A STRATIGRAPHIC FRAMEWORK FOR THE MIOCENE FROM THE LOWER TAGUS BASIN (LISBON, SETÚBAL PENINSULA, PORTUGAL) DEPOSITIONAL SEQUENCES, BIOSTRATIGRAPHY AND ISOTOPIC AGES

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Abstract: Lithostratigraphy, main biostratigraphic events (first and last ocurrence), $^{87}Sr/^{86}Sr$ as well as K/Ar isotopic ages, are presented for the Lower Tagus basin (LTB) Miocene (Lisboa and Península de Setúbal regions). Eight depositional sequences (DS) delimited by regional disconformities related with transgressive surfaces are defined. The main features of the Depositional Sequences are as follows: **Depositional sequence (DS) A** (Aquitanian). Biostratigraphy (Biost.): Small mammals from Km 10: MN2 (MN3?); ostracoda: Aquitanian fauna. Isotopic age (IA): glauconites (K/Ar) values between 19 and 24 Ma. $^{87}Sr/^{86}Sr$ ages from the glauconite levels: 22.3 (+0.4-0.7) Ma. Lower and upper boundaries not well established. **DS BO** (Lower Burdigalian). Biost.: foraminifera - FO *Globigerinoides altiaperturus* (N5); mammals - FO *Brachyodus intermedius* (MN3); ostracoda - LO *Hemicyprideis helvetica* and *Pokornyella lusitanica* at the LTB. IA ($^{87}Sr/^{86}Sr$): Foz da Fonte -19.5 (±0.2) Ma, Penedo Sul (base) - 20.0(±0.4)Ma; Almada (top) - 18.3 (+0.-0.2) Ma. Mammal sites: Av. do Uruguai - 21.5(+0.5-0.3) Ma; Univ. Católica - 20.5 (+0.3-0.2) Ma. **DS B1** (Middle Burdigalian). Biost.: foraminifera - *Catapsydrax unicavus* and *Globigerinoides altiaperturus* (N6); mammals - FO *Gomphotherium,* LO of *Brachyodus* (MN4); ostracoda - LO *Ruggieria (R.) micheliniana, Cnestocythere truncata, Pokorniella minor* and *Triebelina raripila. IA* ($^{87}Sr/^{86}Sr$) Foz da Fonte - 19.7 (+0.3-0.2) to 18.5 (+0.2-0.5) Ma. **DS B2** (Upper Burdigalian). Biost.: mammals - FO *Bunolistriodon* and *Megacricetodon primitivus* (MN4); ostracoda - LO *Miocyprideis fortisensis.* IA ($^{87}Sr/^{86}Sr$): Penedo Norte 17.7 (+0.7-0.5) Ma; 17.8 (+0.7-0.5) Ma. **DS L1** (Upper Burdigalian and Langhian). Biost.: foraminifera - FO *Praeorbulina* (N8); mammals - FO (upper part) *Hispanotherium* and *Megacricetodon collongensis,* LO *M. primitivus* (MN5); ostracoda - FO *Pterigocythereis (P.) siveteri* and *Loxoconcha (L.) ducasseae.* IA ($^{87}Sr/^{86}Sr$): Penedo Norte 17.3 (+0.6-0.5) Ma. **DS S1** (Upper Langhian and Serravallian). Biost.: foraminifera - FO *Orbulina suturalis, O. universa* and *Globorotalia* cf. *menardii;* ostracoda - FO *Aurila (U.) oblonga, Ruggieria (R.) nuda, R. tetraptera tetraptera, Nomurocythereis seminulum, Pterygocythereis (P.) jonesi y Olinfalunia costata.* IA ($^{87}Sr/^{86}Sr$): Chelas 14.7 (+1.5-0.5) Ma, Almada (Brielas)(lower part) - 14.0 (±0.4) Ma, Penedo (upper part) 12.5 (+1.0-2.0) Ma. **DS S2?** (Upper Serravallian) is poorly characterized due to strong condensation (Foz da Fonte-Rib. Lage) and poor outcrops (Lisbon region). Biost.: foraminifera - LO *Globigerinoides subquadratus* (top). **DS T1** (Tortonian). Biost.: foraminifera - LO *Globorotalia mayeri* (lower part), FO *Neogloboquadrina acostaensis* (upper part); ostracoda - FO *Aurila (U.) zbyszewskii, Celtia quadridentada* and *Cyheretta (C.) simplex.* IA: Penedo Norte: K/Ar - 10.95±0.25 Ma; $^{87}Sr/^{86}Sr$ - 11.3 (+1.7-2.8) Ma; Almada (Foz de Rego) - 8.3 (+1.9-3.3) Ma; Fonte da Telha 5.2 (+3.1-1.2) Ma.

Key words: lithostratigraphy, biostratigraphy, foraminifera, mammals, ostracoda, depositional sequences, $^{87}Sr/^{86}Sr$ ages, Miocene, lower Tagus Basin, Portugal.

Resumen: Se presentan la litoestratigrafía, los principales eventos bioestratigráficos (primera y última aparición: FO y LO), isótopos estables de Sr ($^{87}Sr/^{86}Sr$) y edad (isótopos de K/Ar) del Mioceno de la Cuenca del Bajo Tajo (CBT) (Lisboa y Península de Setúbal). Se han definido 8 secuencias deposicionales (DS) limitadas por discontinuidades regionales relacionadas con superficies transgresivas. Las características más importantes de estas secuencias deposicionales son las siguientes: Secuencia deposicional (**DS**) **A** (Aquitaniense); Bioestratigrafía (Biost.): pequeños mamíferos del Km. 10: MN2 (?MN3); ostrácodos - fauna Aquitaniense. Edad isotópica (IA): glauconitas (K/Ar): valores entre 19 y 24 Ma. Edad $^{87}Sr/^{86}Sr$ a partir de los mismos niveles de glauconita: 22.3 (+0.4-0.7) Ma. Límites inferior y superior aún sin establecer bien. **DS B0** (Burdigaliense inferior). Biost.: foraminíferos - FO *Globigerinoides altiapertura* (N5); mamíferos -FO *Brachyodus intermedius* (MN3); ostrácodos - LO *Hemicyprideis helvetica* y *Pokornyella lusitanica* junto a CBT. IA ($^{87}Sr/^{86}Sr$): Foz da Fonte - 19.5 (±0.2) Ma, Penedo Sur (base) - 20.0 (±0.4) Ma; Almada (techo) - 18.3 (+0.4-0.2) Ma. Yacimientos de mamíferos: Av. do Uruguai - 21.5 (+0.5-0.3) Ma; Univ. Católica - 20.5(+0.3-0.2)Ma.

DS B1 (Burdigaliense medio). Biost.: foraminíferos - *Catapsydrax unicavus* y *Globigerinoides altiaperturus* (N6); mamíferos - FO de *Gomphotherium*, LO de *Brachyodus* (MN4); ostrácodos - LO *Ruggieria (R.) micheliniana, Cnestocythere truncata, Pokorniella minor* y *Triebelina raripila*. IA ($^{87}Sr/^{86}Sr$) Foz da Fonte 19.7 (+0.3-0.2) a 18.5 (+0.2-0.5) Ma. **DS B2** (Burdigaliense superior). Biost.: mamíferos - FO *Bunolistriodon* y *Megacricetodon primitivus* (MN4); ostrácodos - LO *Miocyprideis fortisensis*. IA ($^{87}Sr/^{86}Sr$): Penedo Norte - 17.7 (+0.7-0.5) Ma; 17.8 (+0.7-0.5) Ma. **DS L1** (Burdigaliense superior y Langhiense). Biost.: foraminíferos - FO *Praeorbulina* (N8); mamíferos - FO (parte superior) *Hispanotherium* y *Megacricetodon collongensis*, LO *M. primitivus* (MN5); ostrácodos - FO *Pterigocythereis (P.) siveteri* y *Loxoconcha (L.) ducasseae*. IA ($^{87}Sr/^{86}Sr$): Penedo Norte - 17.3 (+0.6-0.5) Ma. **DS S1** (Langhiense superior y Serravaliense). Biost.: foraminíferos - FO *Orbulina suturalis, O. universa* y *Globorotalia* cf. *menardii*; ostrácodos - FO *Aurila (U.) oblonga, Ruggieria (R.) nuda, R. tetraptera tetraptera, Nonurocythereis seminulum, Pterygocythereis (P.) jonesi* y *Olinfalunia costata*. IA ($^{87}Sr/^{86}Sr$): Chelas - 14.7 (+1.5-0.5) Ma, Almada (Brielas) (parte inferior) - 14.0 (±0.4) Ma, Penedo (parte superior) - 12.5 (+1.0-2.0) Ma. **DS S2**? (Serravaliense superior) está pobremente caracterizada debido a una fuerte condensación (Foz da Fonte-Rib. Lage) y a malos afloramientos (región de Lisboa). Biost.: foraminíferos - LO *Globigerinoides subquadratus* (techo). **DS T1** (Tortoniense). Biost.: foraminíferos - LO *Globorotalia mayeri* (parte inferior); FO *Neogloboquadrina acostaensis* (parte superior); ostrácodos - FO *Aurila (U.) zbyszewskii, Celtia quadridentata* y *Cytheretta (C.) simplex*. IA: Penedo Norte: K/Ar - 10.95±0.25 Ma; $^{87}Sr/^{86}Sr$ - 11.3 (+1.7-2.8) ; Almada (Foz do Rego) - 8.3 (+1.9-3.3) Ma; Fonte da Telha-5.2 (+3.1-1.2) Ma.

Palabras clave: litostratigrafía, biostratigrafía, foraminíferos, mamíferos, ostrácodos, secuencias deposicionales, edades $^{87}Sr/^{86}Sr$, Mioceno, Cuenca del Bajo Tajo, Portugal.

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During Miocene, the western margin of Iberia lied in the foreland of the Betic Chain, although collision with the former basement (Maciço Hespérico) was accomplished by late Lower Miocene. Alpine orogeny had effects in quite far away areas. Secondary extension within the Eurasian plate led to differentiation of NNE-SSW-oriented grabens, one of which being the Lower Tagus Basin. Subsidence and reactivation of Hercynian fractures concurred to this. Among its infillings there is a dominance of Miocene sediments more than 1200 meters in thickness in the deepest part. These were known to range from lowermost Miocene, Aquitanian, to lower Upper Miocene, Tortonian. Some still Miocene, less well-dated beds may be somewhat later.

In the Lisbon and Setubal Peninsula areas Miocene sedimentation corresponds to time and space shifting interfaces between marine and continental domains. The latter are most developed in Lisbon. Correlation by means of stratigraphic position is possible between levels with planktic foraminifera and others with land mammals. Datation may be obtained for most units by means of K/Ar on glauconites, Sr isotopes, and planktic foraminifera. Mammals ensure a fine datation for non marine and some littoral marine levels as well. Palaeomagnetic approaches were not very successful.

The wealth in fossils - flagellates, pollen and spores, calcareous nannoplancton, algae, plant macro-remains, foraminifera, ostracoda and other crustacea, molluscs, echinoderms, fishes, reptiles, mammals - and O and C isotopes offer a wide range of data useful for palaeoecologic studies.

There are however unanswered questions. Some units are much better known than others. Lateral facies shifts are a source of difficulties, i.e. in trying to correlate the classic Lisbon lithostratigraphic units with those from Setubal Peninsula

Another kind of difficulties arises from stratigraphic control: indeed there is irrefutable evidence of more different mammal associations than those accounted for the same time span in the accepted mammal-unit scale. Some mammal-units should be split.

Notwithstanding the referred difficulties, the situation is excellent for marine-continental correlations, at least for the Lower and early Middle Miocene, and for sequential sedimentation studies. A new synthesis on the whole available data, and based on a sequential approach and on the latest time scales is needed.

Previous works

Lisbon is placed on the distal part of the basin. Miocene beds are (or were) well exposed. The geologic observation has been carried on since long ago (Almeida, 1762).

An important period of research concerns early 19th century and José Bonifácio de Andrada e Silva, then in charge of Mining and Metallurgy. Among his activities there is the reopening of gold mining at Adiça, a former medieval exploitation. An account of this, including the first description of sections where Miocene beds crop out, was presented (Silva, 1817).

Gold exploitation at Adiça went on under Wilhelm-Ludwig, baron von Eschwege. His geologic, mining and palaeontologic observations were published (Eschwege, 1831, with extra plates about marine miocene vertebrate fossils added by Alexandre

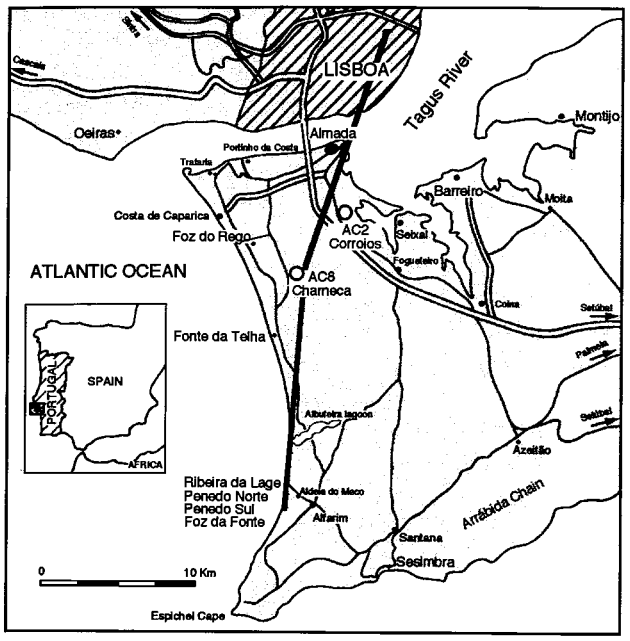

Figure 1.- Lower Tagus basin, studied area: position of the sections, boreholes, and the interpreted section of the figure 2.

Vandelli). For the first time, a generalized section between Sintra and Arrabida and concerning part of the Basin was produced.

The next step in the study of the Lower Tagus Basin's Neogene is related to Daniel Sharpe who described units as the *Almada beds* that correspond to the mostly marine Miocene infillings (Sharpe, 1834, 1841). Early correlation attempts with Miocene units in France, Switzerland, Italy and Austria were based on molluscs, partly described by G.B. Sowerby in J. Smith (Smith, 1847). There were nearly no more British contributions ever since. They were succeeded by papers by Portuguese and other researchers, mostly in French.

An increase in research on Miocene beds has been accomplished by the 2d Commissão Geológica (1857-1868), by Carlos Ribeiro (in charge of field work) and F. Pereira da Costa (the author of excellent work on molluscs). The stratigraphic frame was basically that of Sharpe, whose *Almada beds* appeared under *Miocène moyen et supérieur III.- Formation marine avec fossiles analogues à ceux du bassin méditerranéen et des environs de Vienne en Autriche* (Ribeiro, 1878).

A hallmark in portuguese stratigraphy is the sketch on the marine Miocene in Portugal by J.C. Berkeley Cotter, who was in charge of the Tertiary at the Geologic Survey (Cotter, 1904 *in* Dollfus, Cotter & Gomes, 1903-1904). His classification of the Lisbon Miocene units is still in use. Stratigraphic work was accompanied by high-standard palaeontologic research by Swiss and mostly by French authors (i.e. O.Heer, P. de Loriol, G. Dollfus, F. Roman).

There were also contributions by P. Choffat (Choffat, 1950), posthumous paper; 1:20000 geologic map of Lisbon). His chapter about marine Miocene is largely an abridged version of Cotter's.

G. Zbyszewski restored the studies on the portuguese Tertiary since 1937. Among many other contributions, there are some broad scope ones (Zbyszewski, 1954; 1957; 1962; 1963; 1964 a, b; 1967). Zbyszewski adopted a conservative stance. In a certain way, he maintained - if with many further data, including palaeontologic contributions - the empiric approach of his predecessors. No logs, only approximative descriptions often very difficult to recognize were produced.

The development of studies on sedimentation led to new concepts. Our previous work on Lower Tagus Basin (mainly Lisbon - Setubal Peninsula) allowed the recognition of rhythmic sedimentation, erosion and sedimentation cycles and sequences. Cunha (1992,1996) established several unconformity-bounded sequences for the post Lower Aptian record of Central Portugal. The unconformities recognized in the continental infill of the Lower Tagus Basin have been tentatively correlated with those established, and well dated, in Lisbon and Setubal Peninsula regions (mainly littoral deposits) as well as those of other Tertiary basins of Iberia. Barbosa (1995) recognized several allostratigraphic units for the continental infill of the Lower Tagus Basin.

A high resolution stratigraphic strategy was deviced (M.T. Antunes), comprising: (a) detailed studies on important sections (Antunes & Torquato, 1969-1970, and later contributions); (b) the improvement of datation by means of biochronologic research, mostly on mammals and planktic foraminifera, K-Ar and (later) Sr isotope ages, sedimentology, palaeoecology, magnetostratigraphy, etc., rendering possible the development of regional syntheses and broad-scale correlations (Antunes *et al.*, 1973 and other papers; Antunes & Pais, 1992;1993; Antunes *et al.*, 1987; Antunes *et al.*, 1996a; Antunes *et al.*, 1996b).

Objectives and methods

Our main goal is to present an updated synthesis based on the lithologic, biostratigraphic and isotopic data available for the distal part of the Lower Tagus basin (Fig. 1). We try to characterize the stages of the sedimentary infilling (depositional sequences) as well as their evolution (Fig. 2).

The origins of the main accounted data are as follows:

Data from previously studied sections

- Foz da Fonte/ Ribeira da Lage (Zbyszewski *et al.*, 1965; Zbyszewski,1967; Antunes *et al.* (1995); Antunes *et al.* (1996a,b));
- Almada (Antunes *et al.*, 1987; Antunes *et al.*, 1991; Antunes *et al.*, 1992; Antunes *et al.*, 1995; Antunes *et al.*, 1996b; Nascimento, 1988; Pais, 1981);
- Lisboa (Cotter, 1956; Antunes, 1984; Antunes *in* Ribeiro *et al.*, 1979; Antunes & Torquato, 1969-1970; Antunes & Mein, 1986; Antunes *et al.*, 1973; Antunes & Pais, 1992; Nascimento, 1983; 1988; Pais, 1981; Zbyszewski, 1957, 1962, 1964a, b, c, 1967).

Data from boreholes

Lithological data have been obtained from water boreholes (AC2, Corroios, 1967; AC8, Charneca, 1974) carried out by Sondagens e Fundações A.Cavaco for the Câmara Municipal de Almada (Setúbal Peninsula).

Lithological and micropaleontological data have been obtained from two boreholes (S135 - Palença; S141 - Cristo Rei) near Cristo Rei (Almada, Setúbal Peninsula) for Tagus bridge construction (samples from the «Instituto Geológico e Mineiro» archives, Lisbon, Portugal).

Isotopic age

- ^{40}K-^{44}Ar dating on glauconites by (a) J. Torquato at the S.Paulo University (Brazil); (b) C. Regêncio Macedo at the Departamento de Ciências da Terra, Coimbra University (Portugal).

- ^{87}Sr-^{86}Sr dating on pectinid and oyster shell fragments by H. Elderfield at the Department of Earth Sciences, University of Cambridge (U.K.). Method: after cleaning, samples were washed (distillate water and methanol) in an ultrasound device. Sr was extracted with Sr-SPEC, Eichrom Industries specific resin. The ^{87}Sr-^{86}Sr ratio was obtained on a VG spectrometer, sector 54. For age determination, the 1.0 (12/03/97) version of the Cambridge curve callibrated according to the Berggren (1995) chronostratigraphic scale was used. Results are largely new (Table I).

Magnetostratigraphy

- Data contributed by S. Sen, University of Paris VI (sections of Foz da Fonte and Trafaria, Sen *et al.*, 1992) and by C. Langereis, Utrecht University (sections of Penedo, Penedo Norte and Ribeira da Lage, not published).

Biostratigraphy

For dating purposes, the most important groups are planktic foraminifera for marine facies and mammals for continental (or eventually littoral marine) ones. The first datation attempt based on planktic foraminifers had many lacunes (Antunes *et al.*, 1973). This theme was developed later, at the Centro de Estudos Geológicos/ Departamento de Ciências da Terra (Universidade Nova de Lisboa), by P. Legoinha (Legoinha, 1993, Antunes *et al.*, 1992; Antunes *et al.*, 1995; Antunes *et al.*, 1996a, b). Samples were obtained from boreholes and surface collecting.

The knowledge of mammals progressed very much. Most of the larger mammal remnants, which were studied by M.T. Antunes and L. Ginsburg (Muséum, Paris), have been obtained from workers at commercial sand and claypits until about 1967. Small mammals were collected through washing and sieving of sediments, in part reconcentrated with diluted bromoform. The most productive deposits were found to be littoral, marine sands with disperse oyster valves and fish teeth. Small mammals studies are mostly due to P. Mein, Lyon I University, France.

Among other data there are those about ostracods (by A. Nascimento), also presented here for all the main levels; pollen, spores and plant macro-remains (by J.Pais); molluscs, whose revision barely begun; bryozoans (Carvalho, 1971); echinoids; calcareous nannoplankton, currently under study; fishes (under revision by A.Balbino, from the Évora University, H.C.Cappetta, Montpellier II University, and M.T.Antunes); Squamata, described by M.T.Antunes and J.C.Rage (Antunes & Rage, 1974); and Crocodylia (Antunes, 1987, 1994). Vertebrate fossils were often found at the surface.

Sequence stratigraphy

Eight depositional sequences (DS) bounded by regional disconformities related to transgression surfaces have been characterized: A, B0, B1, B2, L1, S1, S2(?) and T1. Sequences B1, B2, L1 and S1 had already been defined in the Lisbon-Almada area (Antunes *et al.*, 1996b). Correspondence with the previously referred sedimentary cycles, defined by each transgression event (T0 to T7) until the next regression one (R0 to R7) are shown (Fig. 2).

Depositional sequence A (Aquitanian)

Lithostratigraphy

The sediments of Depositional Sequence A (A DS) correspond to most of the unit («division») I of Cotter (Cotter, 1956). They overlie the Benfica Formation (poorly dated, probably Eocene and Oligocene), the Late Cretaceous, Lisbon-Mafra Volcanic Complex, or earlier Cretaceous units. In some places, the upper part of the Benfica Fm seems to grade up into the marine lowermost Miocene, but elsewhere there is a disconformity or even an angular unconformity.

This DS begins with conglomerates that grade upwards into marls and hermatypic coral, barrier reef limestones (index fossil, according to Cotter: *Venus ribeiroi)* (Antunes & Chevalier, 1971; Chevalier & Nascimento, 1975), followed up by lignites and glauconitic marls (Choffat, 1950; Cotter, 1956). Bryozoan reefs are known in Lisbon.

Biostratigraphy

A small-mammal faunula including (among others) *Cainotherium* sp., *Lagopsis spiracensis, Ligerimys antiquus, Pseudodryomys simplicidens,* and *Heteroxerus rubricati* (archaic) was collected in a very low position - in coarse deposits from the upper part of the first marine conglomerates at Km 10, Lisbon-Oporto highway (Antunes & Mein, 1992). Earlier evolutive stades undoubtedly point out to a somewhat older age than Universidade Católica and correlative sites reported to the MN3 mammal-unit. Hence it seems that the Km 10 association can still be ascribed to MN2.

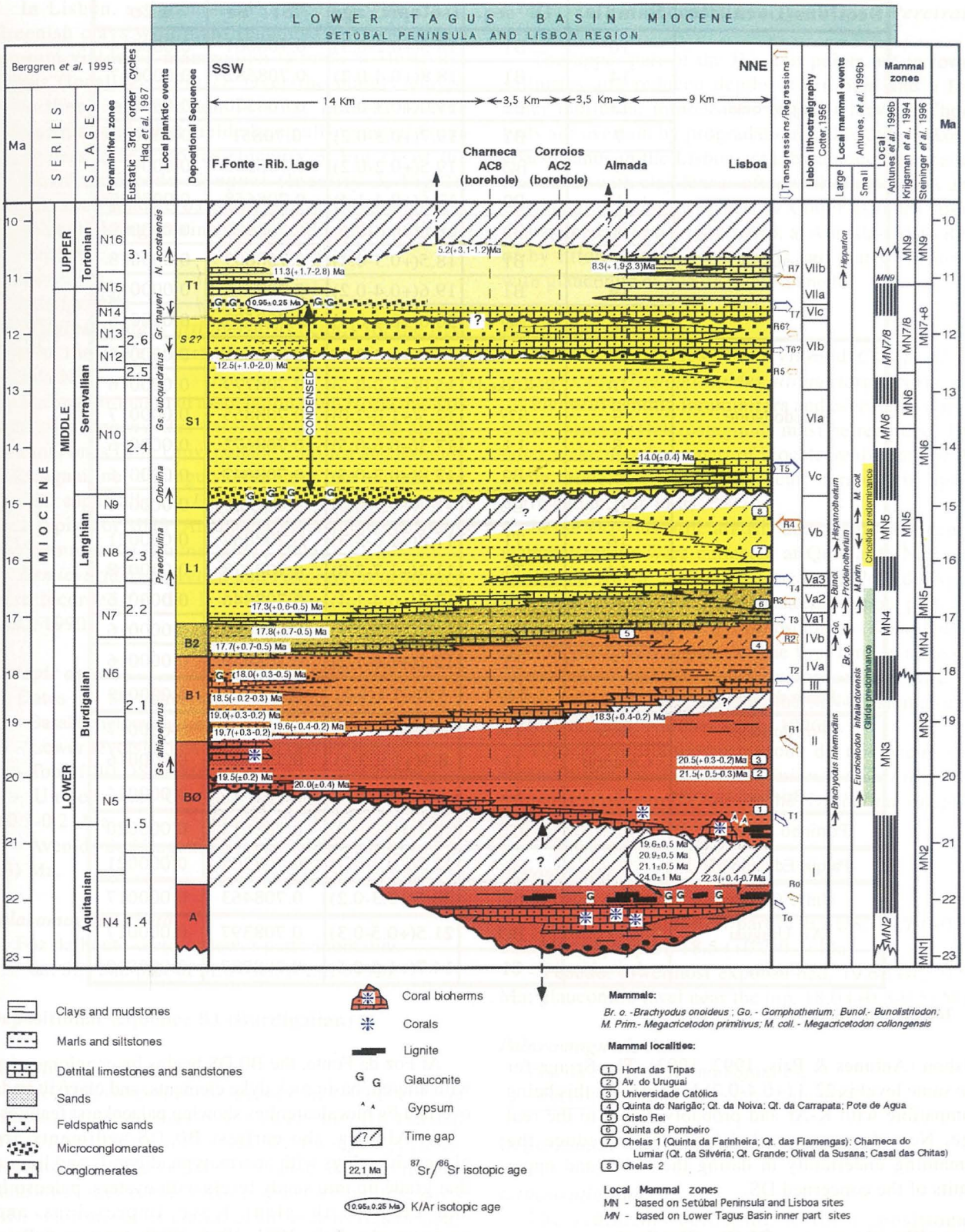

Figure.2.- Lower Tagus basin, Lisbon and Setúbal Peninsula areas - Miocene biostratigraphy, isotope ages, transgression and regression events, and depositional sequences. Correlation of Haq's (1987) eustatic cycles with the Berggren (1995) Chronostratigraphic and Chronometric scale was based on Blow's planktic foraminifera biozones N4 to N16. Lisbon Mammal fauna units according to De Bruijn *et al.* (1992).

Ostracods from the A DS point out to an Aquitanian age, *Aurila (C.) peypouqueti* and *Hermanites ruggierii* being unknown later (Nascimento, 1988, 1990, 1993).

Isotopic ages

Glauconite K-Ar dates between 24 and 19 Ma were obtained for the same level at Parque Eduardo VII,

Sections/Localities	Samples	D. seq.	Isotopic age	$^{87}Sr/^{86}Sr$	± 2σ
Foz da Fonte	16	B1	18.5(+0.2-0.3)	0.708601	0.000014
	14	B1	18.8(+0.4-0.2)	0.708582	0.000017
	13	B1	19.0(+0.3-0.2)	0.708570	0.000016
	7	B1	19.7(+0.3-0.2)	0.70851	0.000020
	3	BØ	19.5(+0.2-0.2)	0.708539	0.000017
Penedo Sul	1	B2	17.6(+0.4-1.4)	0.708658	0.000020
	5	B1	18.0(+0.3-0.5)	0.708629	0.000018
	7	B1	18.5(+0.3-0.4)	0.708603	0.000018
	14	B1	19.6(+0.4-0.2)	0.708513	0.000017
	18	BØ	20.0(+0.4-0.4)	0.708509	0.000016
Penedo Norte	12	Reworked?	14.5(+1.0-0.7)	0.708801	0.000016
	10	Reworked?	15.0(+1.0-0.5)	0.708779	0.000016
	9	S2?	12.5(+1.0-2.0)	0.708855	0.000017
	8	L1	17.3(+0.6-0.5)	0.708672	0.000016
	5	B2	17.8(+0.7-0.5)	0.708647	0.000016
	1	B2	17.7(+0.7-0.5)	0.70865	0.000016
Ribeira da Lage	16	T1	11.8(+1.6-3.3)	0.708862	0.000021
	14	T1	11.3(+1.7-2.8)	0.708878	0.000018
	8	T1	12.7(+0.4-1.4)	0.708846	0.000016
	7	T1	11.7(+1.3-1.3)	0.708869	0.000016
	3	T1	12.2(+1.0-1.2)	0.708859	0.000016
Fonte da Telha		T1?	5.2(+3.1-1.2)	0.708980	0.000023
Foz do Rego	*Arca*	T1	8.7(+1.8-3.5)	0.708918	0.000017
	Chlamys	T1	8.3(+1.9-3.3)	0.708925	0.000016
Brielas		S1	14.0(±0.4)	0.708819	0.000016
Portinho da Costa		BØ	18.3(+0.4-0.2)	0.708612	0.000020
Parque Eduardo VII		A	22.3(+0.4-0.7)	0.708365	0.000021
Univ. Católica		BØ	20.5(+0.3-0.2)	0.708463	0.000017
Av. Uruguai		BØ	21.5(+0.5-0.3)	0.708397	0.000017
Chelas	*Anomia*	S1	14.7(+1.5-0.5)	0.708787	0.000018

Table I.- $^{87}Sr/^{86}$ Sr results

Lisbon (Antunes & Pais, 1992, 1993). The Sr age for the same level is 22.3 (+0.4-0.7) Ma (Fig. 2), this being compatible with K-Ar and probably closer to the real age. New data are needed in order to reduce the remaining uncertainty in dating the lower and upper limits of the concerned DS.

Depositional sequence B0 (Burdigalian)

Lithostratigraphy

The Depositional Sequence Bo (Bo DS) comprises sediments from Cotter's units I (upper part) and II, whose index fossil is *Chlamys pseudopandorae (Pecten pseudopandorae,* according to Cotter) (Cotter, 1956). These overlie disconformably the A DS or, at Foz da Fonte (Setúbal Peninsula), the Lower Cretaceous in angular unconformity.

At Foz da Fonte, the B0 DS begins by conglomerates with altered, basic rock dyke elements, and clay/silt beds overlain by biocalcarenites showing palaeokarst features.

At Almada, the earliest B0 DS sediments are glauconitic clays with ahermatypical corals and lignite that grade up into sandy levels with oysters, paleosoils and clays with plant leave impressions and sporomorphs (Pais, 1981, 1986, 1989; Antunes & Pais, 1984). At the top, there are sandstones with plentiful molluscs. The rare nautiloid *Aturia aturi* was recorded.

At these levels (as well as higher up) beach sand facies often are rich in *sand-dollar* type, very flat urchins as *Amphiope* and *Parascutella,* rapid burrowers just below the sediment-water interface sea. Biocalcarenites often show large *Clypeaster* spp., and mudbottom facies the frequent deep-burrowing, thin-shelled *Schizaster.*

In Lisbon, sedimentation proceeded with clays. Greenish clays with plant remains (Pais, 1981) and gypsum yielded a mammalian faunula at Horta das Tripas (locality 1, Fig.2). Over the mainly clayey beds there are medium to fine, littoral marine micaceous sands that yielded a small-mammal fauna at Universidade Católica (locality 3, Fig.2). At the top, at Avenida do Uruguai (locality 2, Fig.2), argillaceous sands crossed by oyster-filled channels and also yielding marine fishes and small mammals are exposed.

Biostratigraphy

Globigerinoides altiaperturus occurs for the first time at the lowest part of Bo DS. It points out to Blow's N5.

The macro-mammal association from Horta das Tripas, with *Brachyodus intermedius,* and the small-mammal ones from Universidade Católica and Avenida do Uruguai, not distinguishable from one another and marked especially by *Eucricetodon infralactorensis,* seem typical of MN3 (Antunes, 1984; Antunes & Mein, 1986; Antunes *in* Antunes *et al.,* 1996).

Hemicyprideis helvetica and *Pokorniella lusitanica* were recorded for the last time (Nascimento, 1978, 1980, 1990).

Isotopic ages

Dates (all Sr) concern the following sites:

- Basal conglomerate at Foz da Fonte, 19.5(±0.2) Ma;
- Lower levels at Penedo, 20.0 (±0.4) Ma;
- Top of B0 DS at Almada, 18.3 (+0.4-0.2) Ma;
- Universidade Católica mammal locality, 20.5 (+0.3-0.2) Ma;
- Avenida do Uruguai mammal locality, 21.5 (+0.5-0.3) Ma.

Palaeomagnetic data

Foz da Fonte section (lower part) anomalies:

- 6n, 5Er and part of 5En (Sen *et al.,* 1992).

Depositional sequence B1 (Burdigalian)

Lithostratigraphy

The Depositional Sequence B1 (B1 DS) is composed of sediments from Cotter units III, IVa and IVb (Cotter, 1956). It overlains B0 through a regional disconformity and begins by coarse shallow marine sandstones very rich in often fragmented mollusc casts (III). Shallow, photic marine environments rich in algae and higher plants *(Zostera,* etc.) are indicated by beds with plentiful gastropod grazers as *Turritella terebralis* and often remnants of other herbivores as Sirenians *(Metaxytherium).* These deposits grade upwards into fine, greyish to bluish clayey silts (euxinic facies) with molluscs, fishes and microfossils (calcareous nannoplankton, dinoflagellates, pollens and spores, foraminifers, ostracods) that correspond to a transgression apogee (IVa). The index fossil of the IVa Cotter unit is the beautiful gastropod *Pereiraia gervaisi.*

The upper part of the IVa unit points out to lower salinities and reduced depths *(Cerithium* and a few other molluscs, impressions of plant leaves). These beds are overlain by progradational, fluviatile, arkosic coarse sands in the Lisbon area; by deltaic, micaceous fine sands with clay lenses often with plant fossils and *Gryphaea gryphoides* (taken by Cotter as index fossil then named *Ostrea crassissima),* at Almada-Cristo Rei; or by littoral marine, fine sands and marly siltstones with glauconite at Foz da Fonte-Penedo.

Biostratigraphy

The deeper facies (IVa) yielded *Catapsydrax unicavus* and *Globigerinoides altiaperturus* (N6).

Plentiful benthic foraminifera and especially warm-water forms as Heterosteginids must be recorded. The latter make up a large part of biocalcarenites at Foz da Fonte (Heterosteginids still occur, if rarely, in upper Serravallian, VIb unit).

In the IVb fluviatile/arkosic and deltaic sediments, mammal fossils were collected at Quinta do Narigão, Quinta da Noiva, Quinta da Carrapata, Pote de Água (all from the lower part) and Cristo Rei (upper part, the only small-mammal site). Proboscidians *(Gomphotherium angustidens)* appear for the first time in an association which includes the last anthracotheres *(Brachyodus onoideus)* and indicates the MN4 mammal-unit (Antunes, 1984; Antunes *et al.,* 1996b).

Typical Aquitanian ostracods do not occur any more. *Ruggieria (R.) micheliniana, Cnestocythere truncata, Pokorniella minor* and *Triebelina raripila* were recorded for the last time.

Isotopic ages

Sr dates concern:

- Foz da Fonte, lowest part of B1 DS, 19.7 (+0.3-0.2) Ma; upper part, 18.5 (+0.2-0.3) Ma.
- Penedo, lowermost exposed bed, 19.6 (+0.3-0.5) Ma; glauconitic level near the top, 18.0 (+0.3-0.5) Ma.

Palaeomagnetic data

Foz da Fonte section anomalies:

- Part of 5En and 5Dr (Sen *et al.,* 1992).

Depositional sequence B2 (Burdigalian)

Lithostratigraphy

The sediments belonging to the Depositional Sequence B2 (B2 DS) correspond to the Cotter's units Va1 (index fossil: *Chlamys scabrellus,* formerly ascribed to *Pecten)* and Va_2. *Placuna miocenica* was regarded by Cotter as index fossil for the latter. A regional disconformity separates Va_1 from B1 DS.

In Lisbon, the lowermost (Va_1) layer is an often very coarse, coralline algal and mollusc-rich biocalcarenite, that is replaced in the Setúbal Peninsula by marly siltstones and clayey, fine sandstones with microfauna.

This layer, whose upper part contains frequent land snails (a further indicator of a regression event in progress), is overlain by fluviatile, coarse yellow sands with black pyrolusite impregnations that also occur in bones and teeth. There is an important mammalian datum, the arrival of *Prodeinotherium.* The same levels yielded plentiful remains of warm water fishes, some of which *(Lates* and catfishes) being tolerant to brackish and freshwaters (Antunes, 1989).

The upper part of B2 DS comprises white, fine, partly eolian sands alternating with thin clay layers. It probably corresponds to littoral dunes, and deltaic environments.

In the Almada area, the presence of a warm water bivalve as *Placuna (Indoplacuna) miocenica is* noteworthy (Fonseca, 1974).

Biostratigraphy

Globigerinoides trilobus and *Globigerinoides immaturus* are plentiful. Some forms can be ascribed to *Globigerinoides bisphericus. Globigerinoides obliquus, Globigerinoides altiaperturus* and *Globorotalia obesa* are common. This association indicates N7.

In Lisbon, fluviatile sands yielded at Quinta das Pedreiras, Quinta do Pombeiro and Quinta da Conceição mammal associations characterized by the first presence of immigrants *Bunolistriodon, Dorcatherium, Prodeinotherium, Megacricetodon primitivus* and *Democricetodon hispanicus,* MN4 mammal-unit (Antunes, 1984; 1990; Antunes *et al.,* 1996b). It also represents the apogee of very large or huge longirrostrine crocodylians as *Gavialis* sp. and *Tomistoma lusitanica,* most typical warm-region dwellers (Antunes, 1987, 1994).

Cytherella (Cytherelloidea) jonesiana and *Cyamocytheridea strigulosa* are especially interesting, as well as the last record of *Miocyprideis fortisensis.* These ostracods indicate the end of the Burdigalian, and warm waters (Nascimento, 1988; 1990).

Isotopic ages

Sr dates only concern:

- Penedo Norte, B2 DS lowermost exposed bed, 17.7 (+0.7-0.5) Ma; upper part, 17.8 (+0.7-0.5) Ma.

Palaeomagnetic data

None.

Depositional sequence L1 (Upper Burdigalian and Langhian)

Lithostratigraphy

The Depositional Sequence L1 (L1 DS) corresponds to sediments that integrate the Cotter's *(idem)* Va_3 *(index* fossil: *Chlamys scabriusculus) and* Vb (i. fossil: *Gryphaea gryphoides)* units. Another regional disconformity separates Va_3 from the underlying B2 DS. The lowermost layer is a very coarse, algal biocalcarenite rich in molluscs.

Biostratigraphy

The first occurrence of *Praeorbulina* (N8) is an important datum.

Near Lisbon (Olival da Susana, Quinta da Silvéria, Casal das Chitas, etc. at Charneca do Lumiar, Quinta da Farinheira and a few others near Chelas grouped as Chelas 1) are known mammal sites at the fluviatile, arkosic, coarse sands from the Cotter's Vb unit. The most remarkable feature of the mammalian fauna is the very common presence of asiatic immigrants as the rhinocerotid *Hispanotherium. Megacricetodon primitivus* was found for the last time. Although this mammalian fauna is clearly distinct from the Va_2 one, both have been included in MN4 mammal-unit. At higher levels, littoral, coarse sands with oyster valves (Chelas 2) yielded a small mammal faunula with *Megacricetodon collongensis,* MN5 (Antunes, 1984; 1990; Antunes *et al.,* 1996b).

Ostracods: first occurrences of *Pterigocythereis (P.) siveteri* and *Loxoconcha (Loxoconcha) ducasseae* (Nascimento, 1980, 1990).

Isotopic ages

Sr dates concern:

- Penedo Norte, L1 DS lower part, 17.3 (+0.6-0.5) Ma.

Palaeomagnetic data

None.

Depositional sequence S1 (Serravallian)

Lithostratigraphy

The Depositional Sequence S1 (S1 DS) comprises sediments from the Cotter units Vc (index fossil, *Anomia choffati),* VIa (i. fossil: *Pitar islandicoides,* formerly referred to *Venus brochii)* and the lower part of VIb (i. fossil: *Schizaster scillae)* (Cotter, 1956).

S1 DS is separated from L1 DS by a regional disconformity. It begins in the Lisbon area by shallow marine conglomerates with large amounts of oyster valves, followed up by sands.

Correlative sediments in the Almada area (shallow marine sandstones alternating with shelf mudstones) show a more distinct marine character.

At Penedo there is strong condensation. Deposition began by a glauconite-rich conglomerate with black abraded mollusc casts followed up by fine clayish sands.

The Vc unit represents the early stades of the most important transgression (Serravallian), whose apogee corresponds to the deepest facies that ever occurred in the Lower Tagus basin (VIa unit of Cotter): pyritous, bluish euxinic silty clays alternating with somewhat more carbonated mollusc beds (shelf mudstones). Deep water fishes occur -sharks (big-eyed thresher, *Alopias* cf. *superciliosus;* saw-shark, *Pristiophorus;* Squaliforms) as well as teleosts (Lepidopids, Myctophids) (Antunes & Jonet, 1969-1970). Cetaceans

became frequent at S1 and later DS, whereas Sirenia apparently disappear from the basin.

In Lisbon, S1 DS upper part indicates a regression event. The blue, euxinic VIa silts and clays are overlain by shallow facies biocalcarenites with abraded shell fragments; by some mud bottom, probably estuarine facies with *Schizaster;* and by coarse yellow sandstones with molluscs (plentiful, more or less abraded valves of *Gryphaea gryphoides),* overlain by greyish to yellow clays with impressions of plant leaves.

Biostratigraphy

The first *Orbulina suturalis* and *Orbulina universa* point out respectively to N9 and N10. Among other planktic forms, *Globigerinoides subquadratus, Globorotalia mayeri* and *Globorotalia menardii* are present.

Aurila (Ulicznina) oblonga, Ruggieria (R.) nuda, R. tetraptera tetraptera, Nonurocythereis seminulum, Pterygocythereis (P.) jonesi and *Olinfalunia costata* occur for the first time (Nascimento, 1980, 1990).

Isotopic ages

Sr dates concern:

- Chelas (Lisbon), base of S1 DS, 14.7 (+1.5-0.5) Ma.
- Brielas (Costa de Caparica), lower part of S 1 DS, 14.0 (±0.4) Ma.
- Penedo, upper part of S1 DS, 12.5 (+1.0-2.0) Ma.

Palaeomagnetic data

None.

Depositional sequence S2 (Serravallian)

Lithostratigraphy

This depositional sequence is not well established due to poor outcrops and to important lateral facies shifts.

In Lisbon area the sequence begin by dark yellow rather thick silty shallow marine sandstones alternating with silty clays with *Gryphaea gryphoides* and sea urchins. Near the top, there are mica-rich, whitish sandstones with a varied marine fauna, followed up by grey to yellow clays with impressions of plant leaves. These deposits have been included in the VIb unit of Cotter (1956).

In the Setúbal Peninsula, sedimentation was always marine. Near Costa de Caparica, marine, yellowish, fine sandstones yielded the last Heterosteginids, Bryozoans, the worm *Ditrupa,* minute *Echinocyamus* urchins, and a fish fauna distinctly shallower than that from the Vla blue clays. At Penedo, there was an important condensation event; grey conglomerates with glauconite include fragments of phosphate crusts, and are rich in pectinids, sea urchins, fish teeth and cetacean bones.

Biostratigraphy

Last occurrence of *Globigerinoides subquadratus.*

Palaeomagnetic data

None.

Depositional sequence T1 (Upper Serravallian - Lower Tortonian)

Lithostratigraphy

This depositional sequence comprises sediments from the Cotter units VIc, VIIa and VIIb; index fossils, respectively *Ostrea crassicostata* var. *gigantea* (now, *Pycnodonta squarrosa), Pecten tenuisulcatus* (now ascribed to *Flabellipecten),* and *Pecten scabrellus* var. *macrotis (a Chlamys)* (Cotter, 1956). In Lisbon, it begins with coarse biocalcarenites very rich in often very-large-sized molluscs as *Pycnodonta squarrosa,* grading upwards into fine, light yellow fine sandstones with plentiful *Flabellipecten* and other molluscs, a rich fish fauna, and frequent cetaceans. *Tomistoma lusitanica* was recorded for the last time (a single, huge individual, probably killed by other(s) of its kind that was attacked by sharks after death). Upwards, sediments are richer in *Chlamys macrotis.* The uppermost layers are composed of fine, micaceous sands with intercalated, carbonate-cemented sandstones.

At Penedo and Ribeira da Lage there are outcrops of dark grey, glauconite-rich middle-grained sands that grade upwards into micaceous, somewhat clayey fine sands with levels rich in concretions. At the top, there are yellowish, sandy levels with pectinid (mainly *Chlamys macrotis)* concentrations.

Between Foz do Rego and Fonte da Telha there are grey clayey silts with marine fauna outcrops.

An erosion surface cuts the T1 DS deposits.

Biostratigraphy

Globorotalia mayeri occurs for the last time, while there is the first record of *Neogloboquadrina acostaensis* at Fonte da Telha. The known associations still point out to N14 (lowest levels), N15 (most part), and N16 at the higher levels.

Among the Ostracoda, there are the first occurrences of *Aurila (Ulicznina) zbyszewskii, Celtia quadridentata,* and *Cytheretta (Cytheretta) simplex* (Nascimento, 1988, 1990).

Isotopic ages

K-Ar ages:

- Penedo Norte, lower part of T1 DS, 10.95(±0.25) Ma.

Sr dates:

- Ribeira da Lage, lower part of T1 DS, 12.7(+0.41.4) and 11.3(+1.7-2.8) Ma.
- Foz do Rego, upper part of T1 DS, 8.7(+1.8-3.5) and 8.3(+1.9-3.3) Ma
- Fonte da Telha, uppermost part of T1 DS, 5.2(+3.1-1.2) Ma.

Palaeomagnetic data

None.

Conclusions

The Miocene infilling of the Lower Tagus Basin in the Lisbon and Setúbal Peninsula areas correspond to a very broad marine facies that span from littoral/ shallow ones and barrier reefs to deeper, schlier-type euxynic, pyritous silts and clays. Intercalated transitional and non marine units range from dunes to estuarine oyster banks, deltaic and even fluviatile feldspathic sands carried down from Paleozoic granites and other rocks from the Variscan Hesperic massif. Sedimentary record covers nearly the whole Miocene and affords a rich set of data.

Direct comparison and accurate dating of continental and marine levels under direct stratigraphic, biostratigraphic and isotopic datation controls is possible, as are possible some correlations between marine and continental biostratigraphic scales.

New developments led to this synthesis, based on the present status of our knowledge. The main conclusions are as follows:

1. The paramount importance of the Lower Tagus Basin as a key source of information for knowledge of the marine and continental Miocene of western Europe is confirmed.

2. An exceptionally complete and accurate set of Sr datation was recently obtained. This represents for the concerned Miocene succession an excellent framework and a much better approach for geologic, paleontologic and paleoclimate phenomena, as well as for correlation at the basin's level or at a much broader scale. A time calibration of biostratigraphic scales is possible. Paleomagnetism results were not so positive.

3. Eight depositional sequences (DS) delimited by regional disconformities related to transgressive surfaces are defined. Most DS begin with coarse fossiliferous sandstones (biocalcarenites) upgrading to thin sands or marls sometimes (DS B1 and DS S1) of euxinic character. In the Lisbon region, the DS end with estuarine/deltaic or, even, fluvial arkosic deposits sometimes rich in mammalian fossils.

The DS S1 and S2 at Penedo (SSW of the Setúbal Peninsula) are condensed.

As there are lithologic and significant isotope age differences between Foz do Rego and Fonte da Telha, it cannot be excluded that the latter may belong to another, more modern DS that would correspond to the final infilling of the Tortonian gulf. Later ages suggest an Uppermost Miocene, Messinian age, but there is no definite proof of this hypothesis; on the contrary, planktic foraminifera still seem to point out to the Tortonian.

The diachronism of the transgressive surfaces of the DS B1, DS B2 and DS L1 may result from correlation problems between mammalian and marine biostratigraphic scales.

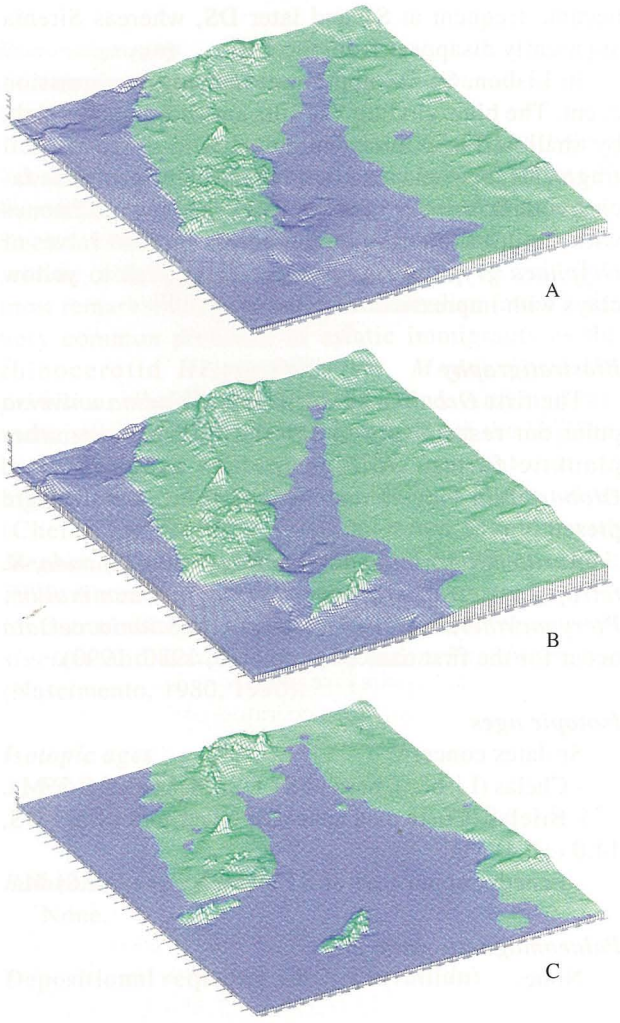

Figure 3.- A) Paleogeographic model of the terminal part of the Lower Tagus Basin during Lower Aquitanian (ca.23Ma). B) Paleogeographic model of the terminal part of the Lower Tagus Basin during Burdigalian (after Arrábida Chain uplift, ca.17 Ma). C) Paleogeographic model of the terminal part of the Lower Tagus Basin during Serravallian (ca.14 Ma).

4. The disconformities have an eustatic control and correspond to erosion surfaces.

5. The deposition of prograding, upward thinning arkosic deposits, seems to be a consequence of continental uplift related to tectonic events. The deposits of the upper part of DS B1 (Lisbon and Almada area) are a consequence of the intra-Burdigalian rupture (Antunes *et al.*, 1996b) possibly correlated with the paroxysmal Burdigalian tectonic phase of the Betic domain (Soria, 1994).

The arkosic fluviatile sands of the upper part of DS L1 may be correlated to the Betic area intra-Langhian phase and to the intra-Middle Aragonian sedimentary break of the Ebro, Tejo and Douro basins (Calvo *et al.*, 1993; Cunha, 1996).

The upper part of DS S1 (and, may be, of S2) sands can be correlated with the Upper Serravallian tectonic

phase recognized in several Iberian basins (Calvo, 1993; Soria, 1994; Cunha, 1996).

6. Biostratigraphic dating of many marine levels by planktic foraminifera is accurate. Reference levels may be ascribed to Blow's N zones. Calcareous nannoplancton associations are generally poor and lack in most marine levels. Dinoflagellata are under study.

7. From earliest Miocene to early middle Miocene, there are five different mammal associations, in transitional or non marine levels, directly correlated to marine levels. This offers the possibility of dating continental sites and faunas in Ma. Upper Middle Miocene to the lower upper Miocene (Vallesian) mammalian faunas from the inner part of the basin may also be correlated with marine levels, even if not so accurately.

8. It is possible to establish correlations with the general third order eustatic cycles (Haq *et al.,* 1987) although the time boundaries do not fit well (Fig. 2). The discrepancies may result from local tectonics including strong subsidence rates and the Arrábida Chain uplift.

9. Several gulfs, oriented SE-NE, developed during the Miocene in the marginal region of the Lower Tagus Basin. Arrábida Chain was often an island (Fig. 3).

During the first transgression (Aquitanian) the gulf was narrow and coral barriers occurred locally. In the most important Burdigalian transgression the gulf covered larger areas to NE and SE and the Arrábida Chain was rising. During the Serravallian, the major Miocene transgression occurs and the Sintra massif also becames an island. In the Tortonian, the gulf was reduced to the Fonte da Telha - Foz do Rego region.

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