THE JURASSIC OF THE PENICHE PENINSULA (PORTUGAL): SCIENTIFIC, EDUCATIONAL AND SCIENCE POPULARIZATION RELEVANCE

El Jurásico de la Península de Peniche (Portugal): relevancia científica, educativa y divulgativa

Luís Vítor Duarte1, Ricardo Louro Silva2, Francisco Félix3, María José Comas-Rengifo4, Rogério Bordalo da Rocha5, Emanuela Mattioli6, Ricardo Paredes4, João Graciano Mendonça Filho7 and Maria Cristina Cabral8

1 MARE — Marine and Environmental Sciences Centre, Department of Earth Sciences, University of Coimbra, Portugal. lduarte@dct.uc.pt
2 Basin and Reservoir Lab, Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, Canada. Ricardo.Silva@Dal.Ca
3 Escola Secundaria de Peniche, Peniche, Portugal. ffelix43@hotmail.com
4 Department of Paleontology, Faculty of Geological Sciences, University Complutense de Madrid, Spain. mjcomas@geo.ucm.es; ricardo.paredes@ucm.es
5 Department of Earth Sciences and GeoBioTec, Faculty of Sciences and Technology, Universidade NOVA de Lisboa, Caparica, Portugal. rbr@fct.unl.pt
6 Univ. Lyon, Université Claude Bernard Lyon 1, Ens de Lyon, CNRS, UMR 5276 LGL-TPE, F-69622, Villeurbanne, France. emanuela.mattioli@univ-lyon1.fr
7 Department of Geology, Geosciences Institute, Federal University of Rio de Janeiro, Brazil. graciano@geologia.ufrj.br
8 Universidade de Lisboa, Faculdade de Ciências, Departamento de Geologia and Instituto Dom Luiz (IDL), Portugal. mccabral@fc.ul.pt

Abstract: The Peniche Peninsula shows the most continuous carbonate sedimentary succession of the Jurassic in Portugal. In this paper, supported by several important scientific arguments from the different domains of Sedimentary Geology, we highlight this locality as a focal point to understand the Early Jurassic time interval. Among several other themes we emphasize the definition of the Toarcian GSSP, the discussion around the Early Toarcian oceanic anoxic event and the organic-rich deposition occurred in the Sinemurian–Pliensbachian of the Peniche Peninsula section. These key geological themes have been the focus of significant educational/scientific outreach, involving Geology promotion activities directed towards different audiences, on a local and international scale.

Key-words: Lower Jurassic, global reference geosite, scientific relevance, educational activities, Peniche, Portugal.

Resumen: La Península de Peniche, situada en la Cuenca Lusitánica, muestra la sucesión carbonática sedimentaria más continua del Jurásico Inferior de Portugal. En ella ha quedado registrada la evolución y los principales cambios paleoambientales ocurridos en el Margen Occidental ibérico durante este intervalo. Investigaciones recientes sobre varias peculiaridades científicas relacionadas con diferentes aspectos de la Geología Sedimentaria han convertido esta localidad en un punto clave para entender este intervalo de tiempo del Jurásico Inferior. Esto se debe principalmente a: i) la definición de la Ponta do Trovão como el GSSP (Global Boundary Stratotype Section and Point) de la base del Piso Toarciense; ii) la discusión sobre el Evento Anóxico Oceánico del Toarcienense y su correlación con una extinción en masa de 2º orden y, iii) la sedimentación rica en materia orgánica que tuvo lugar durante la parte superior del Sinemuriense y el Pliensbachienense. Además, se hace hincapié en las características sedimentarias únicas de gran parte de los depósitos del Toarcienense relacionadas con un episodio notable y singular de la sedimentación dentro del contexto de la Cuenca Lusitánica. Estos temas geológicos claves han atraído a numerosos equipos de investigadores de diferentes partes del mundo. La sección de Peniche ha sido el objeto de importantes y significativas actividades de divulgación científica y educativa por su interés científico global, el excelente conocimiento estratigráfico de dicha sección, así como por su accesibilidad y extraordinario valor paisajístico. También ha sido el foco de atención para realizar acciones de promoción de la Geología dirigidas a diferentes públicos a escala local e internacional. Dichas actividades han consistido en clases de campo
Significant parts of the Earth’s history are told from exceptional geological sites across the planet. Inevitably, at the top of the list are those locations that record the main episodes of global change that occurred on the surface of the Earth, with a more or less pronounced impact in the biosphere (e.g., Raup and Sepkoski, 1982; Wignall, 2001; White and Saunders, 2005). The Fransfontein section in north-west Namibia, where the latest Neoproterozoic succession supports the Snowball Earth theory (e.g., Hoffman and Schrag, 2002) or Gubbio in Italy, including the classic iridium record that was used as the first argument for the end of Cretaceous meteorite impact theory (e.g., Alvarez et al., 1980), are, among others, examples of exceptional sites that contribute to our understanding about Earth’s history.

The Jurassic series of the Lusitanian Basin stand out as a highlight of the Portuguese sedimentary geology (e.g., Brilha et al., 2005; Henriques et al., 2005), particularly the Lower Jurassic succession cropping out on the Peniche Peninsula (Duarte, 2004, 2005; Rilo et al., 2010; Fig. 1). Located in the western Iberian margin, this locality presents a continuous record of marine carbonate sediments, from inner ramp to hemipelagic settings, dated from the Sinemurian (Early Jurassic) to the possible beginning of Middle Jurassic (Fig. 2) (e.g., Mouterde, 1955; Wright and Wilson, 1984; Duarte and Soares, 2002; Duarte et al., 2004). Due to the excellent outcrop conditions, high-resolution stratigraphic control, and singular sedimentological and geochemical features, Peniche is regarded as a reference to the study of the Portuguese Lower Jurassic (e.g., Duarte, 2004, 2005; Suan et al., 2010; Silva and Duarte, 2015) and the evolution of the Proto-Atlantic Ocean. Recent research developed at Peniche, especially that to the Toarcian Global Boundary Stratotype Section and Point (GSSP) (e.g., Rocha et al., 2013, 2016) and the Early Toarcian Oceanic Anoxic Event (T-OAE; e.g., Hesselbo et al., 2007; Suan et al., 2008a, 2008b, 2010), make this location a global geosite in terms of the Jurassic System.

In this review, we aim to summarise and put into context the stratigraphical, sedimentological and palaeoenvironmental importance of the geological record of the Peniche section for the study of the Jurassic interval, from local basinal evolution to a global scale point of view, tes-
tified by the high number of publications in international geosciences journals. At the same time, and while exploring other themes, we document the diversity of training activities developed with several educational communities, from primary school to undergraduate/postgraduate university students, secondary school teachers, and petroleum geologists. Lastly, we present an overview of several activities (developed over the last 15 years) aimed a public engagement. All actions are advantaged by the excellent geological knowledge, exposure conditions and scenic value of this site.

The Jurassic of the Peniche Peninsula: a stratigraphic review

There is profuse literature on the geology and stratigraphy of the Jurassic record at Peniche, mostly starting from the late nineteenth century (e.g., Choffat, 1880; Mouterde, 1955; França et al., 1960). Overall, the sedimentary series is more than 450 m-thick and is dated from the Early (?) Sinemurian to the extreme base of Middle Jurassic (Aalenian?) (Mouterde, 1955; Duarte and Soares, 2002; Duarte et al., 2004, 2017).

On the Peniche Peninsula, the Lower Jurassic is divided into five formations, corresponding to the Coimbra, Água de Madeiros, Vale das Fontes, Lemede, and Cabo Carvoeiro formations (see Duarte and Soares, 2002; Duarte et al., 2004) (Fig. 2). The later three have their type-sections defined in the Peniche Peninsula (Duarte and Soares, 2002). Despite the abundance and diversity of ammonites, particularly between the topmost Sinemurian (Raricostatum Zone) to the Middle Toarcian (base of the Gradata Zone) (Mouterde, 1955; Phelps, 1985; Dommeregues, 1987; Mouterde et al., 2007; Paredes et al., 2013a, 2013b; Silva et al., 2015), they are almost absent at the base (Coimbra Formation) and at the top of the succession (last member of the Cabo Carvoeiro Formation) due to its shallow-water depositional setting (see Wright and Wilson, 1984; Duarte, 1997; Duarte and Soares, 2002). However, recent high-resolution ammonite biostratigraphic studies developed in several parts of the series, and their integration with the overall ammonite record of the Lusitanian Basin, allowed the refinement of the Sinemurian–Pliensbachian (Raricostatum–Jame soni) and Margaritatus–Emaciatum (= Spinatum) ammonite zone boundaries (e.g., Silva et al., 2011, 2015; Paredes et al., 2013a, 2013b; Duarte et al., 2014). Supported by these works, chronostratigraphic limits have been redefined, slightly altering the age limits of the Água de Madeiros–Vale das Fontes and Vale das Fontes–Lemede formations (Fig. 2). These inferences are confirmed by several calcareous nanofossils biostratigraphic studies, focusing on the Pliensbachian–Toarcian interval of Peniche (e.g., Perilli and Duarte, 2006; Oliveira et al., 2007; Mattioli et al., 2013).
According to Duarte and Soares (2002), and corroborated by previous works (e.g., Wright and Wilson, 1984; Elmi et al., 1988; Dommergues, 1987; Duarte, 1997; Fernández-López et al., 2000) and recent works (e.g., Duarte, 2007a; Duarte et al., 2004, 2010b; Silva et al., 2011, 2015), each formation displays singular sedimentological and palaeontological (essentially invertebrate fossils and ichnofossils) features that allow the identification of the formal Polvoeira and Praia da Pedra Lisa members, and the three and five informal members of Vale das Fontes Formation (Marls and limestones with Uptonia and Pentacrinus, Lumpy marls and limestones, Marly limestones with organic facies) and Cabo Carvoeiro (CC1 to CC5 members) Formation, respectively (Fig. 2). Micropalaeontological results from ostracod studies revealed the occurrence of several species (Pinto et al., 2007b; Loureiro et al., 2013), some of them new with relevance for Jurassic ostracods diversity (Cabral et al., 2014).

Scientific relevance of the Peniche Peninsula

The Lower Jurassic of Peniche is currently an international reference for the study of several subjects with high scientific impact. Examples are the definition of the Toarcian GSSP and the discussion revolving around the T-OAE record, supported by the extraordinary number of papers in international reference journals (Table I). In addition to these two subjects, several other relevant themes have been developed in the Jurassic of Peniche, such as the occurrence of the organic-rich deposits of latest Sinemurian–Pliensbachian age and the several unique sedimentary features, within the evolutionary context of the Lusitanian Basin, recorded in the Cabo Carvoeiro Formation. These four main geological themes of discussion, here synthesised in terms of scientific relevance, have attracted numerous teams of researchers from different parts of the world and the development of several projects.

The Toarcian GSSP

The Toarcian is the fourth stage of the Jurassic System, and its name is derived from the city of Thouars (Western France) that was firstly introduced by Alcide d’Orbigny (1842-1851). The Thouars section (Vrines quarry; Fig. 3a) is now considered the “historic” stratotype section for the Toarcian. After a long deliberation, initiated by Dr. Serge Elmi and collaborators in 1996, the Ponta do Trovão site (Figs. 1 and 3b) is, since December 2014, the formal worldwide reference to the Toarcian–Toarcian boundary (Toarcian GSSP, ~182.7 Ma; Gradstein et al., 2012). This resolution, supported by the International Commission on Stratigraphy and ratified by the International Union of Geological Sciences (IUGS), arises from a report authored by 20 researchers (Rocha et al., 2013) and developed after the meeting “The Peniche section (Portugal); Contributions to the definition of the Toarcian Global Stratotype Section and Point”, organised in June 2005 at Peniche, under the auspicious of the International Subcommission on Jurassic Stratigraphy (Elmi et al., 2005; Rocha, 2007). This stratigraphic boundary (Fig. 4) is defined by the ammonoid record but sustained by a wide range of biotic and abiotic stratigraphic markers, including calcareous nannofossils, ostracods, brachiopods, carbon and oxygen stable isotopes and cyclostratigraphy (e.g., Mouterde, 1955; Elmi, 2006; Rocha et al., 2013, 2016).

The Early Toarcian Oceanic Anoxic Event and mass extinction

The Early Toarcian corresponds to one of the Earth’s historic intervals where great changes in the lithosphere-ocean-biosphere-atmosphere are recorded, in this case including the emplacement of the Karoo-Ferrar Large Igneous Province (e.g., Jourdan et al., 2007; Sell et al., 2014), a 2nd-order mass extinction (e.g., Little and Benton, 1995; Palfy and Smith, 2000), and the T-OAE (e.g., Jenkyns, 1988). This last event is well testified by the worldwide negative carbon isotope excursion recorded in sediments (e.g., Hesselbo et al., 2000, 2007; Caruthers et al., 2011; Suan et al., 2011; Kemp and Izumi, 2014).

Regarding the geological record of the T-OAE, the portion corresponding to the Abalo beach (Fig. 3c) of the Peniche section is acknowledged internationally, mainly due to the pioneering work of Hesselbo et al. (2007). Based on a high-resolution carbon isotope record measured in bulk carbonate and fossil wood, Hesselbo et al. (2007) presented evidence of a major perturbation in the carbon cycle affecting the oceanic and atmospheric reservoirs (Fig. 4). The relevance of this paper in the scientific community is evident by its high number of citations (Table I). Since then, many others of similar scientific impact have been published, focusing, for example, on cyclostratigraphy, palaeoceanography, palynology and calcareous nannofossil evolution across the uppermost Pliensbachian–Lower Toarcian (e.g., Suan et al., 2008a, 2008b, 2010; Mattioli et al., 2008, 2009; Barrón et al., 2013; Huang and Hesselbo, 2014; Pittet et al., 2014). At the same time, several research projects relating the response of benthic fauna to palaeoenvironmental changes that occurred through the Early Toarcian have been developed, tracing the mass extinction associated with the Poly-

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<th>Scientific Themes</th>
<th>Main Publications</th>
<th>Number of Citations WoS/Scopus</th>
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<tr>
<td>Toarcian GSSP and T-OAE</td>
<td>Hesselbo et al. (2007)</td>
<td>191/210</td>
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<td></td>
<td>Suan et al. (2008b)</td>
<td>98/108</td>
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<td></td>
<td>Suan et al. (2010)</td>
<td>81/89</td>
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<tr>
<td>Sinemurian-Pliensbachian organic-rich deposits</td>
<td>Duarte et al. (2010b)</td>
<td>31/55</td>
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<td></td>
<td>Silva et al. (2011)</td>
<td>22/31</td>
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<td></td>
<td>Reggiani et al. (2010b)</td>
<td>14/18</td>
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<td>Sedimentary aspects of the Toarcian</td>
<td>Wright and Wilson (1984)</td>
<td>43/53</td>
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<td></td>
<td>Pittet et al. (2014)</td>
<td>15/19</td>
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Table I. Main cited ISI papers by each relevant scientific theme about the Jurassic of Peniche presented and discussed in the text (data based on Journal Citation Report and Scopus, both accessed in 14th November 2016). WoS: Web of Science.
morphum-Levisoni ammonite Zone boundary. The Peniche section includes an exceptionally complete record of this extinction event, well observed in ostracods (Pinto et al., 2007a) and brachiopods (Comas-Rengifo et al., 2015). Well documented in other sections of the Lusitanian Basin, the Early Toarcian mass extinction is characterized by the disappearance of the ostracod Metacopina Suborder (see also Cabral et al., 2013) and the brachiopod Spiriferida Order (see also Comas-Rengifo et al., 2013). In addition, Rita et al. (2016) demonstrate that the foraminifera population was also negatively affected at the base of Levisoni Zone, although without evidence of extinction.

Organic deposition in the uppermost Sinemurian–Pliensbachian

Considering its lithological characteristics and organic matter richness, the uppermost Sinemurian and Pliensbachian (Água de Madeiros and Vale das Fontes formations) have been

Fig. 3.- a) The historical Toarcian Stratotype according to d’Orbigny (1842-1851) at Thouars, Western France (July 2012); b) The Toarcian GSSP at Ponta do Trovão, Peniche (dashed line: Pliensbachian–Toarcian boundary); c) The Abalo beach that records the base of the Levisoni Zone (beginning of the T-OAE; see text), dashed line: Polymorphum–Levisoni Zone boundary; d) The organic-rich facies of the MLOF member cropping out at Portinho da Areia do Norte beach; e) Shallow-water carbonates of the Upper Toarcian (CC5 Mb) cropping out at Nau dos Corvos; f) The Pentacrinus penichensis (Loriol) recorded in the Peniche Peninsula between Remédios and Cabo Carvoeiro (see Figure 1).
### Fig. 4.- Main global events well recognised across the Pliensbachian–Lower Toarcian succession cropping out in the Peniche Peninsula (see text).

<table>
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<tr>
<th>Chronostratigraphy</th>
<th>Lithostratigraphy</th>
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<tr>
<td>Lower Jurassic</td>
<td>Cabo Carvoeiro Fm</td>
</tr>
<tr>
<td>Toarcian</td>
<td>CC2 Mb</td>
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<tr>
<td>Lower</td>
<td>CC1 Mb</td>
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<td>Polymorphum</td>
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<td>Upper</td>
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<td>Emaciatum</td>
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<td>Lemeze Fm</td>
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<td>Pliensbachian</td>
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- **Spitzerinids and Metacopina Extinction**
- **Toarcian Oceanic Anoxic Event**

### Fig. 5.- Field sedimentary and stratigraphical details of the Pliensbachian organic-rich deposits and lower Toarcian turbidites cropping out at Peniche: a) Base of the MLOF member of the Vale das Fontes Formation (Portinho da Areia do Norte); b) Subarkosic conglomerate level (C) at the base of CC2 member (base of Levisoni Zone; Abalo beach). LML – Lumpy marls and limestones member.
identified as a potential hydrocarbon source rock interval in the Lusitanian Basin (e.g., Oliveira et al., 2006; Duarte et al., 2010b, 2011, 2012). The Vale das Fontes Formation, formally defined in the Peniche section at Portinho da Areia do Norte (Figs. 1, 3d and 5a; Duarte and Soares, 2002; Duarte et al., 2010b), has been extensively studied over the past years, not only from an organic geochemistry and petroleum potential standpoint, but also investigating palaeoenvironments and palaeoclimates. Concerning the later topics, are highlighted here the contributions of Reggianni et al. (2010a, b), focusing in ocean dynamics of calcareous nannofossils, and of Silva et al. (2011, 2012, 2015) and Silva and Duarte (2015), dealing with high-resolution stratigraphy and geochemical signatures linked with major environmental perturbations (stable isotopes and elemental geochemistry) contemporaneous with the deposition of the organic-rich facies [Marly limestones with organic facies (MLOF) member] of the Vale das Fontes Formation (Figs. 2 and 3d).

The Cabo Carvoeiro Formation: contrasting deposition during the Early Jurassic

The calcarenitic deposits of Cabo Carvoeiro Formation (Towardian) cropping out at Cabo Carvoeiro are one of the main themes of study regarding the Lusitanian Basin sedimentary evolution, contrasting with the general domain of marly-limestone deposits observed elsewhere (see Duarte, 1997; Duarte and Soares, 2002; Pittet et al., 2014). This aspect of the Jurassic depositional record has been the subject of several sedimentological studies, standing out particularly the submarine fan model proposed by Wright and Wilson (1984). This episode of sedimentation starts with siliciclastic turbidites (with quartz and feldspar) (Figs. 2 and 5b), contemporary with the T-OAE (see Hesselbo et al., 2007; Suan et al., 2008b) and interbedded in a marly succession poor in benthic macrofauna, and ends with the deposition of oolitic limestones/grainstones, more or less enriched in quartz and a shallow water platform macrofauna (bivalves, gastropods, crinoids and athermatic corals) (Figs. 2 and 3e). Of particular interest is the occurrence of Pentacrinus penichensis (Loriot, 1890), an iconic invertebrate fossil of the Portuguese record, especially expressive around the Remédios and Cabo Carvoeiro localities (Fig. 3f).

The Cabo Carvoeiro Formation is exclusive to Peniche and represents a 2nd-order regressive phase, also observed in other parts of the Lusitanian Basin (Duarte, 2007a). The causes of the particular siliciclastic deposition in the Early Tornorian, with sediments akin to the nearby Berlengas islands igneous mineralogy (e.g., Wright and Wilson, 1984; Duarte, 1997), seems to be linked to a tectonic event dated from the base of the Levisoni Zone (e.g., Duarte, 1997). This event, with regional expression in the basin (see Kullberg et al., 2001), overlaps the marine flooding event generally observed in other European basins (e.g., Hallam, 1988; Hardenbol et al., 1998) and the major climate change occurred in this period of Earth planet (e.g., Suan et al., 2010; Dera et al., 2011).

Geological Heritage of the Peniche Jurassic

It is extensive the theoretical literature about Geological Heritage and its assessment applied to several case studies (e.g., Gray, 2004; Pena dos Reis and Henriques, 2009; Lima et al., 2010; Fassoulas et al., 2012; Brilha, 2016). The Jurassic of the Peniche Peninsula is recognized as an important part of the Portuguese geohistory, mostly due to its scientific and educational relevance, exceptional exposure conditions, and scenic value, attributes presented and discussed in Duarte (2004, 2005) and Rilo et al. (2010). In conjunction with other geosites (e.g., Henriques et al., 2005), the Jurassic record in the Lusitanian Basin was considered by ProGEO-Portugal as one of the fourteen frameworks of international relevance in Portuguese geology (see Brilha et al., 2005). This particularity is due to the well exposed and studied stratigraphic sections, from the Hettangian to the Tithonian, and from different depositional contexts (continental to marine deposits) (Henriques et al., 2005). Moreover, special attention is paid to the Lower Jurassic carbonate series cropping out in Peniche, S. Pedro de Moel and Rabaçal (e.g., Duarte, 2004). Considering each of these affirmations of relevance, several works of geological heritage inventory and assessment have been performed for the Peniche Peninsula (e.g., Duarte, 2004; Rilo et al., 2010). Although the Peniche sections have not been included in any national geological protection system, the Peniche Municipality declared in 2007 the Ponta do Trovão as a “Site of Municipality Interest” (see Rocha et al., 2013). In addition to the ratification of Toarcian GSPP (Rocha et al., 2016), the aforementioned arguments should compel decision makers to adopt more objective policies for geoconservation (e.g., Gray, 2011; Proser et al., 2013). The comprehensive geoconservation inventory and assessment study performed by Rilo et al. (2010) for the Peniche Peninsula, together with some of the new contributes presented in this paper, are an important support for future geoconservation efforts by local or national authorities. The improvements and requalification efforts made at Ponta do Trovão, resulting of the recent ceremony of placing the Golden Spike (Fig. 6), are a good example of geological valorization promoted by the Municipality of Peniche.

Educational and training activities

Due to its scientific, stratigraphic, and overall geological value and great exposure conditions, the Peniche Peninsula also has the potential to support immersive and focussed educational and training activities (e.g., Duarte, 2004, 2005; Rilo et al., 2010; and references therein). Several practical actions have been performed over the last years at Peniche aimed at primary (elementary), secondary, and university student activities, and high-school teacher educational programmes (e.g., Duarte, 2006). Considering the relevance of the organic-rich deposition of Pliensbachian age, among other interesting sedimentological aspects observed in the whole succession, also included here are activities linked with the training of petroleum geologists.

Practical and field work activities of university students

The Peniche Peninsula has been a preferential place for different practical activities related with Sedimentary Geology, especially on the domains of Sedimentology (as argued
by Duarte, 2004, 2006), Stratigraphy, and Palaeontology of undergraduate level classes of several Portuguese and foreign universities. The large diversity of carbonate facies (e.g., hemipelagites, organic-rich deposits, turbidites, and shallow-water carbonates), the abundance of invertebrate macrofossils (e.g., ammonites, belemnites, bivalves, brachiopods, gastropods, crinoids, echinoids, ahermatypic corals) and ichnofossils (Arenicolites, Chondrites, Diplocraterion, Phymatoderma, Rhizocorallium, Skolithos, Thalassinoides, Zoophycos) (Fig. 2), observed in the whole succession or the integrated stratigraphic analysis related to the definition of the Toarcian GSSP are solid arguments to successfully underpin practical activities linked with these subjects.

At a graduate level, and in addition to the obvious relevance to the teaching of Sedimentary Basin Analysis or other courses of master’s programmes several extra-curricular actions and workshops have been organized at Peniche, including summer courses that involved lectures, field and laboratory work (Figs. 7a,b). However, amongst these potential initiatives, perhaps the most interesting and treating topic is the discussion revolving around the carbon cycle perturbation (evidenced by a carbon isotope curve; see Hesselbo et al., 2007) and mass extinction (Pinto et al., 2007a; Comas-Rengifo et al., 2015) related with the T-OAE and the previous Pliensbachian record (see Silva and Duarte, 2015; Fig. 4). In fact, these themes have been developed in practical activities related with Global Changes and/or Global Changes and Climatology courses (see curricular organization of Geosciences and Environmental Engineering Masters courses of Coimbra University, Portugal; see Duarte, 2010).

Primary and secondary activities

The Peniche Peninsula has a huge didactic potential for high-school practical activities, mostly supported by field trips aimed at students (Dias, 2004) and teachers. Several locations around the Peniche Peninsula, such as Papôa, Luz Fortress, Portinho da Areia do Norte, Ponta do Trovão-Abalo beach, Remédios, or Cabo Carvoeiro (Fig. 1), have been used as a teaching support for students of different levels of education. These sites constitute a solid background to promote the understanding of diverse geological concepts and problems, especially in the domain of Sedimentary Geology. Several educational activities have been developed within the subject of Natural Sciences of different levels of Primary teaching and Biology and Geology (10th and 11th Portuguese grades), and Geology (pre-University level) of Secondary teaching (Table II). The greatest success has been obtained in field classes relating to subjects of Secondary teaching (Félix, 2007, 2010), testified by the number and recurrence of sessions, that include local (Peniche Municipality) and regional schools, as well as institutions of other parts of the country, which lay in different geological contexts (Table II; Fig. 7c). Félix (2007, 2010) synthesize the themes that can be developed in the Peniche Peninsula according to the syllabus of Biology and Geology, and Geology subjects of Secondary level. Each of these activities have been evaluated and monitored over the past ten years.

These themes also provide a good training to teachers from the Secondary level. In fact, based on the high-resolution stratigraphical, palaeontological and sedimentological level of knowledge (references above cited), several training activities have been performed in the Peniche Peninsula involving, for example, the Portuguese Association of Biology and Geology Teachers (2006-2007 and 2009), or other associations of Natural Sciences teachers (Fig. 7d).

Petroleum geologists sessions and training activities

In addition to the diverse array of singular aspects of the stratigraphic succession cropping out in the Peniche Peninsula as the Lower Jurassic reference section of the Lusitanian Basin, with a clear impact in the development of Basin Analysis and Petroleum Geology, several works pointed out
the importance of the Vale das Fontes Formation organic-rich unit as a hydrocarbons source-rock (e.g., Oliveira et al., 2006; Ferreira et al., 2010; Duarte et al., 2010b, 2011; Correia et al., 2012). The good exposure conditions, accessibility, and knowledge (including the high-resolution organic geochemistry studies developed by authors; see references above) of the series, as well as the continuous exploration for hydrocarbon over the last years in the Lusitanian and Peniche basins, turned the Portinho da Areia do Norte outcrop (Fig. 3d) into an obligatory site, for both the training of petroleum geologists (e.g., Duarte, 2007b; Azerêdo and Duarte, 2012) and industry partners during field seminars for energy companies (see also, Duarte et al., 2011). Several groups are developing their training activities in the Peniche Peninsula (e.g., Pena dos Reis and Pimentel, 2015). Besides the source-rock thematic associated to the Vale das Fontes Formation, as pointed out in Pena dos Reis and Pimentel (2015) when addressing hypothetic petroleum systems of the Lusitanian Basin, the Peniche sedimentary basins, turned the Portinho da Areia do Norte outcrop (Fig. 3d) into an obligatory site, for both the training of petroleum geologists (e.g., Duarte, 2007b; Azerêdo and Duarte, 2012) and industry partners during field seminars for energy companies (see also, Duarte et al., 2011). Several groups are developing their training activities in the Peniche Peninsula (e.g., Pena dos Reis and Pimentel, 2015). Besides the source-rock thematic associated to the Vale das Fontes Formation, as pointed out in Pena dos Reis and Pimentel (2015) when addressing hypothetic petroleum systems of the Lusitanian Basin, the Peniche sedimentary succession presents several other characteristics relevant to the study of carbonate reservoirs. For example, the calcilastic carbonate facies of the uppermost Cabo Carvoeiro Formation (mainly the Cabo Carvoeiro 5 member; Fig. 2) is regarded as a potential hydrocarbon reservoir (e.g., Wright and Wilson, 1984; Azerêdo and Duarte, 2012).

### Science to geoscientists and society

Parallel to the educational and training activities, several other actions of scientific dissemination have been performed in the Peniche Peninsula, many coordinated by the authors of this paper. Here we emphasize two different kinds of activities: field trips for geoscientists and scientific sessions to general public.

#### National and international scientific association field trips

Since 2004, the authors have been involved in the coordination of several field trips devoted to the Jurassic of Peniche, often as part of the scientific programme of international scientific meetings and covering different domains of Sedimentology, Stratigraphy, Geochemistry, Palaeontology and Geological Heritage. One of these events was a field trip included in the 23rd International Association of Sedimentologists (IAS) meeting, held in Coimbra during September 2004. This field trip, entitled “Early Jurassic carbonate evolution in the Lusitanian Basin: facies, sequence stratigraphy and cyclicity” (Duarte et al., 2004), was centred in Peniche. Together with the Rabacal and S. Pedro de Moel sections (Fig. 1), these constitute the three main outcrops concerning of the Lower Jurassic of Lusitanian Basin (see also Duarte, 2004). Two different field trips have been performed in Peniche during 2005, under the auspices of the International Subcommission on Jurassic Stratigraphy and ProGEO. The first meeting, mentioned in a previous section (Elmi et al., 2005; Rocha, 2007), brought together members of the Toarcian Working Group and promoted a fruitful discussion about the proposal of the Ponta do Trovão as the Toarcian GSSP (see Rocha, 2007; Rocha et al., 2013, 2016). The second event corresponded to the field trip “Jurassic heritage and geoconservation in Portugal: selected sites” (Henriques et al., 2005), included in the IV International Symposium ProGEO on the Conservation of the Geological Heritage, held in Braga. One stop of this event was dedicated to the Jurassic of Peniche Peninsula (Duarte, 2005).

In addition to several field trips pertaining to “regional meetings”, such as the VII Meeting of Young Researchers in Palaeontology, held in Torres Vedras (Duarte, 2009), or the X Geochemical Meeting of Portuguese Language Countries (Duarte et al., 2010a), that combined involved more than 120 participants, highlighted here two important initiatives sponsored by the International Committee for Coal and Organic Petrology and International Commission on Stratigraphy. In 2011, the Peniche Peninsula was the focus of the only field trip associated with the 63rd Annual Meeting of the International Committee for Coal and Organic Petrology, held in Porto, and dedicated to dispersed organic matter (see Duarte et al., 2011; Fig. 7e). Among the several field trips proposed

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**Table II.- Typology of some educational activities with primary and secondary schools developed in the Peniche Peninsula in the last 15 years.**

<table>
<thead>
<tr>
<th>Level of Education</th>
<th>Title of Activity</th>
<th>Periodicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary School</td>
<td>“A trip with feet and hands on (our) Earth”, Workshop of Geology</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>“A trip to the world of ammonites”, Theater</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>Storytelling and educational games about the fossil record of Ponta do Trovão, Library/Resource Centre of the High-School of Peniche</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>“The magic ship”, pedestrian tour across the Jurassic outcrops of Peniche</td>
<td>Each year between 2012-2015</td>
</tr>
<tr>
<td>Secondary School</td>
<td>Field classes about the Lower Jurassic of the Peniche Peninsula with local Secondary Schools</td>
<td>Each year (several times) between 2002-2016</td>
</tr>
<tr>
<td></td>
<td>Week “So much Sea”; field-trip across the Peniche Peninsula</td>
<td>Each year between 2012-2016</td>
</tr>
</tbody>
</table>

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within the 1st International Congress on Stratigraphy (STRATI2013), held in Lisbon, one of them was dedicated to the recent advances in Stratigraphy of the Jurassic of Peniche (see Duarte et al., 2017). In 2014 a field trip to the Peniche region was included in the series of “behind the scenes” tours of the Geologists’ Association, to show the different geological aspects of the Peniche Peninsula to a group of geologists from a large range of specialities.

The international scope of these different field trips, also demonstrates the scientific impact of the Peniche Pe-
ninsula in the diverse aspects of the Lower Jurassic stratigraphy. Furthermore, these events brought participants from around the world.

**Scientific dissemination to general public**

Several dozen activities of scientific dissemination targeting the general public have been performed in the Peniche Peninsula. These activities usually take form as field trips, but sometimes include lectures, workshops, round-tables, and photography exhibitions (Table III). These are mostly organized by universities, high-schools, environmental and heritage societies, and the Cultural Department of the Peniche Municipality. From this wide range of activities, we emphasize the session “Geology by the sea: Geological histories of Peniche”, included in the national program “Geology in the Summer”. This session was organized by the Earth Sciences Department of University of Coimbra and sponsored by the Portuguese Ministry of Science and Technology. It included participants from all over the country and of varying ages (7 to 75 years old), generally without a formal geological background (Fig. 7f). This session took place on the Peniche Peninsula during summer one to two times a year between 2001 and 2012 (see also Duarte, 2004). Although it is impossible to enumerate all formal sessions carried out over recent years, some of them organised by regional and local groups and associations (Table III); also of significance is the “Senior University of Peniche”, which included the program “Yesterday School, Today School”, aimed at people over 60 years old (Table III).

In all these sessions, the Jurassic leitmotif has been articulated with countless interesting subjects of Geology, extraordinarily preserved on the Peniche Peninsula. They are the cases of the Cretaceous volcanic breccia of Papôa (Romão, 1963-64; Andrade, 1979), the coastal karst that dominates the landscape of the uppermost Toarcian carbonate deposits of Remédios–Cabo Carvoeiro area, and the coastal dynamics recorded since the Pleistocene and evidenced by geomorphological and geological criteria observed around the Peniche Peninsula (e.g., Henriques, 1996; Romão, 2009).

**Table III.** Typology of main promotion science activities developed in the Peniche Peninsula in the last 15 years.

<table>
<thead>
<tr>
<th>Title</th>
<th>Type of Initiative</th>
<th>Periodicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Geology by the sea: geological histories of Peniche” included in the Program “Geology in the Summer”</td>
<td>National</td>
<td>Each year: 2001-2003, 2004-2012</td>
</tr>
<tr>
<td>Field trips with different audiences</td>
<td>Local</td>
<td>Several years</td>
</tr>
<tr>
<td>Field trips with “Senior University of Peniche”</td>
<td>Local</td>
<td>2010, 2014, 2015</td>
</tr>
<tr>
<td>Lectures and field sessions included in Local and Regional Meetings: “Geological Heritage of Peniche: Elements to its characterization”, 1st Journeys of Archaeology and Heritage of Peniche</td>
<td>Regional</td>
<td>2005</td>
</tr>
<tr>
<td>“Histories of seas and shellfishes counted by the Cabo Carvoeiro rocks”, 8th Cultural Week of the University of Coimbra</td>
<td>Regional</td>
<td>2006</td>
</tr>
<tr>
<td>“From the rocks to the palaeogeographic reconstructions. Examples from the Peniche region”, 20th National Meeting of Geography Teachers</td>
<td>National</td>
<td>2006</td>
</tr>
<tr>
<td>Workshop “Geological Heritage of the Peniche Peninsula”, Coastwatch Activity</td>
<td>Regional</td>
<td>2008</td>
</tr>
<tr>
<td>Field-trip “Natural and Cultural Heritage in the Peniche Peninsula”, European Heritage Days</td>
<td>Regional</td>
<td>2011</td>
</tr>
<tr>
<td>“Echo Beach: International Youth Exchange”, Peniche</td>
<td>International</td>
<td>2013</td>
</tr>
<tr>
<td>Book release “Trip to the ammonite’s world”, Peniche Fortress</td>
<td>Regional</td>
<td>2009</td>
</tr>
<tr>
<td>Photography exhibitions: “Surfaces, textures and floors of the Peniche shoreline”, Municipal Museum of Peniche, High-School of Bombarral</td>
<td>Regional</td>
<td>2014/2015</td>
</tr>
<tr>
<td>“Fragments of the Peniche Geology: Aesthetic perspective”, High-School of Peniche</td>
<td>Regional</td>
<td>2015</td>
</tr>
</tbody>
</table>
dence of the societal impact of the geological research projects developed over the last years in the Peniche Peninsula. The diversity of subjects, adapted to different audiences, underline the great success of the Lower Jurassic of Portugal for science dissemination, an obligation and a social responsibility of scientists (e.g., Greenwood and Riordan, 2001; Weigold, 2001; Stewart and Nield, 2013).

Final remarks

In this paper, we highlight the importance of the sedimentary record preserved in the Peniche Peninsula as a singular site for scientific research concerning the Jurassic Stage, sustained by a large diversity of scientific, educational, and general public activities.

The Toarcian GSSP located at Ponta do Trovão, recently approved (2014) by IUGS, and the scientific research developed in the Abalo beach focusing on the record of the T-OAE and associated 2nd-order mass-extinction highlights Peniche as an internationally relevant site to understand planetary-scale palaeoenvironmental dynamics. Moreover, all knowledge of the stratigraphy and palaeoenvironmental evolution of the Jurassic carbonate succession recorded in the cliffs of the Peniche Peninsula, including hemipelagites, organic-rich deposits (potential source rocks), siliciclastic turbidites and shallow-water carbonates, diverse invertebrate fossils and ichnofossils, allows for the continuous improvement of the models constraining Proto-Atlantic evolution.

Favoured by optimal conditions of accessibility to the outcrops, and such as demonstrated in this paper, each of these characteristics have been outlined in a variety of scientific, educational and outreach activities, embracing all educational levels (Primary to University), students and teachers, petroleum geologists, international scientific societies, regional and local environmental and heritage associations, and the general public. The number and variety of sessions performed over the last 15 years, as well as the constant positive feedback given by the participants, confirm the high educational value and impact in the growing popularization of this geologic locality.

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