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The Lourinhã Formation: the Upper Jurassic to lowermost Cretaceous of the Lusitanian Basin, Portugal – landscapes where dinosaurs walked

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Abstract

This work, as a fieldtrip guide, aims to provide a glimpse into the palaeoenvironments, palaeontology, and diagenesis of one of the most productive areas for Late Jurassic dinosaurs and other vertebrates in Europe, namely, the sites of the Lourinhã Formation, which is coeval with the Morrison Formation of the midwest USA.

The Late Jurassic rifting phase of the Lusitanian Basin created several sub-basins separated by major crustal faults. In the western and central areas of the basin, the Caldas da Rainha structure separates three sub-basins with different subsidence and infill characteristics (Consolação to the west, Bombarral–Alcobaça to the northeast, and Turcifal to the southeast). The Upper Jurassic–lowermost Cretaceous succession exposed in the coastal cliffs located between Nazaré and Santa Cruz belongs to the Consolação Sub-basin, whereas the coastal outcrops between Santa Cruz and Ericeira show units of the Turcifal Sub-basin.

To place the stops into a coherent context, selected units of the fieldtrip area are detailed. The stratigraphy of the Upper Jurassic of the Lusitanian Basin is quite complex, and no fully accepted overall proposal exists. Thus, a review of lithostratigraphy, sedimentology, age and environmental interpretations is presented. Interpretations of palaeoclimate, palaeogeography, and taphonomy contribute to establishing an overview of the landscape where dinosaurs lived and to understanding the conditions for their fossilization and preservation. This trip, which takes place from north to south, focuses on the vertebrate content, sedimentology, and stratigraphy of the deposits. The first stop at Consolação examines the upper Kimmeridgian shallow-marine to deltaic Alcobaça Formation, which underlies the Lourinhã Formation. Further south, the Paimogo fort cape gives a scenic view of the Lourinhã Formation: to the north, the Praia da Amoreira and Porto Novo members (lower coastal plain alluvium, including distal fan and meandering fluvial systems; upper Kimmeridgian), and, to the south, the Praia Azul Member (lower coastal plain alluvium with three brackish–marine faunally distinct transgressive carbonate levels; uppermost Kimmeridgian to lowermost Tithonian). In Paimogo, we visit sites where dinosaur eggs and a sauropod skeleton have been found. The stop at the Museum of Lourinhã allows a visit to one of the most important collections of Late Jurassic vertebrates in Europe. The last fieldtrip stop at Porto da Calada examines the top of the Assenta Member of the Lourinhã Formation (meandering fluvial system with intercalations of shallow-marine lagoonal carbonates; upper Tithonian to lowermost Berriasian) and the Porto da Calada Formation (meandering fluvial system with thin levels of estuarine and intertidal flats carbonates; Berriasian) and thus includes the Jurassic–Cretaceous boundary.

Keywords: Upper Jurassic, Lourinhã Formation, Portugal, Lusitanian Basin, Dinosaurs

Resumo

Este trabalho, como um guião de campo, visa dar uma visão sobre os paleoambientes, paleontologia e diagénese de uma das áreas mais produtivas para os dinossauros e outros vertebrados do Jurássico da Europa, nomeadamente para a Formação da Lourinhã, que é contemporânea da Formação de Morrison, no centro-oeste da América do Norte.

A fase de rifting jurássico da Bacia Lusitaniana criou várias sub-bacias separados por falhas principais. Na área ocidental e central da bacia, a estrutura de Caldas da Rainha separa três sub-bacias com diferentes características de subsidência e de enchimento: Consolação a oeste, Bombarral-Alcobaça a noroeste e Turcifal a sudeste. A sucessão do Jurássico Superior à base do Cretá-

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cico exposta nas arribas costeiras localizadas entre Nazaré e Santa Cruz pertence à Sub-bacia da Consolação, enquanto que os afloramentos costeiros entre Santa Cruz e Ericeira expõe unidades da Sub-bacia do Turcifal.

Para enquadrar as paragens num contexto coerente, dá-se destaque e detalhe às unidades da área visitada. A estratigrafia do Jurássico Superior da bacia é bastante complexa e não existe nenhuma proposta totalmente aceita na generalidade, sendo, por isso, apresentada uma revisão de litostratigrafia, sedimentologia, idade e interpretações ambientais. Interpretações sobre o paleoclima, paleogeografia e tafonomia contribuem para uma descrição geral do ambiente onde os dinossauros viveram e para a compreensão das condições para a sua fossilização e preservação.

Esta descrição das localidades e horizontes desenrola-se de norte para sul, incidindo sobre os vertebrados, sedimentologia e estratigrafia. A primeira paragem é no Kimmeridgiano superior da Consolação que mostra um paleoambiente marinho pouco profundo a deltaico da Formação de Alcobaça, na qual assenta a Formação da Lourinhã. Mais a sul, o forte de Paimogo permite uma vista panorâmica sobre a Fm. da Lourinhã: para o norte estão os membros Praia da Amoreira - Porto Novo (planície de aluvião costeira inferior, incluindo a parte distal e sistemas fluviais sinuosos; Kimmeridgiano superior) e o Membro Praia Azul para o sul (aluvião e planície costeira, com três níveis de carbonato transgressivo e faunas salobra-marinhas distintas; Kimmeridgiano superior e base do Titoniano). Em Paimogo encontram-se os locais onde ovos de dinossauro terópode e um esqueleto saurópode foram recolhidos. A paragem no Museu da Lourinhã permite visitar uma das mais importantes coleções de vertebrados do Jurássico Superior na Europa. A última paragem, no Porto da Calada, aborda a parte superior do Membro da Assenta da Formação da Lourinhã (sistema fluvial com meandros e com intercalações de carbonatos de origem lagunar e marinha rasa; Titoniano superior à base do Berriasiano) e Formação Porto da Calada (sistema fluvial meandrico com os níveis de finos de carbonatos estuarinos e intertidais; Berriasiano), incluindo assim o limite Jurássico-Cretácico.

Palavras-chave: Jurássico Superior, Formação da Lourinhã, Portugal, Bacia Lusitaniana, Dinossauros

All lithostratigraphic units referred to in this work are capitalized, even if they have not yet been formally defined.

Institutional abbreviations (used for fossil specimens figured or mentioned): **FCT-UNL**, Faculdade de Ciências e Tecnologia, Univ. NOVA de Lisboa, Portugal; **ML**, Museu da Lourinhã, Portugal.

1. Introduction

1.1. Regional overview

1.1.1. Tectono-stratigraphic setting

The deposits visited during the fieldtrip belong to the North Atlantic rift-related Lusitanian Basin, located on the western coast of Portugal and extending from Aveiro to Cabo Espichel (Fig. 1). The oldest unit was deposited during the Late Triassic and the basin had become almost fully filled by the Cenomanian (Rey *et al.,* 2006). In the region, the later sedimentary cover is relatively thin and ranges from Upper Cretaceous to Holocene.

The Lusitanian Basin underwent a major rifting phase during the late Oxfordian to earliest Kimmeridgian, with fault and fault-related diapiric activity creating several sub-basins, in particular between the Nazaré and Lisbon parallels. These included the Bombarral–Alcobaça, Arruda, and Turcifal sub-basins (Leinfelder & Wilson, 1998; Alves *et al*., 2003), and the recently proposed Consolação (Martinius & Gowland, 2011; Taylor *et al*., 2013) and Lower Tagus (Carvalho *et al*., 2005) sub-basins (Fig. 2).

During the Late Jurassic rifting stage, the Caldas da Rainha fault separated and tilted the half-grabens of the basement. This activity was reflected in the sedimentary cover by faults displacing the Lower and Middle Jurassic limestones and by major movements of the Lower Jurassic marly and evaporitic Dagorda Formation ("salt"). During the extensional activity, the salt pillow that formed over the basement structure enlarged, fed by salt withdrawal caused by the depositional load developing in the sub-basins. Thus, even during the early post-rifting phase, this large feature separated three sub-basins with different amounts of subsidence and infill (Consolação to the west, Bombarral–Alcobaça to the northeast, and Turcifal to the southeast; Fig. 2), controlled the development of marine embayments and the alluvial drainage, and was the locus of enhanced shallow-wa-

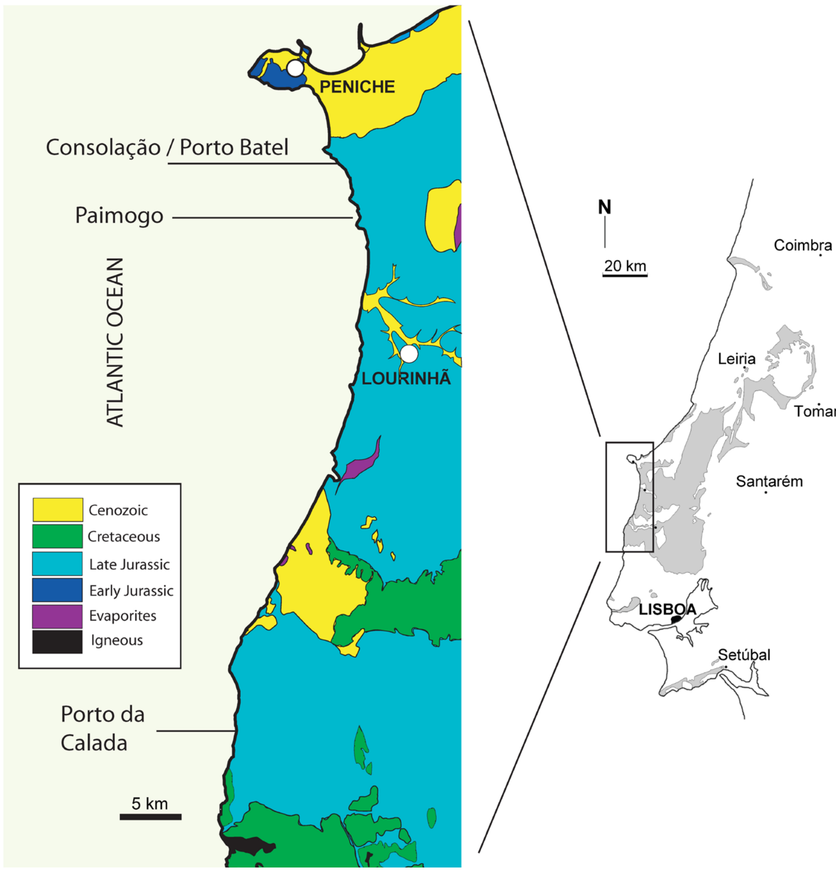

Fig. 1. -Simplified geological map of the central west coast of Portugal (left), and the Upper Jurassic in grey (right) (modified after Manupella *et al*., 1999; Alves, 2003).

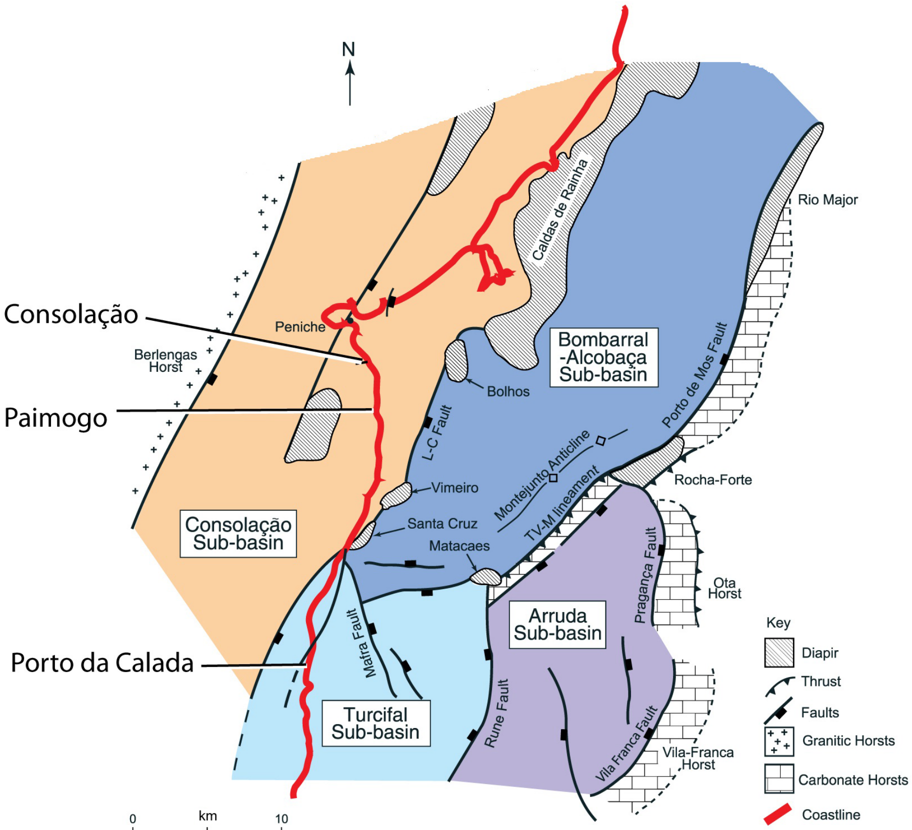

Fig. 2 − Map showing the structural setting of the Late Jurassic sub-basins in the western and central Lusitanian Basin (modified after Taylor *et al*., 2013). L-C: Caldas da Rainha; TV-M, Torres Vedras–Montejunto.

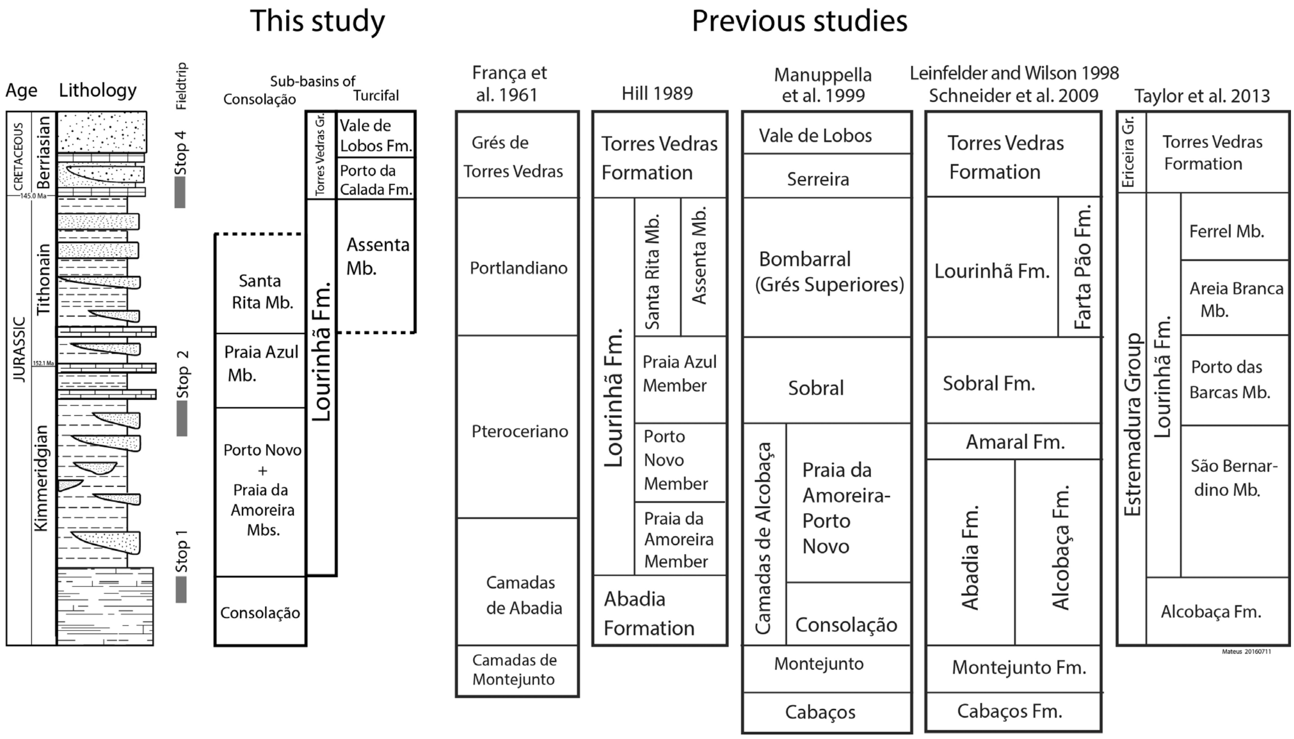

Fig. 3 – Selected lithostratigraphic proposals for the Upper Jurassic–Lower Cretaceous of the fieldtrip area, with the locations of the fieldtrip stops also shown.

ter carbonate production (Wilson *et al.,* 1989; Ravnås *et al.,* 1997; Alves *et al.,* 2003; Leinfelder, 2004).

The Caldas da Rainha fault is currently inverted and expressed in the Mesozoic–Cenozoic cover by several local structures, including the Leiria–Parceiros, Maceira, Caldas da Rainha, Bolhos, Vimeiro, and Santa Cruz extruded diapirs (Canérot *et al*., 1995) as well as several subvolcanic bodies of latest Jurassic to earliest Cretaceous age (Grange *et al*., 2008).

The Upper Jurassic–lowermost Cretaceous rocks of the coastal cliffs between Nazaré and Santa Cruz belong to the Consolação sub-basin, whereas the coastal outcrops between Santa Cruz and Ericeira are part of the Turcifal Sub-basin (Fig. 2). The Consolação Sub-basin is bounded to the west by the Berlengas marginal basement horst system, and the Turcifal Sub-basin is bounded to the east by the Runa fault and to the north by the Torres Vedras–Santa Cruz fault.

Subsidence during the late Oxfordian to early Kimmeridgian rifting climax was pronounced, reaching rates of ~250 m/Myr in the depocenters (Ellis *et al*., 1990; Hiscott *et al*., 1990; Stapel *et al*., 1996) and of up to 2000 m/Myr in the Arruda Sub-basin (Alves *et al*., 2003). The subsequent post-rifting stage was characterized by a low level of tectonic activity, and the accommodation was generated by thermal subsidence and some salt withdrawal. Thus, eustasy was a major control on deposition during the late Kimmeridgian to early Berriasian, coupled with a general trend of siliciclastic progradation to the west and to the south generating diachronic units increasingly continental in character from south to north. The rapid shift from marine- to continental-dominated environments around or shortly after the early to late Kimmeridgian transition is also clear in the faunal assemblages, such as the benthic macrofauna (Schneider *et al*., 2010a). Nevertheless, the Caldas da Rainha structure retained a degree of importance in the palaeolandscape during most of the Tithonian, considering the clear contrast in sedimentary characteristics between the upper members of the Lourinhã Formation, namely, the Assenta Mb. (to the southeast) and the Santa Rita Mb.

The Lourinhã and Alcobaça Formations are of particular interest on this fieldtrip as they are the units that contain the most vertebrate remains in Portugal (and in Europe). The Alcobaça Fm. is older and was deposited in shallow-marine to brackish environments, whereas the Lourinhã Fm. was deposited under continental conditions. Vertebrate fossils are common in the study area (Lapparent & Zbyszewski, 1957; Galton, 1980; Mateus, 1998, 2006), including dinosaurs, crocodiles, and turtles, with fauna and flora assemblages being somewhat similar to those of the Morrison Formation in North America, but with coastal influence and some European-related faunal input (Mateus, 2006).

The importance of the Porto da Calada Formation stems from its position at the Jurassic–Cretaceous boundary, from its extensive outcrops, and from the recently found dinosaur bones.

1.1.2. Lithostratigraphic framework

Building a lithostratigraphic framework for the Upper Jurassic of the Lusitanian Basin has proved to be a complex issue, with many different proposals having been offered by various authors since the late nineteenth century (Fig. 3). The difficulty of establishing such a framework is due to the complex palaeogeography created by the late Oxfordian to early Kimmeridgian rifting phase (Wilson, 1988; Reis *et al*., 1996, 2000; Leinfelder & Wilson, 1998; Alves *et al*., 2003; Leinfelder, 2004), the lack of high-resolution biostratigraphy for most of the record in a shallow-marine to continental sedimentary context, and the isolation of different blocks as a result of Cenozoic inversion. The units presented in detail below are part of this intricate puzzle of both the nature of the deposits and their lithostratigraphic nomenclature.

Choffat was the first to provide a stratigraphic organization for the Upper Jurassic of the Lusitanian Basin (see, for instance, Choffat, 1901), but with a mixed chronostratigraphic and lithostratigraphic approach. He recognized three main units in the onshore deposits of the southern part of the Lusitanian Basin, namely, from bottom to top, the Lower Lusitanian (divided into the Cabaços Beds and the Montejunto Beds), the Upper Lusitanian (the Abadia Beds), and the Neojurassic (subdivided into the *Lima pseudoalternicosta* Beds, the Pterocerian, and the Freixialian). That organization, with some updating, was the main framework until the 1980s. For example, the 1960 edition of the 1:50,000 geological map of the Lourinhã area (sheet 30-A of the "Carta Geológica de Portugal"; França *et al*., 1961), also included the following lithostratigraphic and chronostratigraphic units (from lower to upper): "Lusitaniano Superior–Camadas de Abadia", "Pteroceriano", and "Portlandiano".

After Choffat, attempts to build an integrated lithostratigraphic framework connecting the Upper Jurassic of several sub-basins (Fig. 3) included the studies of Mouterde *et al*. (1972, 1979), Wilson (1979), Leinfelder (1986, 1987), Wilson *et al*. (1989), Reis *et al*. (1996), Schneider *et al*. (2009), Martinius & Gowland (2011), and Kullberg *et al.* (2013).

Schneider *et al.* (2009) proposed another lithostratigraphic scheme, which was soon after reviewed by the same authors (Fürsich *et al*., 2009). Once again, the names that had been used in previous works were used in different senses. The main change was the creation of a new meaning for the Farta Pão Formation, chosen (after Schneider *et al.,* 2009) because it was the oldest available name uniting the (also proposed) Sobral, Arranhó I, Arranhó II, and Freixial Members.

The most recent lithostratigraphic framework for the Upper Jurassic in the Consolação Sub-basin was suggested by Martinius & Gowland (2011), who proposed a different set of members for the Lourinhã Formation, namely, from bottom to top, the São Bernardino, Porto das Barcas, Areia Branca, and Ferrel members (Fig. 3). Those authors further assigned the Lourinhã Fm. to the Estremadura Group, with the formation being stratigraphically located between the Consolação and the Torres Vedras formations. Recently, the same authors in Taylor *et al*. (2013) referred to the Alcobaça Fm. instead of Consolação Fm. In fact, those authors concluded that the Alcobaça Formation (here the Consolação unit) and the Lourinhã Formation cropping out between the Galiota syncline (northeast of Peniche) and Santa Cruz can be assigned to the uppermost Kimmeridgian to lowermost Tithonian based on the occurrence of the dinocyst *Subtilisphaera paeminosa* (their Conclusion 1). This conclusion is consistent with the isotope dates for Praia Azul Mb. (Schneider *et al*., 2009), but does not take into consideration other sections of the Consolação Sub-basin with biostratigraphic results, namely, the ammonites found by Werner (1986) in the lower part of the Consolação unit indicating an early Kimmeridgian age, the Sr isotopic ages of Schneider *et al.* (2009), and the various regional correlations (e.g., Leinfelder, 1987; Leinfelder & Wilson, 1998; Manuppella *et al*., 1999; Reis *et al*., 2000; Mateus, 2006; Fürsich *et al*., 2009). Furthermore, Taylor *et al*. (2013) recognized that the key marker *S. paeminosa* is recovered only from the Porto das Barcas Member (their Conclusion 5) (here the Praia Azul Mb.). By coupling the above conclusions, we can deduce that the work by Taylor *et al*. (2013) points to a latest Kimmeridgian to earliest Tithonian age for the Praia Azul Mb., in agreement with a set of other studies, as discussed below. Thus, the part of the Lourinhã Fm. above the Praia Azul unit represents most of the Tithonian, as proposed in many previous studies. We note that the thickness of Lourinhã deposits can reach almost 400 m (Wilson, 1979; Taylor *et al*., 2013), the same as for the Farta Pão Fm. further south (Ramalho *et al*., 1993).

As pointed out by Leinfelder (1987), the correlation between the many lithostratigraphic proposals for the upper Kimmeridgian and Tithonian can be anchored to an important transgression marked by an extensive set of carbonate levels. In the coastal outcrops of the Consolação Sub-basin, this set is recorded as far north as Paimogo and is included in the unit known as the Praia Azul Mb. (Hill, 1989), the Sobral Mb. (*sensu* Manuppella *et al*., 1999), the Arranhó I Mb. (*sensu* Fürsich *et al*., 2009), or the Porto das Barcas Mb. (Martinius & Gowland, 2011; Taylor *et al*., 2013), as well as corresponding to the base of the "Pteroceriano" (França *et al*., 1961; Leinfelder, 1986).

The meaning of the **Alcobaça lithostratigraphic unit** has been diverse since the original reference made by Choffat (1885). This unit is a shallow-marine to transitional (deltaic and estuarine) fauna-rich sequence with local carbonate levels. It is the most extensive Kimmeridgian unit in the Consolação and Bombarral-Alcobaça sub-basins, interfingering with the Abadia unit of the Turcifal and Arruda sub-basins. The Abadia unit is composed mainly of marls, limestones, mudstones, and fine sandstones, but also includes coarse siliciclastic intervals, forming in the southern part of the fieldtrip area an infill sequence of basinal to shallow-marine environments due to slope and submarine-fan progradation. It is capped by the shallow-marine oolitic and reefal Amaral unit.

The **Lourinhã Formation** and its constituent members have been widely used since they were informally proposed by Hill (1988, 1989). Simultaneously, Hill's PhD supervisor (Wilson, 1988, p. 400) also used the term "Lourinhã Formation" and depicted it in the lithostratigraphic scheme of the Lusitanian Basin. Hill (1988, 1989) includes in the Lourinhã Fm. the Praia da Amoreira (erroneously spelled as the "Praia da Amoeira" location), Porto Novo, Praia Azul, Assenta, and Santa Rita members, comprising sandstone and mudstone facies representing braided to sinuous paralic fluvial systems, distal alluvial fans, and upper deltas, punctuated by episodes of estuarine and lagoon sediments with shallow-marine to brackish macrofauna, such as oysters and sea urchins. The upper part of the Lourinhã Fm. is fully continental to the north of Santa Cruz (Santa Rita Mb. of Hill, 1989; Ferrel and Areia Branca mbs. of Martinius & Gowland, 2011), but it includes transitional to shallow-marine intercalations in the Assenta Mb to the south of Santa Cruz. As the boundaries between the members of the Lourinhã Fm. are essentially transgressive/regressive or retrogradational/progradational transitions, the thicknesses of the units change according to the palaeogeographic location, with the marine to transitional/brackish deposits increasing in proportion southwards along the coastal cliffs. Most of the upper Kimmeridgian and Tithonian of the Consolação and Arruda sub-basins and the northern part of the Lower Tagus Sub-basin corresponds to the siliciclastic Lourinhã Fm., progressively replaced southwards by the shallow-marine limestones and marls of the Farta Pão Fm.

The series of the Lourinhã Formation have always been considered as Late Jurassic in age, in particular Kimmeridgian/Tithonian (Choffat, 1901; França *et al*., 1961; Hill, 1988, 1989; Manuppella *et al*., 1999; Mateus, 2006; Kullberg *et al*., 2012, amongst others). Currently, this formation is considered as late Kimmeridgian (as in the Consolação area) to late Tithonian (as in Porto da Calada) in age, based on regional correlations, biostratigraphy (namely vertebrate and invertebrate faunal assemblages), Sr isotopes, and magnetostratigraphy. However, better age resolution is hampered by the lack of high-resolution age-index fossils or absolute radiometric ages.

1.2. Lithostratigraphic description

1.2.1. Consolação Unit (*sensu* Manuppella *et al.,* 1999) [member or formation] (Figs. 4–5)

Synonyms or correspondences: After França *et al*. (1960, 1961), the coastal outcrops of this unit correspond to the upper part of the Abadia Beds (*sensu* Choffat). Werner (1986), Hill (1988, 1989), Manuppella *et al.* (1999), Fürsich *et al*. (2009), and Taylor *et al.* (2013) included this stratigraphic interval in the Alcobaça Formation, as did Leinfelder (1986), who proposed a member rank but including only the lower 80 m.

Description: The Consolação unit in the study area reaches about 200 m in thickness and has been studied in detail by Werner (1986). According to that study, the lower 110 m of the unit are dominated by marls and sandy marls, with common limestone (marly, sandy, oncolitic, oolitic, or nodular) layers, and minor sandstone levels. The section from 110 to 170 m has a balance between sandstones, usually carbonate-cemented and cross-bedded, and finer marly and mudstone facies, with deformation levels and bioturbation but only rare macrofauna or oncoid levels. The upper 30 m are dominated by mudstone with abundant caliche concretions, some cross-bedded or massive sandstone bodies, rare levels with reworked shells and ooids, and abundant plant remains. The top is marked by the first coarse fluvial bed.

Fig. 4 – Porto Batel outcrop, Upper Jurassic (upper Kimmeridgian). Line A marks the base of the deltaic unit of the Consolação unit (fieldtrip Stop 1).

The marine and brackish beds contain numerous fossil assemblages, which consist mainly of oyster and corals biostromes, bivalves, and gastropods. Other macrofaunal groups (ammonites, brachiopods, sponges, echinoderms) occur only in a few layers, especially in the first brackish beds.

Environment: A synthetic analysis of lithological and biofacial features (microfacies, sedimentary structures, microfauna, ichnofauna) by Werner (1986), coupled with the stable environmental isotope data of Yin *et al.* (1995), indicates a dominance of brackish conditions, with an upward regressive trend from a euhaline regime to brachyohaline, mesohaline, oligohaline, and to a freshwater regime. The consolação unit ranges from marine (0–110 m; nearshore shelf, bay, and distal prodelta) to transitional

Fig. 5 – Fossils of the Porto Batel outcrop (Consolação unit, upper Kimmeridgian): A, plesiocheliid turtle; B, dinosaur track infill; C. *Fuersichella bicornis* (Sharpe, 1850) with colour pattern (ML1804); D, ostreiid reef with corals.

(110–170 m; proximal prodelta, delta front ,and upper delta) to brackish lagoons. This development can also be recognised, albeit less clearly, within the sequence of the epibenthic macrofauna, the microfauna (lituolid foraminifera to ostracod-dominated assemblages), and the ichnofauna (*Thalassinoides*/*Rhizocorallium* to *Diplocraterion*/*Ophiornorpha*/*Polykladichnus* to terrestrial *Scoyenia* facies). The autochthonous macrobenthos associations are controlled mainly by substrate and salinity. The diversity is inversely proportional to the salinity level, which ranges from euhaline to oligohaline waters. The typical brackish water environments are dominated by euryhaline opportunists or endemic brackish elements (e.g., *?Neomiodon*). The only association that lived in freshwater lakes is represented by the gastropod *Valvata*.

Age: The 46 to 72 m interval was dated by ammonites as lower Kimmeridgian (Hypselocyclum Zone) by Werner (1986). In accordance, the Sr isotope ages obtained by Schneider *et al.* (2009) indicate the early to early late Kimmeridgian. Thus the top can be correlative of the eastern Amaral Formation, attributed by Leinfelder & Wilson (1998) to the Eudoxus Zone (middle of the upper Kimmeridgian) albeit some diachronism can be admitted.

1.2.2. Praia da Amoreira and Porto Novo members (Fig. 6–9)

Synonyms or correspondences: The Porto Novo and the Praia da Amoreira Members (Hill, 1989) were mapped together by Manuppella *et al.* (1999) and we follow this approach in this work. Since Manuppella *et al.* (1999) considered this sedimentary package as part of the Alcobaça Beds, with an implicit Formation rank, the Praia da Amoreira–Porto Novo unit can be considered as a member. It corresponds to the São Bernardino Member of the Lourinhã Fm. after Martinius & Gowland (2011), to the lower part of the "Pteroceriano" (França *et al.*, 1960, 1961) and to the lower part of the Sobral Mb. *sensu* Fürsich *et al*. (2009).

Description: This stratigraphic interval overlies conformably the Consolação unit, but the lower boundary seems to be an erosional surface (Ravnas *et al*., 1997; Manuppella *et al*., 1999) marked by a conglomeratic level, already referred by França *et al*. (1961, 1962), possibly related to the progradation of the alluvial systems (Hill, 1989). The thickness appears to change a great deal in the region, with quite different numbers mentioned in several publications, reaching in the coastal cliffs between S. Bernardino and Paimogo 370 m (Werner, 1986) to 340 m (Martinius & Gowland, 2011); between Areia Branca and Porto Novo, Taylor *et al*. (2013) mention 450 m (but including the Praia Azul Mb.), and Hill (1988) refers 140 m for the Praia da Amoreira Mb. and 95 m for the Porto Novo Mb. Silicified and or coalified fossil wood (namely the conifers *Protocupressinoxylon* and *Prototaxoxylon,* Martinius & Gowland, 2011) and reptile bones are relatively frequent in the unit (França *et al*., 1961), especially in the upper Porto Novo Mb. (Hill, 1989; Martinius & Gowland, 2011). The abundant coarse pink feldspar or even granite clasts are noteworthy, especially at the base of the unit, proving a provenance from the Berlengas Horst. The proportion of sandy facies is between 34 and 44%, and the trace fossils *Taenidium barretti* and *Planolites montanus* are locally common (Taylor *et al*., 2013).

The Praia da Amoreira Mb. was described in detail by Hill (1989) as being formed by sand and mudrock heterolithic facies, lenses of meter-thick massive sandstone, and massive mudrock with calcrete horizons. The mudstone forms about 60% in volume, kaolinite dominates among clay minerals, and the heterolithic facies show frequent bioturbation and soft-sediment deformations (*ibid*.). At the base a slight marine influence was detected by the presence of dinocysts (Taylor *et al*., 2013).

Fig. 6– Bay of Vale das Pombas (north of Paimogo) – upper Kimmeridgian outcrop of the Porto Novo Member of the Lourinhã Fm. (Fieldtrip Stop 2), with the dinosaur fossil locations: A, *Lourinhanosaurus* eggs and nest; B, Turiasaur sauropod *Zby atlanticus*.

The overlaying Porto Novo Mb. is composed of larger bodies of sandstone, often stacked and usually with lateral accretion surfaces, frequently forming heterolithic wings. Carbonaceous particles are frequent in laminae of cross-bedded sandstone. The channel sandstone lenses are usually isolated within thick floodplain mudstone volumes. The mudrocks are rich in calcrete soils, and include also flat lenses of finer sandstone of probable crevasse-splay origin. Caliche concretions are found as intraformational conglomerates at the base of channels. The internal architecture of some sandstone bodies points to tidal modulation (Martinius & Gowland, 2011). The upper 50 m was described by Fürsich (1981) in the Amoeiras beach as cross-bedded sandstones, sometimes pebbly, fining upwards to reddish-greenish floodplain fines.

Environment: The Praia da Amoreiras Mb. was interpreted by Hill (1989) as deposited in the distal mudflat of alluvial fans with both sheetflood and channelized flows shifting on the surface, draining southeastward from the Berlengas basement block; however, Taylor *et al*. (2013) consider it as deposited by a meandering river system. The Porto Novo Mb. comprises distal deposits of a fluvial meander system grading laterally to tide-influenced upper deltaic deposits with more straight channels, thus including the fluvial–tidal transition zone during limited transgressions. Both units show prominent caliche development. The palynomorphs associations of two levels of this member at Porto Dinheiro (Mohr, 1989) include only continental *taxa*. The Praia da Amoreira–Porto Novo unit was deposited in a context of relatively high rate of accommodation creation, as inferred by the low amalgamation between channel bodies, but decreasing upward. Since the alluvial fans were probably coeval with the fluvial system to the east (Hill, 1989), the vertical transition corresponds to the progradation of the axial fluvial drainage over the fans in a colmatation trend, possibly in a context of declining tectonic activity.

Age: Since it is essentially continental and siliciclastic, it does not possesses fossils allowing high-resolution age assignment, but it includes ostracods pointing to a late Kimmeridgian to early Tithonian age in its middle part (Werner, 1986) and the dinocyst *Cribroperidinium granuligerum* (Klement) "complex" indicating a mid Kimmeridgian to late Tithonian age for the lower part (Taylor *et al*., 2013). Thus, the unit is dated as latest Kimmeridgian essentially by considering the encompassing units.

Dinosaur fauna: *Ceratosaurus* sp., *Torvosaurus gurneyi, Zby atlanticus*, *Lourinhasaurus alenquerensis*, *Lusotitan atalaiensis*, Diplodocidae indet., *Miragaia longicollum*, cf. *Hypsilophodon* sp., *Trimucrodon cuneatus* (holotype), *Lourinhanosaurus antunesi*, aff. *Compsognathus,* Abelisauridae indet. (Mateus & Antunes, 2000b; Hendrickx & Mateus, 2014).

Other vertebrates: aff. *Lepidotes*, aff. *Plesiochelys,* Crocodyliformes indet., Rhamphorhyncoidea indet., *Kuehneodon hahni, Pinheirodon pygmaeus, P. vastus, Bernardodon atlanticus, Iberodon quadrituberculatus, Ecprepaulax anomala* (Antunes, 1998; Hahn & Hahn, 1999).

Invertebrates: *Gervilleia* sp., Gastropoda aff. *Paludina* sp.

Flora: *Brachyphyllum lusitanicum* or *Pagiophyllum*; *Protocupressinoxylon* and *Prototaxoxylon.*

1.2.3. Praia Azul Member (Fig. 8 – 9)

Synonyms or correspondances: This sedimentary package was named as Praia Azul Member by Hill (1989) and as Porto de Barcas Member by Martinius & Gowland (2011, misspelled as Porto de Barças in Taylor *et al*., 2013); both papers include the unit in the Lourinhã Fm.. It corresponds to the upper part of the "Pteroceriano" in França (1960, 1961), and to the Sobral unit of Manuppella *et al.* (1999). To the south, the Praia Azul Mb. corresponds to the Arranhó I Mb. and part of the Arranhó II Mb., both from the Farta Pão Fm. (*sensu* Fürsich *et al*., 2009). Leinfelder (1986) considered these series as the Santa Cruz Member of the Bombarral Fm. and correlated it with the upper part (formed by intercalating laterally extensive carbonate layers) of his "Pteroceriano" Formation in the Arruda Sub-basin. This unit was later named as Arranhó Mb. of the Farta Pão Fm. and the laterally extensive carbonates included in sequence 7 by Leinfelder & Wilson (1998). Note that the Sobral unit was considered as a formation by Leinfelder (1986), and later as a member of the Lourinhã Fm. by Leinfelder & Wilson (1998). According to Fürsich *et al.* (2009), the coastal cliffs between Paimogo and Areia Branca are the northernmost identified outcrops of the Arranhó I Mb.

Description: In the cliffs between Paimogo and Areia Branca the unit is mainly composed by marls and mudstone with a tabular geometry (88 to 75%, Taylor *et al*., 2013), rare sandstone bodies with a

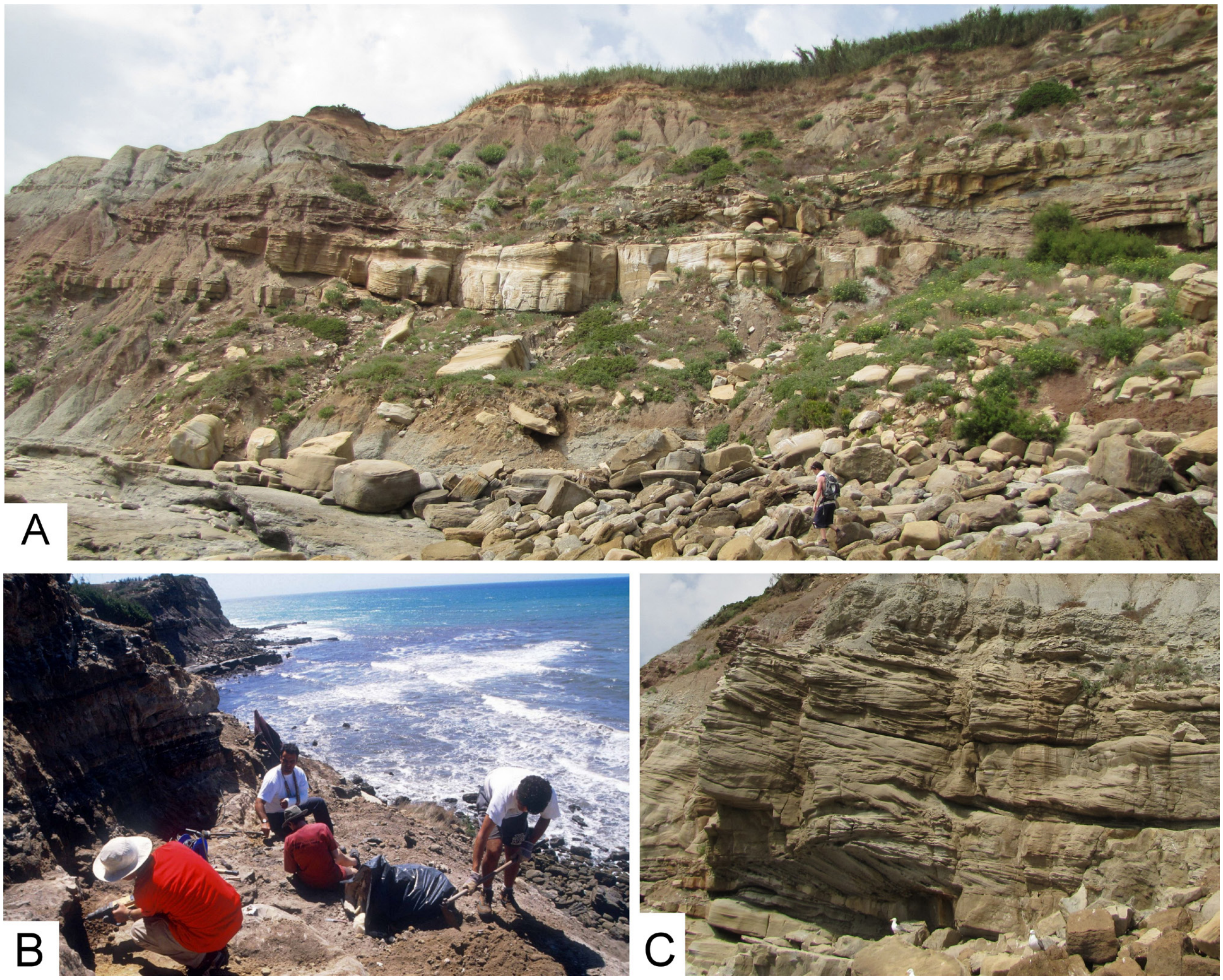

Fig. 7 – Upper Kimmeridgian outcrops of the Porto Novo Member at Vale das Pombas : A, fluvial channel sandstone body within floodplain and crevasse-splay deposits; B, sauropod dinosaur excavation; C, detail of a sandstone channel with cross bedding showing a wide span of paleocurrents (Fieldtrip Stop 2).

Fig. 8 – Coastal cliff west of the Paimogo fort. The dashed line indicates the *Isognomon* and oyster-rich layer that marks the transition between the Porto Novo Mb. (below) and Praia Azul Mb. (above) of Lourinhã Fm.

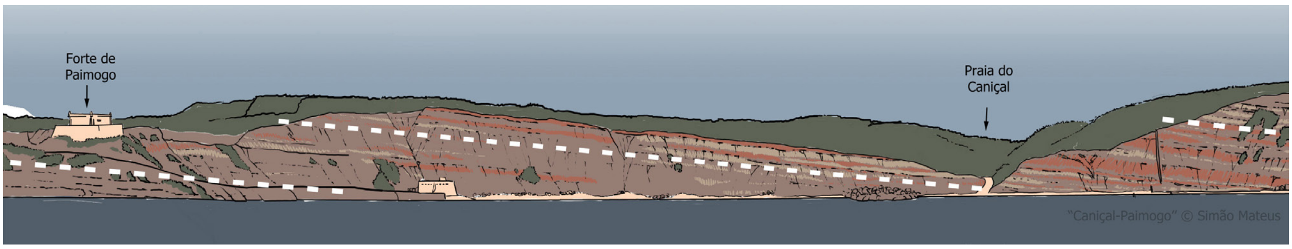

Fig. 9 – Cliff between the Paimogo fort and the Caniçal beach (illustration by Simão Mateus). The dashed lines mark the three transgressive beds with shells of the Praia Azul Mb. (Lourinhã Fm.) in their northernmost occurrence.

low-relief channel architecture, some displaying intense bioturbation, wave ripples, planar cross-bedding and abundant carbonaceous debris. The unit is characterized by three conspicuous carbonate levels, with the lower and the upper ones used as the lithostratigraphic boundaries. These faunally distinct, laterally extensive shelly layers can be traced over distances of 20 km, with a brackish bivalve association (Werner, 1986; Taylor *et al*., 2013) and including locally at the base some bivalve patch-reefs mentioned by Seifert (1958, cited in França *et al*., 1961). This unit was described by Fürsich (1981), namely the lower 85 m between Santa Cruz and the Sizandro river mouth, detailing the characteristic banks and patch-reefs of benthic macrofauna. It is also rich in bioturbated levels, including the widespread *Taenidium barretti* and *Planolites montanus* and diverse trace fossils assemblages in the shelly beds, this comprising *Thalassinoides*, *Rhizocorallium* and *Diplocraterion* species, among others (Manuppella *et al*., 1999, Taylor *et al*., 2013). Horizons of carbonate palaeosols (caliche levels) are frequent in the mudstones. After Manuppella *et al*. (1999) south of Santa Cruz the unit is composed by *ca*. 130 m of sandstones with some conglomeratic layers, occasionally with large-scale cross bedding, alternating silty or sandy to clayey marls and mudstone. Further north it reaches about 80 m in Santa Rita (Wilson, 1979) and 110 m in the cliffs between Paimogo and Areia Branca (Fürsich, 1981; Taylor *et al*., 2013). Dinocysts forms diverse assemblages and some foraminifers, ostracods and charophytes were identified by Taylor *et al*. (2013).

In the Paimogo to Areia Branca coastal cliffs the overlaying predominantly meandering deposits corresponds: *i*) to the upper part of the Porto Novo Mb. after Hill (1989) (implying that the Praia Azul Mb. is an intercalation within this unit), *ii*) to the Areia Branca Mb. after Martinius & Gowland (2011), or *iii*) to the Bombarral Fm. in Manuppella *et al.* (1999).

Environment: Most of the unit was deposited by meandering fluvial systems flowing in a low-lying coastal plain, connected with transitional systems like deltas, sandy bay shorelines and brackish lagoons (Fürsich, 1981; Werner, 1986; Taylor *et al*., 2013). The fine deposits of paralic floodplains and restricted lagoons are thicker than channels bodies, both fluvial and deltaic.

The brackish faunas of the shelly layers indicate brief marine incursions (Werner, 1986) forming brackish–marine bays, an interpretation supported by stable isotope data (Yin *et al*., 1995). In general, a regressive trend can be identified, continuing in the overlying coarser braided fluvial deposits of the Santa Rita Mb. (of the Lourinhã Fm).

Age: In the fieldtrip area the unit was considered by Fürsich (1981) as upper Kimmeridgian–lower Tithonian due to the presence of the ostracod *Cetacella armata* Martin in the lower–middle part of the unit. It includes the bed with *Protocardia gigantea* that marks, according to Schneider *et al.* (2010b), the Kimmeridgian–Tithonian boundary in the Lusitanian Basin.

The biostratigraphy based in a combination of forams, ostracods and dinocysts presented by Taylor *et al*. (2013) indicates for the two lower shelly levels a latest Kimmeridgian to earliest Tithonian age (tethyan ammonites Beckeri and Hybonotum Zones).

By plotting the strontium isotopes data from oyster shells in the established global curves, Schneider *et al.* (2009) provide reliable ages for shallow-marine to brackish units interfingering with the Lourinhã Fm., namely latest upper Kimmeridgian to middle lower Tithonian for the Arranhó I Mb. (probably the upper part) in the Santa Cruz area. This view agrees with the correlations established with the Arruda Sub-basin by Leinfelder (1986) and Leinfelder & Wilson (1998), where the transition from the Sobral unit to the expressive transgressive level at the base of the Arranhó unit was dated as earliest Tithonian.

In conclusion, the Praia Azul/Sobral Member can be considered with confidence as latest Kimmeridgian to earliest Tithonian.

Dinosaur fauna: *Supersaurus lourinhanensis* (holotype, ML414), *Lourinhanosaurus antunesi* (holotype ML370), *Lusotitan atalaiensis* (lectotype, MG), *Miragaia longicollum*, *Dryosaurus* sp., *Allosaurus europaeus* (holotype, ML415), *Draconyx loureiroi* (holotype).

Other vertebrates: Plesiochelyidae, Pleurosternidae *Selesemys*, *Goniopholis*, *Machimosaurus, Hybodus.* Sites with microvertebrate remains show the occurrence of anurans, albanerpetontids, bony fishes, plesiosaurs, pterosaurs, lizards, early snakes, small crocodyliforms, and mammaliforms.

Invertebrates: *Jurassicorbula edwardsi*, *Isognomon rugosa*, *Eomiodon securiformes*, *Archaeomytilus*, Ostreiidae, *Protocardia gigantea*.

Flora: *Porochara westerbeckensis*.

1.2.4. Assenta Member (Figs. 10 – 11)

Synonyms or correspondences: This member of the Lourinhã Fm. (Hill, 1988) is laterally equivalent, to the north of the Caldas da Rainha structure (Santa

Fig. 10 − Praia da Escadinha outcrop (north of the Praia do Porto da Calada): the line J/K marks the Jurassic–Cretaceous boundary (Salminen *et al.*, 2013), the line A marks the boundary between the Lourinhã Fm. (below) and the Porto da Calada Fm. (above).

Cruz), to the Santa Rita Mb. (after Hill, 1989), and to the association of the Areia Branca plus Ferrel members of Martinius & Gowland (2011), all included in the Lourinhã Fm.. It is also synonymous of the Bombarral Formation in Manuppella *et al.* (1999), of the Portlandian in França *et al.* (1961) and Zbyszewski *et al.* (1955), and correspond to most of the upper sandstones with plants and dinosaurs ("Grés superiores com vegetais e dinossáurios") in França *et al.* (1960). It intertongues laterally to the east and to the south with the Farta Pão Fm (*pars*).

Description: The unit is dominated by mudstones, with frequent levels of pedogenic carbonate concretions (caliche), intercalated with channelized cross-bedded sandstones, including large scale point-bars, and thin flat lenses (almost tabular) crevasse and levees bodies. It includes several levels of nodular and marly bioclastic limestones, with a diverse bivalve fauna (Zbyszewski *et al.*, 1955), benthic foraminifera and ostracods (Rey, 1972) that can be considered as tongues of the Farta Pão Fm. thinning out northward. The caliche levels can be well developed, even forming resistance belts in the cliffs. Reworked nodules often constitute conglomerates at the base of channels. Carbonaceous fragments are common, frequently as trunks and pyritized. Deformation structures, namely load-casts and slumps, are recurrent. The top boundary of the unit is defined by the transition from a mudstone dominated interval to the sandstone-rich with thin micritic and dolomitic layers of the Porto da Calada Formation, marked in detail by a thick sandstone channel body (in accordance with Rey, 1993).

The carbonate intercalations of the upper part of the unit (around 20 and 40 m in Fig. 11) include laminated marls, and limestones with a marked nodular characteristic resulting from intense *Thalassinoides* ichnofabric, a facies typical of the Farta Pão unit further south (Ramalho, 1971).

It is difficult to give the unit's exact thickness, since the base is covered and affected by faults, but it can be estimated around 300 m (Wilson, 1979; Hill, 1988). The dominant clay minerals association is illite–smectite (Manuppella *et al.*, 1999).

Age: According to Rey (1972) the microfossil association (foraminifera and ostracods) of the topmost marine limestone intercalation in the Porto da Calada section (37–40 m in Fig. 11) is similar to the one found in the Farta Pão Fm. (dated as latest Kimmeridgian to latest Tithonian, Schneider *et al.,* 2009), including the foraminifera *Anchispiroyclina lusitanica* (Egger) and *Everticyclammina virguliana* (Koechlin) indicating in the region, respectively, a late early Tithonian to Berriasian and a late Oxfordian to Tithonian age (Rey, 1972; Ramalho, 1981). This agrees well with the ages admitted to the enclosing units and with the lateral correlations with the southern marine units (e.g., Leinfelder & Wilson, 1998; Fürsich *et al.*, 2009) and the unit should be essentially Tithonian. In detail, the upper carbonate level of the Assenta Mb. in the Porto da Calada section is quite likely the upper tongue of the Freixial Mb. of the Farta Pão Fm. in the Arruda Sub-basin, correlated by Leinfelder & Wilson (1998) with the base of the latest Tithonian T5 sequence of the European Sequence Stratigraphic Chart of Jacquin *et al.* (1998).

Considering its own age arguments and the age admitted for the units above and below, a late early Tithonian to earlier Berriasian age can be proposed for the unit. Bearing this in mind, the recent magnetostratigraphic study conducted by Salminen *et al.* (2013) tentatively identified the M19 to M17 magnetochrons in the polarity log of the Porto da Calada section. Following the Ogg *et al.* (2012) scale, the J/K Tithonian–Berriasian boundary is at the base of magnetozone M18r, around 52 m in the Porto da Calada section (Fig. 11). After this work the last few meters of the Assenta Mb. can be considered as earliest Berriasian.

Environment: Upper fluvial-dominated delta to meandering fluvial systems flowing in a paralic plain (Hill, 1988), with occasional transgressions allowing the short-lived establishment of inner and restricted (lagoonal) zones of shallow carbonate platforms (Ramalho, 1981). The overall trend is regressive (Hill 1988), as marked by the siliciclastic facies and architecture, as well as the fauna of the carbonates changing from marine to brackish. Accordingly, Martinius & Gowland (2011) interpreted the further north Areia Branca Mb. as recording paralic meandering fluvial to upper delta systems (including tidal modulation and mouth-bars), grading upward to the pebbly sandstones of braided systems that forms the Ferrel Mb..

1.2.5. Porto da Calada Formation (Figs. 10–11)

Synonyms or correspondences: The Porto da Calada Formation was formally defined by Rey (1993). It is laterally equivalent to the north and to the east to the fluvial Serreira Formation (*op. cit.*) and to the south, in the Sintra region, to the limestones and marls with *Anchispirocyclina lusitanica, Mantelliana purbeckensis* and *Trocholina*, including the "nankeen-yellow limestone levels" ("Infravalanginian") (Ramalho *et al*., 1993). It corresponds to the top of the Farta Pão Formation (*sensu* Wilson, 1988) and to the uppermost part of the Feixial unit, considered as a formation by Leinfelder (1986) and as a member of the Farta Pão Formation by Fürsich *et al*. (2009). It is equivalent to the lower part (C.1–5) of the "Hauterivian and Valanginian" of Zbyszewski *et al.* (1955) to the NE.

Description: In the Porto da Calada section, the unit was studied by Rey (1972, 1993) and Salminen *et al.* (2013). It is 43 m thick and is dominated by cross-bedded sandstones, often conglomeratic, with minor mudstones. The sandstone bodies usually show lateral accretion sigmoids, sometimes heterolithic, and include several amalgamated channels; reworked calcrete nodules forms breccia-like conglomerates at the base of the larger channels. The overbank mudstones include frequent laminae of fine sandstone and calcrete levels. The carbonate levels are micritic limestone with gastropods and bivalves (namely the bivalve *Pterotrigonia caudata* (see Rey, 1972), and dolomitic facies, including thin nodular yellowish beds at the top. Several limestone levels along the unit shows the large foraminifera *Anchispirocyclina lusitanica*.

Age: The unit was dated as Berriasian based on dinocysts (Berthou & Leereveld, 1990) and correlated with the top of the Farta Pão and Freixial units, both also considered as Berriasian based on foraminifera, ostracods and charophytes (Ramalho, 1971; Rey, 1972), namely by including the foram *Anchispirocyclina lusitanica*, indicating a Tithonian to lowermost Cretaceous age (Ramalho, 1981; Leinfelder, 1986). About 2.5 km to the south of Porto da Calada the unit shows an increase in the proportion of marginal marine beds and a more diverse fossil association, including in the lower levels the bivalve *Pterotrigonia caudata* in Rey (1972) that indicates the Early Cretaceous. In the magnetostratigraphic study recently conducted in the Porto da Calada section (Salminen

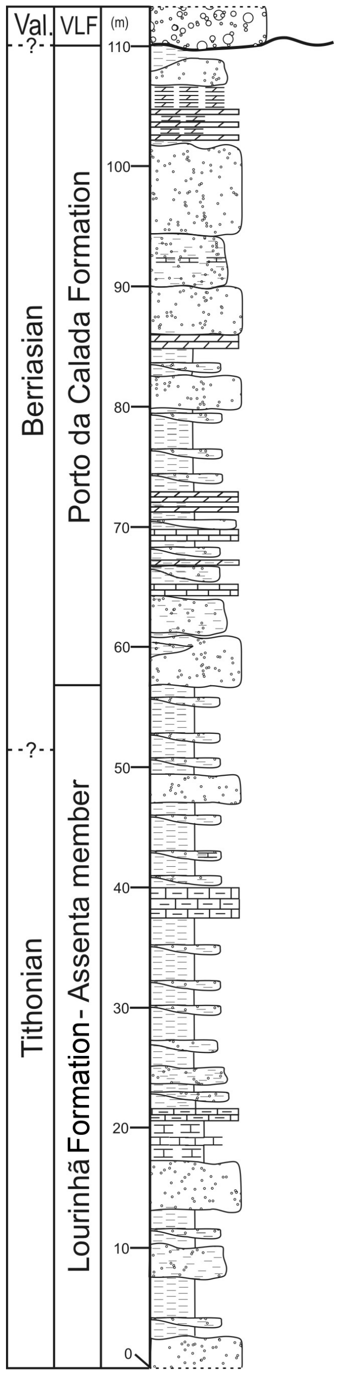

Fig. 11 – Porto da Calada stratigraphic log (see text for details on the lithology). Top of Lourinhã Formation.

et al., 2013), considering the biostratigraphic constraints, the Tithonian–Berriasian boundary (at the base of magnetozone M18r) was tentatively located at 51–53 m (Fig. 11), about 5 m below the limit between the Assenta Mb. and the Porto da Calada Fm.

Environment: Rey (1993) identified five 3rd order depositional sequences, with late transgressive to highstand intervals represented by carbonate and laminated fine sandstone beds deposited in intertidal plains to internal marine platform. The lowstand to early transgressive systems correspond essentially to sandy meandering fluvial channels, linked to estuarine channels and bars, interbedded and cutting the floodplain and intertidal flats (Rey, 1993; Salminen *et al.,* 2013). These low energy deposits had developed paleosols, as shown by the *in situ* and the reworked calcrete nodules. Batten & MacLennan (1984) studied ten samples of the Porto da Calada section with large assemblages of well preserved palynomorphs, dominated by a high diversity of *Classopollis* pollen but with a low representation of ferns. The associations were interpreted as reflecting a source vegetation composed by conifers, mainly of the Cheirolepidiaceae family, with a sparse undergrowth.

1.2.6. Palaeoclimatic interpretation

The interest in palaeoclimate in the scope of this work is twofold: as main control on *i*) palaeoecology and palaeoenvironment, and on *ii*) vertebrates taphonomy, namely on the preservation of bones in the stratigraphic record. Paleosols are relevant since they are controlled by precipitation, temperature and seasonality, as well as they are major contributes for the geochemical environment of burial areas.

Calcretes, found in the Lourinhã Fm. (Myers, 2011) and the Porto da Calada Fm. (Rey, 1993; Salminen *et al*., 2013), indicate a semi-arid climate with a seasonal rainfall lower than 500 mm and mean annual temperature from 16 to 19 °C. Myers *et al.* (2012a) estimated the soil pCO2 by measuring carbon-isotope values of pedogenic carbonates and plant-derived organic matter. The Lourinhã Fm. has a slightly higher average estimates for soil pCO2 when compared with the coeval Morrison Formation, implying for the Lourinhã Formation a deposition under somehow wetter conditions, higher productivity and an estimated greater faunal richness. After Myers *et al.,* (2012b), the geochemistry and morphology of paleosols profiles show warm and wet paleoclimatic conditions with a strongly seasonal precipitation pattern, and the oxygen isotopes suggest surface temperatures reaching between 27º C and 34º C (average 31ºC) and a mean annual precipitation of 1100 mm/yr.

The plant macroremains of the Upper Jurassic in the study area (Pais, 1998) include as the most common forms the bennetittale *Otozamites* and the conifer *Cupressinocladus*, which have aridity adaptation as thick cuticles and strongly protected stomata, suggesting a warm and dry climate. After Mohr (1989) the middle part of the Lourinhã Formation (Porto Novo Mb.) at Porto Dinheiro holds an exclusively continental e relatively diverse palynological assemblage suggesting a warm climate with pronounced dry seasons, possibly of Mediterranean type.

The dominance of the cheirolepidiaceous *Classopolis* pollen in the Porto da Calada Fm. (Batten & MacLennan, 1984) probably indicates a preference for dry conditions, at least seasonally (*op. cit*., Mendes *et al.,* 2010). After Mendes *et al.* (2011) the probably coeval (latest Tithonian?–Berriasian) upper part of the Bombarral Fm. in the Juncal–Nazaré region bears palaeobotanical associations indicating a xerophytic coniferous forest dominated by Cheirolepidiaceae with an understory vegetation of ferns typical of dry soils and other pteridophytes, as well as members of the BEG group, a community clearly adapted to a subtropical and (at least seasonally) dry palaeoclimate. However, as pointed out by Leinfelder *et al.* (2004), a fully arid climate can be ruled out by humid indicators like the frequent meandering river, delta, freshwater and brackish systems, as well as abundant lignite-rich deposits.

Martinius & Gowland (2011) run a palaeoclimatic model developed by the Hadley Centre (Bristol, UK) applied on a Statoil plate reconstruction (inhouse MERLIN project data), as well as interpreted the growth rings and cellular structure of the conifers trunks found in the Porto Novo Mb. as revealing contrasting growing conditions probably due to seasonal changes in water availability. According to the same paper, these arguments, coupled with the abundant calcretes, indicate a warm climate marked by a seasonal change from a dry summer with a dominant WSW palaeowind, to a wet winter with ENE palaeowind. This characterization suggests a monsoonal pattern and agrees well with the above referred interpretations.

1.3. Dinosaurs and other vertebrates

The Lourinhã Fm. become famous by their dinosaurs, which include some taxon names based on the toponomy: *Lourinhanosaurus antunesi* Mateus, 1998, *Lourinhasaurus alenquerensis* (Lapparent &

Zbyszewski, 1957), and *Supersaurus lourinhanensis* Bonaparte & Mateus 1999 (see Mannion *et al*., 2012 and Tschopp *et al*., 2015). Besides the skeletal material, the Lourinhã Fm. yielded also abundant dinosaur tracks, normally preserved by the natural sandstone infill in the muddy substrate (e.g., Milàn *et al*., 2005; Mateus & Milàn, 2008, 2010), and eggs and nests (e.g., Mateus *et al*., 1998; Cunha *et al*., 2004).

The vertebrates fossils are common, including dinosaurs, crocodiles, and turtles (Mateus, 2006), a fauna assemblage somehow similar to the Morrison Formation in North America, but with coastal influence and some European-related fauna input. In particular, the dinosaur fauna shares several genera, such as *Ceratosaurus, Torvosaurus* and *Allosaurus* (Mateus & Antunes, 2000a, 2000b).

The nest at Porto das Barcas is in the Praia Azul Member that corresponds to a transgressive episode with euryhaline bivalves and rare sea urchins, but also including dinosaur bones and tracks, and other continental fossils (see, for example, Mateus & Milàn, 2010). The Lourinhã Fm. is also one of the richest areas for Late Jurassic dinosaur and crocodile eggs, which are mainly concentrated in Praia Azul Member (Ribeiro *et al*., 2013). The nests of Porto das Barcas and Paimogo provide exquisitely preserved eggs and embryos of theropod dinosaurs (Mateus *et al*., 1998; Araújo *et al.,* 2013).

1.4. Paleogeography

Most of the Late Jurassic paleogeographic reconstructions indicate a marine separation between Iberia (Portugal and Spain) and North America prior to the Kimmeridgian–Tithonian (Figs. 12 and 13; Mouterde *et al.,* 1979; Ribeiro *et al.,* 1979; Ziegler, 1988; Schudack & Schudack, 1989; Smith *et al*., 1994; Rees *et al.,* 2004; Golonka, 2005). The paleogeography of the European margin (Ziegler, 1988; Schudack & Schudack, 1989; Sibuet *et al*., 2012) indicates that Iberia was separated from continental Europe as well as from North America by seaways, but several islands occurred between the Iberian western margin and Newfoundland, namely the Galicia Banks, the Great Banks and the Flemish cap blocks. If we consider emerged and shallow coastal areas, the reconstructions do not preclude transient and temporary terrestrial connections during eustatic lowstands.

The early stages of the Atlantic can be traced back to the Hettangian, when separation begun between North America and the Iberian. The Lower Jurassic rocks of the Lusitanian Basin show ammonites and clear marine deposition. By the Late Jurassic, when a large part of the Lourinhã Fm. rocks were deposited, the proto-Atlantic was already a few hundred of kilometers wide at this paleolatitude.

However, the presence of shared large vertebrates propose a land connection palaeogeographical North

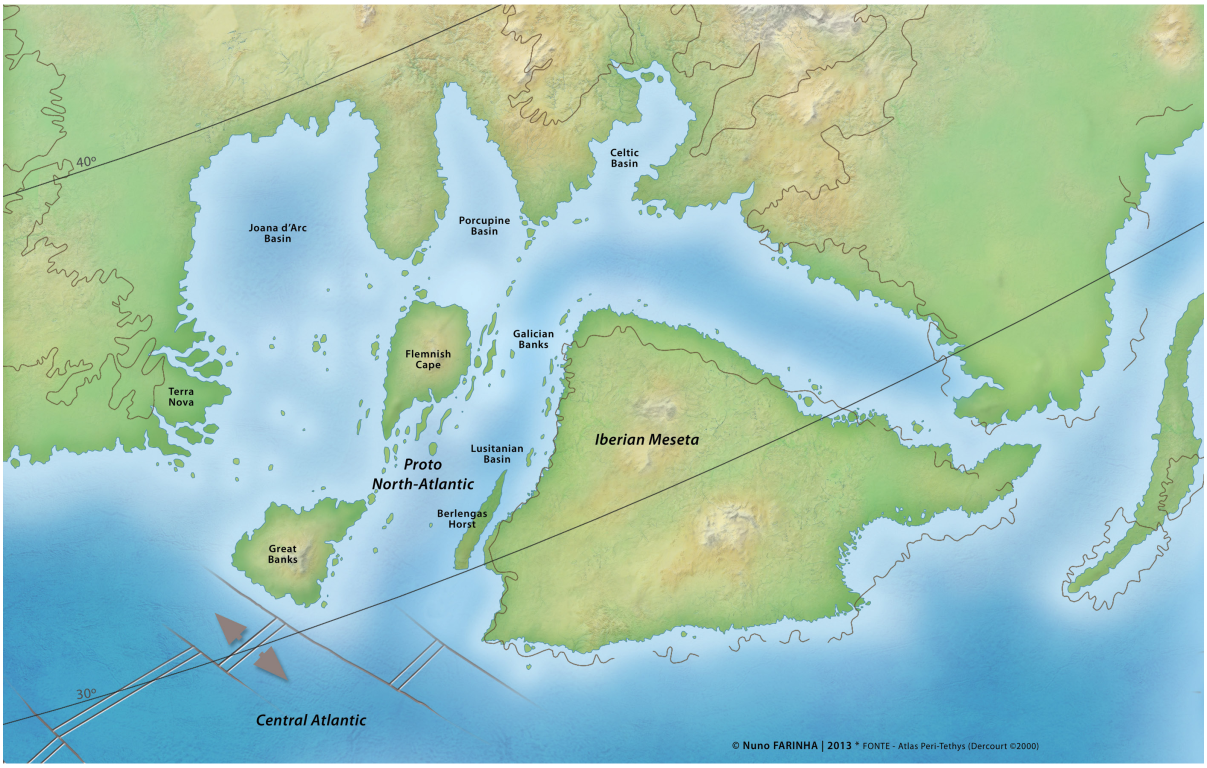

Fig. 12 - Tithonian paleogeographic map of the Iberia region (illustration by Nuno Farinha after Dercourt *et al*., 2000).

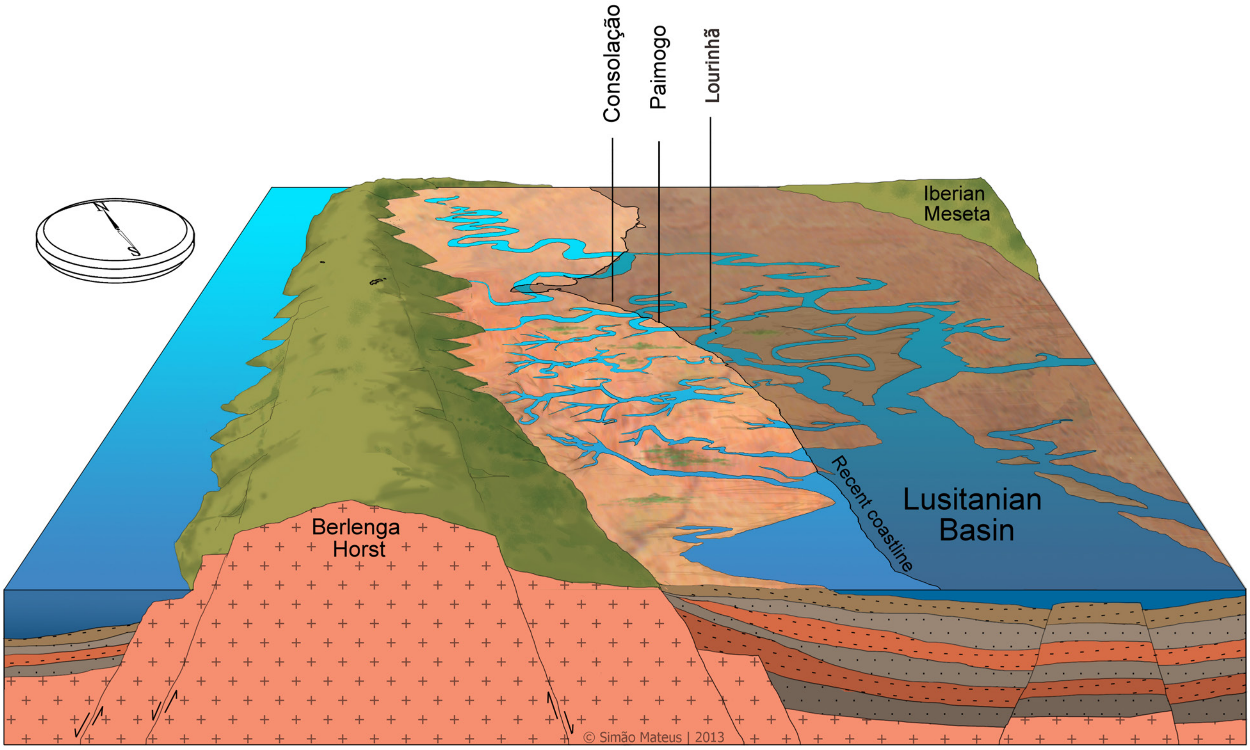

Fig. 13 - Palaeogeographic interpretation of the Lusitanian Basin during the lower Tithonian (illustration by Simão Mateus), with the location of the north stops of this fieldtrip (Porto da Calada is even further south).

America and Iberia. The dinosaurs *Torvosaurus*, *Allosaurus, Ceratosaurus, Stegosaurus, Supersaurus*, brachiosaurids and others have a restricted distribution Morrison Formation in North America and Lourinhã Fm. in Portugal. As mentioned before, numerous dinosaurs show faunal similarities with the Kimmeridgian/Tithonian Morrison Fm. in North America. Taking in consideration that the dinosaur usual generic longevity is below 10 Myr (the average is 7.7 Myr according to Dodson, 1990), the origin of the several genera shared between Portugal and Morrison Fm. should had occurred during the late Middle Jurassic to early Late Jurassic. This is much more recent than the early Jurassic first marine proto-Atlantic sediments in the Lusitanian Basin. Some land passages between the Iberian Block and North America must have occurred during the Callovian–Kimmeridgian interval. The most significant regression and sea-level drop during that interval is latest Callovian to early Oxfordian and may have allowed the passage of terrestrial fauna between Iberia and North America. An Oxfordian timing for a possible migration of dinosaur fauna is consistent with the expected diversity and speciation observed in the Late Jurassic fauna of Portugal.

During the Late Jurassic, especially the late Kimmeridgian and the Tithonian, major eustatic changes (Haq *et al*., 1988; Sahagian *et al.,* 1996) could have alternatingly increased the isolation of Iberia continental areas and contributed to speciation, or allowed the connection and spreading of terrestrial *taxa*.

By the Callovian–Oxfordian transition between there was a major paleoceanographic and paleoclimate reorganization (Rais *et al*., 2007) coincident with a large drop of the eustatic sea level, exposure and unconformity (Leinfelder & Wilson 1998; Kullberg *et al*., 2014) and associated with the Callovian–Oxfordian Atlantic Regressive Event. That condition created an ephemeral land bridge that presented a temporary opportunity for probably terrestrial gateways through the landmasses Flemish Cap and Galician Bank, so that large dinosaur could cross the northern proto-Atlantic in both directions. Finally, the time between the fauna exchange of Callovian–Oxfordian around 163 Ma until the occurrences in late Kimmeridgian at 152 Ma in Morrison and Portugal, was sufficient to allow speciation but keep generic resemblance. That explains why most genera are shared but species are unique.

This model is consistent with the chronology and taxonomy for speciation of Iberian and American forms, exemplified by pairs coeval sister taxa *Torvosaurus tanneri* and *T. gurneyi*, *Allosaurus fragilis* and *A. europaeus* or *Supersaurus vivianae* and *S. lourinhanensis*.

While some of the smaller animals in the fauna show Morrison/Portugal affinities (*Saurillodon, Dorsetisaurus, Dryolestes, Laolestes*), most from Iberia have European or even Asian affinities (as for *Asteracanthus, Caturus, Craspedochelys*, Paulchoffatinae, *Plesiochelys*, and *Rhamphorhynchus*). The larger bodied fauna is more closely related to Morrison than to mainland Europe (except for dacentrurine stegosaurs).

The migration may have taken place in both directions. For instance, the closest relative of *Torvosaurus* is probably the Bathonian European *Megalosaurus* that the presence of this genus in North America suggests an European origin. On the other hand, *Allosaurus* and *Supersaurus* origins are consistent with a North American origin and with an east–west migration.

1.5. Vertebrates taphonomy

The landscape of the studied units, where dinosaurs lived, had a variety of environments with a wet and soft muddy surface, mainly fluvial floodplains, deltaic interdistributary areas, intertidal plains and shallow coastal lagoons. Many of such places could turn into mires where animals weakened by a prolonged dry season may have been trapped and died (Benton *et al*., 2012). The sudden and violent flash-floods typical of the hydrological regimes of mediterranean or monsoonal climates can also be evoked to explain the burial of skeletons and nests.

After its burial, the preservation of the bones and eggshells depends on the diagenetic geochemical conditions. We believe that the vertebrate richness of the upper Kimmeridgian, Tithonian and Berriasian of the Portuguese western margin (namely the Alcobaça, Lourinhã, Bombarral and Porto da Calada formations) results from the particular conditions below mentioned that favors fossilization.

<u>Rock-body hydrology</u>: bone decay is directly related with the fluid circulation in the enclosing rock massif. Thus, preservation is favored by impermeable material or larger-scale hydraulic confinement. In fact, most of the Portuguese Upper Jurassic vertebrate sites are either in lutitic deposits or sand bodies isolated within muddy sediments, thus with very reduced hydraulic connection. For instance, the most productive unit, the Porto Novo Mb. of the Lourinhã Fm., corresponds to sandy channels or set of amalgamated channels isolated within thick floodplain and paleosols volumes.

<u>Carbonate availability</u>: There is a direct correlation between pH and bone preservation (e. g. White & Hannus, 1983), since one of most important factors promoting bone decay is an acidic environment. The pH is raised by carbonate-rich waters like those found in most of the Portuguese Upper Jurassic, due to the presence of limestone layers (e.g., the Consolação, Praia Azul, Assenta and Porto da Calada units) and or the frequent occurrence of widespread and well developed caliche/calcrete levels (like the Porto Novo, Assenta and Porto da Calada units). This is particularly relevant in units with abundant coal, since it counteracts the acidification promoted by the formation of sulfuric acid during the hydro-oxidation of the pyrite fixed in coal.

The preservational effect of carbonate ions is clear when we compare the stratigraphic distribution of vertebrates in the Upper Jurassic and Berriasian *vs*. the remaining Lower Cretaceous of Portugal (Antunes & Mateus, 2003). In fact, the lower interval is rich in calcrete paleosols and vertebrate remains (see above), whereas the upper one lacks caliche layers (Rey *et al*., 2006), due to a wetter climate (Mendes *et al*., 2010; Heimhofer *et al*., 2012), and bears bones only in units with marginal marine limestone layers. Even in the Upper Jurassic continental to transitional units, when limestone or pedogenic carbonate nodules (caliche) are rare, vertebrate bones are also scarce. This correlation should have same causality.

2. Field Trip – Upper Jurassic to Lowermost Cretaceous of the Lusitanian Basin

2.1. Stop 1. Consolação Unit, Alcobaça Fm. (upper Kimmeridgian, mixed siliciclastic–carbonate, with the earlier record of dinosaurs from the area). Consolação - Porto Batel beach;

Coordinates: N 39.31º; W 9.35º

The NE dipping Consolação section between Consolação and Areia Branca is 740 m thick and was studied by Werner (1986), with particular detail in the lower 200 m interpreted as deposited in calm and protected environments of shallow-marine or brackish bays and lagoons. The same work divided the detailed section in a lower part dominated by carbonates with minor sandstones of open lagoon, bay and nearshore shelf (lower 107 m), followed by a sandy and muddy dominated interval (107 to 172 m) of delta and delta front environments. Mudstone and minor sandstone sediments of brackish lagoons constitute the 172 to 200 m of the detailed log of Werner (1986).

The transition from the lower carbonate dominated sector (towards north) to the sandy/marly/muddy deltaic interval outcrops at the Porto Batel beach (Fig. 4).

Invertebrates, ichnofacies and dinosaur tracks show a shallow and nearshore palaeo-setting. Sandstone bodies are frequently channelized and show diverse paleocurrents, with herringbone character, revealing probable tidal influence. Reworked caliche nodules occur in the channel sandstones.

Here are visible the older dinosaur tracks of the this section of the Lusitanian Basin, as natural infills and skin striations (in levels 116 to 123 m of the section by Werner, 1986; Fig. 5B). This kind of dinosaur tracks preservation, as natural infills, is common in the Lourinhã Fm. (Milàn *et al*., 2005). The lower bone remain is a Crocodylomorpha vertebra, about 10 m above the dinosaur track presented in Fig. 5B.

2.2. Stop 2. Paimogo (Kimmeridgian/Tithonian boundary, dinosaur-rich series); Coordinates: N 39.28º; W 9.34º

This second fieldtrip stop at the Paimogo fort (also erroneously spelled Pai Mogo in some scientific literature) shows the Kimmeridgian–Tithonian transition within the Lourinhã Fm. and one of the richest areas for dinosaurs and other terrestrial vertebrates in the Upper Jurassic of Portugal and Europe. Two members are well exposed: the older Praia da Amoreira and Porto Novo members. towards north (Fig. 6 and 7) underlies the Praia Azul Mb. to the south (Fig. 8 and 9). The dinosaur sites are located at the top of the Porto Novo Mb., where *in situ* developed calcrete paleosols and reworked caliche nodules are frequent, namely in the vertebrate-rich beds (Fig. 7), which may relate a more basic groundwater geochemistry with bone preservation.

The highlight of vertebrate findings in Paimogo includes an important dinosaur nest with embryos (Mateus *et al*., 1998; Ricqlès *et al*., 2001; Cunha *et al*., 2004) of the theropod dinosaur *Lourinhanosaurus antunesi* Mateus, 1998. Moreover, Paimogo is the type-locality of the multituberculate mammal *Kuehneodon hahni* Antunes, 1998 and the provenance of the sauropod dinosaur *Zby atlanticus* Mateus *et al.,* 2014. A couple of kilometers further south, at the shoreline, Vale Frades (Praia Azul Mb.) is the type-locality for the theropod *Allosaurus europaeus* Mateus *et al*. (2006) and the ornithopod *Draconyx loureiroi* Mateus & Antunes, 2001.

2.3. Stop 3. Museum of Lourinhã – Overview of dinosaur and other fauna; Coordinates: N 39.24º; W 9.31º

The Museum of Lourinhã, in Portugal, has a rich palaeontology collection (Mateus, 2010), particularly of Late Jurassic dinosaurs of the Lourinhã Formation (Kimmeridgian–Tithonian). Most salient highlights comprehend the following dinosaur holotype specimens: stegosaur *Miragaia longicollum*, theropod *Lourinhanosaurus antunesi*, sauropod *Supersaurus lourinhanensis*, ornithopod *Draconyx loureiroi*, theropod *Allosaurus europaeus*, as well as the holotype of the mammal *Kuehneodon hahni*. Other dinosaur specimens deserving a mention include the nest with eggs and embryos of *Lourinhanosaurus*. We believe that this collection proves that Portugal is very productive in Late Jurassic vertebrates, being within the top ten countries bearing more dinosaur taxa.

2.4. Stop 4. Porto da Calada (J/K boundary, with dinosaur occurrences); Coordinates: N 39.04º; W 9.41º

The stop at the Praia da Escadinha coastal cliff, north of Porto da Calada, allows the observation of the Assenta Mb. (Lourinhã Fm., late early Tithonian to earlier Berriasian) and the Porto da Calada Fm. (Berriasian).

The Assenta Mb. (Lourinhã Fm.) outcrop is mainly composed by floodplain mudstone containing calcrete levels and thin lenses of bioturbated sandstone of crevasse-splay origin. Crossbedded channel sandstone bodies have a sigmoidal to oblique internal architecture and bears frequent concentrations of reworked caliche nodules. Coalified plant remains are abundant and thin dolomitic beds or nodules alignments occurs. Two levels of nodular limestone and marls with some bivalves show a tabular geometry along the cliff, allowing a good correlation between two logged sections.

The Porto da Calada Formation includes several positive sequences composed of medium to coarse crossbedded sandstones, sometimes with reworked caliche nodules, followed by mudstone including fine sandstone lenses, coal, horizontal laminations, ripple marks and bioturbation, culminating in carbonate beds composed by yellow dolomicrites or gray limestones with gastropods, bivalves and the foraminifer *Anchispirocyclina lusitanica*. Such deposits represent sedimentation in intertidal environments and meandering rivers crossing a coastal plain (Rey, 1993).

Besides some dinosaur tracks, the only vertebrate remains from this section are a couple of recent findings of dinosaur bones made by the geologist Vasco Ribeiro, and here reported. The first is a specimen of a stegosaur osteoderm, more precisely a stegosaur tail spine, ascribed to *Stegosaurus* sp. and found at

Escadinha, a few meters above the base of Porto da Calada Formation and near layers with the foram *A. lusitanica*. The specimen here reported has the distinctive morphology of stegosaur spines: a spear-like elongated osteoderm with acute point and expanded oblique base, normally with foramina at the base and superficial interwoven bone fibers structures. The parascapular spines normally have a wide base, often with lateral flanges, while caudal spines have moderated expansions at the continuity of the spine body. The fusiform outline of the cross section of the tail spine (specimen ML1920) differs from the most common stegosaur *Miragaia longicollum* Mateus *et al.*, 2009 that presents an inverted S-shaped section, and is seen commonly in the stegosaurines such as the *Stegosaurus*, rare in Portugal (Escaso *et al.*, 2007) but widespread in the Morrison Formation. This confirms the presence of Stegosaurinae in the Early Cretaceous of Europe and is the only Berriasian vertebrate fossil in Portugal, thus the oldest vertebrate occurrence within the Portuguese Cretaceous.

The second specimen (FCT-UNL 702) is a partly articulated ankylosaur found below the top of the Assenta Mb. The specimen is tentatively ascribed to 'polacanthid' nodosaurid but the laboratorial preparation is still in progress. Ankylosaurs are very rare in Portugal and the only specimen is the holotype of the poorly known *Dracopelta zbyszewskii* Galton, 1980.

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