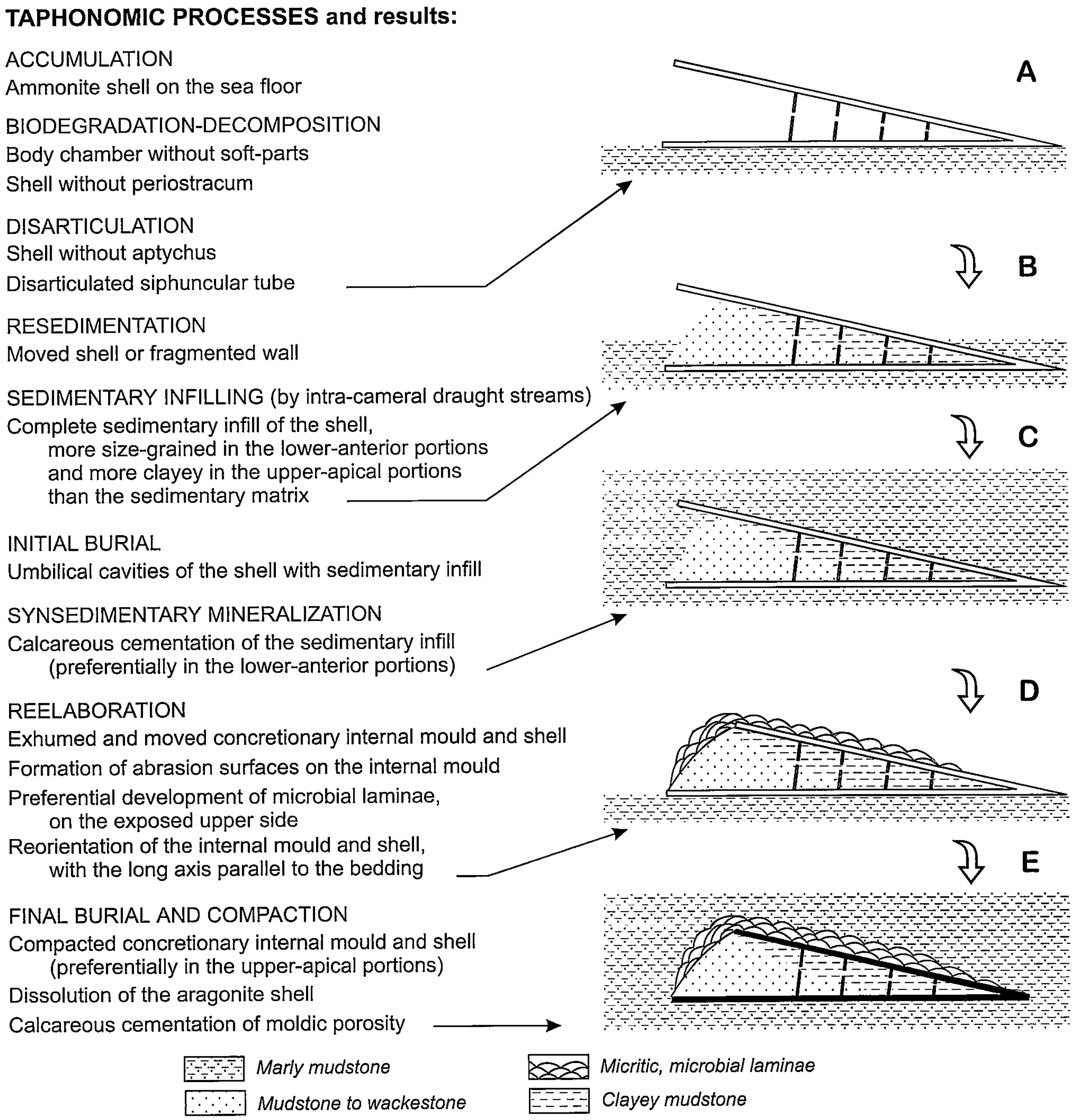

Figure 8.- Processes leading to the development of "ammonite half-lumps" (a particular case of reelaborated ammonites) in condensed deposits from Early Pliensbachian of Portugal (in Fernández-López *et al.*, 1999).

joint 49/51, 65 top, 67 base, 67 top, 69 base, 69 top and 79). Some shallow erosional surfaces occur within this facies, being onlapped by limestones of taphofacies 1 or 3. Laminated intervals show low values of organic carbon (TOC, total organic carbon, commonly between 2,5 and 4,5%). A black shale interval (TOC up to 15%) has been identified in the Renzi Subzone (Ibex Zone), within the organic-rich intervals of the Lower Pliensbachian at Peniche (level 65 in Fig. 3). This black shale interval shows a well laminated texture, yet traces of bioturbation of *Chondrites* are present.

Ammonite associations in taphofacies-2 are dominated by non-reelaborated elements (*i.e.*, resedimented or accumulated elements). Reelaborated internal moulds are virtually absent. Accumulated shells, showing no signs of removal, may be locally common. Resedimented shells are dominant (Figs. 10-11). The degree of removal (*i.e.*, the ratio of reelaborated and resedimented elements to the whole of recorded elements) is variable, but the degree of taphonomic heritage (*i.e.*, the ratio of reelaborated elements to the whole of recorded elements) is very low to 0%. There is no biostratigraphic evidence of taphonomic condensation in the ammonite recorded associations. Taphonic populations of types 2 or 3 are dominant among these associations, those of type 1 being very scarce.

Biostratinomic processes of biodegradation-decomposition are less intense than in the taphofacies 1. Ammonite shells usually lack soft-parts and aptychus in the body chamber, but they can maintain the periostracum and the connecting rings during the burial (Figs. 7, 10-11). Skeletal remains of intrathalamous or extrathalamous serpulids are only developed on some resedimented shells.

Buried shells usually lacked sedimentary infill in the phragmocone and were preserved as hollow ammonites, indicative of very rapid sedimentary infill and high rate of sedimentation. Body chambers and phragmocones of some resedimented shells are filled by homogeneous sediments.

Pyritic internal moulds with septa, resulting from early mineralization, may be locally common. However, calcareous, concretionary internal moulds formed by early cementation processes are absent. Signs of abrasion and bioerosion on shells are virtually absent.

Hollow ammonites (*i.e.*, showing no sedimentary infill in the phragmocone) and hollow phragmocones (*i.e.*, without septa) are the dominant fossils, but they are usually compressed by gravitational diagenetic compaction. Septa and walls of the shells can disappear by early dissolution, whilst the periostracum may still remain, giving rise to compressed elements showing continuous deformation by gravitational diagenetic compaction. Hollow ammonites maintaining their original volume and form are scarce, as a result of the high rate of sedimentation and slow early cementation.

In this taphofacies, where accumulated elements and pyritic ammonites may be found, complete shells are common. Fragmentary shells can occur, but bearing no signs of rounding, encrustation or bioerosion during resedimentation processes on the sea-bottom, due to the low turbulence near the water/sediment surface. Shells are not azimuthally reorientated, but they tend to be horizontal on the bed surface. Siphuncular tubes are usually articulated. Disarticulated aptychi may be common.

The fine-grained nature of the mudstones suggests deposition in a low-energy setting. Laminated marls and bituminous shales were developed on a sea-bottom under suboxic to anoxic conditions. The general scarcity of calcareous benthic body fossils in these mudstones was noted by Hallam (1971), who considered that it might have been caused by a soupy consistence of the substrate. However, the abundant reorientated shells, aligned with their long axes parallel to the bedding surfaces, implies sedimentary surfaces of softground stage. Currents were very slight or absent, but ammonite shells were horizontally reorientated and fragmented by resedimentation after their accumulation on softgrounds. Consequently, substrates were of type softground, rather than soupy-grounds. The sea bottom was poorly oxygenated, although calcareous benthos is absent and active-burrowing, soft-bodied infauna was present. The abundant pyrite at some horizons suggests that reducing conditions extended to very near the sediment-water interface, allowing unrestricted diffusion of seawater sulphate to occur. The finely laminated bituminous shales were deposited during periods when anoxic conditions actually extended up to, and above the sediment surface, thereby preventing burrowing and oxidation of organic matter. The preservation of organic matter at such horizons may reflect relatively high organic sedimentation rates, preventing the destruction of organic matter by sulphate-reducing bacteria (cf. Morris, 1980; Wright & Wilson, 1984; Sethi & Leithold, 1997).

Taphofacies 3: Homogeneous limestones with resedimented ammonites

Homogeneous limestones of this taphofacies represent less than 41% of the whole of beds in Peniche. They are normally under 20 cm thick, yellowish or greyish. There are two lenticular beds among them (in levels 25 and 79), showing sharp boundaries. The bases are erosional. The tops are sharp or burrowed, and they grade into the overlying

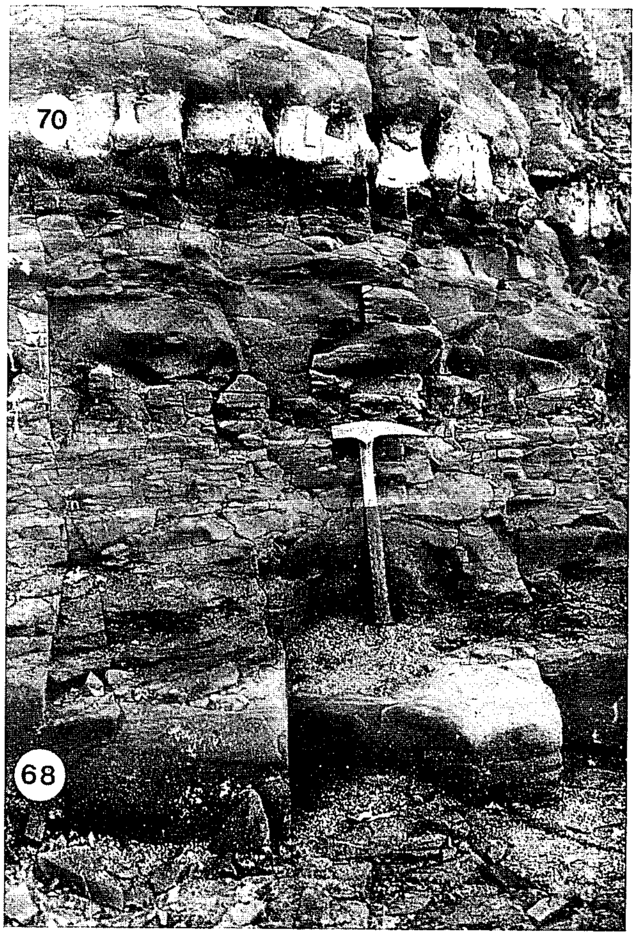

Figure 9.- Outcrop view of Lower Pliensbachian deposits, Peniche (Portugal). Numbers of calcareous levels are indicated as in the log represented in text-figure 3. Limestone beds 68 and 70 correspond to the taphofacies 3 (homogeneous limestones with resedimented ammonites). The stratigraphic interval between them corresponds to the taphofacies 2 (laminated marls and bituminous shales with accumulated ammonites). Hammer for scale is 33 cm long.

marly intervals or laminated shales. However, this lenticular limestones show no typical turbidite features such as normal grading or current ripples. Taphofacies of type 3 may be intercalated with those of type 1 and type 2 (Figs. 3 and 9).

Accumulated shells are virtually absent. Reelaborated elements are scarce, resedimented shells being dominant. The degree of removal is variable, but the degree of taphonomic heritage ranges from very low values to zero. There is no biostratigraphic evidence of taphonomic condensation in the ammonite recorded associations. Taphonic populations are usually of type 1 or 2.

Biostratinomic processes of biodegradation-decomposition are generally intense. Soft-parts and aptychus in the body chamber, as well as periostracum and connecting rings, are normally lost before burial.

Resedimented shells may be overgrown by intrathalamous and extrathalamous, encrusting organisms (most particularly, serpulids and bryozoans).

Phragmocones are normally filled with sediment. Partial, concretionary internal moulds of the body chamber and phragmocone, indicative of low rate of sedimentation, are common. Hollow ammonites maintaining their original volume and form are also common, indicating low rate of sedimentation and rapid early cementation.

Calcareous concretionary internal moulds can be formed during the early diagenesis. Pyritic internal moulds are found only locally.

Shells can acquire truncational abrasion facets, as well as fractures, but signs of abrasion and bioerosion on shells are very scarce. Septa and walls of the shells are usually preserved during the burial.

Complete shells are scarce. Incomplete phragmocones are dominant. Ammonite fossils can maintain their original volume and form due to early cementation, showing no evidence of gravitational deformation by diagenetic compaction. Moulds with discontinuous compaction represent crushed shells during early diagenesis, before dissolution of the wall.

Figure 10.- Resedimented ammonite, with complete peristome. The sedimentary infill is restricted to the body chamber and the last portion of the phragmocone, showing structural continuity with the sedimentary matrix across the peristome. The septa have been dissolved during syndiagenesis, but the wall of the shell still remained and the body chamber shows discontinuous deformation by gravitational compaction. The asterisk indicates the end of the phragmocone. *Acanthopleuroceras* sp., Lower Pliensbachian, specimen PE51/3, Peniche. Scale in centimetres.

Figure 11.- Resedimented ammonite. Hollow ammonite (*i.e.*, showing no sedimentary infill in the phragmocone) and hollow phragmocone (*i.e.*, without septa) compressed by gravitational compaction. Sedimentary infill is restricted to the last portion of the body chamber. Siphuncular tube is articulated. Septa have been dissolved and the width of the internal mould is reduced to some millimetres as a result of sedimentary compaction during syndiagenesis. The asterisk indicates the end of the phragmocone. *Dayiceras* sp., Lower Pliensbachian, specimen PE67/1, Peniche. Scale in centimetres.

Shells are commonly reoriented and regrouped. Recorded associations may show normal grading. Shells without aptychus, showing disarticulated siphuncular tubes, are common.

These homogeneous limestone beds of taphofacies 3 show several features indicative of rapid deposition, in contrast to the slow rates of sedimentation and accumulation inferred for the lumpy limestones of taphofacies 1. Burrowing is not evenly distributed throughout the beds, as in taphofacies 1, but it is concentrated in the last few centimetres of each bed. The lower surface of the beds is erosional, nongradational. The decrease in grain-size and bed thickness, observed from taphofacies 1 to taphofacies 3, also suggests a more distal and deep deposition. The homogeneity of the limestones of the taphofacies 3 is interpreted as a result of sediment gravity flows (distal turbidites or tempestites) from aerobic environments (Fig. 7). Distal deposition by gravity flows (taphofacies 3), carrying homogeneous hemipelagic muds from oxic conditions, interrupted a background sedimentation from suboxic to anoxic conditions characteristic of taphofacies 1 and 2. This background sedimentation showed a lateral change from dysaerobic, bioturbated lumpy muds (taphofacies 1) to anaerobic, laminated muds (taphofacies 2).

Palaeoenvironmental implications

On the western margin of the Iberian Plate, a carbonate ramp system developed since the Early Jurassic until the end of the Middle Jurassic. Deposition of carbonate and terrigenous muds occurred in an open sea, on a margin in process of differentiation, in quiet waters below effective wave base. The abundance of cephalopods is an indication of normal marine salinity. The nodular structures of the Lower Pliensbachian deposits were developed on a sea-bottom undergoing rhythmic oscillations between suboxic conditions (energy-devoid) and oxic ones (slight and episodical agitation, essentially bound to biological activity; Hallam, 1971, 1986; Dommergues *et al.*, 1981; Dromart & Elmi, 1986; Elmi *et al.*, 1988; Watkinson, 1989; Soares *et al.*, 1993).

In aerobic to dysaerobic environments, where a decrease in the rate of sedimentation is associated with an increase in turbulence, the preserved associations of ammonites show a gradual increase in removal and taphonomic heritage. This results from the intensification of such taphonomic processes as biodegradation-decomposition, encrustation, sedimentary infill, concretion, abrasion, bioerosion, fragmentation, reorientation, disarticulation, regrouping and removal of ammonite remains. In dysaerobic to anaerobic environments, in contrast, where an increase in the rates of sedimentation and accumulation is associated with a decrease in turbulence, the same taphonomic processes lead to the formation of ammonite associations showing decreasing values of removal and taphonomic heritage. The degree of removal (*i.e.*, the ratio of reelaborated plus resedimented elements to the whole of recorded elements) and the degree of taphonomic heritage (*i.e.*, the ratio of reelaborated elements to the whole of recorded elements) of ammonite associations are both inversely proportional to the rates of sedimentation and accumulation. A decrease in any or both sedimentary rates will produce an increase in the degree of taphonomic removal and taphonomic heritage, leading to the development of condensed associations.

Ammonite shells of these three taphofacies were accumulated in a low energy, oxygen-depleted (dysaerobic) environment, where anoxic-bottom conditions locally developed, within a setting bypassed by fine-grained gravity flows. In the lumpy facies (TF1), the common bioturbation structures and the presence of reelaborated, concretionary internal moulds of ammonites, including azimuthally reorientated elements, evidence availability of oxygen and episodic agitation of bottom waters. However, bituminous and laminated facies (TF2), which include horizontally reorientated elements and resedimented shells, must have been laid down in totally or nearly anaerobic conditions. The rate of sedimentation was usually very low, but the rate of accumulation of sediment was very variable. Low oxygenation and low substrate consistence of the bottom could be a consequence of relatively high rates of sedimentation and accumulation. In contrast, lumpy limestones with reelaborated ammonites, showing gradational boundaries and inverse grading, represent environments of starving and the lowest rates of sedimentation and accumulation in deep areas.

Taphofacies of type 1 alternate with taphofacies of type 2 composing stratigraphic cycles of metric order. Relationships between the different cyclical processes that have conditioned the cyclicity of the stratigraphical-record and the fossil-record can be tested on the basis of the relative duration of such processes. Biostratigraphic and geochronometric analysis indicate that the studied stratigraphic interval, from level 48 to level 80, has been deposited continuously for about 1 million years, from 193 to 192 Ma before present, according to the geochronological and geochronometric data published by Dommergues *et al.* (1997) and Odin *et al.* (1995). Consequently, the stratigraphic cycles identified in the lumpy limestones of the Lusitanian Basin resulted from cyclical environmental changes of hundreds of thousands of years. Recurrent depletion of benthic oxygen associated with high-frequency sea level changes has been studied by several authors (cf. Morris, 1980; Barron *et al.*, 1985; Hallam, 1987; Borrego *et al.* 1996; Quesada *et al.*, 1997; Sethi & Leithold, 1997; Gale, 1998). According to this hypothesis, 4th-order deepening episodes led to the development of dysaerobic to anaerobic environments, whilst subsequent shallowing episodes led to a relative increased of the levels of bottom oxygenation.

Conclusions

Lower Pliensbachian lumpy limestones of the Lusitanian Basin can be subdivided into three main facies which are distinguished by the preservational features of the ammonites. Lumpy intervals containing reelaborated ammonites, and showing gradational boundaries and inverse grading, were developed in deep environments, induced by sedimentary starving.

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