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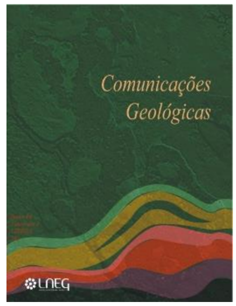
$^{87}Sr/^{86}Sr$ dating of the Alcácer do Sal Formation (upper Miocene, mainland Portugal)



Datação $^{87}Sr/^{86}Sr$ da Formação de Alcácer do Sal (Miocénico superior, Portugal continental)

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Abstract: The Lower Tagus Basin was subjected to several marine transgressions along the Neogene, related to positive eustatic oscillations and also controlled by the regional tectonic activity. In the Alcácer do Sal-Sines region, previous studies identified an episode of marine sedimentation interpreted as having occurred during the late Serravalian to early Tortonian interval, based on biostratigraphic data. This episode is represented in the Alcácer do Sal Formation. The study of the SMS-12-01B borehole, drilled for mineral prospection purposes, located about 10 km NNE of Melides, allowed the identification of a 3 m thick layer of sediments containing marine fossils. $^{87}Sr/^{86}Sr$ determinations of oyster shells point to deposition about 11.5 Ma ago, validating previous proposals for the age of the formation. These data correspond to the first numerical ages obtained for the Alcácer do Sal Formation, allowing a solid correlation with other known marine units in the Lower Tagus and Algarve basins related to the same transgression episode.

Keywords: Lower Tagus Basin, upper Miocene, Alcácer do Sal Formation, $^{87}Sr/^{86}Sr$ ages.

Resumo: Ao longo do Neogénico, a Bacia do Baixo Tejo foi afectada por várias transgressões marinhas, relacionadas com oscilações eustáticas positivas articuladas com a tectónica regional. Na região de Alcácer do Sal-Sines, estudos anteriores identificaram um episódio de sedimentação marinha interpretado como tendo ocorrido durante o Serravaliano final a Tortoniano inicial, com base em dados biostratigráficos. Este episódio está representado pela Formação de Alcácer do Sal. No estudo da sondagem SMS-12-01B, efectuada para prospecção mineral e localizada a cerca de 10 km a NNE de Melides, foi identificado um nível de sedimentos com 3 m de espessura contendo fósseis marinhos. A determinação de razões isotópicas $^{87}Sr/^{86}Sr$ em conchas de ostras indica idade próxima de 11,5 Ma, validando interpretações anteriores sobre a provável idade da formação. Corresponde à primeira idade numérica obtida para esta unidade sedimentar, permitindo uma correlação sólida com outras unidades conhecidas nas bacias do Baixo Tejo e do Algarve associadas ao mesmo episódio transgressivo.

Palavras-chave: Bacia do Baixo Tejo, Miocénico superior, Formação de Alcácer do Sal, idades $^{87}Sr/^{86}Sr$.

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1. Introduction

The Lower Tagus Basin is an elongated tectonic depression with general trending NNE-SSW, being the largest Cenozoic sedimentary basin in Portugal (*e.g* Pais *et al.*, 2012). It was formed during the Middle Eocene as a consequence of the Iberia-Eurasia collision, in the context of the Alpine orogeny event responsible for the genesis of the Cantabrian-Pyrenean Cordillera (*e.g* Cunha, 1992, 2019; Barbosa, 1995; de Vicente *et al.*, 2011, 2018).

In the southwestern/distal sector of the Lower Tagus Basin, the Cenozoic sedimentary record, is strongly related to sea level oscillations. Since the Aquitanian until the middle Tortonian, the basin was partially invaded by Atlantic waters for several times, as shown by the interbedding of marine and alluvial facies (*e.g* Cunha *et al.*, 2009; Pais *et al.*, 2012). An extensive stratigraphic analysis based on faunal assemblage and other methods, such as K-Ar dating and comparison of $^{87}Sr/^{86}Sr$ ratios with the curve of Sr isotopic composition of seawater through time, among other data, has been crucial to the definition and dating of several depositional sequences (*e.g* Antunes *et al.*, 2000; Pais *et al.*, 2012, Legoinha and Flores, 2014). In the Lisbon-Setúbal region, the geological record shows the existence of ten sequences that can be correlated with the third-order cycles of Haq *et al.* (1987) (*op. cit.*).

To the south of the Arrábida Chain the record is less diversified and evidence of only one transgression exists. Between Alcácer do Sal and Sines, this event is represented by predominant coastal to marine siliciclastic sediments detected both in outcrops and boreholes, corresponding to the Alcácer do Sal Formation. This unit has been considered of late Serravalian to early Tortonian age based solely on biostratigraphic data (Antunes, 1983; Antunes and Mein, 1983).

In the Algarve basin (south of mainland Portugal), the upper Serravallian is overlain by lower Tortonian marine deposits, through an erosive discontinuity and a basal conglomerate with phosphatic nodules and glauconite, yielding *Globigerina concina* and cf. *Neogloboquadrina acostaensis*, and an oyster shell Sr isotopic age of 10.7 (+0.8 / −1.2) Ma (Armenteros *et al.*, 2019).

In this paper we present new numerical ages for this unit given by $^{87}Sr/^{86}Sr$ measured in oyster shells sampled from the SMS-12-01B borehole (Alcácer do Sal-Melides region), being the first time this sedimentary unit is dated with a technique that provides numerical values. The importance of these results for a better understanding of the Alcácer do Sal Formation will be discussed, as well as its meaning in the context of the Lower Tagus Basin geological evolution. Figure 1 shows the Alcácer do Sal Formation geographic distribution, its cartographic relationship with other Cenozoic units and the location of the SMS-12-01B borehole.

2. The Alcácer do Sal Formation: general aspects and problematics

This lithostratigraphic unit was first proposed by Antunes (1983). In general, these sediments consist of micaceous sandstones, often clayey, with frequent carbonate-rich layers and fossiliferous sandstones, deposited in a shallow marine environment, as indicated by the faunas of ostracods, foraminifers, lamellibranchs, gastropods, fishes and mammals. The identification of small mammals at Cerrado da Pedra (Alcácer do Sal), cf. *Metaxytherium medium* (DESMAREST), *Galerix socialis* (von MEYER), *Prolagus oeningensis* (KONIG), *Heteroxerus* aff. *rubricati* CRUSAFONT et VILLALTA, *Armantomys tricristatus* LOPEZ-MARTINEZ, *Miodyromys hamadryas* (MAJOR),

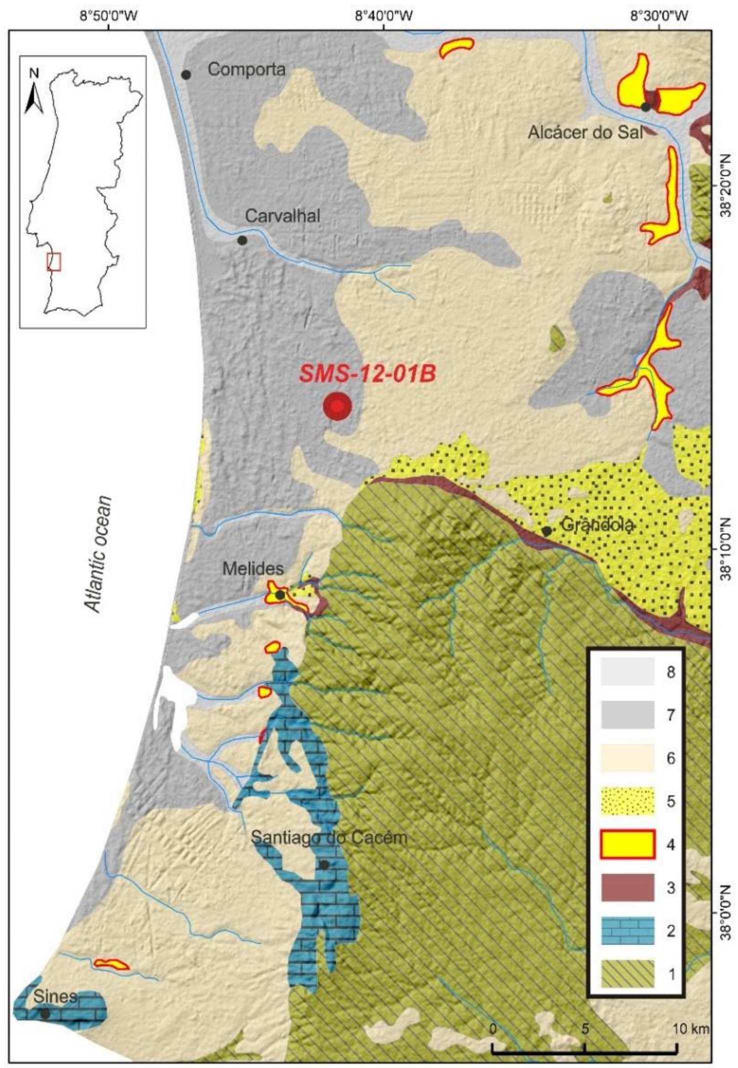


Figure 1. Simplified geological map of the study area showing the SMS-12-01B borehole location. 1, Paleozoic; 2, Mesozoic; 3, Paleogene (Vale do Guizo Formation); 4, upper Serravallian-lower Tortonian (Alcácer do Sal Formation); 5, Messinian (Esbarrondadoiro and Melides formations); 6, Zanclean-Gelasian (Ulme, Alvalade, Galé and Vale Figueira formations); 7, Holocene (aeolian and beach sands); 8, Holocene (alluvium). Cenozoic stratigraphy according to Antunes and Pais (1983), Antunes *et al.* (1991), Pimentel (1997), Pais *et al.* (2012), Ressurreição (2018), Cunha (2019). Adapted from published geological maps at 1:50 000 scale (Antunes and Pais, 1983; Antunes *et al.*, 1991; Inverno *et al.*, 1986; Dias *et al.*, 2011).

Figura 1. Mapa geológico simplificado da área de estudo com a localização da sondagem SMS-12-01B. 1, Paleozóico; 2, Mesozóico; 3, Paleogénico (Formação de Vale do Guizo); 4, Serravaliano superior-Tortoniano inferior (Formação de Alcácer do Sal); 5, Messiniano (formações de Melides e Esbarrondadoiro); 6, Zancleano-Gelasiano (formações de Ulme, Alvalade, Galé e Vale Figueira); 7, Holocénico (areias eólicas e de praia); 8, Holocénico (aluviões). Estratigrafia do Cenozóico com base em Antunes e Pais (1983), Antunes *et al.* (1991), Pimentel (1997), Pais *et al.* (2012), Ressurreição (2018), Cunha (2019). Adaptado da cartografia geológica publicada na escala 1:50 000 (Antunes e Pais, 1983; Antunes *et al.*, 1991; Inverno *et al.*, 1986; Dias *et al.*, 2011).

Megacricetodon aff. *minor* (SCHAUB), *Megacricetodon* cf. *ibericus* (SCHAUB), *Hispanomys aguirrei* (SESE-BENITO) allowed a relatively precise stratigraphic positioning, compatible with the mammal unit MN8 (Antunes and Mein, 1983), corresponding to the late Serravalian to early Tortonian, between 11.9 and 11.1 Ma (Agustí *et al*., 2001; Alba *et al*., 2011; Casanovas-Vilar *et al*., 2011).

It correlates with the upper part of the allostratigrafic unit UBS10 (Unconformity Bounded Sequence), proposed by Cunha (1992) and updated in subsequent studies (Cunha *et al.*, 2009; Pais *et al.*, 2010; Pais *et al.*, 2012; Cunha, 2019). The Alcácer do Sal Formation is limited at the top and bottom by erosional surfaces. Usually, it overlies, by disconformity, the Paleogene (Vale do Guizo Formation – UBS7 to 8) and is covered by the Upper Miocene (Melides/ Esbarrondadoiro formations – UBS12) or Plio-Quaternary (Alvalade/Ulme/Galé formations – UBS13) (Antunes and Pais, 1983; Pimentel, 1997; Dias *et al.*, 2011, 2016; Ressurreição 2018). Figure 2 presents the stratigraphic correlation between the several Cenozoic units in the study sector and adjacent sedimentation areas.

The exact geographical extension of the Alcácer do Sal Formation is still unknown. There is an apparent geographic continuity of Miocene marine/parallic sediments along the eastern margin of the Lower Tagus Basin, between the Lavre and Alcácer do Sal regions, extending south to the Sines area as shown by the published geologic maps at 1:50 000 scale (Zbyszewski and Ferreira, 1972; Zbyszewski *et al.*, 1976; Antunes and Pais, 1983; Inverno *et al.*, 1986, 1993; Carvalhosa and Zbyszewski, 1994, Dias *et al.*, 2011). Despite this continuity, the resolution of the stratigraphic knowledge is different from place to place.

The coastal and marine sediments ascribed to the Alcácer do Sal Formation (deposition during the late Serravalian to early Tortonian) were identified in the Alcácer do Sal, Melides and Sines regions (Antunes, 1983; Inverno *et al*., 1993; Dias *et al*., 2011, 2016). However, the age of the Melides sediments has been matter of debate. Besides the cited studies, Dollfus *et al*. (1904) considered deposition during the Tortonian; Cachão (1995) defined the "Melides Calcarenites" of Serravalian age, but older than the Alcácer do Sal Formation.

To the north of the Alcácer do Sal area, in the right margin of the Sado River, the mapping of the Miocene marine sediments is older and a "Vindobonian" age was proposed, based on its fossil content (Zbyszewski *et al*., 1972; Zbyszewski and Ferreira, 1976; Carvalhosa and Zbyszewski, 1994). These are the "Complexo argilo-gresoso de Palma e do Vale de Marateca", "Complexo flúvio-marinho de Lavre" and "Complexo argiloso marinho de Lavre" (*op cit.*). The "Vindobonian" age, which corresponds to the Langhian to Tortonian time interval (Glaessner, 1953), covers a time span larger than that presently attributed to the Alcácer do Sal Formation. Whilst we can reasonably assume that the sediments occurring near Alcácer do Sal are part of this unit (following Antunes, 1983), for those positioned in the Lavre region, about 50 km to NNE, this correlation might not be accurate, and a better stratigraphic resolution should be pursued with the aid of techniques that can provide numerical ages.

Despite its small surficial (outcrop) representation, borehole data suggests a significant extension and continuity for this unit below younger sediments, covering a large area located to the west

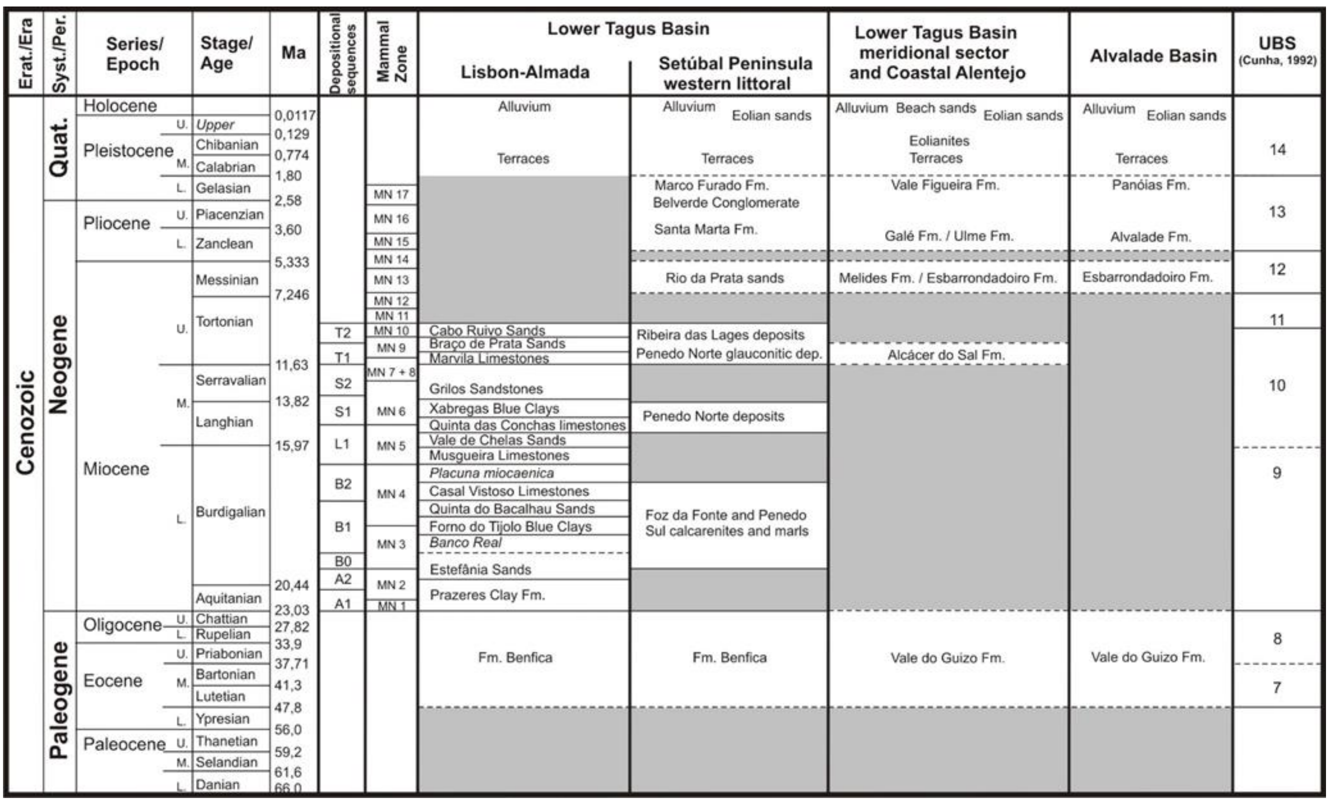


Figure 2. Stratigraphic correlation between the Cenozoic units in the sector under study and adjacent sedimentation areas. Modified from Cunha *et al.* (2009), Pais *et al.* (2010), Pais *et al.* (2012), Ressurreição (2018), Cunha (2019).

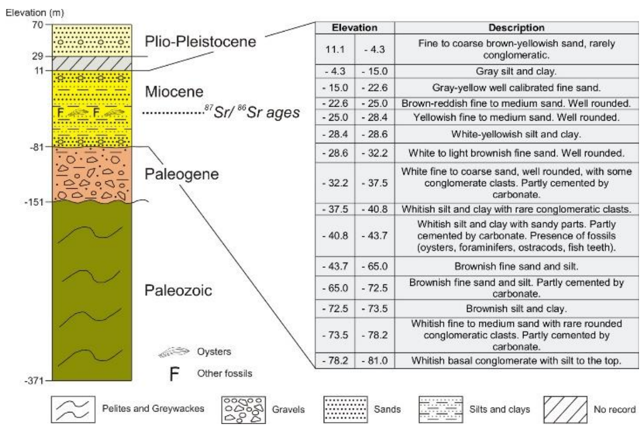
Figura 2. Correlação estratigráfica entre as unidades cenozóicas existentes no sector em estudo e áreas de sedimentação adjacentes. Modificado de Cunha *et al.* (2009), Pais *et al.* (2010), Pais *et al.* (2012), Ressurreição (2018), Cunha (2019).

and south of Alcácer do Sal and to the west of the Grândola range, until the present-day coastline.

3. Description of the SMS-12-01B borehole

The SMS-12-01B borehole (Fig. 3) was drilled by the Colt Resources mining company for massive sulphides prospection purposes. It is located at the Brejinho de Água area, near the Porqueira geodesic vertex, about 10 km NNE of Melides and 22 km SW of Alcácer do Sal. The borehole is 441 m deep, starting at an elevation of 70 m. At elevation -151 m, Paleozoic metasediments of the South Portuguese Zone were intercepted. Above these, from -151 to -81 m Paleogene reddish and whitish conglomerates, sandstones and mudstones with carbonate cement occur. Between -81 and 11 m) there is a succession of yellowish, whitish and brownish clayey sands and silts, sometimes with carbonate cement, interpreted as deposited during the Miocene. From 29 to 70 m, yellowish, whitish and brownish Plio-Pleistocene sandstones exist (UBS13 allostratigraphic unit); no record was obtained between 11 and 29 m. The surficial horizon corresponds to Holocene aeolian sands, however, their thickness at the borehole location is negligible. This stratigraphic interpretation is based on knowledge obtained from regional surface surveys and previously published studies (*e.g* Antunes, 1983; Pimentel, 1997; Dias *et al*., 2011, 2016; Ressurreição *et al*., 2014; Ressurreição, 2018).

It is not clear if at the SMS-12-01B location, the Miocene succession (92 m thick) corresponds entirely to the Alcácer do Sal Formation.



Elevation		Description
11.1	- 4.3	Fine to coarse brown-yellowish sand, rarely conglomeratic.
- 4.3	- 15.0	Gray silt and clay.
- 15.0	- 22.6	Gray-yellow well calibrated fine sand.
- 22.6	- 25.0	Brown-reddish fine to medium sand. Well rounded.
- 25.0	- 28.4	Yellowish fine to medium sand. Well rounded.
- 28.4	- 28.6	White-yellowish silt and clay.
- 28.6	- 32.2	White to light brownish fine sand. Well rounded.
- 32.2	- 37.5	White fine to coarse sand, well rounded, with some conglomerate clasts. Partly cemented by carbonate.
- 37.5	- 40.8	Whitish silt and clay with rare conglomeratic clasts.
- 40.8	- 43.7	Whitish silt and clay with sandy parts. Partly cemented by carbonate. Presence of fossils (oysters, foraminifers, ostracods, fish teeth).
- 43.7	- 65.0	Brownish fine sand and silt.
- 65.0	- 72.5	Brownish fine sand and silt. Partly cemented by carbonate.
- 72.5	- 73.5	Brownish silt and clay.
- 73.5	- 78.2	Whitish fine to medium sand with rare rounded conglomeratic clasts. Partly cemented by carbonate.
- 78.2	- 81.0	Whitish basal conglomerate with silt to the top.

Figure 3. SMS-12-01B borehole log description.

Figura 3. Descrição do *log* da sondagem SMS-12-01B.

However, since neither ruptures nor major lithological changes were identified in the well, we assume a thickness of approximately 90 m for this unit. According to Antunes (1983), this unit has a thickness of at least 69 m at Alcácer do Sal and of 146 m at Asseiceira-Albergaria (respectively 22 km and 15 km NE of the SMS-12-01B location). Around elevation -40 m, there is a 3 m thick horizon rich in bioclasts, being the only fossiliferous level identified in the Miocene succession. In this horizon fragments of oysters, benthonic foraminifers (*Elphidium crispum*, *Cibicides refulgens*, *Ammonia beccarii*), ostracods and fish teeth were identified, which are compatible with shallow marine environment, with moderately warm waters, generally of low energy levels, in a sheltered gulf with depth not exceeding the photic zone (~20 m), sandy bottoms and salinity sometimes lower than normal (as indicated by *Terebralia* and oysters), as stated by Antunes (1983). The absence of planktonic foraminifera also excludes an open ocean environment.

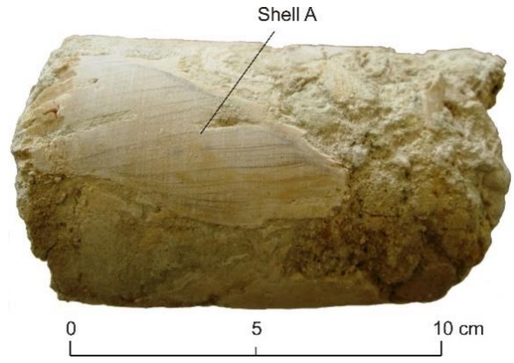


Figure 4. Siliciclastic sandstone cemented by carbonate sampled from the SMS-12-01B borehole, containing oyster shells (*Crassostrea*) A, B and C.

Figura 4. Amostra de arenito siliciclástico com cimento carbonatado da sondagem SMS-12-01B, contendo as conchas de ostreídeos (*Crassostrea*) A, B e C.

3. Methods and analytical results: Sr isotopic analysis and conversion of $^{87}Sr/^{86}Sr$ ratios to numerical ages

Three shells (A, B, and C) *of Crassostrea* from the fossiliferous sediment SMS-12-01B were used for Sr isotopic analysis at the Laboratory of Isotope Geology of the University of Aveiro (Portugal).

The shells were collected from a 12 cm thick portion of the borehole (Fig. 4) and occupy the same stratigraphic position. Shell A was the largest one and it was sampled into four different aliquots (1, 2, 3, and 4) to be analysed separately. From shells B and C only one aliquot was obtained in each case.

To avoid hypothetical alteration or contamination in the surface of the shell, a 1 cm hole was drilled in each specimen and the inner material was sampled. All the samples were coarse crushed into 1 - 3 mm sized fragments in agate mortar.

About 0.5 g from the fragmented samples were previously cleaned with Milli-Q water and then submitted to an acid-leaching process to remove the soluble labile Sr component from diagenetic or alteration provenance. Four ml of 5 M hydrochloric acid solution was added to each sample in a centrifuge tube at room temperature for some minutes. After that, the liquid was discarded, and the sample was rinsed three times with Milli-Q water to remove all the acid. Following leaching, and to ensure that only carbonate fraction was sampled, a weak acid was used for the dissolution. Each sample was dissolved with 10 ml acetic acid (1M – environmental grade), in a PTFE vessel during 1 - 2 h in a hotplate. For the $^{87}Sr/^{86}Sr$ analysis, the solution was transferred to a new vessel, dried and the precipitate was redissolved in 3 ml of nitric acid (conc.) and dried. Sr-Resin (50 - 100 μm, Eichrom) ion chromatography columns were used to separate Sr from the other elements. Strontium obtained this way was loaded onto Ta filaments with phosphoric acid, and the isotopic ratio was measured with a VG Sector 54 thermal ionization mass spectrometer in dynamic mode. Typical runs consisted in the acquisition of 60 isotopic ratios, with peak measurements at 1 - 2 V for ^{88}Sr, and the analytical data were corrected for mass fractionation relative to $^{88}Sr/^{86}Sr = 0.1194$. All reagents used in the global procedure were sub-boiling distilled, and the water was produced by a Milli-Q Element (Millipore) apparatus. The procedure average blanks levels were less than 2 ng, which are negligible compared to the total amount of Sr processed in the analytical protocol. During this study, the SRM-987 standard gave an average value of $^{87}Sr/^{86}Sr = 0.710245 \pm 0.000015$ (conf. lim. = 95%: N = 12).

The obtained $^{87}Sr/^{86}/Sr$ ratios were converted to numerical ages (Tab. 1) based on the works by Howarth and McArthur (1997), McArthur *et al*. (2001), and McArthur *et al*. (2012), and using the Look-Up Table Version 3:10 / 99.

$^{87}Sr/^{86}Sr$ ratios obtained in four portions of shell A go from 0.708869 to 0.708822**.** By comparing these values with the curve of variation of the Sr isotopic composition of seawater, as proposed in the quoted works, the obtained age values vary between 10.73 and 12.76 Ma. Measurements in the other two smaller shells gave $^{87}Sr/^{86}Sr$ ratios of 0.708889 (shell B) and 0.708921 (shell C), that would correspond to ages of ca. 10 Ma and 9 Ma, respectively.

4. Discussion and conclusions

The $^{87}Sr/^{86}Sr$ ages indicate that the sampled Miocene sediment, considering its sedimentological properties and geographical location, corresponds to the Alcácer do Sal Formation. They also strengthen the plausibility of a correlation between the Melides sediments and this unit, as done by other authors (Antunes, 1983; Dias *et al*., 2011, 2016).

The obtained ages, 8.64 - 12.76 Ma, imply a larger time interval than that proposed by the biostratigraphic data collected from the Alcácer do Sal Formation (Antunes, 1983; Antunes and Mein 1983), meaning that the unit could extend to the upper Tortonian. At first sight, this would have implied the maintenance of the same depositional environment for approximately 4 Ma and a very low sedimentation rate, which seems unlikely, in the place where the sample was collected.

A reasonable hypothesis is that the larger shell has better preserved in its inner parts the original strontium isotopic composition, whilst the smaller shells could have been affected by interaction with post-depositional fluids, which are usually expected to contribute to increase the $^{87}Sr/^{86}Sr$ ratio (*e.g* Macdougall, 1991, and references therein), therefore leading, in the case of the shells studied in this work, to apparent younger "ages". The "ages" obtained in shells B and C could also be explained by a process of differential enrichment in the precipitation of Sr^{2+} transported by diffusion and/or advection from younger stratigraphic levels (Baker *et al*., 1982). Regardless of the origin and the precise mechanism of Sr mobility, the larger shell is most likely giving results more closely representative of the isotopic composition of the seawater contemporary of the oysters, and consequently, its $^{87}Sr/^{86}Sr$ values may be viewed as the most reliable in the determination of the true age of the sedimentation.

Despite the mentioned uncertainties, Sr mean ages of the larger shell point to a deposition at 11.53 (+0.28 / -0.29) Ma ago (Fig. 5), in the early Tortonian, not totally excluding the late Serravalian.

The Alcácer do Sal Formation is associated with the transgressive event also represented in the Lisbon - Setúbal area by the "Marvila sandstones", "Braço de Prata Sands", "Penedo Norte Glauconitic deposits" and "Ribeira das Lages deposits", which largely correspond to the T1 depositional sequence and with the third-order cycle 3.1 of Haq *et al*. (1987) (Legoinha, 2001). The paleogeographic reconstruction during the early Tortonian was proposed by Pais *et al*. (2012) and Cunha (2019) (Fig. 6).

The data here presented have high relevance for the characterization of the Alcácer do Sal Formation since it validates previous interpretations based on biostratigraphy with new numerical ages. However, for a more complete understanding of this unit, namely its spatial and temporal evolution, more extensive sampling and numerical dating should be done. The verification if the marine Miocene sediments that crop out along the left margin of the Lower Tagus Basin correspond to this transgressive event has a significant implication on the knowledge of this sedimentary basin evolution. Since the mentioned sediments reach the Lavre region, located about 80 km far from the present coastline, they are related to one of the broadest transgressions that affected the basin.

Acknowledgments

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Table 1. Sr isotope ratios and corresponding ages using the curve of variation of the Sr isotopic composition of seawater.

Tabela 1. Razões isotópicas Sr e idades correspondentes utilizando a curva de variação da composição isotópica de Sr da água do mar.

Sample	Specimen	**$^{87}Sr/^{86}Sr$**	Error (2σ)	**Age (Ma)**	Age error a)	Age error b)
A-1	A (large shell)	**0.708869**	0.000021	**10.73**	+0.23 / -0.26	+0.98 / -1.14
A-2	A (large shell)	**0.708822**	0.000020	**12.76**	+0.33 / -0.41	+1.70 / -1.40
A-3	A (large shell)	**0.708851**	0.000024	**11.30**	+0.28 / -0.25	+1.54 / -1.06
A-4	A (large shell)	**0.708850**	0.000013	**11.34**	+0.28 / -0.26	+0.92 / -0.66
B	B (small shell)	**0.708921**	0.000017	**8.64**	+0.35 / -0.46	+1.07 / -1.50
C	C (small shell)	**0.708889**	0.000017	**10.00**	+0.28 / -0.32	+0.87 / -1.02

Notes: Sr isotope ratios were converted to numerical ages based on the works by Howarth and McArthur (1997), McArthur *et al*. (2001) and McArthur *et al*. (2012) and using the Look-Up Table Version 3:10/99 of R. J. Howarth and J. M. McArthur. Age error a) assumes only the error of the curve of variation of the Sr isotopic composition of seawater; age error b) assumes both the error of the curve and the analytical error of Sr isotopic analysis in this work.

Notas: As razões isotópicas de Sr foram convertidas em idades numéricas com base nos trabalhos de Howarth e McArthur (1997), McArthur *et al.* (2001) e McArthur *et al.* (2012) e na utilização do documento "Look-Up Table Version 3:10/99", de R. J. Howarth e J. M. McArthur. O erro da idade a) assume unicamente o erro da curva de variação da composição isotópica de Sr da água do mar; o erro da idade b) assume conjuntamente os erros dessa curva e o erro da análise isotópica de Sr neste trabalho.

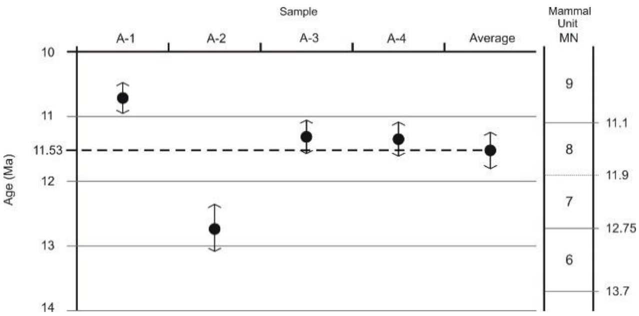

Figure 5. Graph projection of Sr ages and average for shell A, using age error a) from table 1 (assumes only the error of the curve of variation of the Sr isotopic composition of seawater). MN zonation based on Alba *et al.* (2011) and Casanovas-Vilar *et al.* (2011).

Figura 5. Projeção gráfica das idades de Sr e da média aritmética para a concha A, utilizando o erro da idade a) constante na tabela 1 (assume unicamente o erro da curva de variação da composição isotópica de Sr da água do mar). Zonação MN baseada em Alba *et al.* (2011) e Casanovas-Vilar *et al.* (2011).

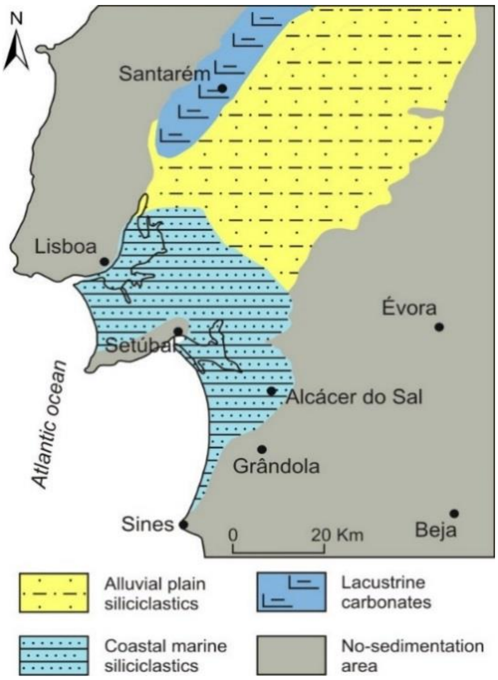

Figure 6. Paleogeographic reconstruction of the Lower Tagus Basin for the early Tortonian (adapted from Pais *et al.*, 2012 and Cunha, 2019).

Figura 6. Reconstrução paleogeográfica da Bacia do Baixo Tejo para o Tortoniano inicial (adaptado de Pais *et al.*, 2012 e Cunha, 2019).

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