The tectono-stratigraphic evolution of an Atlantic-type basin: an example from the Arrábida sector of the Lusitanian Basin

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Abstract
The Arrábida chain is an impressive basin inversion structure of Miocene age that is exposed over almost the entire Mesozoic sedimentary sequence of the southern sector of the Lusitanian Basin (LB). This field trip provides a complete cross-section through some of the key outcrops, illustrating important moments in the tectono-stratigraphic evolution of an Atlantic-type basin, namely: a) the extensional tectonic control on Early–Middle Jurassic sedimentation in a low- to high-energy carbonate ramp setting; b) the presence of a basin-wide unconformity at the Middle–Upper Jurassic transition; c) the tectonic rejuvenation of the eastern border of the LB, the effects of rift shouldering, and the progressive exhumation of the eastern margin in the sedimentary infill; d) the distal expression of the basin’s breakup unconformity (rift to drift stage); and e) magmatism in a passive margin.

Keywords: Atlantic-type basin, tectono-stratigraphic evolution, Lusitanian Basin, Arrábida

1. Introduction
The Arrábida chain was defined by Ribeiro (1935) as the relief located in the southern part of the Setúbal Peninsula and composed mainly of Jurassic and Lower Cretaceous carbonate units. The chain is almost exclusively formed by sedimentary rocks deposited during the evolution of the Lusitanian Basin (LB), an Atlantic-type basin that evolved during the Miocene (late Burdigalian to Tortonian) over a period of approximately 10 Myr.

This short mountain chain is 7 km wide and 35 km long and is oriented WSW–ENE. It corresponds to a peripheral chain of the Alpine belt, which resulted from the collision between the Euro-Asiatic and African plates. The chain is relatively recent, having evolved during the Miocene (late Burdigalian to Tortonian) over a period of approximately 10 Myr. Deformation has particularly affected the regional cover sediments deposited during the Mesozoic in the LB, which is located on the West Iberian Margin (WIM) (Fig. 1). Tectonic inversion of the basin, a consequence of the aforementioned Iberian Margin collision, has uplifted this ~4-km-thick sedimentary series. Only in Arrábida is the whole sedimentary succession deposited in the southern sector of the LB exposed, as
is a series of structures that provide evidence for the tectonic style associated with the early extensional phases of the opening of the North Atlantic.

The sedimentary record of Arrábida is not restricted to Mesozoic units. In fact, the most complete and continuous Cenozoic, in particular Miocene, sedimentary succession of Portugal crops out in this region. These Cenozoic deposits are related to the evolution of the Tagus River basin, whereby the formation of the Arrábida chain altered the original course of this river and is responsible for its present channel position. In contrast to the predominantly carbonate Mesozoic sedimentary series, the Cenozoic succession is composed mainly of clastic deposits.

The Upper Cretaceous to lower Miocene sedimentary record in Arrábida, as well as in the entire southern and western Iberian margin, is scarce and difficult to date because of the continental nature of the rock facies. According to recent research (Miranda et al., 2009), the scarcity of the sedimentary record may be related to the occurrence of important magmatic activity between 100 and 60 Ma, as revealed by the existence of a number of different structures and massifs located fairly close to Arrábida: 1) the Mafra radial dyke complex, dated at ~100 Ma (~50 km to the NNW of Arrábida); 2) the Sintra Massif (around 40 km to the NW), dated at 85–72 Ma, and coeval with two other massifs to the south of Arrábida (the Sines and Monchique massifs); and 3) the Lisbon Volcanic Complex (25 km to the N), dated at ~60 Ma. Although smaller in size, some outcrops of magmatic rocks are found in Arrábida, which, as seen at Stop 7 (Foz da Fonte beach), are relevant to understanding the emplacement of those major intrusions.

In short, the Arrábida chain is a key region for gaining better knowledge and understanding of the three fundamental stages of the post-Palaeozoic evolution of the western margin of the Iberian sub-plate: 1) the opening of the North Atlantic (Triassic to latest Early Cretaceous); 2) magmatism and consequent crustal uplift (Late Cretaceous to Palaeogene); and 3) collision with the African plate (Miocene).

The Pleistocene–Holocene dynamics of Arrábida are also a significant feature, in particular with regard to the evolution of the morphology of the current landscape. During this time, the relief generated by the tectonic inversion was reduced along an Atlantic-facing coast characterized by coastal erosion dynamics and important and repeated eustatic variations. These characteristics, together with the properties of the predominant lithologies (limestones, marly
limestones, and dolomites), have given Arrábida an enormously varied and spectacular morphology that is of very significant scientific and educational value.

1.1. The geological evolution of the West Iberian Margin as documented in Arrábida

1.1.1. Mesozoic extension: the opening of the North Atlantic

In a general way, the sedimentary series that crops out in Arrábida does not considerably differ from that found in the remainder of the LB, although in the central and northern sectors of this basin (Fig. 1), sequences with such continuity are known only in deep wells. Carbonate sequences are predominant, and crop out in association with the main thrusts and the Sesimbra diapir, register the progressive marine flooding from the Tethys Ocean to the south and from the Boreal Sea to the north. These deposits, which are of evaporitic facies and related to the first rifting episode, are locally very thick, reaching more than 2 km in some wells in the central sector of the LB. These deposits played a very important role in the Mesozoic evolution of the LB, influencing not only the basin’s structural development but also the formation of salt diapirs, which are distributed throughout most of the basin, including in Arrábida. The deposits also conditioned the style of tectonic inversion. According to Kullberg et al. (2014), these sedimentary series are bounded by unconformities. These unconformities,

![Fig. 2 - Diagram showing the tectono-sedimentary evolution of the Lusitanian Basin. The simplified lithostratigraphic units are unconformity bounded, and the respective depositional environments are shown as being closely controlled by the main tectonic events and the consequent general geometry of the basin (modified from Kullberg, 2000).]

but of lesser depth compared with those in the rest of the basin, suggesting that the Arrábida area was the basin’s southernmost sector.

The extension associated with the earliest phases of rupture of the Pangaea super-continent occurred during the Triassic, when the final exhumation of the Variscan chains was taking place. Clastic continental deposits were formed in most of Iberia as well as in other areas such as North Africa and the Great Banks. The deposits, which formed during the Hettangian which were tectonically induced, are shown in Fig. 2 and are described in the following paragraphs.

After Soares et al. (1993), D2 is expressed as a low-angle regional unconformity overlying the underlying continental units of the Silves Group, which were associated with the proto-LB. This unconformity has been considered as pertaining to the first rifting episode (e.g., Wilson et al., 1989; Soares et al., 1993; Kullberg, 2000), but this proposition needs to be re-evaluated. There is no reliable age control avail-
able, but D2 is probably of Late Triassic origin. D2b also marks a reorganization from continental to transitional environments, with the first marine episode recording a significant change in the sedimentary record, namely, a gradual transition to mixed carbonate siliciclastic inter- to supra-tidal transitional environments (sabkha).

- **Unconformity D4** has a basin-wide expression and marks major modifications in the geometry of the LB and its consequent facies distribution. The LB was at that time structured as a homoclinal ramp deepening from the SE to the NW, although the differentiation of the sedimentary environments is conditioned by the ENE–WSW-oriented main transfer faults. D4 also marks an acceleration of the subsidence of the basin and a progressive evolution from shallow to low-energy, deep-marine environments.

During the second rifting phase, the record of a very unusual Toarcian deposit is of utmost importance. This deposit is formed by a series of intraformational conglomerate levels known as the Flat Pebble Conglomerates (Geographic Coordinates (GC): 38°26’38.93''N, 09°52’23.34”W), whose best sequence crops out east of Sesimbra (Stop 6). Owing to the excellence of this extremely rare outcrop (a detailed literature review has revealed only six other similar deposits throughout the world), and also to the synsedimentary tectonic structures that are present, the origin of this type of conglomeratic deposit has been able to be established with a high degree of confidence. Considering the proposed genetic evolution, and because these deposits are the most recent of all known flat pebble conglomerates, this deposit assumes an increased value in terms of its rarity and, consequently, with respect to its scientific importance (Kullberg *et al.*, 2001).

One of the most impressive examples of a syn-sedimentary normal fault that has conditioned the bedding geometry crops out as a scarp more than 100 m high at Praia da Figueirinha (Stop 4) (GC: 38°29’4.25”N, 08°56’40.05”W). This fault has produced a progressive change in sedimentary depth and in thickness as well as layer-parallel deformation.

In the sedimentary sequences of the LB representing the period from the second rifting phase to the transition into the third rifting stage, several tectonically induced unconformities are recognizable (Kullberg *et al.*, 2013):

- **Unconformity D5b** of the lower Toarcian (Serpentinus Zone) is marked by an erosional surface that has a more substantial expression in the Coimbra and southern areas. The unconformity is also marked by seismites (flat-pebble conglomerates, see Kullberg *et al.*, 2001, and Stop 6) in the southern sector of the basin, and, close to the western limit of the basin, large siliciclastic submarine gravity fans that accumulated following the rejuvenation of the Berlenga Horst. Nevertheless, the general facies distribution is clearly divided by ENE–WSW-trending main faults and a northwestward deepening of the basin's floor.

- **Unconformity D7** of the lower Bajocian marks the initiation of syn-sedimentary mass movements controlled mainly by intra-basinal, northward-directed faults. These mass movements, which are well documented in the central sector of the basin, show, on the one hand, a strong tectonic control with normal faults limiting rotated blocks and, on the other hand, a relatively large accommodation space at the bottom of the basin that allowed large volumes of sediments (some of kilometric dimensions) to be emplaced. This means that although the sedimentary package above D7 is very thick (>900 m, Kullberg *et al.*, 2014), the LB during the Bajocian–Bathonian behaved as a starved basin. D7 also marks the transition from the previous low-energy environment to a high-energy carbonate ramp. The Callovian is incomplete as it is partially truncated by unconformity D9.

- **Unconformity D9** is the best expressed unconformity in the LB. It is basin wide and represents a hiatus of about 3 Myr, representing the upper Callovian (Athleta Zone) to the middle Oxfordian (Plicatilis Zone). It is expressed as i) an angular unconformity, ii) an erosional surface, or iii) a paraconformity with a sudden facies change, but there is no evidence of condensation horizons or clastic influxes. The origin of D9 has been discussed, and different possible causes for its occurrence have been proposed, all involving tectonics at a regional, supra-basinal scale, namely: i) regional uplift related to the opening of the Central Atlantic (Rasmussen *et al.*, 1998); ii) tectonic inversion caused either by thermal uplift of a distal stretched portion of the lithosphere or by distal compression induced by thermal subsidence (Terrinha *et al.*, 2002); or iii) regional factors, including climatic, that intensified the global sea-level regressive trend in Iberia (Azerêdo *et al.*, 2002). After this event, the basin returned progressively from lacustrine conditions to a deep-marine external carbonate platform topped by turbidites. At this time, the late Oxfordian, the basin experienced an acceleration in the subsidence rate (up to 200 m/Myr), anticipating a sudden and widespread modification of the basin morphology.
- **Unconformity D10** marks the most important and sudden morphological change in the basin's sub-stratum and modification of its facies related to the initiation of the third episode of rifting. These changes were associated with a marked increase in lithospheric stretching, which encouraged an influx of siliciclastics from the exposed Palaeozoic magmatic and metamorphic rocks of the uplifted borders of the basin. The proximal marginal sequences (to both the east and the west) are marked by arkosic gravels that were deposited in a submarine fan system more than 2200 m thick (Wilson *et al*., 1989), while epibathyal clays (~1000 m thick) were deposited in the deeper distal part of the basin. The whole basin became progressively infilled, firstly with peri-reefal carbonates during the late Kimmeridgian and secondly by continental fluvial siliciclastics until the end of the Tri-thonian.

The Mesozoic units in the Arrábida sector are tectonically inverted allowing the continuous exposure of almost all the sequence (Fig. 3). Thus, in the area, outcrop in continuity the pre- and post-breakup units, that is the result of the being the most distal and deeper area in the Lusitanian Basin when the continental rupture was settled in the Aptian-Albian limit to the West.

Another important geological event recorded only in Arrábida is a transient inversion episode during the extensional history of the LB. The El Carmen Normal Fault (GC: 38°30′43.11″N, 8°59′0.38″W) affected Callovian carbonate deposits as a normal fault, was later reactivated as a reverse fault, and was finally sealed by the Upper Jurassic basal conglomerate, which represents the initial sedimentation associated with the third episode of rifting in the West Iberian Margin. The outcrop located in the Terras do Risco area (see the GC above and Kullberg *et al*., 2000), together with similar outcrops in the Algarve Basin (southern Portugal) (Terrinha, 1998), has allowed crustal geodynamic models to be established for describing transient inversion tectonics in extensional regimes associated with rift evolution (Terrinha *et al*., 2002).

The crustal mechanisms that caused this inversion could also have been responsible for the uplift that is recorded across the entire LB, marked by a 3- to 4-Myr hiatus (late Callovian–early Oxfordian). In Arrábida, the sedimentation restarted with the deposition of a unique type of rock in Portugal (in terms of both facies and aesthetic value), and quite possibly in the world: the so-called “Arrábida Breccia” (Stop 5) (GC: 38°27′28.04″N, 09°0′37.52″W). This “breccia”Fig. 3 - Synthetic lithostratigraphic column from the 1:50,000 38-B (Setúbal) Geological Map (modified from Manuppella *et al*., 1999), showing the main extensional Mesozoic events (rifting episodes associated with the opening of the North Atlantic) and the compressive Cenozoic events (associated with the collision between Africa and Eurasia) The red arrow shows the stratigraphic position of the base of the formation defined as “marls, clays, limestone with black pebbles, and conglomerates of Arrábida” (Manuppella *et al*., 1999), commonly called Arrábida Breccia (see Stop 5).
is, in fact, a polymictic carbonate conglomerate, with a red clayey matrix, whose genesis is associated with a submerged karst (Wright & Wilson, 1987). This is the local and very particular record of a process of extra-basinal dimension (Azerêdo et al., 2002; Kullberg et al., 2006a), with different types of signatures across the LB.

Until the end of the Middle Jurassic, sedimentation occurred in a shallow carbonate platform environment, but the coastline at that time must have lain much further to the east compared with the present eastern boundary of the mountain chain, which is marked by the Setúbal–Pinhal Novo Fault (passing through Palmela). This evidence is also found in other sectors of the LB, demonstrating a half-graben geometry evolution, as the clastic inputs are persistent in the Lower and Middle Jurassic sedimentary sequences that are found near the western margin of the basin (e.g., the Peniche region, which was strongly influenced by clastic inputs originating from the Berlenga horst) (Wilson et al., 1989; Kullberg, 2000).

However, from the earliest Kimmeridgian onwards, during the second rifting phase, the geometry of the LB clearly changed: it developed a graben geometry roughly symmetrical between the external northward-oriented margins, with the formation of marginal highs to both the east and the west, as a result of rift shouldering. It is in Arrábida, close to the eastern margin, that this structural change is most clearly recognised. The series of units known as the Conglomerates of Vale da Rasca, which are perfectly exposed just to the north of S. Luis hill (stops 2 and 3) (GC: 38°32′41.37″N, 08°55′34.24″W and 38°32′41.57″N, 08°55′49.24″W, respectively), show a sequence of alluvial fan clastic deposits that correspond to successive episodes of rift shouldering and exhumation of the marginal highs. These deposits show evidence of subaerial exposure of the Lower and Middle Jurassic units, then of the Triassic units, and, finally, of the Palaeozoic basement, the former substratum of the basin to the east of the new geographic and tectonic boundary (the Setúbal–Pinhal Novo Fault) of the southern sector of the LB (Kullberg et al., 2000).

The Mesozoic units in Arrábida are not particularly rich in fossils because of the general proximal character of the marine units and also because of the secondary dolomitization that affects the thick and irregular Lower and Middle Jurassic sedimentary sequence. However, dinosaur trackways are particularly common and important in the Upper Jurassic and Lower Cretaceous units. Three of these trackways (Lagosteiros, Pedra da Mua, and Avelino) (Fig. 4) (GC: 38°25′33.91″N, 09°12′59.60″W; 38°25′19.86″N, 09°13′1.24″W; and 38°27′15.57″N, 09°7′23.84″W, respectively) are classified as natural monuments (Decreto-law number 20/97 of 7 May) and are particularly important because of: 1) The number and extent of the preserved trackways; 2) their age, making them among the oldest known worldwide; 3) the rare evi-
dence of the gregarious behaviour of these animals; 4) the signs, in one of the trackways, pointing to the limping gait of one individual; and 5) the association with the popular legend that tells of Our Lady being carried up the cliffs at Cape Espichel, mounted on a giant mule (Antunes, 1976; Lockley & Santos, 1993; Dantas et al., 1994; Lockley et al., 1994a, b).

1.1.2. Magmatism and diapirism

The LB ceased its activity by the end of the Early Cretaceous (the age of the post-break-up unconformity is late Aptian) (Rey 2006; Rey et al., 2006; Kullberg et al., 2006a), with all the extension of the WIM having migrated to the mid-oceanic ridge of the North Atlantic, whose sea-floor spreading is of that age. As mentioned above, for a period of ~80 Myr, the onshore sedimentary record of the margin is very scarce and dispersed, both in time and space, and Late Cretaceous magmatic activity is the only geological activity that was recorded during this hiatus.

The main groups of magmatic occurrences (Fig. 5) are those of the Sintra, Sines, and Monchique massifs, which are distributed in a linear arrangement and show significant genetic, geochemical, and temporal affinities (Miranda et al., 2006a, 2007; Kullberg et al., 2006b). However, at the surface, there is no continuous cartographic evidence for the existence of this alignment. The linearity raises the hypothesis of a deep crustal discontinuity with a non-continuous propagation towards the surface. It is in Arrábida, positioned between the Sintra and Sines massifs, that the best evidence supporting this hypothesis can be found, namely, the sill at Foz da Fonte beach (Stop 7) (GC: 38°27′10.94″N, 09°11′57.68″W), a dolerite structure injected into the top of the Lower Cretaceous sedimentary sequence.

Following Ribeiro (2002), these major intrusions are interpreted as being included as part of a more extensive lineament of magnetic anomalies (extending from the Tore Seamount to the Guadalquivir Bank, a distance of >500 km) that resulted from the ascent of magma along a fault generated by the supercritical propagation of a fracture in the lithosphere. This fracture may have been caused by i) a meteorite impact that would have generated the Tore Seamount or ii) magmatism triggered by the movement of deep-seated dextral strike-slip faults reactivated as a result of the anticlockwise rotation of the Iberian microplate during the opening of the Bay of Biscay. In the latter case, the major fracture would have favoured the formation of release bends where magma would be generated by decompression and subsequently ascended (Terrinha, 1998; Kullberg & Kullberg, 2000). Recent research based on geochemistry, petrography, the anisotropy of magnetic susceptibility, and isotopic dating (Miranda et al., 2006a, b) of the Foz da Fonte sill have led to the conclusion that its feeder could have used a previous anisotropic structure corresponding to one of the many NNE–SSW-trending Late Variscan basement faults and could correspond to the superficial expression of the deep-seated NNW–SSE-trending dextral strike-slip fault that, according to several studies (e.g., Ribeiro et al., 1997; Terrinha & Kullberg 1998), controlled the emplacement of the subvolcanic massifs.

Establishing the age of the diapiric events in the LB has been a somewhat controversial issue among both Portuguese and international authors, but one hypothesis that has recently gained support has been sustained by, among other evidence, the Sesimbra diapir. The analysis of geological maps, the lithology of the surrounding Palaeogene units (conglomerates
with carbonate clasts from regional Mesozoic units), and the age of the magmatic intrusions found within the diapir, together point with some certainty to a Late Cretaceous age for the occurrence of diapiric events in Arrábida as well as in most of the LB.

The outcrops of the Hettangian evaporitic units in the diapir core, in particular at the Sesimbra Gypsum Quarry (Gesseira de Sesimbra) (GC: 38°27′28.38″N, 09°6′4.64″W), further support the above hypothesis in genetic terms. This site, an ancient gypsum quarry, possesses features that are crucial for the establishment of the above-mentioned hypothesis: (i) A dolerite dyke, petrographically and geochemically similar to the sill at Foz da Fonte beach, crops out in the quarry; (ii) gypsum is found in three different crystalline habits, namely, fibrous, saccharoid, and hyaline (which, to be found together in a single outcrop, is in itself very rare); and (iii) abundant bi-pyramidal quartz crystals, up to 1 cm in size, can be found mixed in the saccharoid phase. These quartz crystals must have been formed by the impregnation of hydrothermal silicate fluids, rich in calcium sulphate and fused/dissolved by the heat and by the fluids existent around the intrusive dyke. This liquefaction would have favoured a viscose behaviour of the evaporitic clays by partial fluidization and heat and volume increase, which, in turn, would have led to the movement of these materials to more shallow levels. This would likely have been the triggering mechanism of diapiric events in Arrábida and in the rest of the WIM. This mechanism is practically unknown in Portugal and is only very rarely cited in the international literature as the mechanism responsible for diapiric movements in other areas of the world.

1.1.3. Cenozoic compression – the collision between Africa and Eurasia

The Arrábida chain is the only structure in Portugal that allows the collision between the African and Euro-Asiatic plates to be dated, particularly the early phases of this collision, which took place in the Iberian Peninsula region. The event that formed the Arrábida chain was associated with the formation of the Alpine chains around the Mediterranean belt, in particular, the Betic chain in southern Iberia, with which it shares the same orientation. The Arrábida chain is not located on a convergent plate boundary; it is a basin margin inversion chain that formed through its proximity to the convergent boundary located ~300–400 km to the south.

The Arrábida chain corresponds to an overstep imbricate structure related to a system of frontal ramps, with a general ENE–WSW orientation and a SSE-verging overthrust movement, and NE–SW to N–S-oriented lateral ramps, with sinistral strike-slip movement and overthrust to the SE. This association between frontal ramps and their respective lateral ramps has formed several sets of duplex structures. These structures increase in complexity to the east because of the constriction produced by the transport of material in a direction oblique to that of the main lateral ramp (the Setúbal–Pinhal Novo Fault), which, locally, besides defining the basin margin, worked as a buttress during the
compressive episodes that generated the chain. Convergent simple shear was clearly the deformation regime in this region (Kullberg et al., 2000) (Fig. 6).

The Hettangian marly evaporitic complex, which constitutes the basal unit of the sedimentary sequence, is the level that has accommodated most of the ductile deformation, and it also marks the location of the basal detachment that has allowed transport to occur along the frontal ramps. Above and below the frontal ramps, fault-propagation-type folds have been formed (anticlines and synclines, respectively). The synclines show axes systematically plunging ~20° to the ENE, and the main anticlines (Formosinho, Viso, and S. Luís) show periclinal terminations near to the lateral ramps.

In general, the deformation found in the Arrábida chain, which formed during the main inversion episode in the LB during the Miocene (Burdigalian to Tortonian), is the result of the combination of two different styles: i) thin-skinned tectonics associated with the cover rocks above the basal detachment, and ii) thick-skinned tectonics associated with the important vertical movements of the basin’s basement rocks, strongly compartmentalised into blocks limited by the two main sets of faults generated during the extensional phase of the basin (Kullberg et al., 2000, 2006b).

Although Arrábida is not a large mountain chain, it is acknowledged as representing the most elegant example of Cenozoic inversion tectonics in Portugal (Ribeiro et al., 1990). In addition, Arrábida is of particular significance within the western Alpine orogenic belt (central Mediterranean Europe and Iberia), as it constitutes the most recent and peripheral example of this orogeny, demonstrating a migration of the deformation across southern Iberia and the westernmost part of the Thethys Ocean from east to west.

Adding to our understanding of the development of the Arrábida chain are the timings of the two main compressive phases that formed it. One of the most spectacular and well-exposed examples of an angular unconformity (approximately 90°) known in Portugal, that is, the Portinho da Arrábida unconformity (GC: 38°27′40.01″N, 09°00′58.34″W), provides information regarding the timing of the first compressive phase, which led to the uplift of Formosinho hill and most of the chain itself. This unconformity corresponds to a level of marine erosion that separates Upper Jurassic carbonates, deformed as a result of the proximity of a frontal ramp and bioturbated by lithophagous organisms, from the overlying lower Miocene oyster-rich bio-calcarenites (Fig. 7), which have provided a post-unconformity isotopic age of 17.6 Ma (Burdigalian) (Antunes et al., 1995). The second compressive phase was responsible for the uplift of S. Luís hill and is marked by a regional unconformity and a cartographic unconformity between Tortonian units.

The excellent outcrop quality of both materials and structures in Arrábida is well demonstrated, for example, by the very accessible outcrop of the core of the anticline fold of Serra do Formosinho (GC: 38°27′40.01″N, 09°00′58.34″W), which is the main structure of the Arrábida chain (Arrábida hill in Fig. 8), and of the frontal ramp (thrust) that formed it.

The Miocene outcrops in Arrábida are fundamental to gaining an understanding of the regional palaeogeography, particularly the evolution of the Cenozoic Tagus Basin. Good examples are the almost continuous exposures of lower Miocene–Pliocene sequences at Foz-Penedo beach (Stop 7 and surroundings) (GC: 38°28′1.51″N, 09°11′29.21″W), in the western part of Arrábida, and at Azeitão, in the eastern part. Another important sedimentary sequence, and the only one of its kind in Portugal, corresponds to the foreland basin molassic deposits of Portinho da Arrábida (GC: 38°28′56.43″N, 08°58′23.24″W), which were fed by the main structural relief of the chain.

The relatively rapid formation of the main reliefs of the Arrábida in the proximity of a structural boundary—the Setúbal–Pinhal Novo Fault—generated very abrupt interruptions in the morphology of the region. Important neighbouring reliefs, in this case S. Luís hill, meant that a vast plain extended towards the east, very similar to the present topographical configuration. This topographic gradient favoured the formation of a large-scale gravity slide, which corresponds to the hill on which the town of Palmela is built (Stop 1). The dimensions of this slide
Fig. 8 – Simplified tectonic model of the Arrábida chain (mod. Kullberg et al., 2000), and digital terrain model showing the diversity of geomorphological features.

Fig. 9 – Locations of the field trip stops (image from Google Earth): [1] Palmela hill, [2 and 3] Conglomerates of Vale da Rasca, [4] Praia da Figueirinha, [5] Jaspe quarry, [6] Alto da Califórnia flat-pebble conglomerates (Sesimbra), and [7] Foz da Fonte beach. The white dashed rectangles represent the locations of detailed geological maps presented in other figures as labelled. A Google Earth file with a precise location of all stops and with complementary information and illustrations can be reached in the following address: http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/368.
are unique in Portugal and very rare in other parts of the world, even in areas close to larger orogens.

The relief produced over a period of approximately 10 Myr is the main factor that has controlled the present spectacular morphology of Arrábida. Other factors are the predominantly carbonate but varied lithology, as well as the climate and coastal dynamics.

2. The field trip stops

The field trip stops that best illustrate the geological history for both the extensional and compression- al periods and for the magmatic and diapiric episodes are distributed along the entire chain. It should be noted that the stops illustrated in Fig. 9 are numbered from east to west for logistical reasons, and the sequence of stops does not reflect the sequential geological history of the region.

2.1. Stop 1. Palmela hill (GC: 38°32′41.34″N, 08°55′33.31″W)

On the top of Palmela hill, Stop 1 is a quick stop to enjoy the landscape and pinpoint localities to visit during the field trip, including an overview on the tectonic and stratigraphical framework related to the initial stages of the North Atlantic opening, and also the major structures and reliefs of the Arrábida chain. As it is shown in Fig. 3, almost all the Mesozoic and the Neogene are represented in the Arrábida range. In Arrábida, only the basal unit of the LB, the Group of Silves, does not crop out and there is also an important hiatus encompassing the Upper Cretaceous and the Paleogene.

This is also an important stop to show a general view of the linear morphologic structures related both to the general trend of bedding (E–W) in northern flance of the S. Luís anticline and to the important lithological contrasts. These contrasts are related to the hard limestones and conglomerates from the Lower Jurassic to the lowermost Upper Jurassic (S. Luís and Gaiteiros hills), the siliciclastics of the Upper Jurassic in the Comenda valley, and the Paleogene limestones to the north (Louro hill) (Fig. 10).

2.2. Stops 2 and 3. Vale da Rasca (GC: 38°32′41.37″N, 08°55′33.31″W and 38°32′56.05″N, 08°56′28.75″W, respectively)

These two stops near the eastern border of the LB correspond to a cross-section through the sedimentary sequence from Upper Jurassic to Cretaceous – the Conglomerates of Vale da Rasca, a basin edge sequence.

These conglomerates correspond to the basal unit of the third rifting episode that affected the LB. Geological mapping (Fig. 10) reveals that these conglomeratic units are arranged in a wedge format, reaching their maximum thickness in the Louro–Gaiteiros hill area (Fig. 11) until they pinch out in the Sesimbra region, where they are replaced by sandy clay. The facies and geometry of these conglomeratic units suggest deposition in a continental system of alluvial fans for the Conglomerates of Vale da Rasca and fluvial deposition in anastomosed channels for the Conglomerates of Comenda (Fig. 12).

Some highlights of this sequence of Stops (2 and 3):

1 – These conglomerates represent the start of a rifting phase, the third in the LB, thus, on the Western Iberian Margin and, therefore, in the North Atlantic.

2 – This is the only location in the LB that records the tectonic activation of a previously inactive edge with a consequent rift-shouldering effect.

3 – The conglomerates reflect the drastic alteration in the tectonic style and geometry of a basin that changes from asymmetric or half-graben to symmetric graben. To our knowledge, this is the only example of its type in Mesozoic sedimentary basins in any part of the world and, certainly, the only example with these characteristics in the entire North Atlantic region.

4 – These conglomerates provide extremely rare evidence of the progressive exhumation of a block raised towards the subsiding basin area. The Louro–Gaiteiros hills and the adjacent Barris valley, in a rarely observed manner, create a connection between the lateral and vertical variations of the facies.

2.3. Stop 4. Figueirinha beach (GC: 38°29′5.72″N, 08°56′39.36″W)

In this site a carbonate sequence of Early–Middle Jurassic age with a sealed normal growth fault - the normal synsedimentary Praia da Figueirinha Fault - crop out in a vertical extent of more than 200 m height. In this stop it can also be seen one the rare outcrops of the Arrábida thrust, showing a decametric duplex.

The structure of the LB, which has provided the framework for the units of Arrábida since the Mesozoic, is controlled by E–W extension (Ribeiro et al., 1996a; Kullberg, 2000) related to the initial phases of the opening of the North Atlantic. This extensional deformation has been accommodated by normal faults in a sub-meridian alignment (NNW–SSE to NNE–SSW). These faults are clearly marked in cartographic representations and by seismic reflection profiles obtained in various hydrocarbon prospe-
Fig. 10 - Geological map showing the location of the Conglomerates of Vale da Rasca (J3VR) (red arrow). The blue arrow indicates an exposed section of the Setúbal–Pinhal Novo Fault. For the legend, see Fig. 3. The green circle shows the approximate location (at 2.25 km of altitude) where the view of Fig. 11 was taken and the green arrow its direction. The map is an excerpt from sheet 38-B of the Geological Map of Portugal at a scale of 1:50,000 (Costa et al., 2005).

Fig. 11 - Oblique “aerial” view obtained from Google Earth for the region depicted in Fig. 10, highlighting the extent of the slopes of the “Arrábida foothills”, with São Luís hill on the right and the mountains of Louro and Palmela in the background (vertical exaggeration ×2).
Fig. 12 - Different features observed in the Conglomerates of Vale da Rasca (north of São Luís hill); A – with clasts with an exclusively carbonate composition, at the unit’s base; B – with a predominantly siliceous component (towards the top); C – channel structures typical of alluvial/anastomosed environments.

Fig. 13 - Exposed synsedimentary structures in the Jurassic strata of the Arrábida chain. A – cartographic details of the horst of Baralha (red arrow); B – cartographic details of the normal Praia da Figueirinha Fault (red arrow), which show that this fault affects Lower Jurassic units and is sealed underneath the units of the Middle Jurassic. For the legend, see Fig. 10. The maps are excerpts from sheet 38-B of the Geological Map of Portugal at a scale of 1:50,000 (mod. Costa et al., 2005).

campaigns in the basin, both onshore and offshore (e.g., Alves et al., 2002, 2006; Carvalho et al., 2005). Various synsedimentary faults cropping out in Arrábida were preserved during the inversion process, despite the concentration of compressive deformation that occurred in this area during the Cenozoic. Of these faults, we point out those forming the horst of Forte da Baralha (Kullberg et al., 2000) (Fig. 13A) and the normal Praia da Figueirinha Fault (Figs. 13a, and 14) (see also video 2 @ http://cienciasdaterra.novaidct.pt/index.php/ct-esj/article/view/354/364).

Some highlights of Stop 4:

1 – This fault illustrates the only onshore outcrop of a datable fault (Middle Jurassic) formed during a
rift episode of the initial phases of the North Atlantic opening, in marine facies, in the LB.

2 – Besides being the only such outcrop on the Western Iberian Margin (the oldest section of the North Atlantic opening), according to the literature it is also one of the very few such occurrences in all other Mesozoic basins of the North Atlantic.

3 – The outcrop presents a very complete and varied set of deformation structures, extremely rare as they are all coeval, which demonstrates the contemporaneity of tectonic and sedimentary processes.

4 – For the above reasons, the fault is exceptional from both scientific and educational perspectives.

2.4. Stop 5. “Jaspe quarry” (GC: 38°27′27.56″N, 09°0′39.30″W)

In this stop one can observe various tectonic and sedimentation evidences related to the basin-wide Middle–Upper Jurassic unconformity D9, namely the “Brecha da Arrábida” lithotype or Arrábida Breccia..

1 Jaspe (Pt) = Jasper (En). Although jasper is not found in this quarry, the reddish colour of the Brecha da Arrábida led people in the past to use this name to identify it.
The Arrábida Breccia is a rock with very particular geological characteristics in terms of its genesis, its composition (Fig. 15), its aesthetic aspects, and even its cultural significance (Fig. 16).

When examining a hand specimen, this rock is very similar to the relatively dense sequence of conglomerates (the Conglomerates of Vale da Rasca – Stops 2 and 3) that crop out in the Louro–Gaiteiros hills and which extend, markedly decreasing in thickness, up to 5 km west of the mountain, in the Vale de Barris valley. A detailed account of the Arrábida Breccia is contained in Prego (2008).

It is a very chromatic rock an unusual texture, that appears only in the current geographical area of the Natural Park of Arrábida; thus, its extraction is definitively finished. It has had a wide variety of uses for at least 2,000 years since the occupation of Iberia by the Romans, and which evolved over time from exterior to interior structures, and finally, since the beginning of the Baroque, almost exclusively linked to the interior decorative arts, in polished form. These applications were mainly used in monuments of the area of Setúbal and Lisbon, but are also known in many other places, including in the Convent of Santiago de Compostela (Spain), Brazil (e.g. S. Salvador da Bahia) and in the Louvre (France). Some literature also mentions an important application in the interior columns of the Carlos V Palace in La Alhambra (Spain); in fact it is not the Arrábida Breccia, it is a resembling rock at a first and fast look, but in fact it is a local siliciclastic breccia. See video 3 @ http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/365.

**Some Highlights of Stop 5:**
1 – The breccia is rare evidence, together with other geological occurrences in other parts of the world,
of a large-scale event that was brought about by a major discontinuity of a tectonic–eustatic nature that affected various areas within the Atlantic domain.

2 – The breccia overlies Jurassic palaeokarst with a rare quality of exposure, not only on the Western Iberian Margin but also in the entire North Atlantic.

3 – It infills (“fossilises”) pre- and syndepositional structures, particularly normal faults representing the previous extensional episode, and especially in the outcrops of the “Jaspe quarry”.

4 – From educational and scientific perspectives, the breccia reveals a number of features of stratigraphic, sedimentary, and tectonic importance, with an extremely rare quality of exposure and showing relationships with other geological and structural elements.

5 – From an aesthetic perspective, the applications of the breccia are unrivalled. It is a material used for very rare decorative and architectonic purposes, mainly religious architecture.

2.5. Stop 6. Alto da Califórnia (Sesimbra) (GC: 38°26′38.08″N, 09°05′22.75″W)

There is evidence at this stop of an important extensional pulse during the second rifting episode of the LB (Sinemurian–Oxfordian, Fig. 2) in Arrábida, namely, a deposit dated from the Serpentinus Zone of the lower Toarcian (~180 Ma). The deposit consists of a number of intraformational conglomerates of the Flat-Pebble Conglomerates type, with the best sequence of layers cropping out at Alto da Califórnia (East of Sesimbra) and, on a smaller scale, at Cova da Mijona (Fig. 17). These features are described and analysed in detail in Kullberg et al. (2001).

These outcrops are extremely rare, with the literature indicating only another six similar outcrops worldwide. The quality of the exposure and of the tectonic synsedimentary structures in Sesimbra has made this the only outcrop for which the genesis of this type of deposit has been established (Fig. 18). These outcrops are believed to have been caused by sliding in an unstable carbonate platform produced by earthquakes generated by the movement of normal faults related to the structure of the LB.

The sedimentary features related to the mechanism involved in the formation of these deposits are diverse and are expressed in a well-exposed succession of beds. The succession generally demonstrates a progressive upward decrease in the dynamics of the substratum responsible for the deformation of each bed. Some of the beds in the lower part of the succession show both an arrangement parallel to bedding (Fig. 18b, c) and random (Fig. 18d), generally confined to the lowermost part of the calcarenitic layer. In some cases, mostly in the upper layers, synsedimentary extensional deformation is also evident, with mesoscale normal faults being sealed at the top (Fig. 18e) or filled by soft sediments and intraclasts (Fig. 18f, arrow) (see also video 4 @ http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/366).

Some highlights of Stop 6:

1 – The breccia is rare evidence, together with other geological occurrences in other parts of the world, of a large-scale event that was brought about by a major discontinuity of a tectonic–eustatic nature that affected various areas within the Atlantic domain.

2 – The breccia overlies Jurassic palaeokarst with a rare quality of exposure, not only on the Western Iberian Margin but also in the entire North Atlantic.

3 – It infills (“fossilises”) pre- and syndepositional structures, particularly normal faults representing the previous extensional episode, and especially in the outcrops of the “Jaspe quarry”.

Fig. 17 – Locations (red ellipses) of the deposits of Flat Pebble Conglomerates in Arrábida: A- Alto da Califórnia; and B- Cova da Mijona. For the legend of the lithostratigraphic units and colours, see Fig. 3. The map is an excerpt from sheet 38-B of the Geological Map of Portugal at a scale of 1:50,000 (Costa et al., 2005).
4 – From educational and scientific perspectives, the breccia reveals a number of features of stratigraphic, sedimentary, and tectonic importance, with an extremely rare quality of exposure and showing relationships with other geological and structural elements.

5 – From an aesthetic perspective, the applications of the breccia are unrivalled. It is a material used for very rare decorative and architectonic purposes, mainly religious architecture.

Fig. 18 – Photographs showing different aspects of the deposits of Flat Pebble Conglomerates at Alto da Califórnia (Sesimbra): a – general view over the depression of Sesimbra (south to the left) including the outcrop site at Alto da Califórnia; b to f – photographs showing different expressions of the deformation at a bedding scale (see text for details).

video 4 @ http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/366.
2.6. Stop 7. Foz da Fonte beach (GC: 38°27′10.55″N, 09°11′57.98″W)

In this stop it is observed a) a continuous exposure of the upper most units of Cretaceous age (Aptian to Albian) showing the rift-to-drift sequences separated a condensed level rich in fossils which marks the breakup unconformity; b) a doleritic sill related to the onset of a late Cretaceous magmatic event that affected part of the West Iberian margin in anorogenic conditions; c) the base of the Neogene units deposited with a slight angular unconformity over the Cretaceous (representing a hiatus of 80 Myr), related to the first settlement stages of the Tagus river.

The Foz da Fonte beach site (Fig. 19), which we regard as exceptional, presents a continuous outcrop profile representing various stages of geological history, in some cases at a local level and, in others, at regional, national, or even international levels. A detailed account is available in Monteiro (2007). This beach is located along the western cliffs of the Arrábida range, north of Cape Espichel (Figs. 8 and 9).

This igneous formation (Fig. 20) is about 8 m thick and can be seen from Praia do Seixalinho, to the south of Praia de Rebenta Bois. From a petrographic perspective, the sill consists of dolerite or, more precisely, a microgranular tephrite (Kullberg et al., 2006; Miranda et al., 2009). An 40Ar/39Ar isotopic age of 93.8 ± 3.9 Ma (Miranda et al., 2006, 2009) performed on amphibole (kaersutite) indicates a Cenomanian–Turonian age, revealing that this outcrop is the first known to the south of the Tagus River that may be correlated with the Mafra Complex, and is therefore part of the third alkaline magmatic cycle (Kullberg, 2000). At the top of the sill, there are two hump-like linear reliefs (Fig. 20c). These reliefs, which trend approximately WNW–ESE to NW–SE, probably represent zones under which lay the pipelines/conduits through which the igneous material was injected, fed from the magmatic chamber at a greater depth.

Based on detailed cartography and on observations and interpretations of the outcrops, Kullberg (2000) proposed a three-dimensional model showing the relationships between the various geological elements found at Praia da Foz da Fonte and the coves to the south (Fig. 21) (see also video 5 @ http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/367).

Some highlights of Stop 7:

1 – Over a distance of about 300 m, the profile records various geological processes, with exceptional outcrop quality, and is fundamental for understanding important episodes in the evolution of the Western Iberian Margin and for broader contexts, namely:
Fig. 20 – Different aspect of the doleritic sill: a - Northward view of the Foz da Fonte sill, showing its general configuration, with Praia de Rebenta Bois beach in the foreground; b – Northward view, showing the sill’s total thickness, with a person indicating the scale; c and d – Detailed view of the sill, showing rectilinear relief in its central part, probably associated with the deep supply source (Kullberg, 2000; Monteiro, 2007).

Fig. 21 – Photograph of the Foz da Fonte sill and adjacent beaches. a – General view showing intercalation of units in the Lower Cretaceous. The view reveals onlap of the Miocene units (arrows) over the Cretaceous; b – Block diagram showing the sill’s position under carbonate sediments of the Cretaceous, which, by being semi-lithified (marked at “a”), reveal synsedimentary deformation (Kullberg, 2000).
a) the site contains the first units deposited after the breakup (recorded by the breakup unconformity of the LB) and the consequent oceanization of the North Atlantic in the Iberian sector, which was the sector where North Atlantic seafloor spreading started;

b) the exposures contain the oldest occurrence of magmatism of the alkaline cycle recorded in the Western Iberian Margin;

c) the deposits comprise the oldest sedimentary sequence related to the evolution of the pre-Tagus in the distal domain, at the continent–ocean interface; and

d) the site records the initial tectonic inversion phase of the Western Iberian Margin related to the Africa–Eurasia collision.

2 – The sequence contains the best evidence of alkaline magmatism in the WIM (Foz da Fonte sill) related to the province of the Peri-Atlantic Alkaline Pulse (PAAP), which covers almost the entire South and Central Atlantic, in addition to being:

a) the only occurrence in the European margin of the North Atlantic;

b) the only outcrop in the combined margins of Iberia and Newfoundland; and

c) the northernmost record of the entire PAAP, and, in the case of the sill of Foz da Fonte within the context of the WIM, it is the oldest of the occurrences.

3 – The exposures record the start of the evolution of the Baixo Tejo Basin, which is a small back-arc basin related to the Arrábida range.

4 – From an educational perspective, the area records features of interrelated sedimentary, magmatic, and metamorphic environments that are unique in Portugal and very rare in other regions in the world. The lithological and palaeontological diversity, the structures of various origins and types, and the modern-day processes of morphological evolution of a rocky coastline mean that this location presents an unmatched character, one that is exceptional for teaching many aspects of geology.

Supporting Material

- Google Earth tour (http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/368)
- Video 1 (http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/363)
- Video 2 (http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/364)
- Video 3 (http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/365)
- Video 4 (http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/366)
- Video 5 (http://cienciasdaterra.novaidfct.pt/index.php/ct-esj/article/view/354/367)

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