



Life at the continental–marine interface: palaeoenvironments and biota of the Alcobaça Formation (Late Jurassic, Central Portugal), with a formal definition of the unit appended

Franz T. Fürsich¹ · Simon Schneider² · Winfried Werner^{3,4} · Berta Lopez-Mir^{2,5} · Colm S. Pierce²

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Abstract

The Kimmeridgian Alcobaça Formation of the Lusitanian Basin forms a mixed carbonate–siliciclastic unit between basal deposits of the Abadia Formation, and fluvial–terrestrial strata of the Lourinhã Formation. This study presents >2.5 km of detailed logs of nine outcrop sections of the Alcobaça Formation in its type region. Eight of these sections encircle the Caldas da Rainha Diapir, which was a prominent, emergent, passive salt diapir during the time of deposition. Palaeoenvironments of the unit form a complex mosaic of low- to high-energy, carbonate- or siliciclastic-dominated shallow shelf settings; coastal embayments and lagoons; and coastal plains with rivers, lakes and playas. In the strata, abundant microfauna is often joined by a rich macrofauna, usually dominated by bivalves. Locally, corals, calcareous sponges or oysters form meadows or patch reefs. These autochthonous to parautochthonous remnants of former communities are assigned to 35 benthic macrofaunal associations. The integration of palaeoecological analysis of these associations with microfaunal and sedimentological data provides constraint on their salinity ranges, which range from slightly hypersaline to freshwater. Frequent temporal and spatial salinity fluctuations are attributed to variations in relative sea-level, salt tectonics or climate. The NNE-trending Caldas da Rainha Diapir induced pronounced facies differentiation. Predominantly, non-marine siliciclastic facies in the northwest and carbonate to siliciclastic, marine to brackish facies in the southwest are contrasted by shallow-marine carbonate facies east of the diapir. Comprehensive exposure and well-preserved fossils make the Alcobaça Formation an excellent showcase to demonstrate how biofacies analysis can help to disentangle the interplay of climate changes, sea-level fluctuations and salt tectonics. Based on the improved characterisation of the unit, the Alcobaça Formation is formally defined, and seven members are established.

Keywords Kimmeridgian · Macrofaunal associations · Biofacies · Salinity · Diapirism

Introduction

History of research

The term ‘Couches d’Alcobaça’ was coined by Choffat (1885: 5, 18) for a succession of lignites from Fervença near Alcobaça (Fig. 3), including a horizon with brackish-water invertebrate fossils in its upper part. Alternating marine and freshwater deposits occurring at Batalha (Fig. 3) and Ourém (Fig. 1) (the latter containing freshwater molluscs and plant litter) were also assigned to this unit. Choffat (1885) further mentioned abundant trigoniid bivalves from marine intercalations in the lignites of the Couches d’Alcobaça. In the same study, Choffat (1885) introduced the term ‘Couches à *Lima alternicosta*’ for deposits in the surroundings of Torres Vedras, Cesareda and Sobral da Lagoa, which he regarded as a potential southern equivalent of the Couches d’Alcobaça. In

✉ Franz T. Fürsich
franz.fuersich@fau.de

Simon Schneider
simon.schneider@casp.org.uk

- ¹ GeoZentrum Nordbayern, FG Paläoumwelt, Friedrich-Alexander-Universität Erlangen-Nürnberg, Loewenichstrasse 28, 91054 Erlangen, Germany
- ² CASP, West Building, Madingley Rise, Madingley Road, Cambridge CB30UD, UK
- ³ Bayerische Staatssammlung für Paläontologie und Geologie, Richard-Wagner-Strasse 10, 80333 Munich, Germany
- ⁴ GeoBio-Center LMU, Richard-Wagner-Strasse 10, 80333 Munich, Germany
- ⁵ Instituto Geológico y Minero de España, Subdelegación de Gobierno, Pza. de España - Torre Norte, 41013 Sevilla, Spain

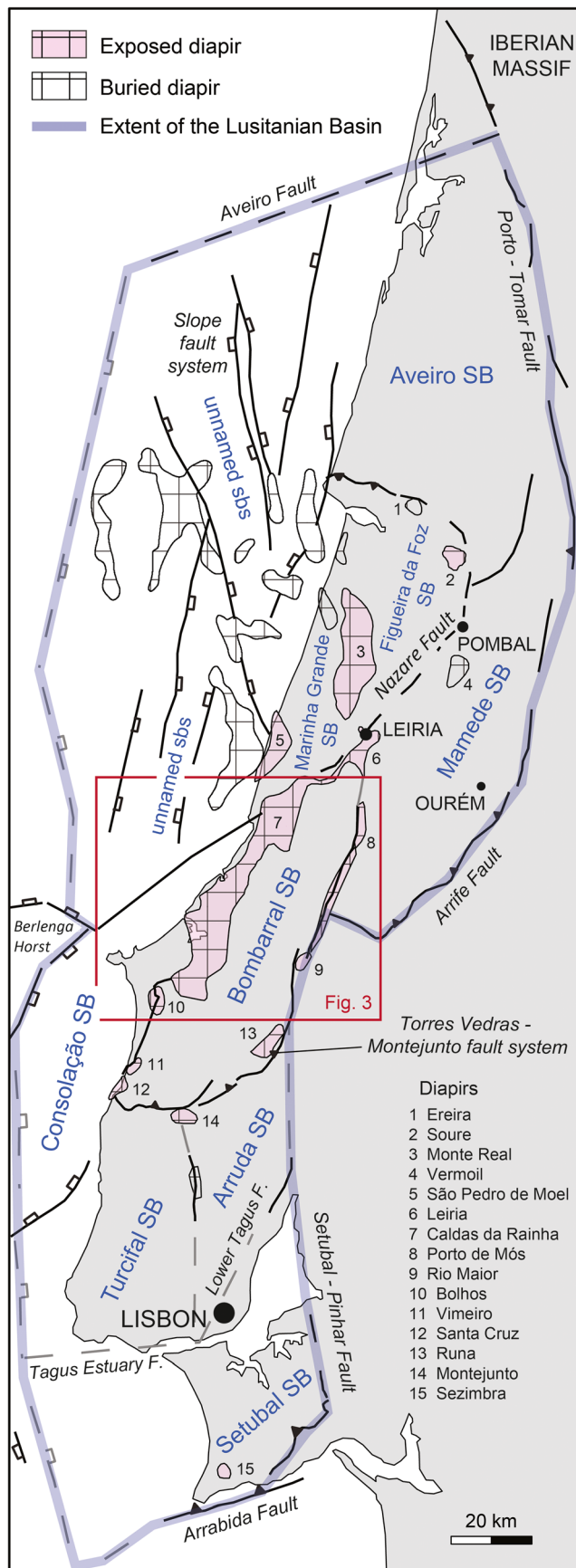


Fig. 1 Main structural elements and sub-basins of the Lusitanian Basin, Portugal. The Aveiro, Figueira da Foz, Marinha Grande, Mamede and Setubal sub-basins are new terms proposed herein. The study region, depicted in Fig. 3, is indicated by a red frame. Modified from Alves et al. (2002)

subsequent papers, Choffat variously included the Couches d'Alcobaça in the 'Marnes d'Abadia' (as a marginal end-member), more generally in the 'Lusitanien' (encompassing all dominantly marine Upper Jurassic rocks), or in the 'Couches à *Lima pseudo-alternicosta*' (note the name change from above). (The name '*Lima pseudo-alternicosta*', attributed to Buvignier by Maync (1959), is an unpublished manuscript name of Choffat and thus not available. The species described by Buvignier is *Lima alternicosta*, which is a junior subjective synonym of *Pseudolimea duplicata* (J. de C. Sowerby, 1827); see Fürsich and Werner (1989b).) Finally, in his stratigraphic note in Koby (1904–1905: 159), Choffat regarded the Couches d'Alcobaça as a northern equivalent of the Couches à *Lima pseudo-alternicosta*. In the Lexique Stratigraphique International, Moitinho de Almeida et al. (1958) listed the Couches d'Alcobaça as part of the Lusitanien.

Zbyszewski and Moitinho de Almeida (1960) and Camarate França and Zbyszewski (1963) issued brief characterisations of the 'Camadas de Alcobaça' and published descriptive logs of representative outcrop sections, which were originally compiled by Choffat; these contain useful information on the thickness, lithology and fossil content of the unit. Ruget-Perrot (1961: 176) summarised the lithology and invertebrate fauna of the Couches d'Alcobaça, also making use of unpublished notes of Choffat. She reported a thickness of 50–200 m for the unit, which she interpreted as the littoral facies of the Marnes d'Abadia (Ruget-Perrot 1961). Witt (1977: 8) introduced the term 'Alcobaça Formation' in an unpublished report of Shell Prospex Portuguesa and provided a concise description of the unit. He characterised the Alcobaça Formation as a shallow-marine to coastal succession of limestones (including oolites, oncolites and coral limestones), marly limestones and marls, with an upward increasing sandstone component. Witt (1977) considered both the contacts to the Montejunto Formation below and to the 'Grés superiores' (= Lourinhã Formation) above as 'possibly unconformable', and reported a total thickness of 300–400 m for the unit. Northward, the Alcobaça Formation grades into the fluvial to continental Lourinhã Formation, and southward into the outer shelf deposits of the Abadia Formation according to Witt (1977). Based on the ammonite-calibrated age of the Abadia Formation, he assumed a Kimmeridgian age for the Alcobaça Formation (Witt 1977). Werner (1986) undertook a detailed analysis of the (bio-)facies of the Alcobaça Formation exposed in the coastal section at Consolação (log reproduced at reduced scale herein), which was assigned to the 'Consolação Member' by Leinfelder (1986). Fatela (1990)

presented a 75-m log of parts of the Alcobaça Formation exposed at the coast south of Salgado (Fig. 3) and provided basic information on its microfossil content. Bernardes et al. (1991) published a sedimentological analysis of the Jurassic succession between São Martinho do Porto and Nazaré (including the part logged by Fatela 1990). The respective strata, collectively assigned to the Alcobaça Formation herein (see “[Geological overview](#)”), were variously attributed to the Camadas de Vale Verde, Camadas com *Pholadomya protei*, Formação Argilosa de S. Martinho do Porto and Camadas de Alcobaça in their study, partly following a concept outlined in an unpublished PhD (Ellwood 1987). Marques et al. (1992) presented logs of a section at Vestiaria and nearby outcrops and proposed an age model for the unit, based on ammonites (discussed in detail below).

In the explanatory notes to sheet 30-A Lourinhã of the Carta geológica de Portugal, 1:50,000, Manuppella et al. (1999) introduced several informal subunits of the Alcobaça Formation for the succession south of the Serra d’El Rei (Fig. 3), some of them also dated by ammonite biostratigraphy. The basal ‘Calcários de Moledo’, 120–150 m thick, are overlain by 180 m of ‘Calcários calciclásticos com oóides, margas e grés de Reguengo Pequeno’. The following 9–12 m of ‘Calcários bioclásticos com corais e calcários oolíticos de Feteira’ are considered a lateral equivalent of the Amaral Formation. Along the coast, the ‘Grés, margas, calcários oolíticos e dolomites da Consolação’, overlain by the ‘Grés margas e arenitos da Praia da Armoreira-Porto Novo’ (considered part of the Lourinhã Formation by Taylor et al. 2014, and herein) were assigned to the Alcobaça Formation.

Finally, Kullberg et al. (2013), in a review of the geology of the Lusitanian Basin, characterised the Alcobaça Formation as an alternation of variably arenaceous marls, detritic limestones and arenites, with subordinate layers of ferruginous oolites, abundant oncolites, oyster reefs, corals and other marine fauna, and plant remains. The total thickness of the unit is given as 150–200 m, and a Kimmeridgian to basal Tithonian age is assigned. The environmental setting is described as a ‘shallow marine carbonate platform with frequent discharge of siliciclastic sediments from the surrounding emergent areas’ (translated from Kullberg et al. 2013: 240). Kullberg et al. (2013) further considered the Abiul Formation, exposed in a restricted area east of Pombal, as a distinct unit, comprising predominantly bioclastic and ooidal packstones and grainstones, with subordinate marls and oncolites. A shallow-marine to lagoonal depositional setting with open marine influence was inferred.

Biota

Goldfuss (1837) was probably the first to describe a fossil from the Alcobaça Formation. His figure and description of *Lyrodon muricatum* Goldfuss, 1837 (= *Myophorella muricata*) conform to a species so far only found in the

Alcobaça Formation, although the figured specimen was said to come from Torres Vedras, which is significantly south of the extent of the unit. Sharpe (1850) mentioned *Perna lanceolata* (presumably *Isognomon rugosus*), *Lithodomus praelongus*? (= *Lithophaga* sp.), *Trigonia* and corals from Aljubarrota ENE of Alcobaça but did not illustrate his finds. In a series of monographs, titled ‘Description de la faune jurassique du Portugal’, Choffat (1885–1888, 1893, 1947), de Loriol (1890–1891) and Koby (1904–1905) described and figured marine and freshwater bivalves (Pholadomyidae, Unionida, Trigoniida), brachiopods, echinids and corals from Jurassic deposits of the Lusitanian Basin, including those of the Alcobaça Formation. Starting in the 1960s, the coal mine of Guimarães south of Leiria, now assigned to the Alcobaça Formation (Schudack 2000a), became famous for its rich vertebrate fauna, most prominently an abundance and diversity of Jurassic mammals so far unmatched (Kühne 1961; Martin and Krebs 2000; Martin 2001). From the 1980s onward, a number of papers addressed Late Jurassic ichnofossils (Fürsich 1981a; Neto de Carvalho and Baucon 2010; Neto de Carvalho et al. 2010; Neto de Carvalho 2016) and bivalves (Fürsich and Werner 1985, 1988, 1989a, b; Schneider and Werner 2007; Schneider et al. 2010a, b, 2011) from Central Portugal. Furthermore, benthic faunal associations and palaeoenvironments of several Late Jurassic units, including the Alcobaça Formation, were characterised (Fürsich 1981b; Fürsich and Werner 1984, 1986, 1991; Fürsich et al. 2009). Mateus (2006) compared the biota of the Alcobaça and Lourinhã formations with those from the Morrison Formation (USA) and the Tendaguru Beds (Tanzania), aiming to demonstrate environmental similarities explaining the common occurrence of dinosaur fossils. He and Mocho et al. (2017) also provided overviews of the Late Jurassic dinosaur remains collected from the Lusitanian Basin, including those from the Alcobaça Formation.

Geological overview

The Lusitanian Basin

The Lusitanian Basin of Central Portugal is an approximately 300-km-long (north–south), up to 180-km-wide Mesozoic salt-floored extensional basin situated at the Atlantic margin of western Iberia and is subdivided into several sub-basins (Fig. 1). The northernmost sub-basin, named the Aveiro Sub-basin herein (Fig. 1), has only remnants of fluvial Upper Jurassic strata preserved (Boa Viagem sandstones; Carta geológica de Portugal, 1:50,000, sheet 19C Figueira da Foz). The area between the Ereira and Soure diapirs and the Nazaré Fault, previously termed the Monte Real Sub-basin, in fact consists of two sub-basins, separated by the Monte Real Diapir; the name Monte Real Sub-basin is thus not

suitable. The southwestern sub-basin is named the Marinha Grande Sub-basin and the northeastern one the Figueira da Foz Sub-basin herein (Fig. 1). Further to the west, several unnamed sub-basins extend offshore. The area east of the Nazaré Fault and the Rio Maior–Porto de Mós salt wall is named the Mamede Sub-basin herein (Fig. 1). The established Consolação, Bombarral, Turcifal and Arruda sub-basins follow to the south (e.g. Montenat et al. 1988; Taylor et al. 2014; Fig. 1). The area south of the Tagus, previously termed the Southern Lusitanian Basin (see e.g. Schneider et al. 2009), actually is no more than another sub-basin, named the Setubal Sub-basin herein (Fig. 1).

Basement-involved extension in the Lusitanian Basin was initiated in the Middle to Late? Triassic. A second, prolonged rifting episode occurred from the Sinemurian to the Pliensbachian. Finally, rifting climaxed in a third, much shorter but intense pulse in the Oxfordian (e.g. Ravnas et al. 1997; Rasmussen et al. 1998; Carvalho et al. 2005; Kullberg et al. 2013). The basin is filled with up to 5 km of sedimentary strata. More than 4 km of these formed during the Mesozoic and are arranged in four unconformity-bound megasequences (Wilson et al. 1989; Pinheiro et al. 1996; Leinfelder and Wilson 1998; Carvalho et al. 2005), the lowermost pair of which are relevant to the present study. The earliest, Triassic to middle Callovian megasequence initiated with the deposition of coarse-grained red bed siliciclastic strata (Silves Group), followed by a Rhaetian to Hettangian basin-wide-developed succession of evaporites, including significant amounts of salt (Dagorda Formation). From the Sinemurian onward, a carbonate ramp system started to develop, with dominantly carbonate rocks deposited on the western slope of the Iberian Massif, and dominantly marly sediments towards the basin depocentre in the northwest (Duarte et al. 2010, 2012). Simultaneously, salt was mobilised above basement-evolved faults and the development of passive diapirs was initiated (Lopez-Mir et al. 2019, 2020; Davison and Barreto 2020; see discussion below). During the Middle Jurassic, a fully developed carbonate ramp system extended over the entire basin, with various shallow- and deep-water carbonate facies recorded (e.g. Azerêdo et al. 2003; Azerêdo 2007; Martins 2008). The first depositional megasequence terminated with the onset of a late Callovian to early Oxfordian phase of non-deposition and widespread erosion (e.g. Azerêdo et al. 1998, 2002).

The overlying, middle Oxfordian to early Berriasian megasequence followed rift climax in the Oxfordian and accounts for up to 2.7 km of sediments (Alves et al. 2002). During this phase, diapirism started to modify basin geometry and sedimentation more significantly, and distinct sub-basins developed. Deposition commenced in the middle Oxfordian with organic-rich, brackish-water to marine limestones and subordinate siliciclastic strata of the Cabaços Formation, followed by a succession of relatively pure carbonate strata

of the Montejunto Formation (middle to late Oxfordian; Fig. 2). Subsequently, deep-water marls and turbidites of the Abadia Formation (latest Oxfordian? to late Kimmeridgian) were deposited in the southern half of the basin (northern Setubal, Arruda and northern Turcifal sub-basins; Fig. 2). From the north (Aveiro, Figueira da Foz and Marinha Grande sub-basins), the fluvial-deltaic, sandstone-dominated succession of the Lourinhã Formation (Kimmeridgian to early Berriasian) started to prograde into the basin (Fig. 2). In the intervening region, the highly heterogeneous Alcobaça Formation (latest Oxfordian to terminal Kimmeridgian) developed at the interface of the sea and the continent (Consolação, Bombarral and Mamede sub-basins). It formed a major component of the halokinetic sequences deposited along diapir flanks (Lopez-Mir et al. 2019, 2020). Towards the end of the Kimmeridgian, the deeper parts of the basin had filled up, the continental-marine interface migrated southward and the Lourinhã Formation prograded over the Alcobaça Formation (e.g. Witt 1977; Alves et al. 2002, 2003; Kullberg et al. 2013). A near-basin-wide middle Berriasian hiatus marks the end of the second megasequence (e.g. Leinfelder and Wilson 1998).

Distribution of the Alcobaça Formation

The Alcobaça Formation occurs in the Mamede, Bombarral and Consolação sub-basins (Figs. 1, 2 and 3). The northernmost and easternmost exposures of the unit are in the Mamede Sub-basin. Outcrops at the southern and western flanks of the Serra de Sicó, in the area between Pombal (Fig. 1) and Abiul (Carta geológica de Portugal, 1:50,000, sheet 23A Pombal), have been assigned to the Abiul Formation in the literature (Almeida et al. 1990; Kullberg et al. 2013; Kullberg and Rocha 2014). The ‘Guimarota beds’ of the now disused coal mine of Guimarota, just south of Leiria (Fig. 1), were referred to the Alcobaça Formation by Schudack (2000a). Further exposures in the Mamede Sub-basin exist between Batalha and Porto de Mós at the western flank of the Serra d’Aire (Fig. 3), in the area around the Vermoil Diapir (Fig. 1; Complexo de Vale de Lagares of Teixeira and Zbyszewski 1968) and in a narrow strip just west of Ourém (Fig. 1; sheets 23C Leiria, 27A Vila Nova de Ourém). Most of these outcrops were visited by the present authors but did not yield contiguous sections of more than a few tens of metres in thickness.

In the central Bombarral Sub-basin, the Alcobaça Formation crops out in a narrow band along the western flanks of the Serra de Porto de Mós and Serra dos Candeeiros, extending from south of Batalha as far south as Rio Maior (Fig. 3; sheets 26B Alcobaça, 26D Caldas da Rainha, 27A Vila Nova de Ourém). Farther to the west, the Alcobaça Formation is exposed in a narrow, discontinuous band along the east side of the Caldas da Rainha Diapir (Fig. 3). From just

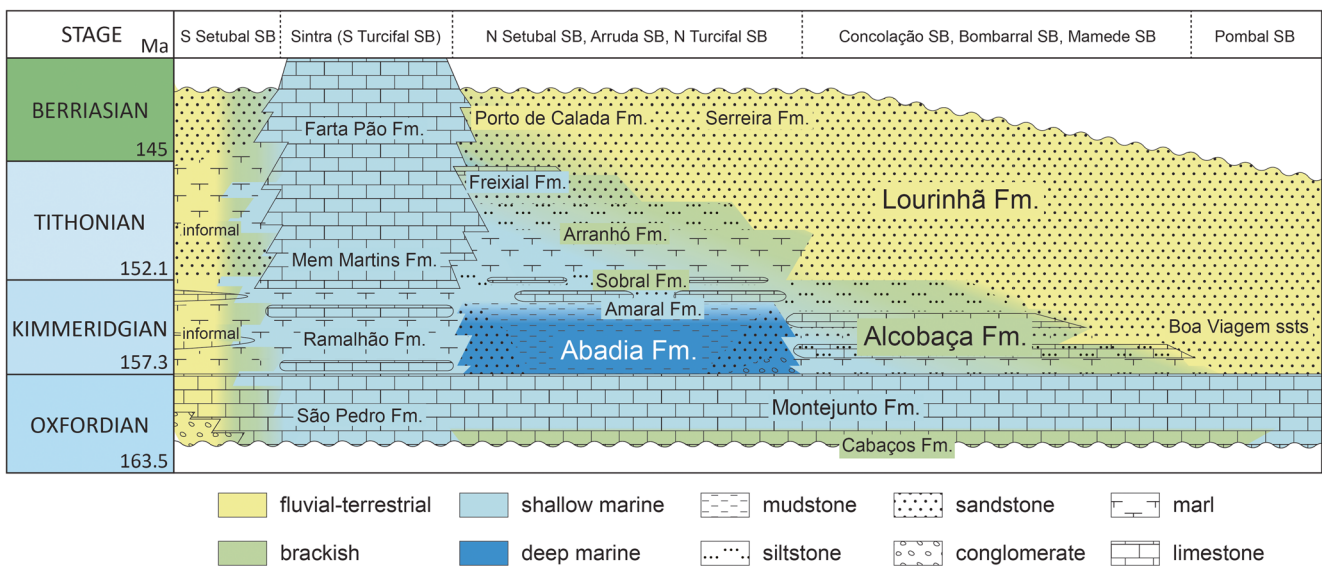


Fig. 2 Lithostratigraphy of the Late Jurassic to Berriasian interval in the Lusitanian Basin

south of the Rio Alcôa, the outcrop follows the diapir flank, turning west in the area of Reguengo Grande, along the southern margin of the Serra d’El Rei, to terminate near Moledo (sheets 26B Alcobça, 26D Caldas da Rainha, 30A Lourinhã, 30B Bombarral).

West of the Caldas da Rainha Diapir, in the Consolação Sub-basin, the Alcobça Formation extends from south of Nazaré to the Lagoa de Óbidos (Fig. 3; sheets 26B Alcobça, 26C Peniche, 26D Caldas da Rainha). The southernmost exposures of the unit are along the coast at Consolação (Fig. 3; sheet 26C Peniche).

Age of the Alcobça Formation

Dating the Alcobça Formation precisely is difficult. Shallow shelf depositional environments within restricted sub-basins result in a dearth of open marine ammonite and dinoflagellate fossils. As a result, useful biostratigraphic markers are rare. Most microfossils are too strongly facies controlled and terrestrial palynomorph taxa too long-ranging to provide precise age control.

Traditionally, the Alcobça Formation was thought to span large parts, if not all of the Kimmeridgian (e.g. Ruget-Perrot 1961; Witt 1977; Wilson 1979; Fürsich and Werner 1986; Rasmussen et al. 1998; Alves et al. 2002). An alternative stratigraphy was proposed by Pena dos Reis et al. (1996), who divided the Alcobça Formation into a lower, latest Oxfordian to early late Kimmeridgian portion and an upper, latest Kimmeridgian to Berriasian portion, with the Amaral Formation separating the two parts. No further explanation

for this interpretation was provided, and thus it has been largely disregarded.

Several attempts to date the Alcobça Formation were based on microfauna, macroflora and microflora and palynomorphs. Helmdach (1971a, b, 1974) studied ostracods from the Guimarota coal mine at Leiria and deduced an early Kimmeridgian age for these sediments. Brauckmann (1978) proposed an (early) Oxfordian age for the Guimarota succession, based on the macroflora contained. Likewise, terrestrial palynomorphs and dinoflagellate cysts from the surroundings of Porto de Mós (Mohr and Schmidt 1988) and from Guimarota (Van Erve and Mohr 1988; Mohr 1989) were thought to support (late) Oxfordian ages for part of the succession. Fatela (1990) proposed a late Oxfordian to middle Kimmeridgian age for the coastal section south of Salgado (Fig. 3), based on foraminifera. Schudack (1993, 2000a) concluded a Kimmeridgian age for the Guimarota beds, based on charophytes and ostracods, refuting the earlier stated Oxfordian age.

Three studies refer to ammonites from the Alcobça Formation. Werner (1986) reported two early Kimmeridgian ammonites, indicative of the *Platynota* and *Hypsolocyclum* zones, respectively, from Consolação. Marques et al. (1992) proposed an earliest Kimmeridgian (*Platynota* Zone) to earliest Tithonian (*Hybonotum* Zone) age for the Alcobça Formation based on scattered ammonite finds from their Casais (between *Vestiarina* and *Barrio*; Fig. 3) and *Vestiarina* sections (not identical with the section described below). Finally, Manuppella et al. (1999) reported various ammonites from the southern slope of the Serra d’El Rei (Fig. 3), which are indicative of early to late Kimmeridgian ages (*Planula*/

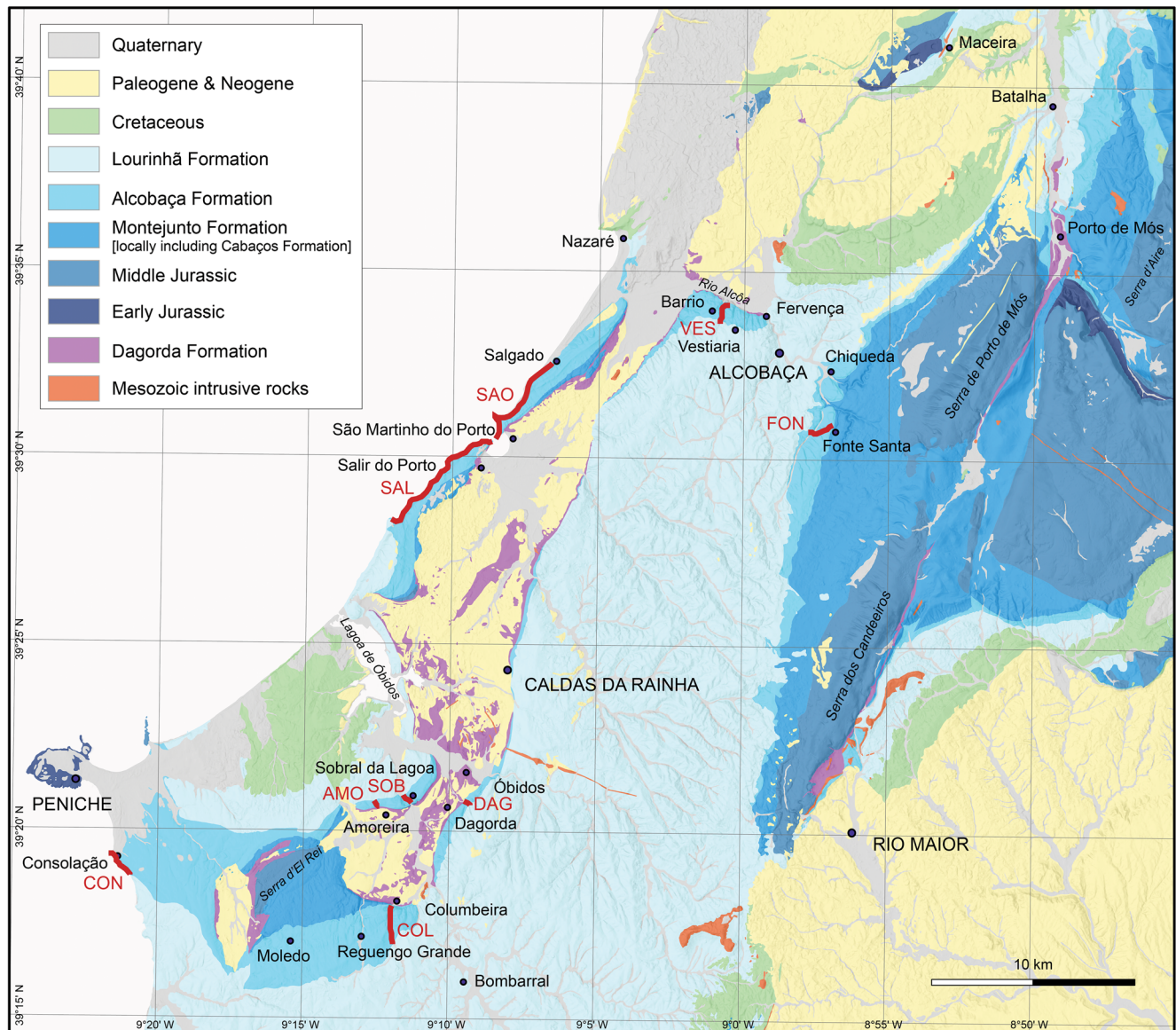


Fig. 3 Geological map of the study region, modified from the 1:50,000 scale map sheets of the ‘Carta geológica de Portugal’. Logged sections are indicated by red lines. AMO Amoreira, COL Columbeira, CON Consolação, DAG Dagorda, FON Fonte Santa, SAL Salir do Porto, SAO São Martinho do Porto, SOB Sobral da Lagoa, VES Vestiaría

Platynota to Eudoxus zones). No ammonites were figured, which makes it impossible to verify the taxonomy and resulting age attributions.

Schneider et al. (2009) analysed strontium isotope values of 29 specimens of oysters from the Alcobaça Formation. Ages were calculated using the strontium isotope stratigraphy (SIS) look-up table of Howarth and McArthur (2003) and range from the latest Oxfordian (Planula Zone) to the late Kimmeridgian (lower Beckeri Zone). Recalculating these ages based on the SIS look-up table recently published by Wierzbowski et al. (2017), the range of the Alcobaça Formation has slightly expanded, extending from the basal Kimmeridgian (late

Bimammatum Zone; 156.9 ± 6 Ma) to the latest Kimmeridgian (Beckeri Zone; 152.5 ± 5 Ma).

Material and methods

The authors have visited and studied various outcrops of the Alcobaça Formation repeatedly, over a period of nearly four decades. The nine sections described and discussed herein were logged by F.T.F. and W.W. during several field seasons between 1980 and 1987. GPS coordinates of starting points and endpoints of several of the logs were taken in 2016. Outcrop conditions along most of the inland sections, situated along newly

refurbished roads in the 1980s, have degraded dramatically, while the three coastal sections are still well exposed and accessible.

Sections were measured bed-by-bed. Colour, lithology, grain size, sedimentary structures, diagenetic features, bed contacts, trace fossils, body fossils and taphonomic features such as biofabrics and degree of articulation were systematically recorded. Lithological samples were taken where the lithology could not be determined using a hand lens. Each horizon that yielded a sufficient number of specimens was attributed to a benthic macrofaunal assemblage/association (Fürsich 1981b; Fürsich and Werner 1986). For this purpose, specimens were determined wherever possible at the species level and ranked by relative abundance. The size of samples varied, depending on availability, between 30 and 500 individuals. Apart from identifying specimens in the laboratory, specimens were also counted in the field. Where necessary, bulk sediment samples were taken and then disaggregated and analysed in the laboratory.

Microfossils (e.g. ostracods, foraminifers, charophyte gyrogonites) were obtained from clay and silt samples, disaggregating the rock by immersion in diluted hydrogen peroxide, and subsequent wet sieving to a mesh size of 0.3 mm. Ostracod specimens were picked from dried residues. Selected specimens were sputter coated with gold, and SEM images were taken. Macrofossils were cleaned from adherent sediment using various mechanical preparation techniques. For photographs, most specimens were whitened with ammonium chloride. Several hundreds of thin sections of rock samples, generally 50 µm thick, were prepared using standard techniques.

Abbreviations and coordinates of localities (WGS84 datum)

Logged sections of the Alcobaça Formation: AMO = Amoreira (39.34759, -9.20684 to 39.35373, -9.20177); COL = Columbeira (road section: 39.2918, -9.19924 to 39.30171, -9.19932); CON = Consolação (39.32457, -9.36151 to 39.31232, -9.34679); DAG = Dagorda (base of section, former quarry SE Dagorda, near 39.34193, -9.16825); FON = Fonte Santa (road section near 39.52335, -8.95225); SAL = Salir do Porto (39.50858, -9.15239 to 39.47342, -9.20301); SAO = São Martinho do Porto (39.51042, -9.14357 to 39.54367, -9.11401); SOB = Sobral da Lagoa (39.34801, -9.18865 to 39.35106, -9.19371); VES = Vestiaria (road section: 39.56882, -9.00305 to 39.56228, -9.00716; NW of village: 39.56485, -9.0094; NE of village: 39.56599, -9.00505).

Members of the Alcobaça Formation: ARR = Arrinhada; COL = Columbeira; CON = Consolação; GRA = Gralha; SAO = São Martinho; SGD = Salgado; VES = Vestiaria.

Additional localities of the Alcobaça Formation studied: BAR = Barrio (39.56825, -9.02117); CAR = Carrascal (approximately 39.5315, -8.94559); CHI = Chiqueda (between 39.54069, -8.94894 and 39.54205, -8.94396).

Additional localities mentioned, exposing younger lithostratigraphic units: SAR = Serra d’Arrábida; ESP = Cabo Espichel; STC = Santa Cruz.

Repositories

Most of the materials this study is based on, as well as the detailed documentation of the sections, including field notebooks and original drawings of the logs, are deposited in the Bayerische Staatssammlung für Paläontologie und Geologie, Munich, under the main inventory numbers SNSB-BSPG 1984 XXI, 1984 XXII, 2002 IV and 2005 V. It should be noted that thin sections, microfossil samples and macrofossils are generally indexed to the bed numbers noted in the original logs. Further material, e.g. macrofossils and ichnofossils figured in previous publications or herein, is deposited in the Museu Geológico of Lisbon (acronym GML).

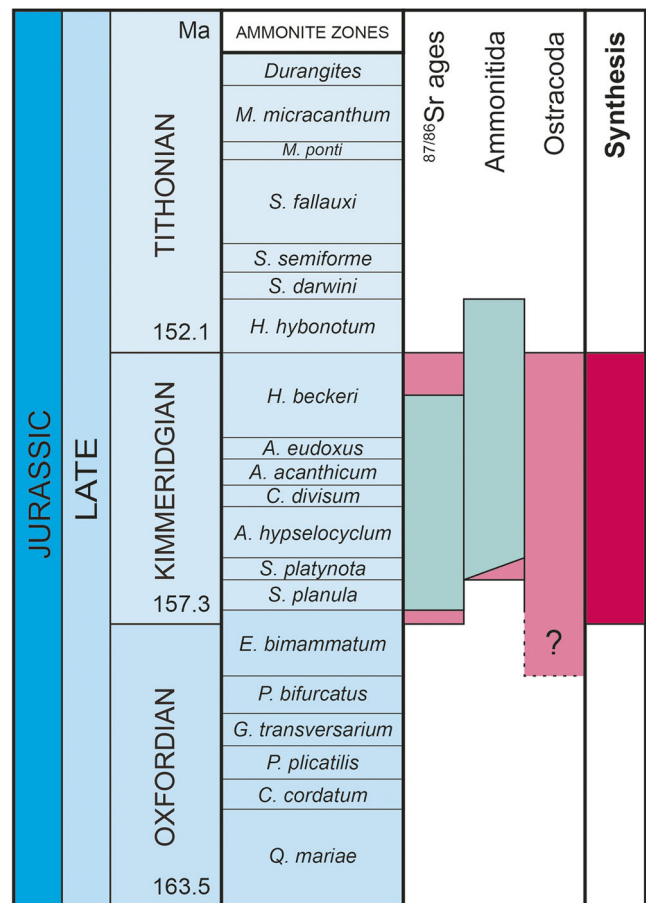


Fig. 4 Age model of the Alcobaça Formation. Turquoise bars indicate ranges taken from the literature. Pink bars indicate ranges adjusted or documented herein

Revised age model

Ammonoidea

Ammonites, if available, are the preferred biostratigraphic tools for dating Upper Jurassic rocks. From the Alcobaça Formation, 15 ammonite taxa are reported in the literature, most probably representing as many specimens. Finds from Consolação were assigned to *Mesosimoceras* and *Ataxioceras*, indicating an early Kimmeridgian age (Platynota to Hypselocyclum zones) (Fig. 4), but were neither described nor figured (Werner 1986). From two closely adjacent sections at Vestiaria and Casais, Marques et al. (1992) reported *Ataxioceras* (*Parataxio-ceras*) aff. gr. *praeomalinum* Atrops, *Ataxioceras* (*Parataxio-ceras*) sp. and *Orthosphinctes* (*Lithacosphinctes*) aff. gr. *pseudoachilles* (Wegele) (all Platynota Zone), *Taramelliceras* (*Taramelliceras*) *compsum* (Oppel) and *Glochiceras* sp. (Divisum–Acanthicum zones transition) and *Hybonoticeras* sp. (Hybonotum–Albertinum [= Darwini] zones transition) (Fig. 4). No specimen descriptions or figures were provided. Subsequently, Manuppella et al. (1999) reported ammonites from two localities at the southern slope of the Serra d’El Rei: *Sowerbyceras* sp., *Phyllopachyceras* sp., *Orthosphinctes* cf. *vandellii* (Choffât), *Lithacoceras subachilles* (Wegele), *Ataxioceras discobolum* (Fontannes) and *A. guentteri* (Oppel), all from a single level at Vale Tomada, assigned to the Hypselocyclum to Divisum zones, and *Nebroditis* cf. *heimi* (Favre) from Feteira (Eudoxus Zone) (Fig. 4). Again, no descriptions or figures are available.

The *Ataxioceras* specimen from Consolação (Werner 1986; at 70 m in the log) is reclassified as *Parataxio-ceras* cf. *oppeli* (Geyer) and figured herein (Fig. 5e). Six additional ammonite specimens from the Alcobaça Formation are reported from this study, and five of these are depicted in Fig. 5. *Taramelliceras kobyi quenstedti* Schairer (Fig. 5a), *Subdiscosphinctes* sp. (Fig. 5c) and *Ataxioceras* (*Schneidia*) sp. all come from a single outcrop at Barrio. Two specimens of *Lithacosphinctes* cf. *janus* (Choffât) were collected in the middle part of the Sobral da Lagoa section (approximately at 90 m); one of them is figured (Fig. 5d). Finally, a specimen of *Ardescia* sp. (Fig. 5b) was collected near Vestiaria, not from the logged road section, but from an outcrop west of the road, corresponding to a height of 350 to 360 m in the log. All determinations were provided by Günter Schweigert (Stuttgart; pers. comm., 28/08/2020), who interpreted all specimens to indicate an early Kimmeridgian, Platynota Zone age.

Ostracoda

Due to the absence of ammonites in large parts of the succession, particularly the brackish and freshwater intervals, Ostracoda are considered useful for dating the Alcobaça Formation. The ostracod fauna of the sediments at Guimarota was first studied by Helmdach (1971a, b, 1974)

and is now regarded to broadly indicate a Kimmeridgian age (Schudack 2000a, b). A more extensive manuscript, incorporating samples collected by two of the present authors (W.W. and F.T.F.) from several of the outcrops and sections studied herein (CHI, CON, FON, SAL, SAO, VES), was in an advanced stage when Friedrich-Franz Helmdach passed away in 1994 and remained unpublished. Nearly half of the ostracod species recovered were also recorded at Guimarota (see Fig. 6 for a selection). As outlined by Schudack (2000a, b), the distinction of lower, middle and upper Kimmeridgian ostracod assemblages advocated by Helmdach is no longer viable, and a Kimmeridgian age is generally supported by these taxa (Fig. 4). Only for samples from the lower part of the São Martinho do Porto section (Gralha Member; proposed herein), Helmdach had suggested a late Oxfordian age (Fig. 4), based on the presence of a different species of *Theriosynoecum* (Fig. 6a; *T. wyomingense* var. *pedrogaoense* of Helmdach 1974). The ostracod assemblage described by Cabral et al. (2013) from ‘the very base of the informal Sobral formation’, directly above the ‘traditional Alcobaça formation’ (i.e. sensu Mannuppella et al. 1999), is considered part of the Lourinhã Formation sensu Taylor et al. (2014) herein. The top of the Consolação Member of the Alcobaça Formation, as proposed below, is situated more than 2 km further north at the Atlantic coast, probably within the lower São Bernardino Member of Taylor et al. (2014).

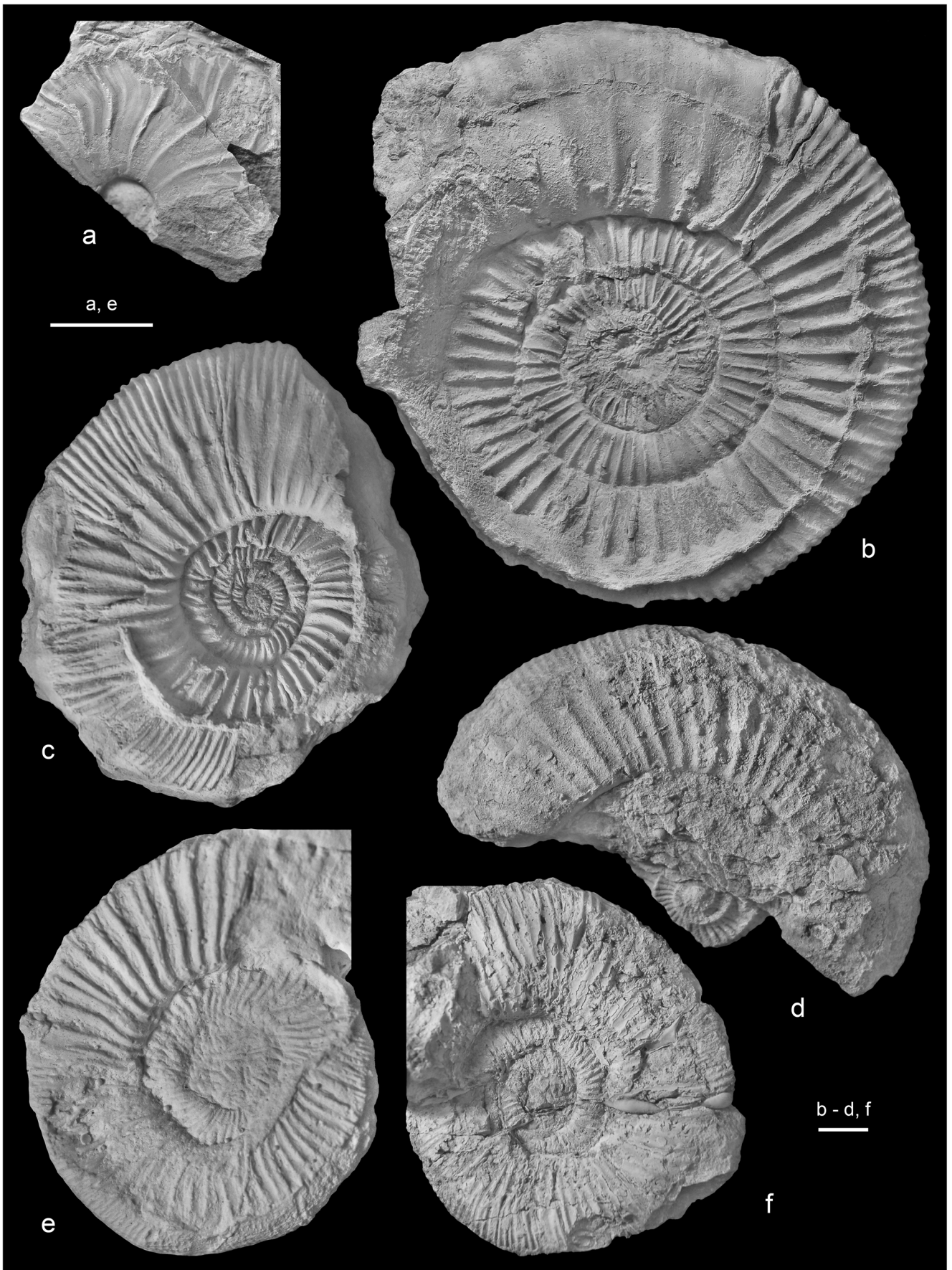
Strontium isotopes

Strontium isotope values extracted from 29 oyster shells from the Alcobaça Formation were published by Schneider et al. (2009). As mentioned above, these values are indicative of basal Kimmeridgian (late Bimammatum Zone; 156.9 ± 6 Ma) to latest Kimmeridgian (Beckeri Zone; 152.5 ± 5 Ma) ages, based on the most recent SIS look-up table of Wierzbowski et al. (2017) (Fig. 4).

Synthesis

Ammonitida, Ostracoda and strontium isotopes collectively indicate a Kimmeridgian age for the bulk of the Alcobaça Formation. A latest Oxfordian age, suggested for the lower part of the São Martinho do Porto section by Helmdach, based

Fig. 5 Ammonites from the Alcobaça Formation. All specimens assigned to the Platynota Zone (early Kimmeridgian). **a** *Taramelliceras kobyi quenstedti* Schairer; Barrio; GML 31980. **b** *Ardescia* sp. (macroconch); NW Vestiaria, corresponding to 350–360 m in the log; GML 31981. **c** *Subdiscosphinctes* sp.; Barrio; GML 31982. **d** *Lithacosphinctes* cf. *janus* (Choffât); Sobral da Lagoa section, at ~90 m in the log; GML 31983. **e** *Parataxio-ceras* cf. *oppeli* (Geyer); Consolação section, 70 m; C-2-49; plaster cast, SNSB-BSPG 1984 XXI 142. **f** *Ataxioceras* (*Schneidia*) sp.; Barrio; GML 31984. Scale bars = 10 mm



on ostracods (unpublished data) is not supported by strontium isotope values from the same section (Schneider et al. 2009) and is thus considered unlikely. Furthermore, the earliest Tithonian age (Hybonotum Zone) proposed for part of the succession exposed near Vestiaria, based on the presence of *Hybonoticerias* sp., by Marques et al. (1992), is controversial. The *Ardescia* sp. illustrated herein (Fig. 5b) was collected from approximately the same level and is supposed to indicate a much older, early Kimmeridgian (Platynota Zone) age. Strontium isotope values of two oysters collected from a distinctive oyster patch reef right below the *Hybonoticerias* level of Marques et al. (1992) at Vestiaria yield slightly conflicting, early and late Kimmeridgian ages (Hypselyclum/Divisum and Mutabilis/Eudoxus zones, respectively; 154.6 ± 6 Ma and 153.9 ± 5 Ma), which range in between the ammonite ages. In conclusion, an earliest to latest Kimmeridgian age for the Alcobaça Formation seems well supported (Fig. 4).

Section summaries

Figure 7 depicts three of the nine outcrop sections logged for this study. In Fig. 8, a key of symbols for the logs presented in Figs. 9, 10, 11, 12, 13, 14, 15, 16 and 17 is provided. Below, the logged successions are briefly characterised, including information on the type and quality of exposure, contacts, assignment to members, lithology, facies and peculiarities, and general interpretation of depositional environments. Two categories of depositional events are marked in the logs, indicating breaks in sedimentation, reversals in trend (transgressive versus regressive) and/or switches from dominantly carbonate to siliciclastic sedimentation or vice versa.

São Martinho do Porto (SAO; Fig. 9)

Exposure and contacts: This 605-m-thick section is almost continuously exposed (97% of total thickness) in coastal cliffs north of the bay of São Martinho do Porto (Fig. 7). The contact with the underlying Dagorda Formation is tectonic in nature, and the basal part of the Alcobaça Formation is brecciated. The section is the type locality of the São Martinho, Gralha and Salgado members established herein (see Appendix). The overlying Arrinhada Member is present, but too poorly exposed for logging.

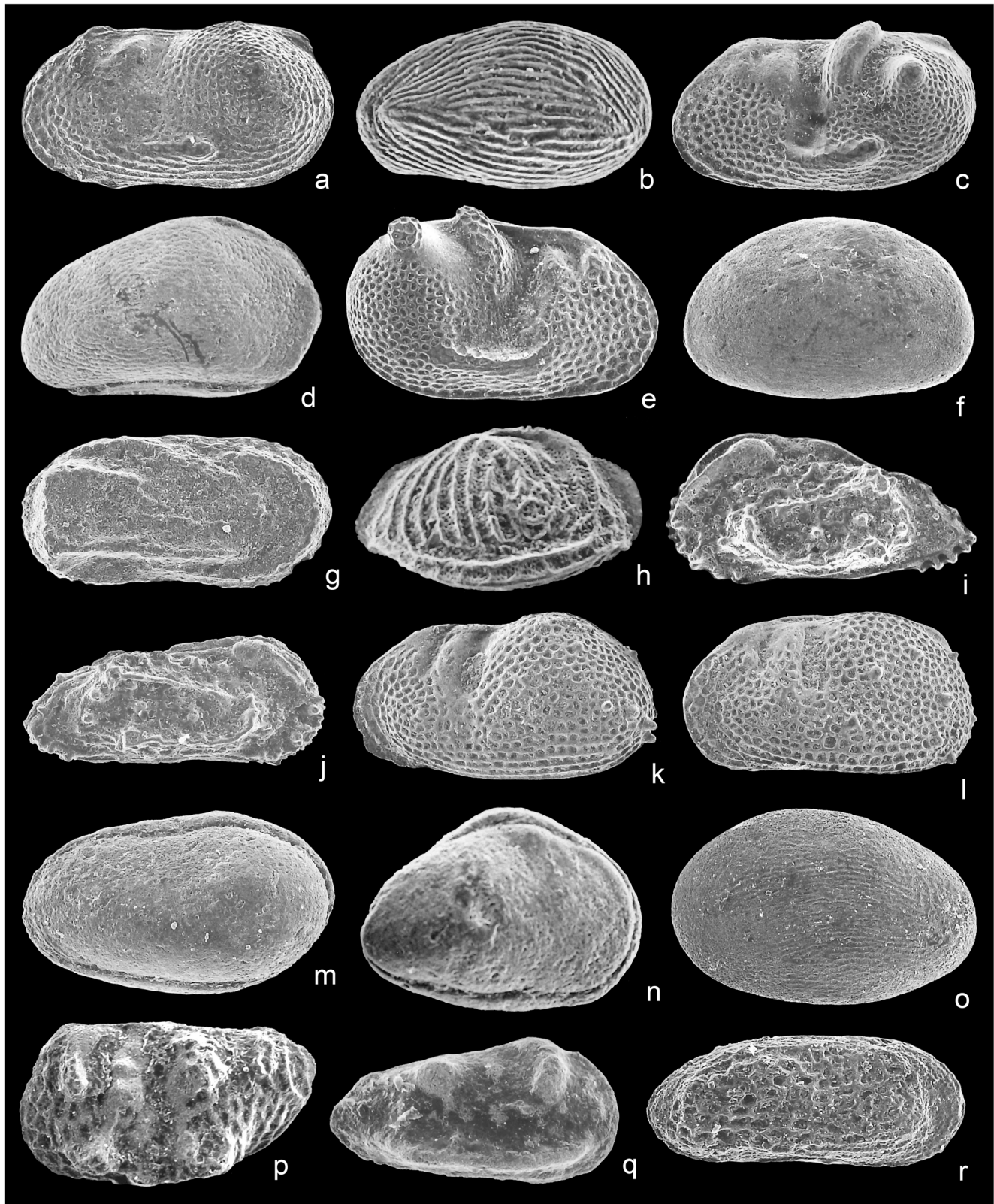
Characteristics: The section starts with 12 m of beige fine- to medium-grained marine sandstones. These are followed by 60 m of limestones, some of which contain varying percentages of silt- to sand-sized quartz grains. The limestones are mainly bioclastic wackestones and floatstones with interspersed intraclastic, bioclastic and ooidal grainstones and contain an abundant autochthonous to parautochthonous bivalve fauna dominated by *Actinostreon* and *Isognomon*, which form biogenic concentrations. Algal laminites occur near the top of

the limestone succession. The carbonate beds are followed by several metres of brackish to marine siliciclastic strata and, subsequently, by a 34-m-thick succession of argillaceous silts and intercalated sandstones (90–124 m; Figs. 7a and 9). A second carbonate intercalation is only 13 m thick (125–138 m) but otherwise resembles the first one in facies and faunal content. The overlying succession starts with a 5-m-thick unit of brackish to freshwater lagoonal sediments, which is superseded by an extensive succession (142–559 m) of non-marine reddish argillaceous to marly silts (Figs. 7a and 9). These commonly contain caliche nodules, some lignite pieces and occasionally the trace fossil *Scoyenia*. Between these fine-grained sediments, fine- to coarse-grained sandstones are intercalated. These exhibit large-scale trough cross-stratification, have an erosional base, fine upwards and change in thickness laterally. They are arranged in several intervals with a broad coarsening-upward trend, topped by medium- to coarse-grained, trough-cross-bedded sandstones. A gradual return to marine conditions is heralded by several brief incursions in the uppermost Gralha Member and becomes evident with the onset of the Salgado Member (559–604 m). From 570 m onwards, fine-grained sandstones, silt, sandy bioclastic grainstones, bioclastic wackestones and nodular bioclastic marlstone alternate. Oncoidal floatstones to rudstones occur at several levels and are characteristic of the member. A trough cross-bedded sandstone bed at 604 m at the top of the log marks the return to dominantly siliciclastic sedimentation.

Fig. 6 Ostracods from the Alcobaça Formation. **a** *Theriosynoecum* sp.; São Martinho Mbr; São Martinho do Porto section, 73 m (A 1/20); $L = 1.28$ mm. **b** *Timiriasevia guimarotensis* Schudack; Gralha Mbr; São Martinho do Porto section, 140 m (A 1/65); $L = 0.46$ mm. **c** *Theriosynoecum wyomingense* (Branson); Gralha Mbr, São Martinho do Porto section; 140 m (A 1/65); $L = 1.17$ mm. **d** *Mantelliana* cf. *perlata* Wienholz; Gralha Mbr; São Martinho do Porto section, 140 m (A 1/65); $L = 0.89$ mm. **e** *Theriosynoecum wyomingense* (Branson); Vestiaria Mbr; Fonte Santa section, 50 m (A 8/1); $L = 0.97$ mm. **f** *Cetacella striata* (Helmdach); Vestiaria Mbr; Fonte Santa section, 50 m (A 8/1); $L = 0.74$ mm. **g** *Cytherelloidea* aff. *weberi* Steghaus; Vestiaria Mbr; Vestiaria section, 59 m (A 15/64); $L = 0.6$ mm. **h** *Poisia bicostata* Helmdach; Vestiaria Mbr; Vestiaria section, 69 m (A 15/78); $L = 0.54$ mm. **i, j** *Klentnicella rodewaldensis* (Klingler); Vestiaria Mbr; Vestiaria section. **i** 73 m; (A 15/84); $L = 0.61$ mm. **j** 73 m; (A 15/84); $L = 0.66$ mm. **k, l** *Bisulcocypsis* aff. *pahasapensis* (Roth); Vestiaria Mbr; Vestiaria section, 393 m (A 15/168). **k** $L = 1.14$ mm. **l** $L = 1.11$ mm. **m** *Cetacella inermis* Martin; Vestiaria Mbr; Vestiaria section, 393 m (A 15/168); $L = 0.68$ mm. **n** *Schuleridea* cf. *minuta* Donze; Consolação Mbr; Consolação section, 2 m (C-1-5); $L = 0.53$ mm. **o** *Cytherella suprajurassica* Oertli; Consolação Mbr; Consolação section, 40 m (C-2-8); $L = 0.66$ mm. **p** *Paranotocythere* sp.; Consolação Mbr; Consolação section, 180 m (C-4-8); $L = 0.4$ mm. **q** *Poisia clivosa* Helmdach; Consolação Mbr; Consolação section, 180 m (C-4-8); $L = 0.5$ mm. **r** *Dicrorygma* (*Orthorygma*) aff. *reticulata* Christensen; Consolação Mbr; Consolação section, 178 m (C-4-6); $L = 0.5$ mm

Interpretation: Over most of its extent, the São Martinho Member (0–142 m) records a shallowing-upward succession, initially dominated by shallow-marine sandstones,

but switching to a carbonate environment at 19.5 m. The algal laminites in the top part of this interval document intertidal conditions, transitioning into brackish



lagoonal (72–90 m) and floodplain environments (90–124 m) up-section, before briefly switching back to carbonate-dominated, very shallow-marine to brackish conditions (124–142 m). The fine-grained sediments of the overlying Gralha Member (142–559 m) are typical floodplain deposits, whereas the intercalated sandstones are the fills of fluvial channels. Comparatively thin coarsening-upward units correspond to crevasse splays or indicate phases of increased sediment input, triggered either by pulses of diapirism or climatic fluctuations. Sporadic, metre-thick grey argillaceous silt intercalations with freshwater gastropods are interpreted as deposits of freshwater lakes or lagoons. Equally thin intercalations containing brackish-water gastropods support the general setting of the succession as an extensive coastal plain. This assumption is also corroborated by 1–2-m-thick beds with marine bivalves and gastropods, as well as trace fossils such as *Psilonichnus*, *Thalassinoides* and *Rhizocorallium* (particularly in the intervals 418–453 m and 412–570 m). The frequent change between non-marine, brackish and fully marine conditions points to environments at the interface between land and sea. From 457 to 526 m, a thick succession of grey fine-sandy marly silt with rare freshwater bivalves, lignite pieces and wood fragments is interpreted as representing a shallow coastal lake. Two intercalated siltstone–sandstone packages most likely correspond to lake shore environments. At 565 m, dinosaur tracks (*Megalosauripus* and *Brontopus*; Neto de Carvalho 2016) are seen on the tops of two successive clearly marine sandy limestone layers, an obvious evidence of very shallow conditions. The trace fossils *Thalassinoides*, *Teichichnus* and *Rhizocorallium*, and stenohaline bivalves, echinoids, corals and gastropods in the overlying mixed carbonate and siliciclastic succession point to fully marine conditions. However, the presence of some brackish bivalves, caliche nodules and a thin intercalation of red beds with *Scoyenia* demonstrate that the shoreline was never very far.

Salir do Porto (SAL; Fig. 10)

Exposure and contacts: The approximately 620-m-thick coastal section of Salir do Porto, extending southward from the bay of São Martinho do Porto, is the thickest exposure of the Alcobaça Formation documented. The basal contact of the Alcobaça Formation with the underlying Dagorda Formation is tectonic. The lowest part of the Alcobaça Formation, including the first carbonate unit of the São Martinho Member, forms a steep sea cliff and was not logged. The following part of the succession is dissected by a number of faults, which made it impossible to log a continuous section. The log is thus composed of two parts, with a 60–90-m-thick faulted interval missing. The logged succession has near-continuous exposure (98%) and covers the São Martinho, Gralha, Salgado and Arrinhada members. The latter has its type locality in the section (see Appendix). The Arrinhada

Member is overlain by coarse-grained fluvial sandstones of the Lourinhã Formation.

Interpretation: Except for the marine to brackish interval of the upper São Martinho Member near the base, the first 400 m of the section represent continental environments of the Gralha Member, for the most part floodplains with scattered ephemeral lakes and small fluvial channels. Most likely, they were part of a coastal plain. This is corroborated by thin intercalations of brackish to marine facies up-section, which are interpreted as lagoonal deposits. As at São Martinho, the sediments are arranged partly in fining-upward packages, partly coarsening-upward packages, documenting either shifting crevasse splays, recurrent pulses of diapirism or freshwater run-off. Small-scale, high-frequency oscillations between marine shoal, lagoonal and mudflat environments are recorded in the top part of the Gralha Member. Marine influence culminates in a relatively short transgressive interval at 496–532 m (Salgado Member). However, birdseyes, a rootlet horizon and desiccation cracks indicate very shallow to supratidal conditions, and for the most part sheltered conditions such as protected bays. In the uppermost 90 m of the succession, which represents the type section of the Arrinhada Member, there is a return to predominantly coastal plain environments with brackish lagoons, small lakes, floodplains, tidal flats and fluvial channels.

Consolação (CON; Fig. 11)

Exposure and contacts: The coastal section at Consolação, close to 200 m in thickness, is well exposed (100%) in low sea cliffs (Fig. 7b, c) and is the type locality of the Consolação Member (see Appendix). The base of the Alcobaça Formation is not exposed. At the top of the unit, the contact with the overlying fluvial sandstones of the Lourinhã Formation is conformable.

Characteristics: Almost the entire succession consists of siliciclastic strata, whereby marly siltstones and fine-grained sandstones commonly form metre-scale coarsening-upward cycles (Fig. 11). Medium-grained sandstones, cross-bedded and

Fig. 7 Examples of logged sections of the Alcobaça Formation. **a** View from south on the lower part of the São Martinho do Porto section, exposing the São Martinho Mbr and the lower part of the Gralha Mbr; member boundary at 137 m, indicated by yellow stippled line. Approximate position of tectonic contact of the Dagorda and Alcobaça formations is indicated by red stippled line. **b** View from south on the middle and upper parts of the Consolação section; foreground: silty sediments characterised by brackish water faunas; background: Peniche peninsula. **c** View from north on the lower part of the Consolação section (ca. 40–70 m). **d** Quarry face exposing the basal carbonate-dominated part of the Sobral da Lagoa section; note dinosaur tracks on the layer top to the right (yellow arrow)





Fig. 8 Key of symbols for logs in Figs. 9, 10, 11, 12, 13, 14, 15, 16 and 17

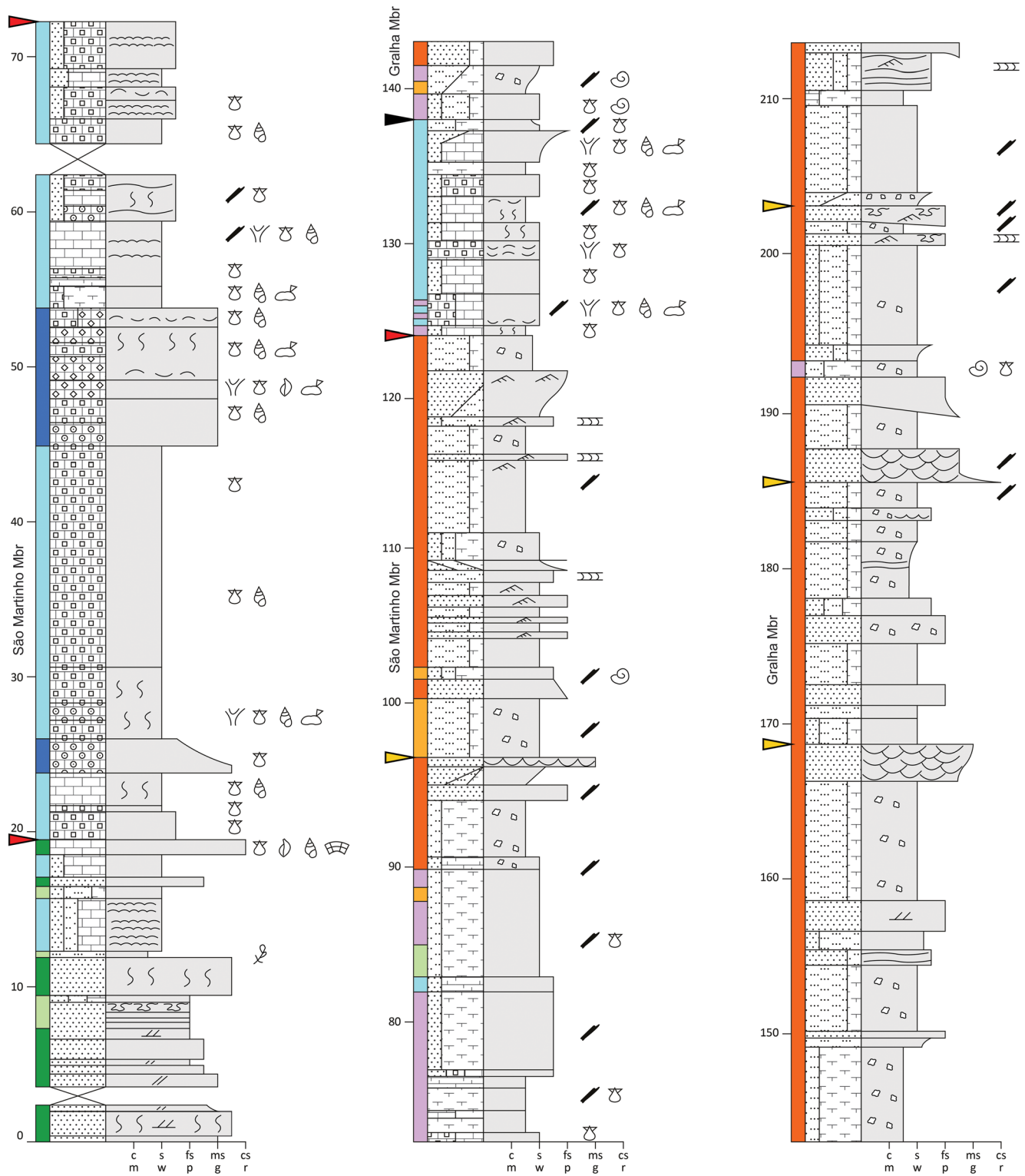


Fig. 9 Schematic log of the São Martinho do Porto section (SAO). See Fig. 8 for the key of symbols

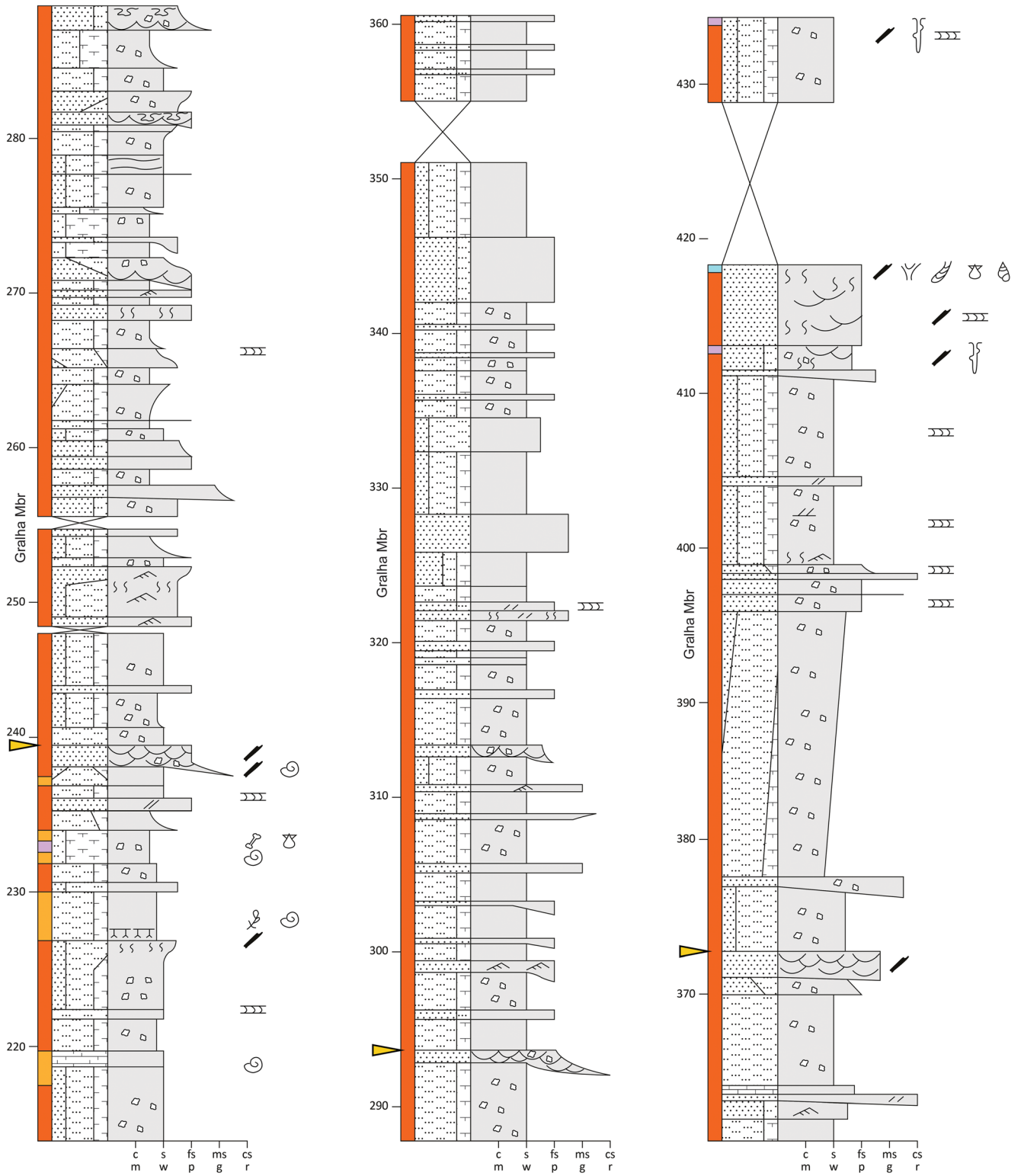


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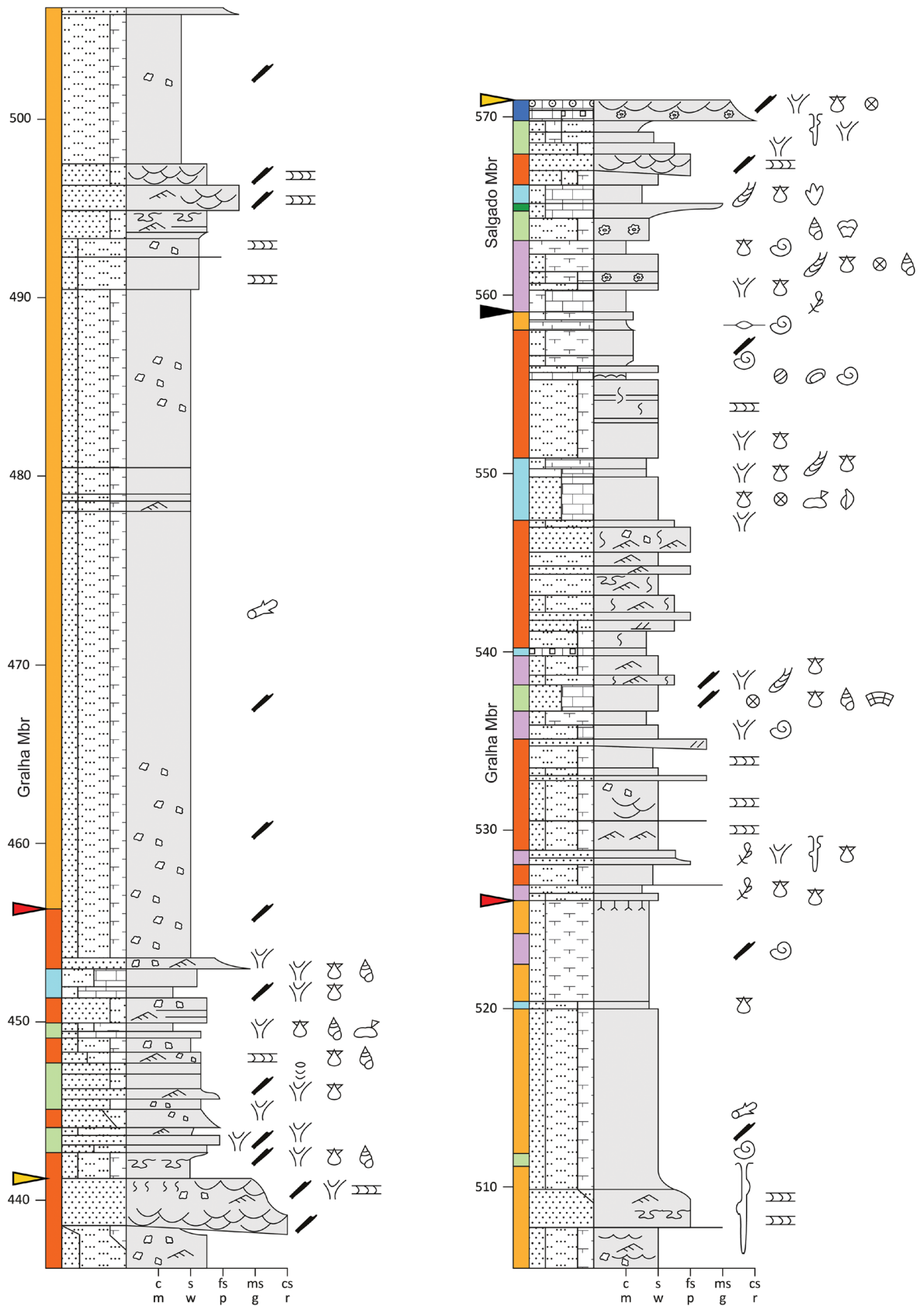


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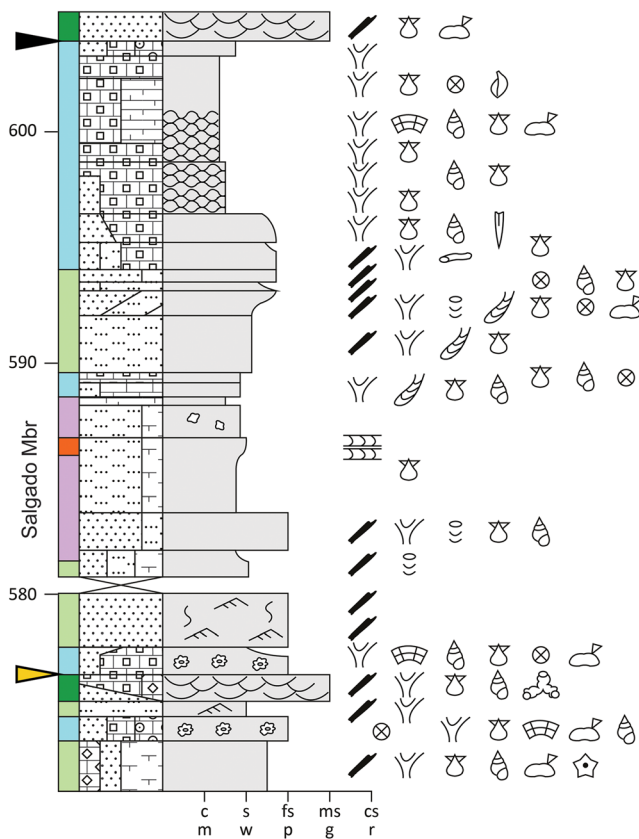


Fig. 9 (continued)

with channelised bases punctuate the section, particularly in the upper part of the succession. The lower 119 m are strongly bioturbated and contain a diverse, fully marine benthic macrofauna with coral meadows, bivalves, gastropods and rare echinoids. Plant debris and the trace fossils *Thalassinoides* and *Rhizocorallium commune* are common. Towards the top of this part of the section, thin packages containing brackish biota become increasingly abundant and dominate from 119 m onwards. Among the benthic macrofauna, gastropods and bivalves prevail, including small patch reefs composed of the oyster *Praeoxgyra* (at 134 m). In the marine lower and middle parts of the section, litiolid foraminifera (e.g. *Alveosepta jaccardi*, *Everticyclammina virguliana*, *Rectocyclammina chouberti*, *Pseudocyclammina parvula*) dominate the microfauna with regard to the number of species and specimens. In the more brackish upper part, assemblages are significantly impoverished in species, often containing only *Pseudocyclammina parvula*, or foraminifera are absent. Ostracod assemblages exhibit a similar development from generally more fully marine taxa (e.g. *Macrodentina tenuistriata*, *Cytherella suprajurassica*, *Schuleridea minuta*) towards more salinity-tolerant or freshwater species in the uppermost part (e.g. *Dicrorygma* (*Orthorygma*) aff. *reticulata*, *Poisia clivosa*) (Helmdach and Werner, unpublished data). Trace fossils include *Thalassinoides*, *Diplocraterion* and *Polycladichmus*. Towards

the top, the species diversity decreases drastically and caliche nodules occur in some layers, partly scattered (e.g. at 172–180 m), partly concentrated in thin conglomerate layers (e.g. at 150 m, 157 m and 167 m).

Interpretation: In general, the Consolação section corresponds to a low- to moderate-energy shallow shelf setting in the lower part (up to 119 m), and a protected nearshore environment with increasing freshwater influence in the upper part. Channel sandstones point to deltaic and tidal influence, and a well-sorted low-angle cross-laminated sandstone has been interpreted as a beach deposit (Werner 1986). Numerous small-scale coarsening-upward cycles document minor fluctuations in sea level, probably relating to pulses of diapirism.

Vestiaria (VES; Fig. 12)

Exposure and contacts: The inland road section of Vestiaria is 403 m thick, but only 47% of its thickness, particularly in the lower 125 m, was exposed when the section was logged; the upper two-thirds have extensive gaps. Acknowledging that Choffat (1885) established the Alcobaca Beds for outcrops in close vicinity, the Vestiaria section is designated as the stratotype of the Alcobaca Formation and of the Vestiaria Member herein (see Appendix). The basal contact of the unit with the underlying Dagorda Formation is tectonic. The contact with the overlying fluvial sandstones of the Lourinhã Formation is conformable.

Characteristics: A 30-m-thick carbonate unit, composed of bioclastic and ooidal wackestones, packstones, and grainstones, containing an abundant marine fauna of corals, sponges, stromatoporoids, echinoids, brachiopods, bivalves and gastropods, occurs at the base of the section. It is followed by several metres of a transitional, but still fully marine facies (fine-sandy marl), which then turns into red non-marine fluvial channel sandstones. From 52 to 70 m, fine-sandy silty marl and marly fine-grained sandstones partly contain freshwater gastropods or brackish-water bivalves. Up-section fine-grained marine siliciclastic sediments with a rich benthic macrofauna including corals, stromatoporoids and echinoids dominate. The benthic microfauna is mainly represented by litiolid foraminifera. Coral meadows occur at two levels (75–79 m and 95 m), as do calcareous sponge meadows (103–105 m). From 107 m onwards, fine-grained greenish siliciclastic rocks, characteristic of brackish environments, prevail. A return to marine carbonate sedimentation is seen from 149 to 154 m. For the remaining succession, outcrops are sporadic (Fig. 12). They show a range of mainly marine siliciclastic and carbonate facies, among them coralline sponge–coral meadows (231–240 m) extending laterally for

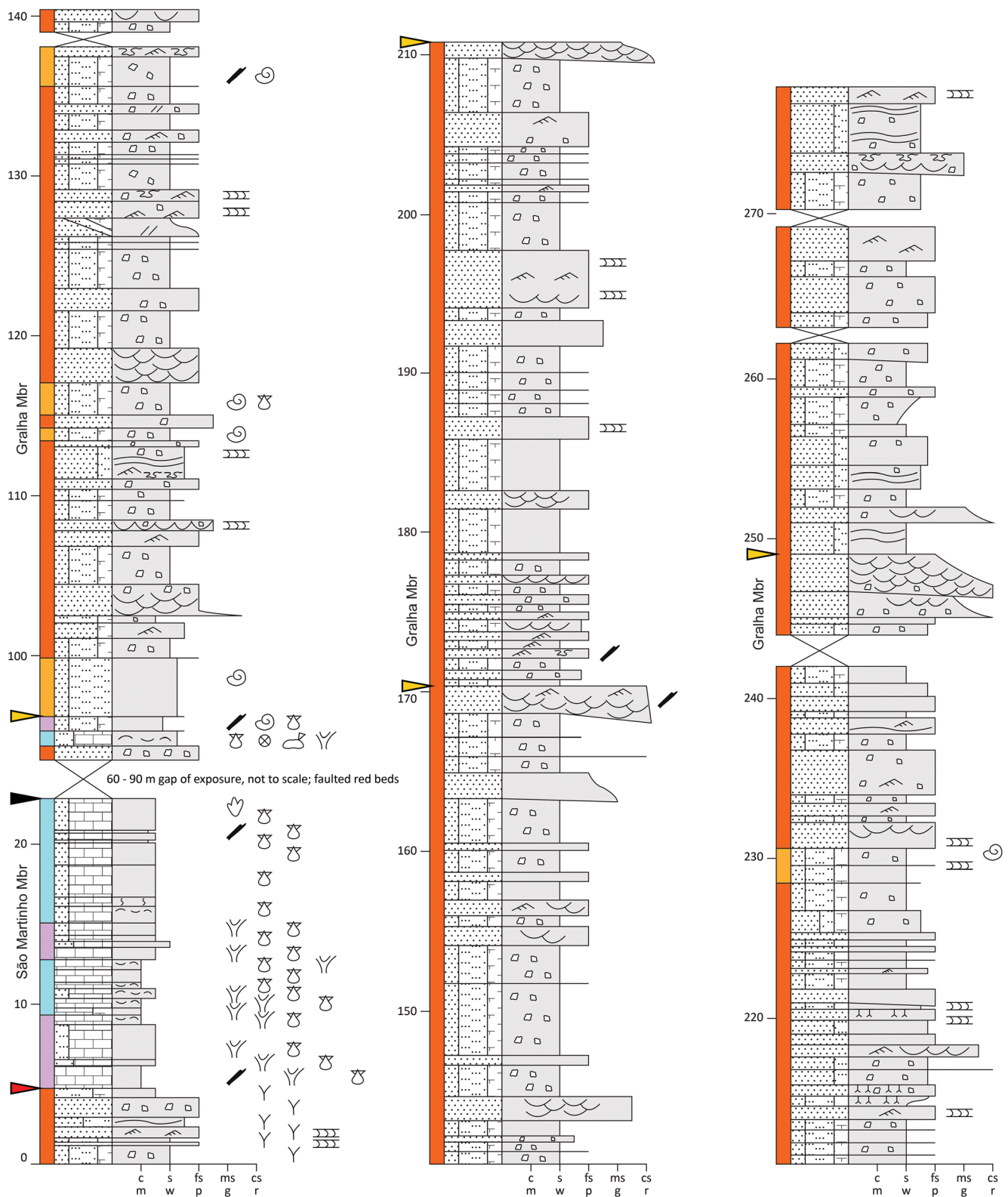


Fig. 10 Schematic log of the Salir do Porto section (SAL). See Fig. 8 for the key of symbols

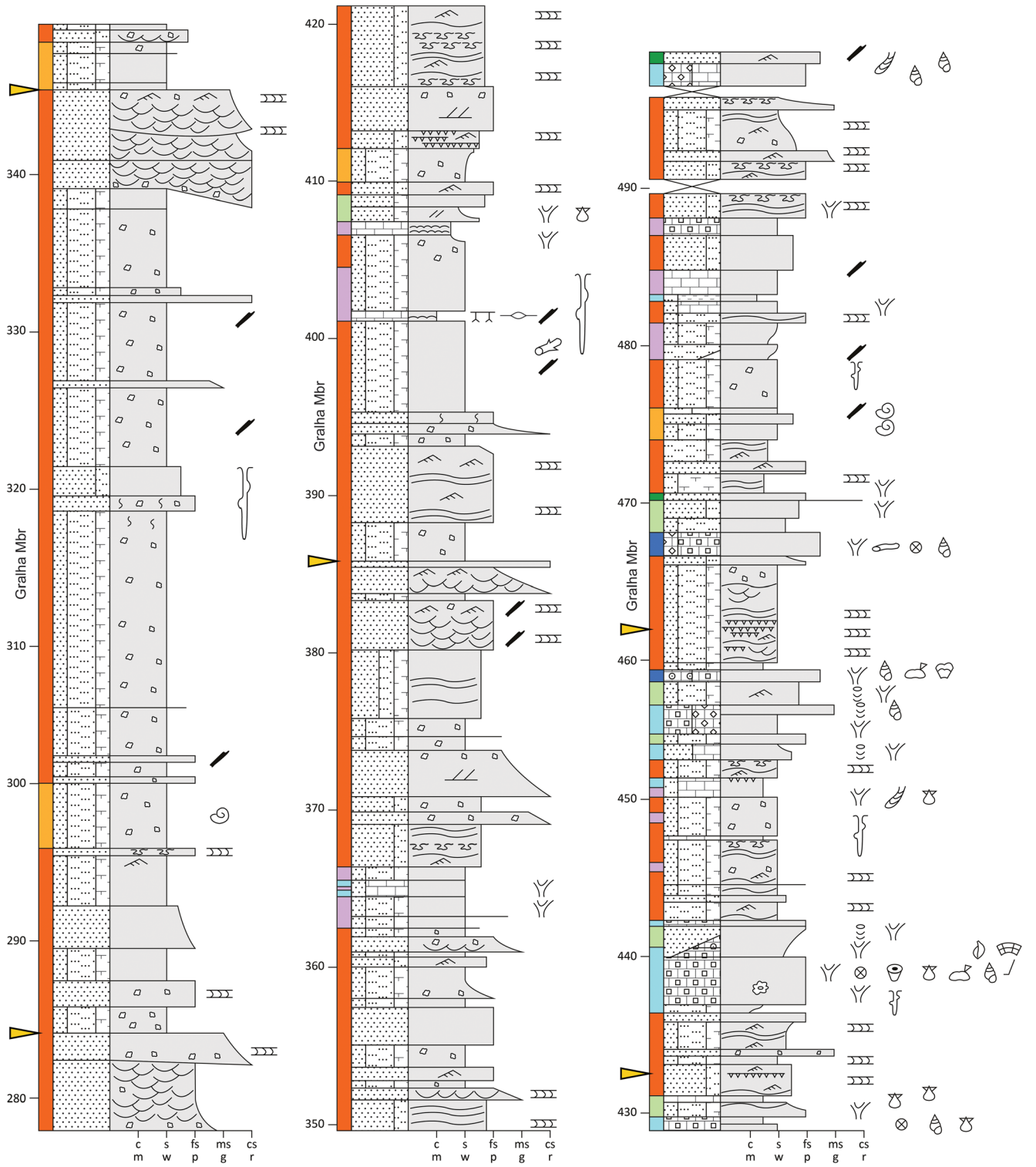


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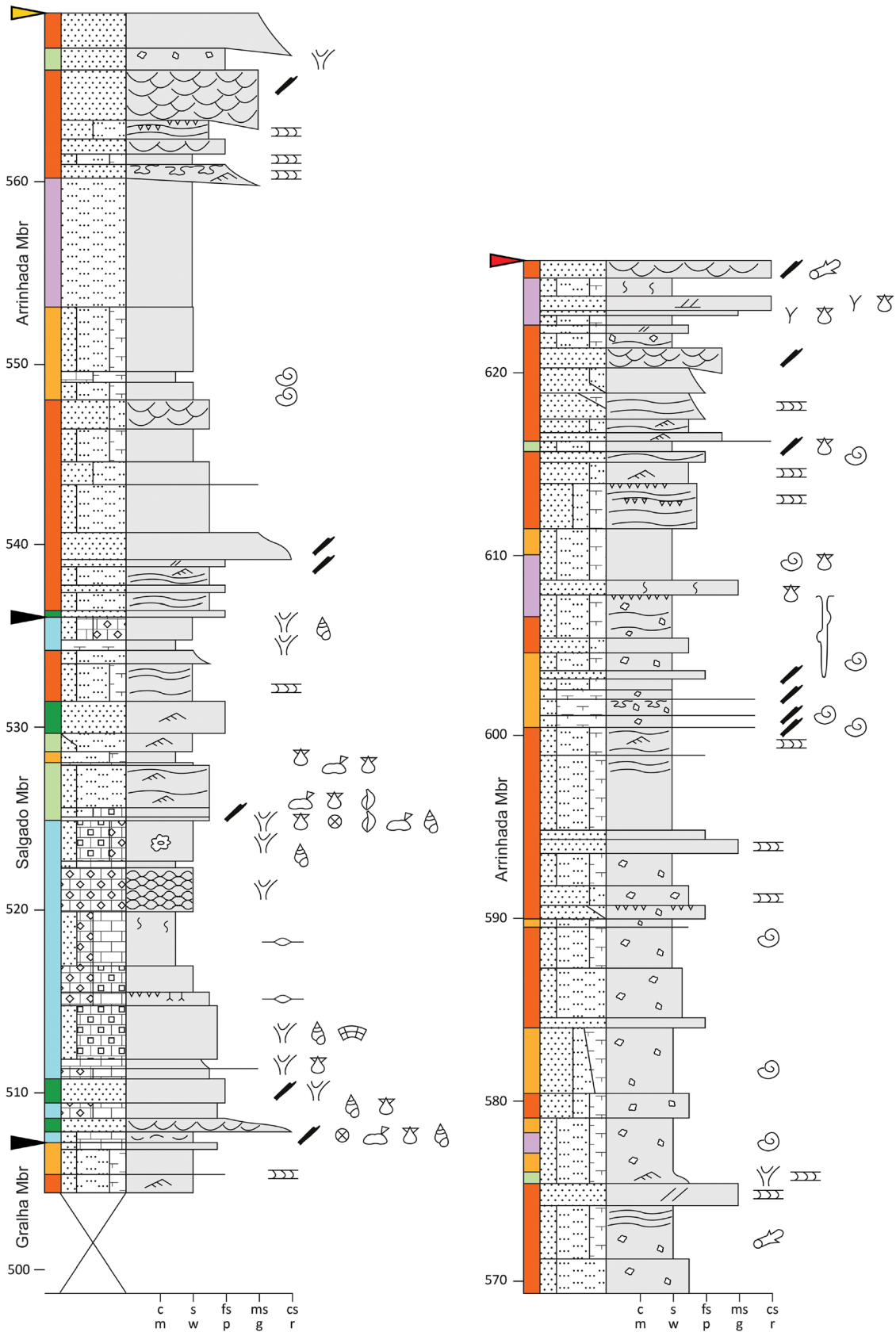


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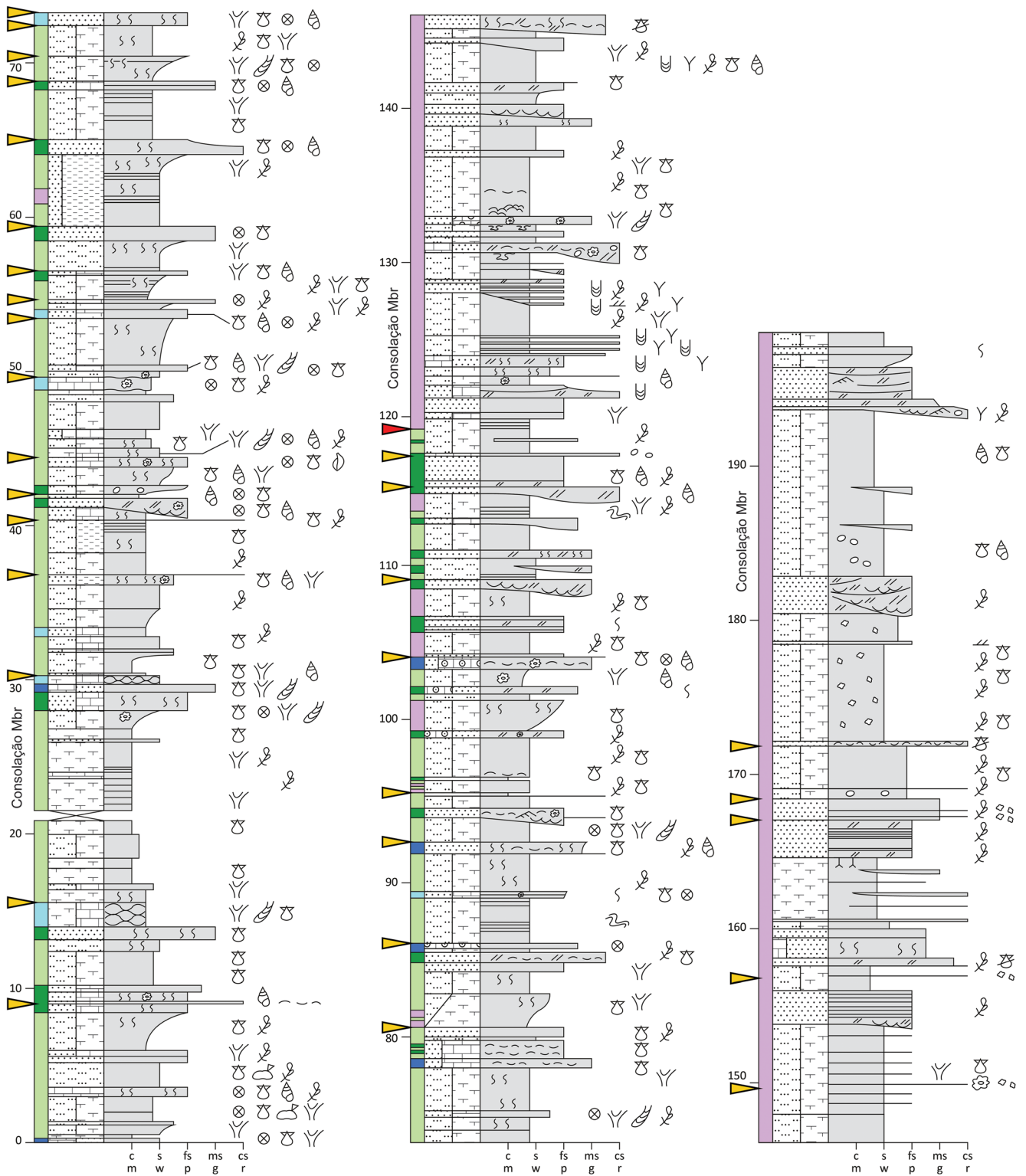


Fig. 11 Schematic log of the Consolação section (CON). See Fig. 8 for the key of symbols

several kilometres (Fürsich and Werner 1991), some brackish silty fine-sandy marl (319–322 m) and a few metres (334–336 m) of silty marl containing remains of freshwater organisms (e.g. gastropods [*Amplovalvata*], ostracods

[*Cetacella*, *Bisulcocypris*] and abundant charophyte gyrogonites). The section concludes with marl containing thin layers of coal and a rootlet horizon, followed by a several-metres-thick trough cross-bedded coarse-grained

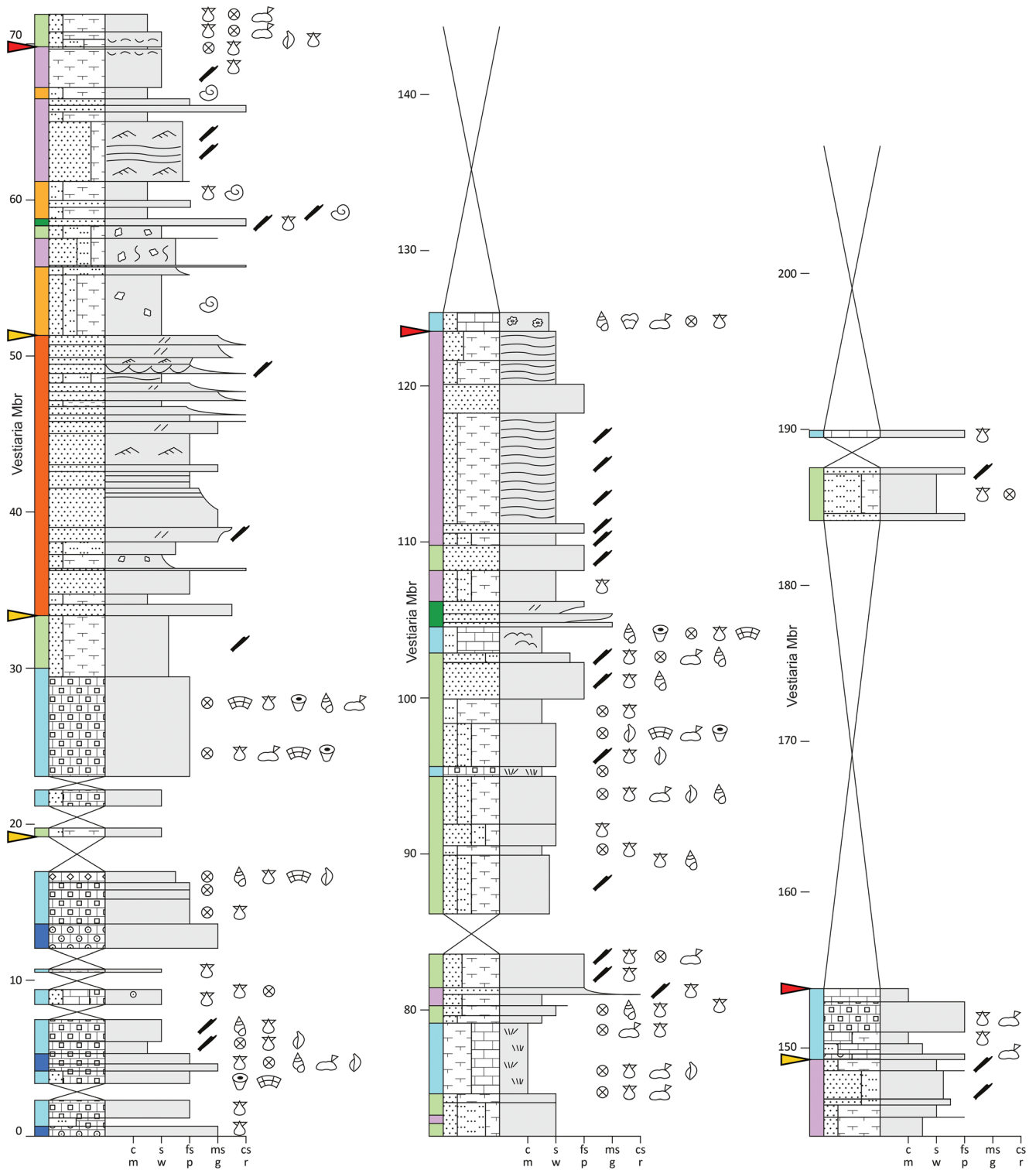


Fig. 12 Schematic log of the Vestiaria section (VES). See Fig. 8 for the key of symbols

sandstone with an erosional base, which is regarded as the basal bed of the Lourinhã Formation.

Interpretation: Similar to other sections, the Vestiaria section shows interbedded shallow shelf, brackish lagoon,

freshwater lagoon and floodplain deposits. The coastal plain must have been very flat and low-lying so that even small-scale sea-level fluctuations, probably mostly driven by diapirism, could produce marked changes in facies.

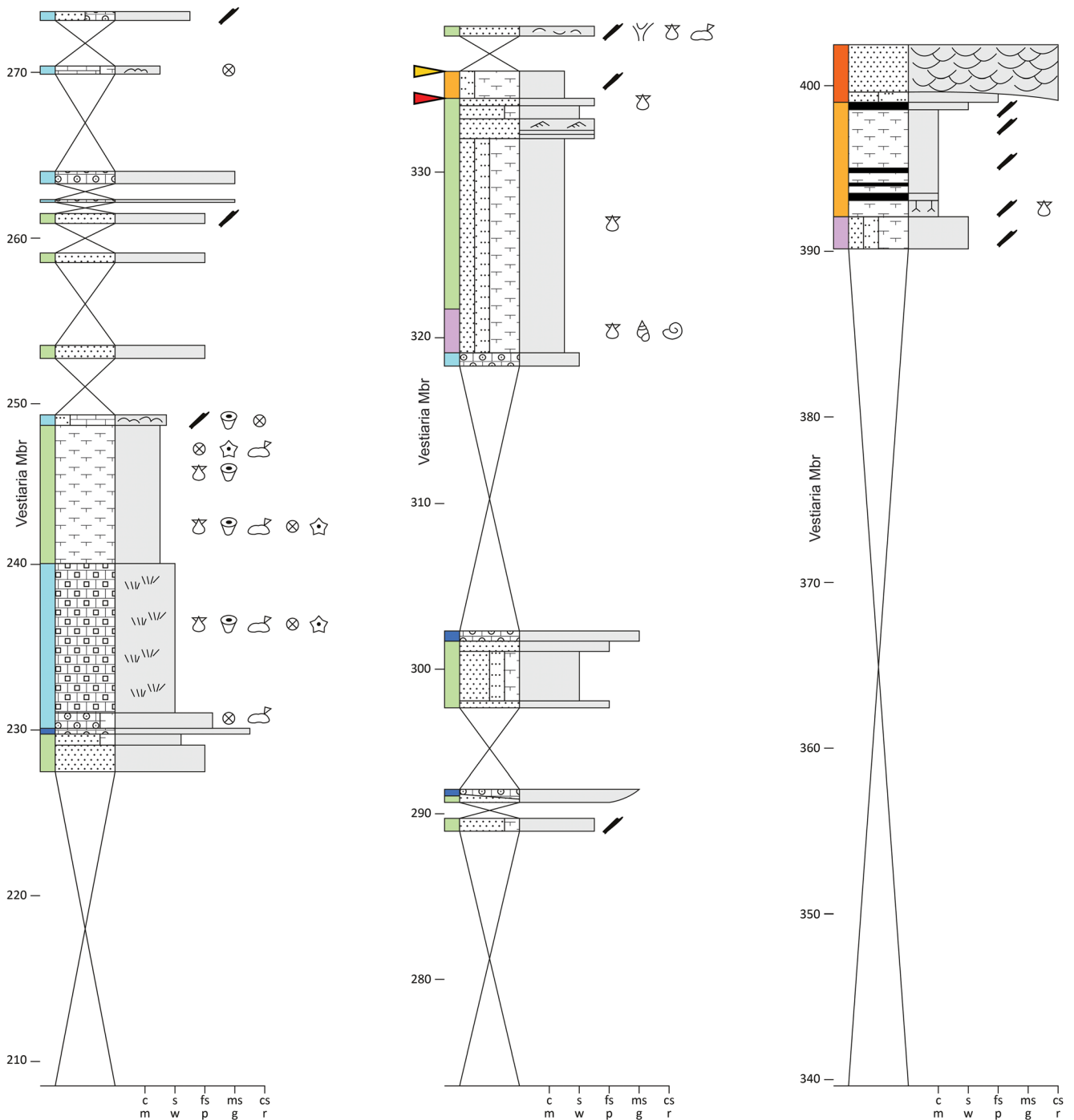


Fig. 12 (continued)

Fonte Santa (FON; Fig. 13)

Exposure and contacts: The Fonte Santa section is an only 106-m-thick road section and has several gaps (66% exposure), which most likely represent fine-grained siliciclastic strata. The succession is assigned to the Vestitaria Member (see Appendix). The basal contact of the Alcobaca Formation with the underlying Montejuento Formation is sharp

and potentially represents a paraconformity. The top of the Alcobaca Formation is not exposed.

Characteristics: While the lower third of the section is composed of carbonate rocks (mainly bioclastic wackestones, more rarely bioclastic–intraclastic grainstones and bioclastic packstones), the middle part is dominated by fine-grained

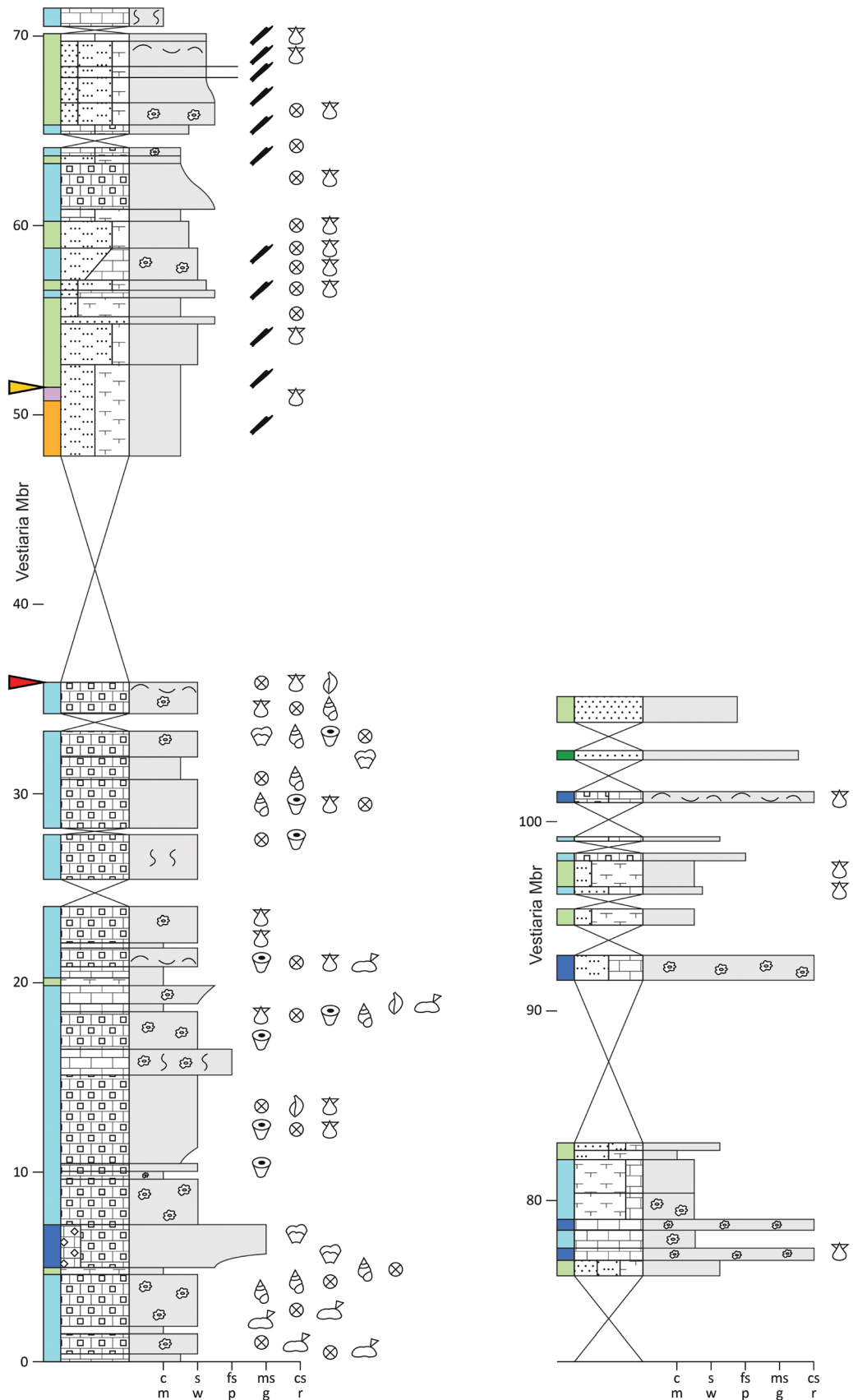


Fig. 13 Schematic log of the Fonte Santa section (FON). See Fig. 8 for the key of symbols

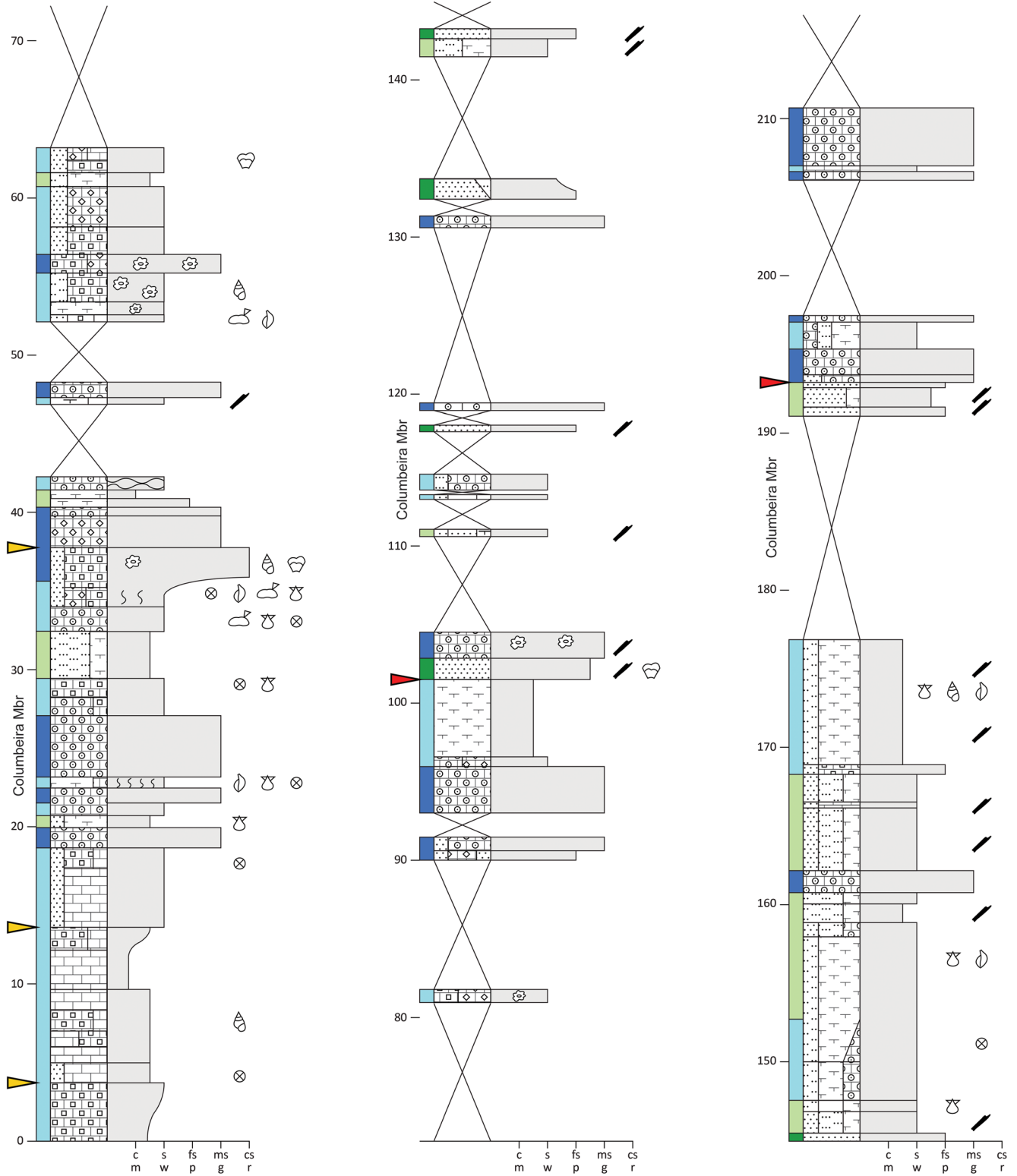


Fig. 14 Schematic log of the Columbeira section (COL). See Fig. 8 for the key of symbols

siliciclastic sediments (marly silt and marly fine-sandy silt with lignite pieces), and the upper third is an alternation of carbonate deposits (oncolidal and bioclastic rudstones, bioclastic packstones and calcareous marlstones) and fine-grained sandstones (Fig. 13). Oncoids are very common, as

are corals, bivalves, sponges, echinoids, brachiopods and red algae. Primary sedimentary structures are absent.

Interpretation: Sediments and benthic macrofauna point to fully marine environments characterised by low to moderate

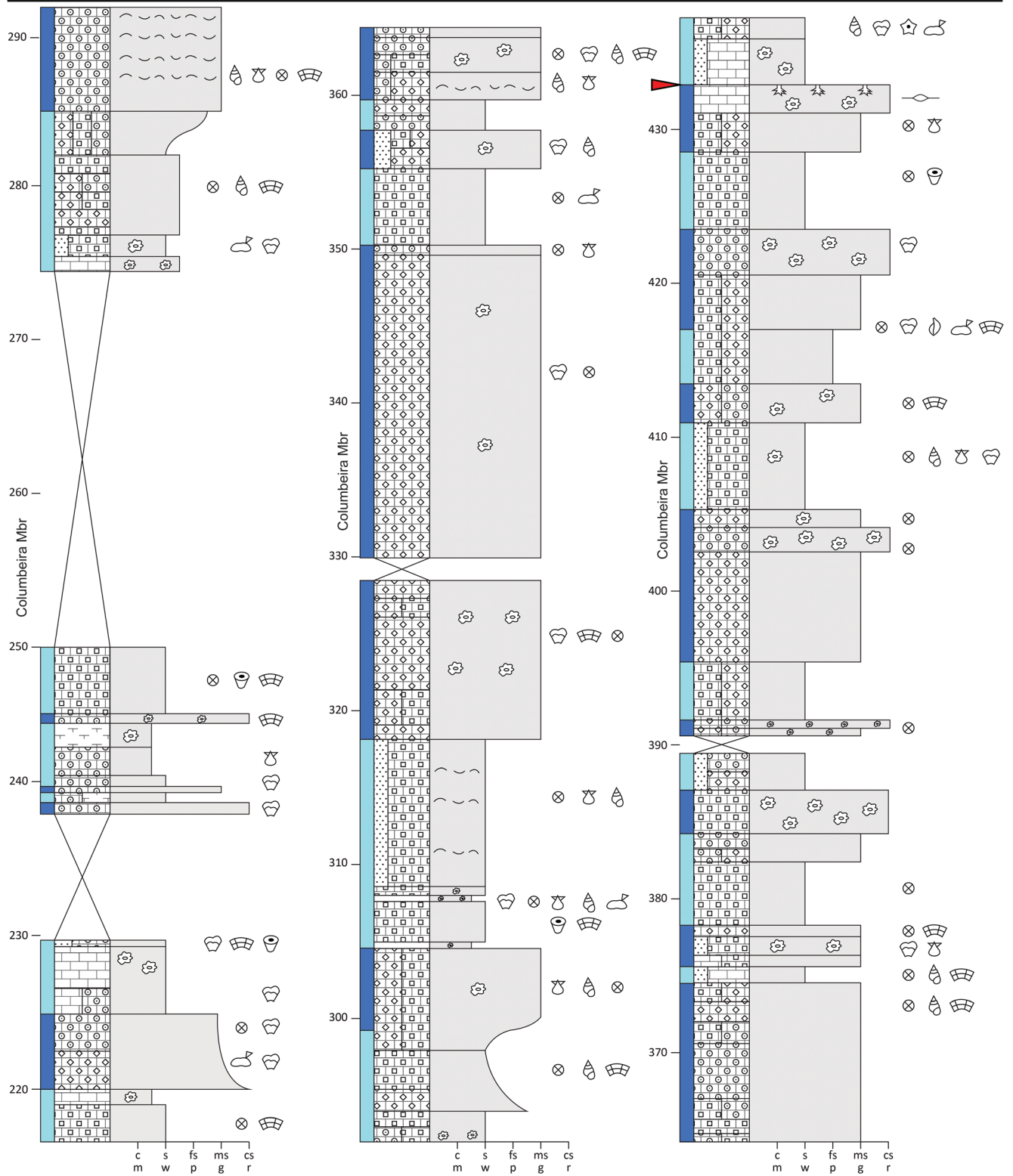


Fig. 14 (continued)

water energy. The few oncoidal rudstone layers most likely represent reworked lagoonal deposits. Environmental fluctuations are mainly expressed in the varying amounts of siliciclastic input, which may be climate related or moderated by diapiric activity.

Columbeira (COL; Fig. 14)

Exposure and contacts: The Columbeira section is a 577-m-thick road section with a total exposure of 68%. The carbonate-dominated succession forms the type locality of

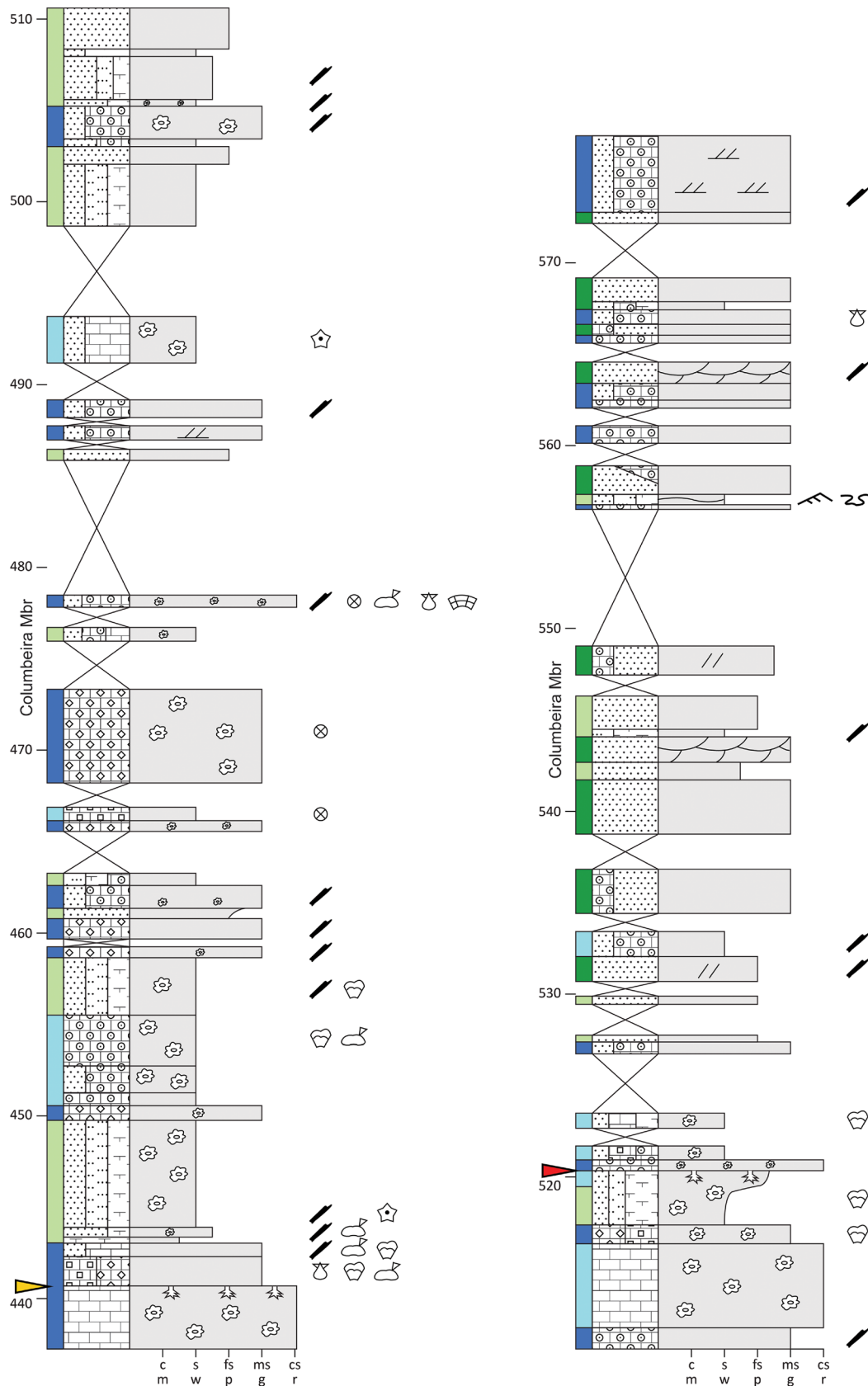


Fig. 14 (continued)

the Columbeira Member (see Appendix). Base and top of the Alcobaça Formation are not exposed.

Characteristics: Although the Columbeira section is generally carbonate dominated, siliciclastic input is evident in two intervals at the base (0–193 m) and the top (442–577 m). In the first 200 m, siliciclastic sediments are mainly fine grained (silty marl to marly silt, oncoïd-bearing sandy marly silt), but in the uppermost 40 m (from 529 m upward), fine- to medium-grained sandstones, partly trough or planar cross-stratified, dominate (Fig. 14). Low-energy carbonate strata consist of mudstones, intraclastic or bioclastic wackestones and oncoïdal floatstones; high-energy carbonate strata are represented by ooida, bioclastic and intraclastic grainstones and oncoïdal rudstones. Large covered intervals, some of them more than 20 m in thickness, probably correspond to soft, fine-grained mixed carbonate–siliciclastic rocks. In the carbonate beds, benthic macrofossils include corals, gastropods, bivalves, cidaroid spines, brachiopods, red algae, sponges and stromatoporoids. In the siliciclastic sediments, the macrobenthic abundance and diversity are lower and the assemblages are composed mainly of bivalves, gastropods, brachiopods, rare crinoid ossicles and echinoid spines. Lignite pieces are restricted to beds with a sizable fraction of siliciclastic components. Polyspecific shell concentrations occur at several levels within the carbonate deposits. Three levels (at 433 m, 441 m and 520 m) show small dissolution cavities, indicative of brief subaerial phases.

Interpretation: The Columbeira section represents shallow-water environments recording numerous short-term alternations between high-energy and low-energy settings. The grainstones and rudstones can be interpreted as shoals and bars, the latter forming barriers, behind which low-energy lagoonal environments existed, in which oncoïds flourished. Within the section, there is a distinct change in the input of siliciclastic material. In the lower part of the section, the siliciclastic input is largely restricted to clay- to silt-sized components. In the middle part, where high-energy platform carbonate strata predominate, it is negligible. In the top 130 m, high-energy siliciclastic strata are common and point to increased input from a close-by source area, driven either by higher freshwater run-off or by increased diapiric activity. The microkarst levels at 433 m, 441 m and 520 m document repeated forced regressions, probably also related to salt tectonics.

Dagorda (DAG; Fig. 15)

Exposure and contacts: Only the lower 96 m of this 364-m-thick section are well exposed, whereas in the remaining part, only half of the strata are exposed (60% total exposure). The covered intervals are probably soft

and, to a large extent, may represent fine-grained mixed carbonate–siliciclastic rocks. The entire succession is assigned to the Columbeira Member. The basal contact of the Alcobaça Formation with the underlying dolomitic marls of the Dagorda Formation is tectonic. The contact to the overlying Lourinhã Formation is obscured.

Characteristics: Except for the interval from 57.5 to 90 m and the uppermost 8 m, where fine- to medium-grained sandstones are fairly common, the succession is dominated by high-energy, partly large-scale trough cross-bedded carbonate strata such as ooida, bioclastic and intraclastic grainstones (Fig. 15). Several of these beds also contain a certain percentage of sand and scattered oncoïds, in addition to a diverse benthic macrobiota of stromatoporoids, red algae, gastropods, bivalves, corals and echinoids. Lignite pieces are comparatively rare. Low-energy carbonate deposits are developed as oncoïdal and bioclastic floatstones and bioclastic and intraclastic wackestones, which may contain variable percentages of sand. A coral biostrome occurs at 235 m. The benthic macrofauna is less diverse than that in the high-energy carbonate beds. Low-energy siliciclastic sediments are represented by fine-grained sandstones, in several cases thinly interbedded with silty marl. Lignite pieces are common. High-energy siliciclastic sediments consist of medium- to coarse-grained sandstones, several of which exhibit large-scale cross-stratification. They occur in relatively widely spaced intervals, often contain a small percentage of ooids and are overlain by ooida grainstones. The most prominent example is a 5-m-thick cross-bedded ooid-bearing coarse-grained sandstone at 84.5 m.

Interpretation: The Dagorda section, dominated by high-energy carbonate strata, depicts fully marine, very shallow environments that were, to a large extent, situated above the fair-weather wave-base. Micritic beds, in turn, were deposited in marine lagoons behind ooida, intraclastic or bioclastic bars. The intermittently introduced siliciclastic material commonly became subsequently mixed with the carbonate matrix. This points to a close source area. Input of sand is short lived and periodic, marking events of high surface run-off and/or diapiric activity.

Sobral da Lagoa (SOB; Fig. 16)

Exposure and contacts: The Sobral da Lagoa section comprises 242 m of sediments, which are assigned to the Columbeira Member. Only the lower 100 m are well exposed (Fig. 7d); in the remaining part, exposed beds and covered intervals are equi-proportional (60% total exposure). The basal contact of the Alcobaça Formation with

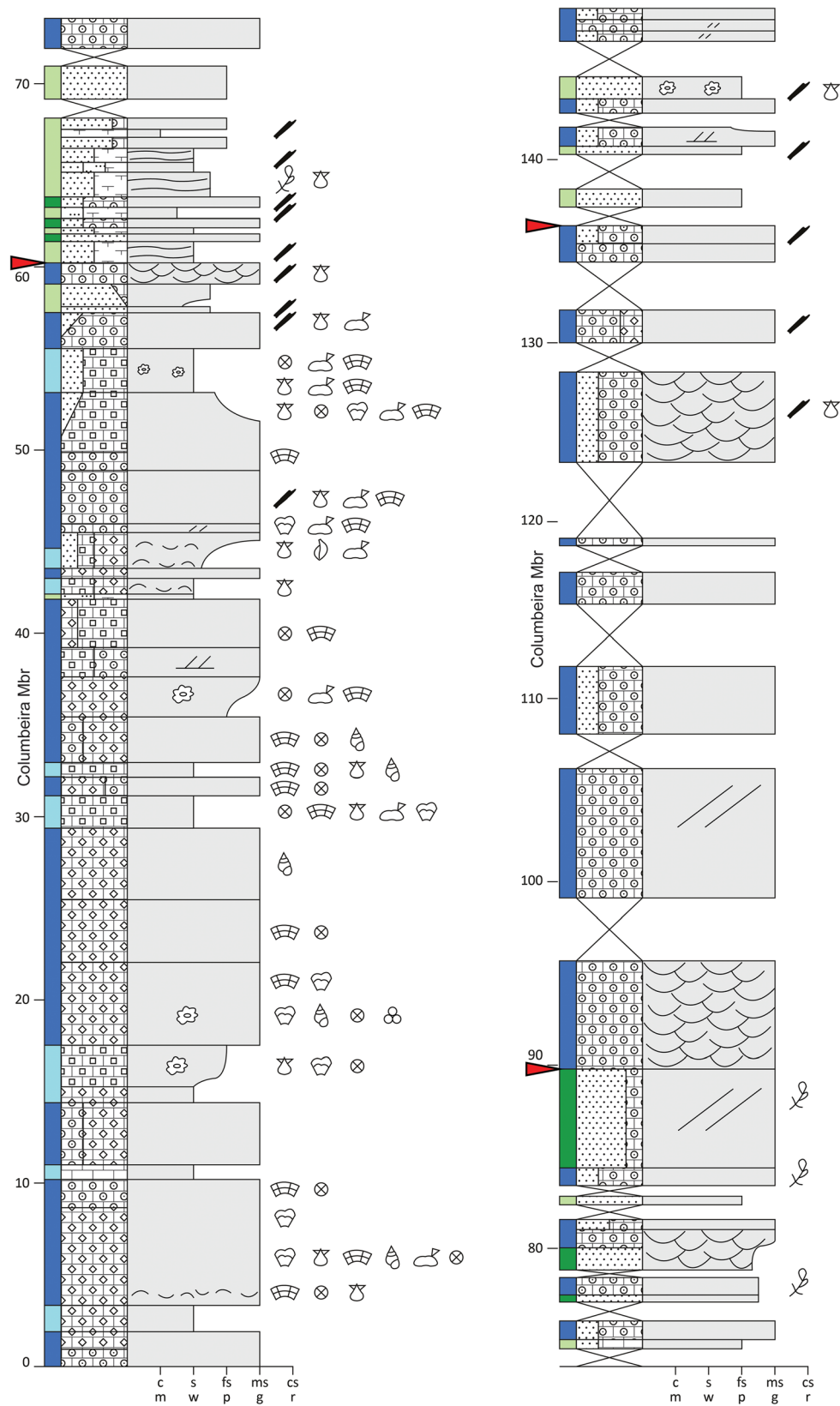


Fig. 15 Schematic log of the Dagorda section (DAG). See Fig. 8 for the key of symbols

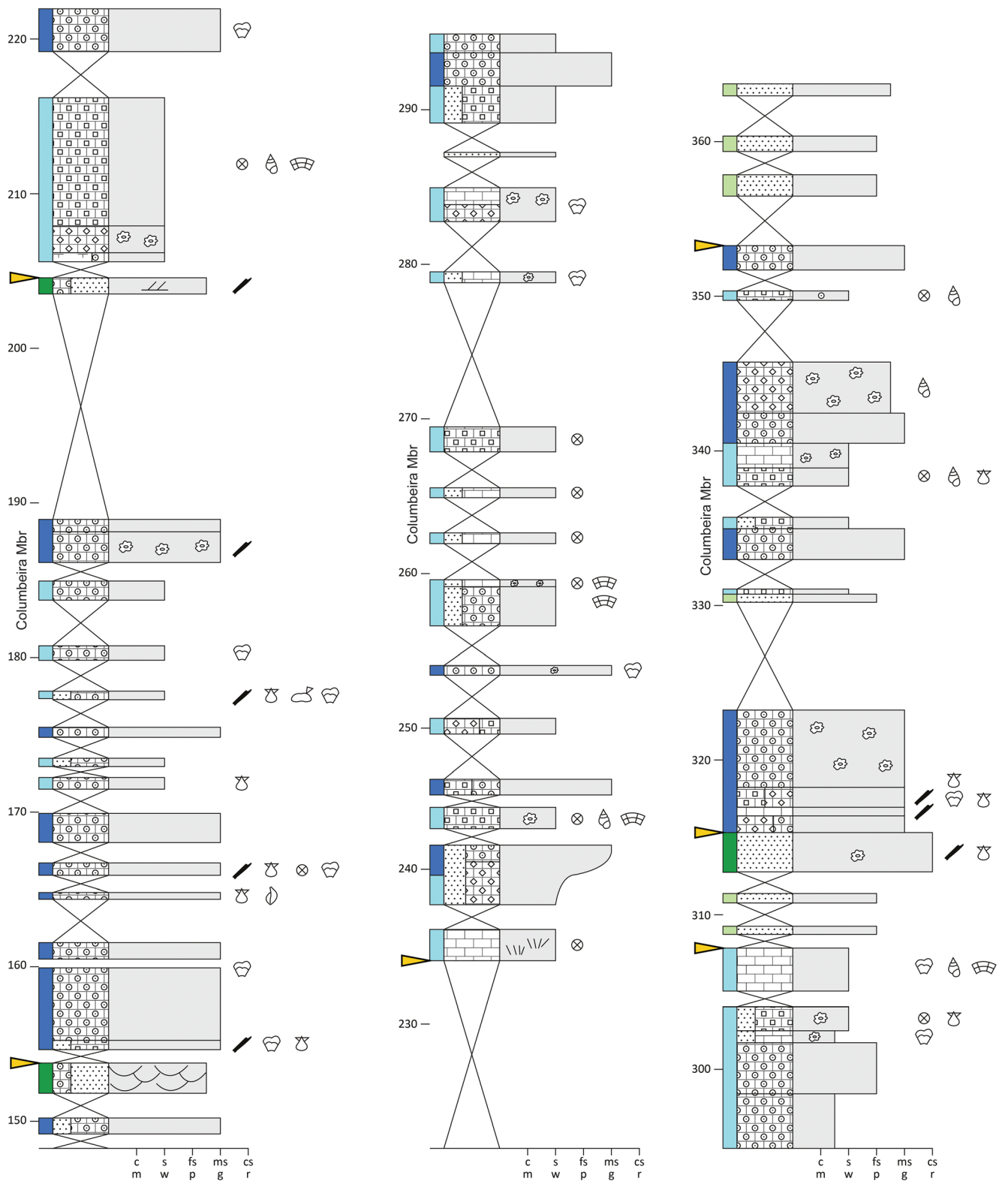


Fig. 15 (continued)

the underlying Middle Jurassic carbonate beds is tectonic, but not exposed. The contact to the overlying Lourinhã Formation is also obscured.

Characteristics: The lower 100 m of the succession consist of carbonate deposits with very minor sand-prone carbonate intervals. Low-energy carbonate rocks dominate (intraclastic and bioclastic wackestones, occasionally also carbonate mudstones, intraclastic or ooidal grainstones and rarely oncoidal rudstones). Scattered lignite pieces occur, as do oncooids. Black pebbles are encountered at six levels (at 3 m, 11 m, 34 m, 36 m, 48 m and 80 m), usually associated with microkarst features. Benthic macrofauna is represented by gastropods, bivalves, stromatoporoids, corals and echinoids. The trace fossil *Thalassinoides* is comparatively rare. Four metres above the base, a sandy carbonate mudstone exhibits dinosaur footprints (Fig. 7d). From 110 to 152 m, fine-sandy siltstones and sandy ooidal packstones are the dominant exposed lithologies. The remaining section consists mainly of high-energy carbonate strata (sandy to silty ooidal grainstones), but some marl and fine-sandy marl intercalations also occur. Plant debris are common in the uppermost 60 m, and another level with black pebbles is found at 227 m.

Interpretation: The section records marine deposition throughout, as demonstrated by the fauna. However, the environments appear to have been mostly very shallow and near-shore, as is indicated by the dinosaur tracks, numerous levels with dissolution cavities indicating emergence and black pebbles that have been eroded from close-by subaerially exposed areas (e.g. Leinfelder 1987). These beds document forced regressions, likely related to salt tectonics or climatic fluctuations.

Amoreira (AMO; Fig. 17)

Exposure and contacts: The 206-m-thick Amoreira section is an only intermittently exposed (36% of total thickness) road section, assigned to the Columbeira Member. The covered intervals most likely correspond to soft marly/silty horizons. The basal contact of the Alcobaça Formation with the underlying dolomitic marls of the Dagorda Formation is tectonic, but not exposed. The contact to the overlying Lourinhã Formation is also obscured.

Characteristics: The exposed section starts with high-energy (oncoidal–intraclastic grainstones, oncoidal–ooidal grainstones) and low-energy (mudstones, bioclastic or ooidal wackestones, intraclastic packstones) carbonate deposits, occasionally with an admixture of fine quartz grains. Towards

the top, the proportion of siliciclastic rocks increases. These are represented by fine- to coarse-grained sandstones and, at the top, by several metres of sandy marly siltstones (Fig. 17). The high-energy carbonate and siliciclastic strata commonly exhibit large-scale trough or planar cross-stratification. In the carbonate beds, stromatoporoids, red algae, corals and gastropods are the dominant fossils, whereas in the siliciclastic sediments, bivalves prevail.

Interpretation: The section represents fully marine, shallow-water, nearshore environments, situated partly above and partly below the fair-weather wave-base. Dissolution cavities in the basal biograinstones are evidence of a brief subaerial phase. Several beds with black pebbles and common lignite pieces indicate the proximity to land areas and, together with short-lived events of increased input of sand, document environmental fluctuations driven by dynamic diapirism and/or climate.

Biofacies associations and palaeoenvironments

A schematic overview of the biofacies of the Alcobaça Formation and their characteristics is provided in Table 1.

Floodplain with overbank deposits (BA1)

Features: This biofacies association dominates in the coastal cliffs north and south of São Martinho do Porto (SAO and SAL sections; Figs. 9, 10 and 18h). The prevalent rock colour is red, but purplish, turquoise and violet colours are also present. The generally fine-grained sediments are poorly sorted, consisting mainly of a mixture of clay and silt with varying admixtures of micaceous fine sand and carbonate. Scattered, cm-sized caliche nodules are very widespread. Thin, laterally continuous calcrete layers are rare (Fig. 19g). The fine-grained sediments are punctuated by thin siltstone and sandstone intercalations that exhibit ripple lamination, rarely parallel lamination and, in some cases, convolute bedding, likely related to dewatering. Caliche nodules are commonly concentrated at the usually sharp bases of such intercalations. Rarely, rootlet traces are preserved in the sandstone intercalations. In addition, desiccation cracks occur in several beds. Interlayered bedding is occasionally present. *Scoyenia* is the only trace fossil present; body fossils are absent.

Interpretation: The fine-grained sediments represent floodplain deposits; the red colour and the abundant pedogenic carbonate facies point to a semi-arid climate (e.g. McPherson 1979; Rao 1990). The coarser

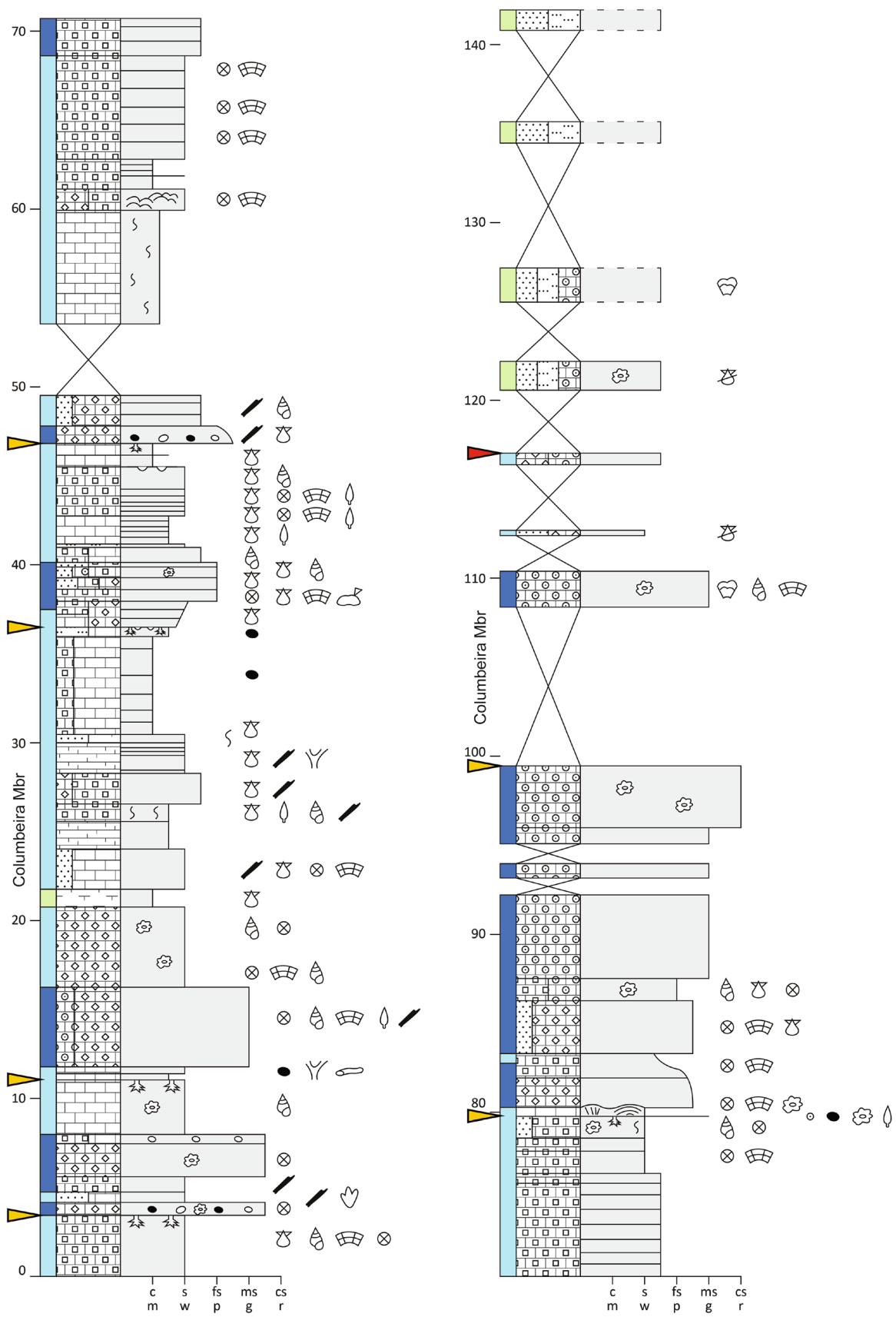


Fig. 16 Schematic log of the Sobral da Lagoa section (SOB). See Fig. 8 for the key of symbols

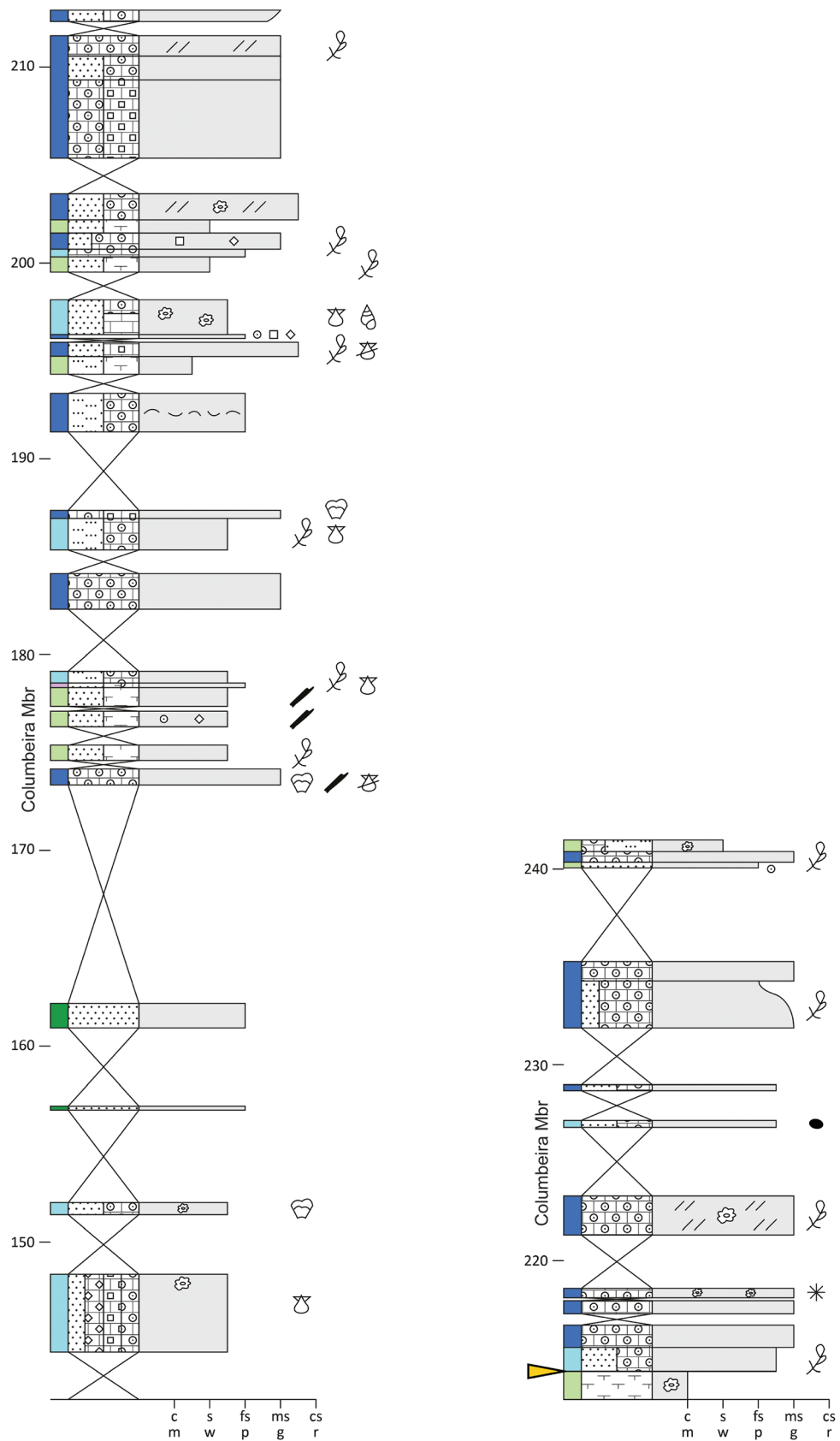


Fig. 16 continued.

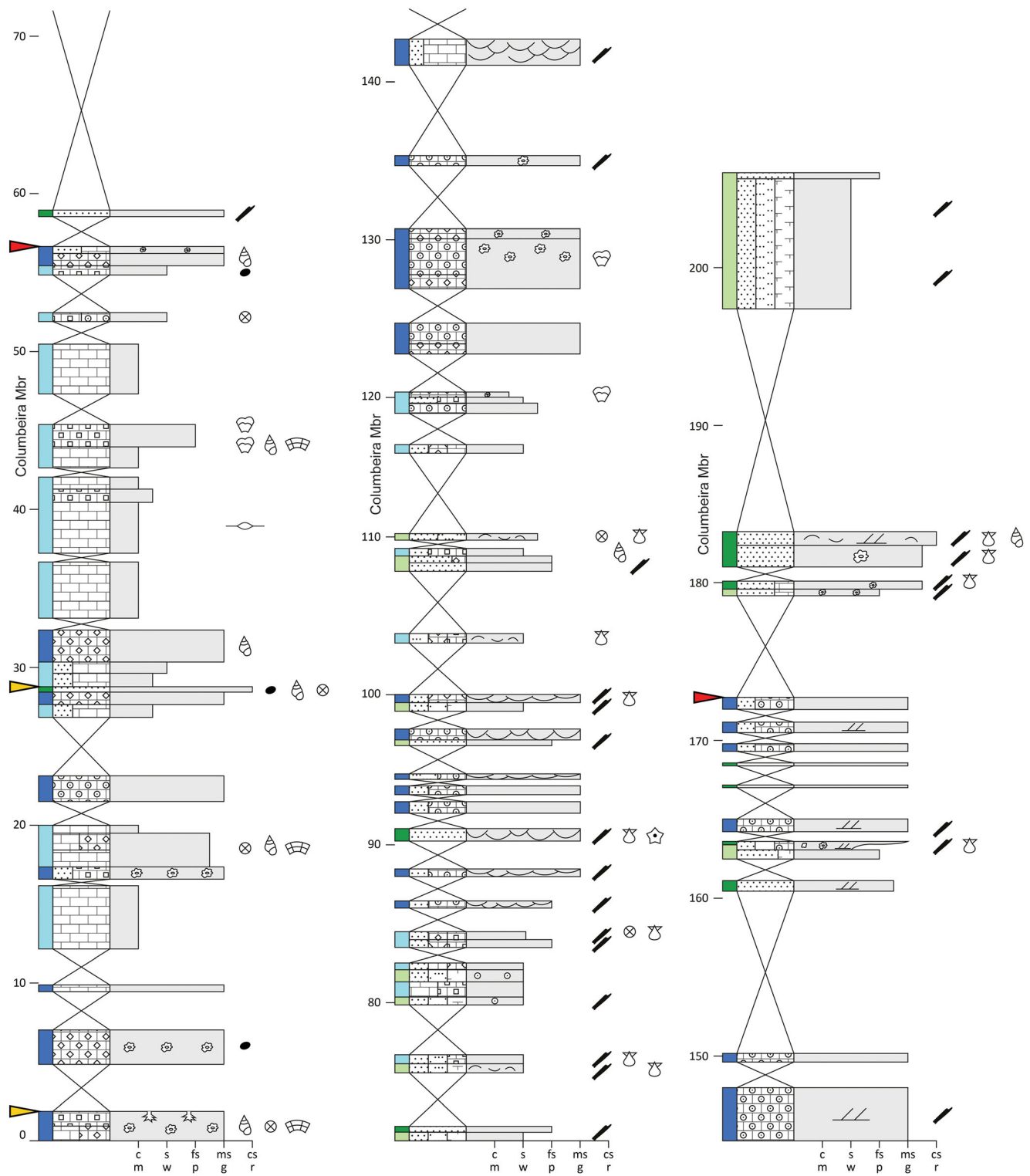


Fig. 17 Schematic log of the Amoreira section (AMO). See Fig. 8 for the key of symbols

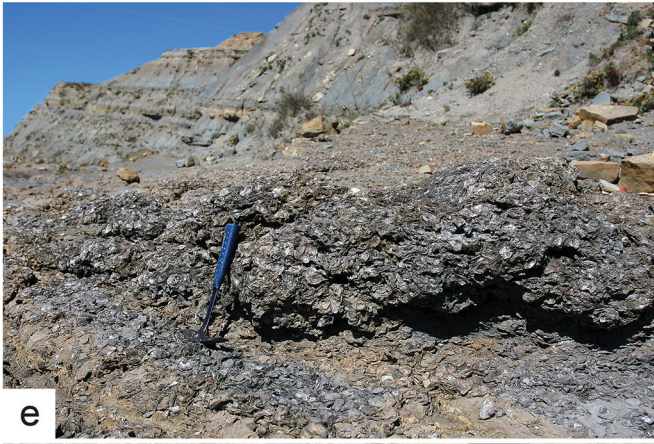
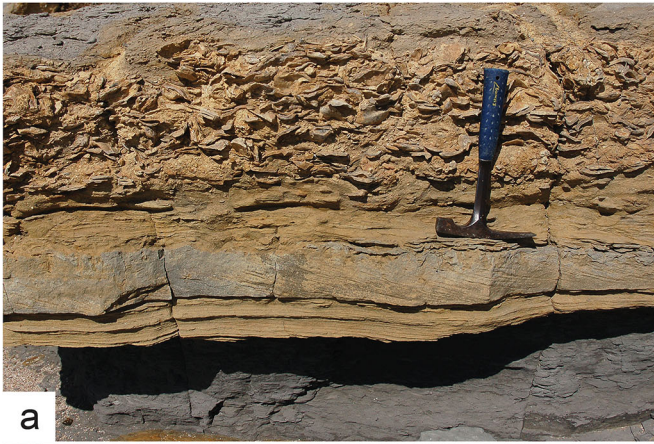
Table 1 Biofacies associations of the Alcobaca Formation, their most important features and palaeoenvironments

Biofacies association	Lithologies	Bedding features, sedimentary structures, diagenetic features	Body fossils, trace fossils	Palaeoenvironment
(1) Reddish fine-grained siliciclastic rocks with <i>Scoyenia</i>	Argillaceous silt (a); mixture of fss-silt-clay (a); fss; silty fss; css (r)	Desiccation cracks (r); trough cross-stratification (o); ripple lamination (o); interlayered bedding (o); convolute bedding (r); caliche nodules (a)	Bone fragments (r); rootlets (o); wood fragments (o); lignite pieces (o); plant fragments (r); <i>Scoyenia</i> (c); <i>Psilonichnus</i> (r)	Flood plain with overbank deposits; coastal plain
(2) Reddish fine- to coarse-grained sandstones	fss; mss; css; conglomerate consisting of caliche nodules (o)	Large-scale trough cross-stratification (a); planar cross-stratification (r); ripple lamination (c); convolute bedding (r) erosional base (a); normal grading (a); caliche nodules (a)	Wood fragments (r); lignite pieces (o); <i>Scoyenia</i> (c)	Channels and levee deposits of predominantly low-sinuosity streams
(3) Grey fine-grained siliciclastic rocks with varying amounts of carbonate	Mixture of fss-silt-marl (a); fss (r); siltstone (r); marly micrite (r); marls (r); coal (r)	Caliche nodules (o); ripple lamination (r); convolute bedding (r)	Rootlets (r); plant fragments (r); lignite pieces (c); <i>Scoyenia</i> (o); freshwater gastropods (o); bivalves (r)	Very shallow freshwater lakes and swampy areas; freshwater lagoon
(4) Marine low-energy siliciclastic rocks with varying amounts of carbonate	Marl (o); marly silt (o); marly fss (o); fine-sandy marly silt (o); silty fss (o); bioclastic marly fss (r); fine-sandy oolitic silt (r); silty clay (r); fss (o)	Interlayered bedding (r); ripple lamination (r); slumping (r); convolute bedding (r)	Lignite pieces (a); plant fragments (c); <i>Thalassinoides</i> (c); <i>Rhizocorallium commune</i> (o); <i>Teichichnus</i> (r); red algae (r); sponges (r); corals (c); bivalves (c); gastropods (c); echinoids (r); crinoids (r)	Low-energy shelf (below fair-weather wave-base); protected bay; protected embayment
(5) Marine high-energy siliciclastic rocks with varying amounts of carbonate	fss; mss; css; oolitic mss (o); oncolithic fss (r); oncolithic css (r); bioclastic mss (o)	Ripple lamination (r); large-scale trough cross-stratification (c); planar cross-stratification (s); small channels (o); thin shell concentrations (o)	Lignite pieces (c); plant fragments (r) <i>Thalassinoides</i> (o); <i>Rhizocorallium commune</i> (r); bivalves (c); gastropods (o); corals (o)	Shallow, open marine shelf, partly above the fair-weather wave-base; shoals and bars; channels
(6) Marine low-energy carbonate rocks with varying portions of siliciclastic content	Carbonate mudstone; marly carbonate mudstone; sandy carbonate mudstone; silty oncolithic mudstone; sandy ooidal wackestone; sandy ooidal–bioclastic wackestone; sandy intraclastic–bioclastic wackestone; sandy bioclastic wackestone; sandy intraclastic–ooidal–bioclastic wackestone; sandy oncoidal–bioclastic wackestone; sandy oncoidal–ooidal wackestone; sandy intraclastic wackestone; marly bioclastic wackestone; oncoidal–intraclastic wackestone; intraclastic–ooidal wackestone; ooidal wackestone; bioclastic wackestone; bioclastic floatstone; oncoidal floatstone; oncoidal–intraclastic floatstone; oncoidal–bioclastic floatstone; intraclastic–ooidal floatstone; sandy intraclastic–oncoidal floatstone; silty marly oncoidal floatstone; silty ooidal wackestone; bioclastic packstone; sandy bioclastic	Birdseyes (r); nodular texture (o); dissolution cavities (r); desiccation cracks (r); black pebbles (r)	Plant debris (r); lignite pieces (o); red algae (o); <i>Teichichnus</i> (r); <i>Psilonichnus</i> (r); <i>Planolites</i> (r); <i>Thalassinoides</i> (o); <i>Rhizocorallium commune</i> (r); <i>Zoophycus</i> (r); sponges (r); stromatoporoids (o); corals (c); bivalves (c); gastropods (c); belemnites (r); brachiopods (r); crinoids (o); echinoids (o)	Low-energy shelf; shallow protected shelf below fair-weather wave-base; marine lagoon

Table 1 (continued)

Biofacies association	Lithologies	Bedding features, sedimentary structures, diagenetic features	Body fossils, trace fossils	Palaeoenvironment
(7) Marine high-energy carbonate rocks and mixed	packstone; ooidal packstone; oncooidal–intraclastic packstone; intraclastic–bioclastic packstone; sandy packstone; oncooidal marlstone; oncooidal rudstone; marly oncooidal rudstone; coral boundstone; algal bindstone; silty–sandy algal bindstone; sandy bioclastic algal bindstone siliciclastic–carbonate rocks	Oncoidal–intraclastic packstone; intraclastic grainstone; ooidal grainstone; bioclastic grainstone; intraclastic–bioclastic grainstone; oncooidal–bioclastic grainstone; oncoidal–intraclastic grainstone; oncoidal–ooidal grainstone; oncoidal–intraclastic–bioclastic grainstone; sandy oncoidal grainstone; sandy oncoidal–intraclastic grainstone; bioclastic rudstone; oncooidal rudstone; ooidal–oncooidal rudstone; sandy oncooidal rudstone	Large-scale trough cross-stratification (c); large-scale planar crossstratification (o); dissolution features (o); black pebbles (o); glauconite (r)	Plant fragments (r); lignite pieces (o); <i>Thalassinoides</i> (r); red algae (c); stromatoporoids (r); corals (o); bivalves (c); gastropods (o); brachiopods (r); echinoids (o)
Open marine high-energy shelf, predominantly above fair-weather wave-base; e.g. coastal bars and shoals	Marl; sandy marl; marly silt; silt/siltstone; argillaceous silt; sandy argillaceous silt; bioclastic wackestone; silty fss; fss; mss; css	Large-scale trough cross-stratification (o); large-scale planar cross-stratification (o); ripple lamination (o); channel structures (o); interlayered bedding (o); desiccation cracks (r); convolute bedding (o); caliche nodules (r)	Plant fragments (o); wood fragments (r); lignite pieces (c); rootlets (r); <i>Thalassinoides</i> (c); <i>Zoophycus</i> (o); <i>Rhizocorallium commune</i> (r); <i>Psilonichmus</i> (o); brackish bivalves (a); brackish gastropods (o); freshwater gastropods (o)	Brackish embayments; brackish lagoons

fss fine-grained sandstone, mss medium-grained sandstone, css coarse-grained sandstone, (r) rare, (o) occurring, (c) common, (a) abundant



◀ **Fig. 18** Outcrop features of the Alcobaça Formation. **a** *Alaperna polita*–*Pteria credneriana* shell bed resting on cross-bedded sandstone; Consolação Mbr; Consolação section, 94 m. **b** *Alaperna polita* shell bed, bedding plane view; Consolação Mbr; Consolação section, 74 m. **c** Oncoid rudstone, bedding plane view; Salgado Mbr; São Martinho do Porto section, 578 m. **d** Nerineoidea-rich bioclast floatstone, bedding plane view; Salgado Mbr; São Martinho do Porto section, 576 m. **e** Low-diversity oyster patch reef dominated by *Praeoxogyra pustulosa*; Consolação Mbr; Consolação section, 133 m. **f** Loosely packed *Actinostreon gregareum* shell bed, bedding plane view; São Martinho Mbr; São Martinho do Porto section, 52 m. **g** Coral meadow dominated by *Calamophylliopsis* partly preserved in growth position; Consolação Mbr; Consolação section, 6 m. **h** Reddish silty floodplain deposits grade upwards into offset lateral accretion packages, truncated by a thin overbank/channel margin sheet sandstone; Gralha Mbr; São Martinho do Porto section, Facho promontory

intercalations are crevasse splay deposits, an interpretation supported by their sharp bases and normal grading. The rare rootlet horizons may correspond to vegetated areas of the floodplain during brief time intervals of higher humidity. Such red beds also occur, albeit not as extensive, in other parts of the Lusitanian Basin, for example in the Sobral member of the Farta Pao Formation (sensu Schneider et al. 2009) at Santa Cruz (Fürsich 1981a). Occasional marine or brackish intercalations suggest that the sediments formed on an extensive coastal plain bordered by lagoons and brackish bays.

Fluvial channel fills (BA2)

Features: Varicoloured, but mainly reddish fine- to coarse-grained, occasionally conglomeratic, arkosic sandstones, ranging from a few decimetres to approximately 3 m in thickness, occur intercalated between the floodplain biofacies (BA1; Fig. 18h). Their base is invariably sharp and often erosional, cutting into the underlying fine-grained sediments. Some of the sandstones are lenticular, others are laterally continuous. The base is commonly conglomeratic and consists of reworked caliche nodules. In several cases, intraformational sandstone or siltstone pebbles and, in a single case, quartz pebbles are present. Sandstones often fine upward. Sedimentary structures include large-scale trough cross-stratification, rarely planar cross-stratification, ripple cross-lamination and, in the upper part, convolute bedding and, more rarely, finely interlayered bedding. In a single case (SAL section at 250 m; Fig. 10), several channels form an amalgamated unit. Small lignite pieces are occasionally concentrated at the base, and fine plant debris covers some foresets. *Scoyenia* is a common trace fossil in the finer-grained upper levels. The only body fossils are rare bone fragments.

Interpretation: Given that gravel bars as well as point bars are absent, the sandstone bodies represent the fills of small, presumably mainly straight-headed to slightly meandering streams, which crossed the floodplain. Conglomeratic channel lags with caliche nodules are indicative of meandering or sweeping low-gradient settings, which cannibalised pedogenic overbank floodplain facies. Rare planar cross-bedded sandstones are interpreted as small sand bars. Levee deposits are represented by the finer-grained top parts of many of the packages, which occasionally exhibit interlayered bedding (cf. Miall 1996).

Lake deposits (BA3)

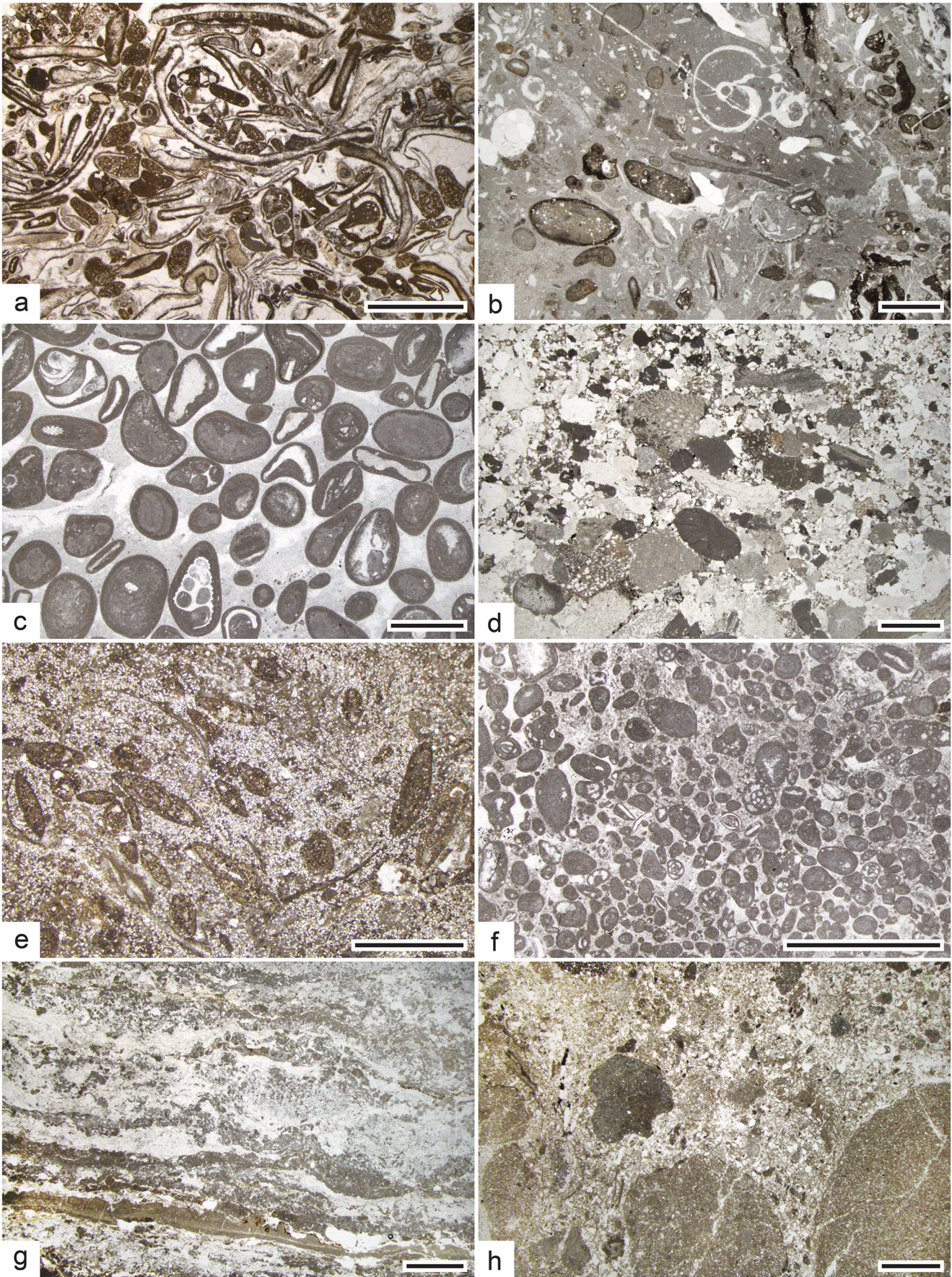
Features: Lake deposits are mainly grey to greenish grey and are dominated by fine-sandy, marly silt. Rarely they consist of calcareous marl and occur intercalated between floodplain deposits of the coastal sections. Generally, they are only a few metres thick but may extend for more than 60 m in the São Martinho do Porto section (from 456 to 520 m; Fig. 9). They commonly contain scattered caliche nodules, plant fragments, lignite pieces and, in one case, wood fragments up to 1 m in length. Rootlet horizons are rare. A several-metres-thick succession of cross-bedded fine- and medium-grained sandstones with *Scoyenia* occurs within the thick lacustrine succession mentioned above. Decimetre-thick coal layers, associated with rootlet horizons, have been encountered only at the top of the Vestiaria section (Fig. 12 at 393–398 m).

Poorly preserved unionid bivalves and gastropods (e.g. *Ptychostylus*, *Amplovalvata*, *Planorbis*), fish scales, ostracods (e.g. *Theriosynoecum*, *Bisulcoocypris*) and charophyte gyrogonites occur and locally are common (Fig. 20d, e).

Interpretation: The fine-grained sediments differ from floodplain deposits by their grey colour and fossil content. The freshwater molluscan and ostracod fauna indicates lacustrine environments of deposition. Their limited vertical extent suggests deposition in small, shallow lakes and, in some cases, also in freshwater lagoons. Rootlets, as well as the coal layers associated with lignite-rich marl at Vestiaria, denote swampy areas at the lake margins, or gradual drying of the lakes. The thick lake sediment interval in the São Martinho do Porto section most likely represents a larger lake. The coarsening-upward siltstone–sandstone package occurring in this succession corresponds to a small delta complex with delta-front sediments and a distributary channel.

Low-energy siliciclastic to mixed carbonate–siliciclastic open shelf deposits (BA4)

Features: As is commonly the case in the geological record (e.g. Lomando and Harris 1991), many of the lithologies in



◀ **Fig. 19** Typical microfacies of the Alcobaça Formation. **a** Intraclastic–bioclastic rudstone with coated grains, lituolid foraminifera, gastropods and quartz; Salgado Mbr; São Martinho do Porto section, 578 m (A-4-8). **b** Bioclastic wackestone to floatstone; Vestiaria Mbr; Vestiaria section, 5 m (A-15-5). **c** Poorly winnowed oncoidal grainstone; predominant nuclei of oncoids are the red alga *Marinella*, echinoid spines and gastropods; Columbeira Mbr; Columbeira section, 239 m (A-28-87). **d** Medium- to coarse-grained sandstone with pebbles and bioclasts (e.g. *Marinella*, calcareous sponge); Vestiaria Mbr; Vestiaria section, 56 m (A-15-59). **e** Sandy siltstone with lituolids; Gralha Mbr; São Martinho do Porto section, 418 m (A-3-18). **f** Ooidal–oncoidal grainstone with abundant lituolid and miliolid foraminifera; Columbeira Mbr; Amoreira section, 6 m (A-21-2). **g** Caliche with fenestral fabric; Gralha Mbr; São Martinho do Porto section, 555 m (A-3-97). **h** Polymict conglomeratic sandstone with algal debris and lignite; Gralha Mbr; São Martinho do Porto section, 452 m (A-3-44). Scale bars = 2 mm

the marine part of the Alcobaça Formation are not purely siliciclastic but contain variable amounts of carbonate material, either components (ooids, bioclasts, intraclasts) or micrite. At the scale of the facies association, compositional mixing dominates (Chiarella et al. 2017), although stratal mixing is also widespread. Lithologies range from marly silt and mica-rich silt to fine-sandy siltstone, marly fine-grained sandstone and bioturbated fine-grained sandstone, the latter partly containing intraclasts or bioclasts (Fig. 19e). Plant fragments and lignite pieces are common; occasionally, convolute bedding is present, as is rare thinly interlayered bedding. Most of these sediments are bioturbated. Trace fossils include *Thalassinoides*, *Rhizocorallium commune* and *Teichichnus*.

Benthic organisms include lituolid foraminifera (e.g. *Alveosepta jaccardi*, *Everticyclammina virguliana*), burrowing bivalves (e.g. *Mesosacella*, *Corbulomima*), oysters, occasional gastropods, brachiopods, echinoids (spines) and rare corals.

Interpretation: The various lithologies mentioned above represent low-energy environments of the shallow open shelf below the fair-weather wave-base, but within the reach of weak storms and/or episodic longshore currents that now and then introduced sediment by bed-load transport, which subsequently became bioturbated. Occasionally occurring interlayered bedding possibly points to a certain tidal influence or else records the influence of distal storm flows. Overall, the sedimentation rate was fairly low, so that siliciclastic material commonly became mixed with fine-grained carbonate components.

High-energy siliciclastic to mixed carbonate–siliciclastic open shelf deposits (BA5)

Features: High-energy siliciclastic sediments are represented by fine- to coarse-grained arkosic to quartzose sandstones, which exhibit large-scale planar or trough cross-stratification

and ripple cross-lamination. Sorting ranges from poor to well sorted. Occasionally, the sandstones are gravelly or conglomeratic and lenticular in nature. Pebbles are intraformational and consist of siltstone or sandstone (Fig. 19h), but gravel consists of well-rounded quartz grains. Lignite flakes and plant debris are common. Carbonate clasts (intraclasts, ooids, bioclasts, rarely oncoids or other coated grains) are commonly associated with the siliciclastic material, and the cement is sparite (Fig. 19d).

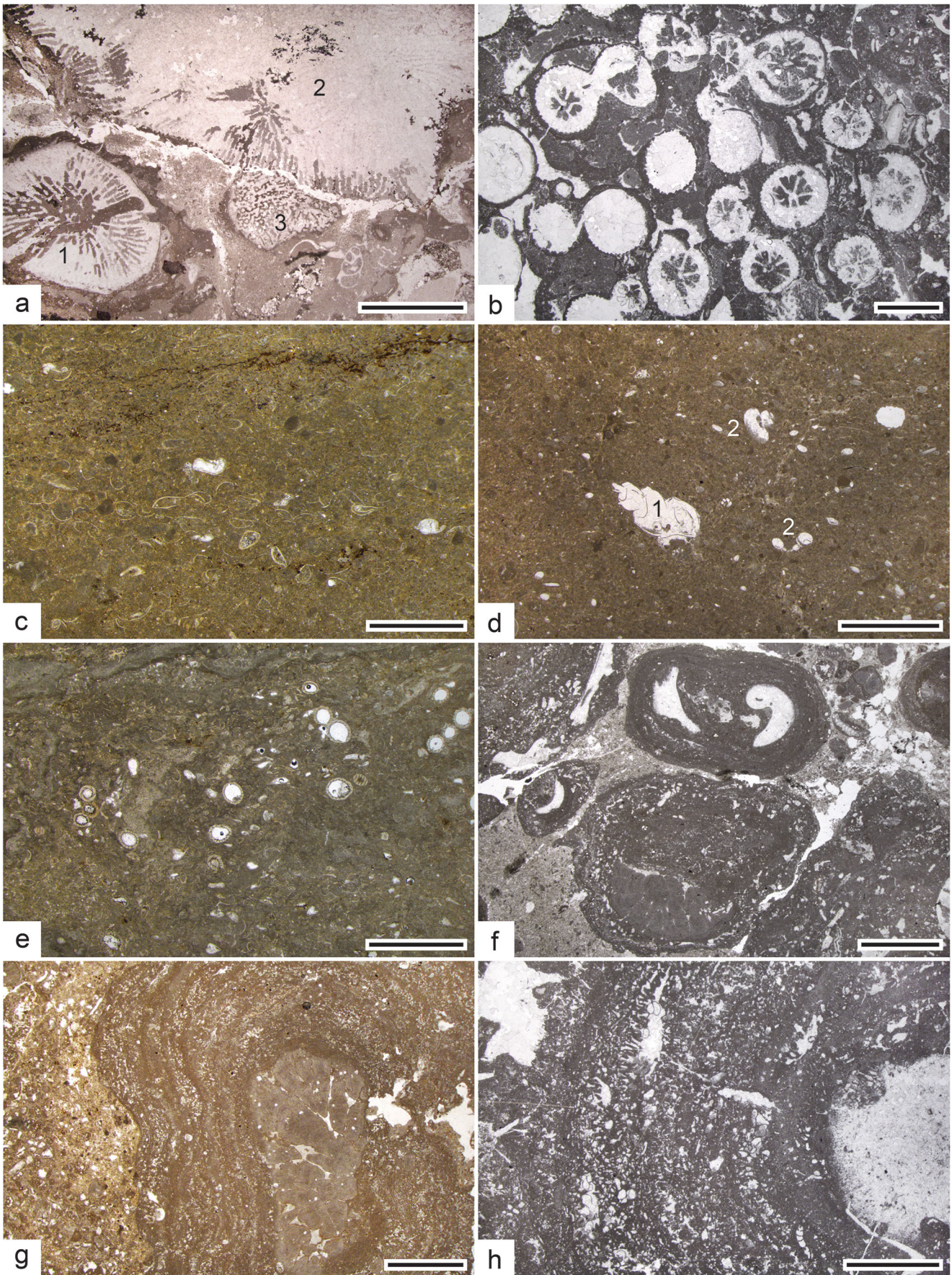
Although many of the sandstones are unfossiliferous, others contain fossils, which, in some cases, have been reworked from underlying strata or else are parautochthonous. The latter include nerineid gastropods, which may form layers, *Isognomon*, oysters, various species of bivalve and pterioid bivalves (Fig. 18a, b), red algae and also corals. Thin shell concentrations are occasionally present.

Interpretation: The large-scale sedimentary structures, including wave and current ripples, clearly indicate that the sandstones were deposited in open marine, shallow water above the fair-weather wave-base. Constant reworking prevented the sediment from becoming bioturbated. Such sandstones probably represent small sand waves, dunes and megaripple fields, which are moved across the shallow near-shore shelf by currents. Lenticular sandstone bodies are across and downslope channel fills, cutting down into underlying beds. Their faunal content is clearly allochthonous and commonly reflects several adjacent environments. This is supported by the carbonate components that are common constituents of the sandstones. The channels might represent subtidal tidal channels or channels connecting lagoons with the open sea. Channel sandstones with a basal lag of quartz gravel more likely are the submarine extension of distributory channels and reflect phases of elevated river discharge. Marine channel sandstones are particularly common in the upper, sand-prone part of the Consolação section (Fig. 11, from 108 m onwards) in a nearshore setting characterised by brackish-water biota. In that section, a several-metres-thick fine-grained, well-sorted sandstone with horizontal to very low-angle cross-stratification, at 155 m, has been interpreted as a beach deposit by Werner (1986).

Low-energy carbonate and mixed carbonate–siliciclastic shallow-water deposits (BA6)

This biofacies association includes deposits of the open shelf and of marine lagoons. Carbonate deposits dominate but are commonly blended with a subordinate siliciclastic component, in variable proportions and grain sizes (clay to fine sand).

Features: The carbonate beds are characterised by a micritic matrix and a fabric that ranges from mudstones (rare) to wackestones and floatstones (abundant) (Fig. 19b), pack-



◀ **Fig. 20** Typical microfacies of the Alcobaça Formation. **a** Coral bindstone; (1) *Thecosmilia* sp. with microbial envelope; (2) ceriod coral; (3) calcareous sponge; Vestiaria Mbr; Vestiaria section, 104 m (A-15–107). **b** Colony of the phaceloid coral *Stylosmilia* with dense microbial crusts and spar-filled cavities; Columbeira Mbr; Columbeira section, 285 m (A-28-97). **c** Ostracod packstone; São Martinho Mbr; São Martinho do Porto section, 61 m (A-1-11). **d** Mudstone with freshwater gastropods; (1) cf. *Ptychostylus*; (2) cf. *Valvata*; note the geopetal fabric within the gastropod shells and the meiofaunal bioturbation; Gralha Mbr; São Martinho do Porto section, 556 m (A-3-101). **e** Packstone with ostracods and gyrogonites; São Martinho Mbr; São Martinho do Porto section, 71 m (A-1-18). **f** Oncoid rudstone with single and composite *Girvanella* oncoids; cortex with *Lithocodium*; Columbeira Mbr; Columbeira section, 285 m (A-28-181). **g** *Girvanella* oncooid with cryptalgal fabric and red alga *Marinella lugeoni* Pfender as a nucleus; Gralha Mbr; São Martinho do Porto section, 563 m (A-3-112). **h** Oncoid cortex with *Lithocodium aggregatum* Elliott and *Bacinella irregularis* Radoičić; Columbeira Mbr; Columbeira section; 387 m (A-28-123). Scale bars: **a** = 5 mm; **b**, **d–h** = 2 mm; **c** = 1 mm

stones (common) (Fig. 20c, e) and rudstones (occurring) (Fig. 20f). Components include peloids (rare), intraclasts (abundant), bioclasts (abundant), oncoids (abundant) and other coated grains (common) (Table 1). Primary sedimentary structures are absent due to intense bioturbation. Recognisable trace fossils include *Thalassinoides* (two size classes), *Rhizocorallium commune*, *Teichichnus*, *Planolites* and *Zoophycus*. Algal lamination occurs at several levels in the São Martinho do Porto section (Fig. 9, at 13–16 m, 66–72 m); coral meadows are common in the lower part of the Consolação section (Figs. 11 and 18g). Small coral patch reefs occur, e.g. in the Sobral da Lagoa section (Fig. 16, at 60–62 m), commonly associated with microbial crusts (e.g. Figs. 12 and 20a, Vestiaria section at 104 m). In the latter section (at 231–240 m), corals, sponges and microbialites form meadows and small patch reefs that can be traced laterally for several kilometres (Fürsich and Werner 1991). Birdseyes occur, for example, in mudstones (Amoreira section, Fig. 17 at 37 m). Larger sparite-filled dissolution cavities occur at three levels in the Sobral de Lagoa section (Fig. 16, at 4 m, 12 m and 80 m). Black pebbles are rare. Desiccation cracks occur, for example in the Salir do Porto section (Fig. 10, at 414 m), associated with birdseyes and a rootlet horizon. Lignite pieces and plant fragments are rare.

The macrofauna is represented by a range of taxa, in particular bivalves (e.g. *Actinostreon*, *Isognomon*, *Trichites*, *Arcomytilus*, *Corbulomima*), gastropods (especially nerineids; Fig. 18d), serpulids, echinoids (spines), rare crinoids (ossicles), colonial and solitary corals, stromatoporoids and calcareous sponges. Occasionally, the molluscs form shell concentrations, but more commonly are scattered. The microfauna contains both ostracods and foraminifera (lituolids, miliolids), and the microflora includes Dasycladaceae. Red algae (*Marinella*) are common. In several horizons, the benthic

macrofauna is the autochthonous relict of former communities (Fig. 21).

Interpretation: Some of the marine carbonate rocks are lagoonal in origin. This is supported, apart from their low-energy features (i.e. the abundance of micrite and oncoids), by their close association with beds indicating brackish conditions. Apparently, during the time interval represented by the Alcobaça Formation, some areas were covered by a large lagoonal system, in which fully marine conditions (indicated by their faunal elements) alternated with brackish ones, depending on climatic conditions and on the degree, to which the lagoons were connected to the open sea.

The common clay- to sand-sized components in the carbonate beds point to nearby siliciclastic sources, most likely small deltas. This is also true of the carbonate deposits that accumulated on the shallow shelf, but generally in protected settings in embayments, or behind barriers, formed, e.g. by ooidal or intraclastic shoals (see below). In these settings, moderately diverse coral meadows flourished and small patch reefs became established. That the water depth was, at least locally, extremely shallow is shown by algal mats, birdseyes and signs of emersion such as desiccation cracks, all typical features of peritidal conditions (e.g. Flügel 2010: 746). Several horizons in the Sobral da Lagoa area exhibit small dissolution cavities, which are commonly linked to pebble lags. These features are interpreted to indicate more extensive periods of emergence and a certain degree of karstification and may signal abrupt local to regional adjustments in sea level.

High-energy, fully marine carbonate and mixed carbonate–siliciclastic shelf deposits (BA7)

Features: These carbonate deposits are mainly characterised by sparite cement and a well-washed fabric (grainstones and rudstones), occasionally also by packstones. Allochems are intraclasts, ooids, bioclasts, cortoids and oncoids (Figs. 18a, c and 19a, c, f). Some of the oncoids have a cortex of *Lithocodium* and *Bacinella* (Fig. 20h), others a nucleus of the red alga *Marinella* (Fig. 20g). Black pebbles occur occasionally, as do lignite pieces and plant debris, the latter concentrated on large foresets. The plant remains are more common in beds that also contain quartz grains. Primary sedimentary structures are widespread and include large-scale trough and planar cross-stratification. Densely to loosely packed shell concentrations occur repeatedly. Some of the carbonate beds contain a high percentage of quartz grains. In a single case (SOB section, Fig. 16 at 218 m), glauconite grains are a common constituent of an ooidal grainstone. Rarely, layers with intraformational sandstone or siltstone pebbles occur. Sparite-filled dissolution cavities occur at the top of an oncoidal–ooidal grainstone in the Columbeira section (Fig. 14 at 433 m).

Benthic associations and assemblages	Salinity [%]			Members	Localities	Environments
	40	30	18			
1 <i>Isognomon</i> association (<i>I. rugosus</i> - <i>Actinostreon gregareum</i> subset) (a)	40-30			SAO	SAO, SAL	fully marine to hypersaline bays and lagoons
2 <i>Trichtes</i> association (<i>Trichtes</i> sp. - <i>Actinostreon gregareum</i> subset) (a)	40-30			SAO	SAO, SAL	fully marine to hypersaline bays and lagoons
3 Diverse coral assemblages, partly with stromatopores; no <i>A. piriformis</i>	30-18			VES, CON, SGD, COL	VES, BAR, CHI, CON, FON, SAO (SGD), DAG, COL, AMO	low to moderate energy fully marine nearshore shelf
4 <i>Comaphyllia polymorpha</i> - <i>Crispispungia</i> cf. <i>expansa</i> association (b)	40-30			VES	VES; BAR, CHI	low energy fully marine shallow shelf
5 <i>Colamaphyllipsis</i> sp. meadows	40-30			CON, SGD	CON, SAO (SGD)	low to moderate energy fully marine bays or lagoons; protected nearshore shelf
6 <i>Pteria</i> sp. - <i>Placophyllia minima</i> assemblage (c)	40-30			CON	CON	moderate energy fully marine shelf
7 <i>Epistreptophyllum typicum</i> - <i>Ampullospira</i> <i>suprajurensis</i> assemblage	40-30			CON, COL	CON, COL	low energy nearshore shelf
8 <i>Stegoconcha occidentalis</i> - <i>Actinostreon gregareum</i> assemblage (a)	40-30			SGD	SAO (SGD)	fully marine bays and lagoons
9 <i>Palaeonucula menkii</i> assemblage	40-30			VES, SGD	VES (?), BAR, SAL	low energy fully marine shallow shelf
10 <i>Ceratomya</i> sp. - <i>Camptonectes</i> sp. assemblage	40-30			COL	SOB	low to moderate energy fully marine shallow shelf
11 <i>Modiolus imbricatus</i> assemblage	40-30			SGD	SAO (SGD)	moderate energy fully marine nearshore shelf
12 <i>Myophorella muricata</i> - <i>Myophorella alcabacensis</i> assemblage	40-30			CON, SGD	CON, SAO (SGD)	fully marine to slightly reduced salinity nearshore shelf
13 <i>Trichtes</i> association (<i>Trichtes</i> sp. - <i>Nanogyra nana</i> subset)	40-30			CON	CON	fully marine to slightly reduced salinity bays and lagoons
14 <i>Mesosaccella sanctaerucis</i> - <i>Corbulomima suprajurensis</i> assoc. (d)	40-30			CON, COL	CON, COL, [ESP, STC]	low energy prodelta with minor salinity fluctuations
15 Diverse coral assemblages, with <i>Amphiastrea piriformis</i>	40-30			VES, SAO	VES, AMO, CHI, FON, SAO	fully marine nearshore shelf, partially with minor salinity fluctuations
16 <i>Thracia depressa</i> - <i>Corbulomima suprajurensis</i> association	40-30			CON	CON	low energy prodelta with minor salinity fluctuations
17 <i>Laternula</i> sp. association	40-30			VES	VES	fully marine to slightly reduced salinity nearshore shelf
18 <i>Alaperna polita</i> - <i>Plicatula armata</i> assemblage (e)	40-30			CON	CON	nearshore shelf with minor salinity fluctuations
19 <i>Isognomon</i> association (<i>I. rugosus</i> - <i>Alaperna polita</i> subset) (e, f)	40-30			CON	CON	slightly reduced salinity nearshore shelf (prodelta)
20 <i>Alaperna polita</i> association (e)	40-30			CON, COL	CON, AMO	moderate energy prodelta
21 <i>Lycetta palkhalina</i> - <i>Juranomia suprajurensis</i> association	40-30			CON	CON	brackish bays and lagoons
22 <i>Isognomon</i> association (<i>I. rugosus</i> - <i>Amphiastrea piriformis</i> subset)	40-30			SAO	SAL, [STC (4)]	bays and nearshore shelf with minor salinity fluctuations
23 <i>Mesosaccella sanctaerucis</i> - <i>Protocardia intexta</i> assemblage (d)	40-30			CON, SGD	CON, SAL	low energy prodelta with minor salinity fluctuations
24 <i>Thracia depressa</i> association	40-30			CON	CON	low to moderate energy delta front with fluctuating salinities
25 <i>Isognomon</i> association (<i>I. rugosus</i> - <i>Praeexogyra pustulosa</i> subset)	40-30			SAO	SAO	brackish bays and lagoons
26 <i>Isognomon</i> association (<i>I. rugosus</i> - <i>Eomiodon securiformis</i> subset)	40-30			SAO	SAO, SAL, [STC (4)]	low to moderate energy protected bays and lagoons
27 <i>Eomiodon securiformis</i> association	40-30			ARR	SAO, [ESP, STC]	high energy delta fronts and protected bays
28 <i>Jurassicorbula viriati</i> - <i>Eomiodon securiformis</i> association	40-30			GRA, ARR	SAO	brackish bays and lagoons
29 <i>Praeexogyra pustulosa</i> - <i>Nanogyra nana</i> association	40-30			VES, CON, COL	VES; CON, AMO, [STC]	brackish bays and lagoons
30 <i>Eomiodon astartoides</i> - <i>Myrene estremadurae</i> assemblage	40-30			CON	CON	brackish lagoons
31 <i>Myrene hannoverana</i> - <i>Jurassicorbula viriati</i> association	40-30			GRA, ARR	SAO, SAL	brackish bays and lagoons
32 <i>Myrene hannoverana</i> association	40-30			ARR	SAO, SAL (top)	brackish bays and lagoons
33 <i>Myrene estremadurae</i> association	40-30			CON	CON	brackish lagoons
34 <i>Valvata</i> sp. - <i>Ptychostylus</i> sp. association	40-30			VES, CON, ARR	VES, CON, SAL, [SAR]	coastal lakes or lagoons with occasional marine influence
35 <i>Anisopsis</i> sp. association	40-30			VES, SGD, ARR	VES, SAO (SGD), [ESP]	freshwater lakes and lagoons

◀ **Fig. 21** Benthic associations and assemblages of the Alcobaça Formation, their salinity range (in ‰), their facies range (c, carbonate, s, siliciclastic, m, mixed), their distribution within members of the Alcobaça Formation, their distribution in logged sections and additional outcrops of the Alcobaça Formation (and elsewhere in the Lusitanian Basin) and their environmental preference. The following letters refer to the terminology used by Fürsich and Werner (1986) (F & W): (a) *Actinostreon gregareum* = *Lopha solitaria* of F & W; (b) *Elasmostoma* sp.–*Comophyllia corrugata* ass. of F & W; (c) *Pteria* sp. = *Pteroperma* sp. of F & W; (d) *Mesosaccella sanctaecrucis* = *M. dammariensis* of F & W. (e) *Alaperna polita* = *Bakevelliid* sp. A of F & W. (f) *Isognomon rugosus* is succeeded by *I. lusitanicus* in younger strata. AMO Amoreira, ARR Arrinhada, BAR Barrio, CHI Chiqueda, COL Columbeira, CON Consolação, DAG Dagorda, ESP Cabo Espichel, FON Fonte Santa, GRA Gralha, SAL Salir do Porto, SAO São Martinho do Porto, SAR Serra d'Arrábida, SGD Salgado, SOB Sobral da Lagoa, STC Santa Cruz, VES Vestiaria

Faunal components include corals, bivalves (in particular oysters; Fig. 18f), gastropods (mainly nerineids; Fig. 18d), brachiopods and stromatoporoids. In addition, red algae of the genus *Marinella* are common, while *Cayeuxia* cyanobacteria are rare. Dinosaur tracks cover a large bedding plane of a sandy bioclast rudstone south of Salgado (SAO section, Fig. 9 at 555 m, Fig. 23a). Similar tracks are present near the base of the Sobral da Lagoa section (Fig. 16 at 4 m; Fig. 7d), where they occur on top of a pebbly bioclast grainstone.

Interpretation: The primary sedimentary structures, fauna and lack of micrite indicate that the sediments formed in high-energy shallow waters above the fair-weather wave-base. There they formed shoals and barriers, the tops of which were constantly reworked. Occasional dinosaur tracks point to extremely shallow water or temporary emergence, and dissolution cavities indicate a longer phase of subaerial exposure and karstification. In some sections (e.g. SOB, DAG, COL), oncoids are common in intraclastic and ooidal grainstones and occasionally form rudstones (Fig. 18c). As oncoids grow under low-energy conditions, only intermittently disturbed by high-energy events (e.g. Flügel 2010: 136), their inclusion in grainstones and rudstones indicates that, apart from the ooids, many of the components of these carbonate beds are allochthonous and were transported from their respective place of origin. This is also true of many of the fossil components, especially those of shell concentrations, which did not live in these turbulent environments. Transport and mixing is also indicated by the siliciclastic components.

Brackish-water deposits of lagoons and protected bays (BA8)

Features: This type of biofacies comprises a wide range of lithologies characterised by microfauna and/or macrofauna, which lived in salinity regimes deviating from fully marine (euhaline) conditions. Various lithologies are included. Low-energy carbonate facies comprise micritic

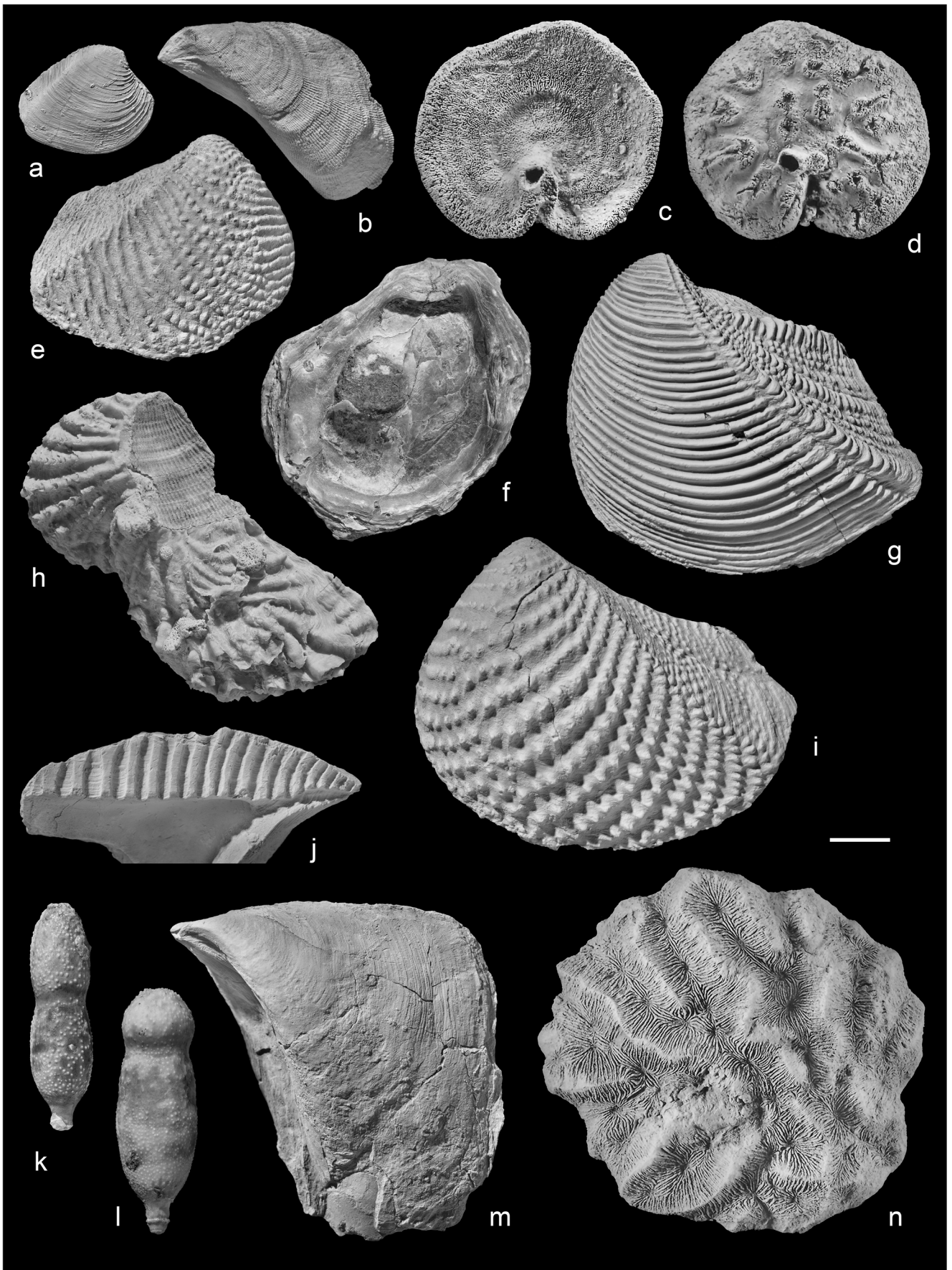
algal laminites, marl and marly wackestone. Mixed carbonate–siliciclastic rocks are represented by silty mudstone with birdseyes, rootlets and the trace fossils *Psilonichnus* and by silty marl with typical brackish-water bivalves (*Isognomon*, *Eomiodon*, *Neomiodon*, *Jurassicorbula*, *Praeexogyra*), ostracods and, more rarely, litiolids. Low-energy siliciclastic rocks include silt, fine-sandy silt, argillaceous silt and fine-grained sandstone, with a similar benthic fauna. High-energy siliciclastic beds (medium- to coarse-grained sandstones, occasionally pebbly and large-scale trough or planar cross-bedded) with the trace fossils *Polycladichnus* and *Diplocraterion* are comparatively rare. Finely to coarsely interlayered bedding is usually associated with abundant plant debris. In rare cases, desiccation cracks occur.

Lignite flakes are generally abundant, and rootlets are occasionally present; fragments of vertebrates (teeth, bones) are rare. Freshwater gastropods, such as *Amplovalvata*, and unionid bivalves are occasionally associated with the typical brackish-water faunal elements. Small patch reefs composed of the oyster *Praeexogyra* occur in the Consolação section (Fig. 11 at 134 m; Fig. 18e).

Interpretation: The predominantly subaqueous lithologies and their benthic microfauna and macrofauna characterise mainly very shallow, low-energy coastal environments such as protected embayments and lagoons, more rarely high-energy environments such as tidal and lagoonal inlets. In these environments, salinities not only were generally lower than in the open sea but also commonly fluctuated. This is indicated in some cases by the presence of freshwater elements, which might have been introduced by rivers, but also could have populated the same area during times when lagoons were temporarily completely cut off from the open sea. The opposite case is demonstrated by fully marine faunal elements in brackish biota, which document occasional influx of fully marine waters. In several horizons (e.g. SAO section between 44 and 53 m; Fig. 9), the benthic macrofauna, dominated by *Isognomon rugosus*, *Trichites* and *Actinostreon gregareum*, suggests slightly elevated rather than lowered salinity values, i.e. in the lower hypersaline regime (Fürsich and Werner 1986). The various salinity regimes indicated by the benthic fauna are discussed below in more detail.

Benthic macrofauna

While nektobenthic ammonites and nektonic belemnites are extremely scarce in the Alcobaça Formation, benthic macroinvertebrates are very common. They are either recurring autochthonous to parautochthonous relicts of former communities (associations) or are allochthonous elements that



◀ **Fig. 22** Typical macrofauna of the Alcobaça Formation. **a** *Eomiodon securiformis* (Sharpe); Vestiaria Mbr, Vestiaria; GML 25919. **b** *Arcomytilus morrisii* (Sharpe); Consolação Mbr, Consolação section; GML 25901. **c, d** *Crispispongia* cf. *expansa* (Quenstedt); Vestiaria Mbr, Vestiaria; SNSB-BSPG 1984 XXII 20. **e** *Myophorella alcobacensis* (Choffat); Vestiaria Mbr; Chiqueda; GML 31985. **f** *Praeexogyra pustulosa* (Sharpe); Columbeira Mbr; Sobral da Lagoa; SNSB-BSPG 2005 V 29. **g** *Trigonia pseudomeriani* Choffat; ‘Environs de Alcobaça’; GML 2027. **h** *Actinostreon gregareum*; Salgado Mbr; Salgado; SNSB-BSPG 2005 V 28. **i** *Myophorella muricata* (Goldfuss); ‘Environs de Alcobaça’; GML 1997. **j, m** *Isognomon rugosus* (Münster); Vestiaria Mbr; Fonte Santa; J: GML 25923; M: GML 25906. **k, l** Club-shaped spines of *Pseudocidaris lusitanica* de Loriol; note the remnants of colour pattern. **k** Vestiaria Mbr; Vestiaria; GML 4115. **l** Columbeira Mbr; Sobral da Lagoa; SNSB-BSPG 1984 XXII 353. **n** *Comophyllia polymorpha* Koby; Vestiaria Mbr; Barrio; SNSB-BSPG 1984 XXII 32. Scale bar = 10 mm

underwent transport and often occur concentrated in shell beds and shell lenses (transported assemblages). Autochthonous to parautochthonous faunas, if occurring only once but not repeatedly, are also termed assemblages. Bivalves are the most abundant macrofossils, followed by corals, gastropods, brachiopods, echinoids (mainly represented by spines), stromatoporoids and serpulids. Bryozoans, crustacean fragments, asteroid ossicles and crinoid skeletal elements are comparatively rare. Some characteristic elements of this fauna are shown in Fig. 22.

A number of papers have been published on the Late Jurassic benthic macrofauna of the Lusitanian Basin during the last few decades (e.g. Fürsich 1981b; Fürsich and Werner 1984, 1985, 1986, 1988, 1989a, b, 1991; Werner 1986; Leinfelder et al. 1996; Nose and Leinfelder 1997; Leinfelder 2001; Fürsich et al. 2009; Schneider et al. 2010a, b, 2011). They concentrated on the taxonomy of bivalves and on the palaeosynecology of the macrobenthos, but a substantial part of that information had been gained from other parts of the Lusitanian Basin. Here, we provide a brief overview on the 35 benthic associations/assemblages identified in the Alcobaça Formation, many of which apparently lived in salinity regimes deviating from normal marine values. Most of the associations/assemblages listed in Fig. 21 were already briefly discussed by Fürsich and Werner (1986), but the present list contains additional data from both fully marine and brackish environments of the Alcobaça Formation. The salinity ranges of associations have been determined based on ecological indicators (species richness and evenness), taxonomy and comparison with modern relatives, species composition, the associated microfauna and microflora, morphological features such as shell thickness and shell size, as well as lithofacies and sedimentary structures. The results were corroborated to some extent by stable isotope data (Fürsich and Werner 1986; Yin et al. 1995). It should be kept in mind that the ranges given in Fig. 21 are

approximations. Moreover, in cases where taxa that are characteristic of different salinity regimes co-occur in the same layers, we are most likely dealing with fluctuations in salinity and not simply with reduced, but stable values. After all, this is what one would expect in marginal marine environments, in particular lagoons. Also, along the salinity range of a particular association, the faunal composition and diversity usually changes, and these features have been used to define the range. The associations are discussed in numerical order and by decreasing salinity regime below.

Only two of the 35 associations in Fig. 21, i.e. the *Isognomon rugosus*–*Actinostreon gregareum* (1) and the *Trichites* sp.–*Actinostreon gregareum* subset (2), tolerated slightly hypersaline waters. This interpretation is supported by small authigenic euhedral quartz crystals occurring in the carbonate to mixed carbonate–siliciclastic rocks, which indicate saline pore waters (e.g. Friedman 1980; Chafetz and Zhang 1998), potentially derived from the underlying diapir. These associations are restricted to the São Martinho Member at São Martinho do Porto and Salir do Porto. Alongside abundant red-bed facies, they suggest a semi-arid climate with little freshwater influx.

Several associations appear to have been restricted to fully marine (euhaline) environments. They include diverse coral meadows, partly associated with stromatoporoids (3); meadows in which the coral *Calamophylliopsis* dominated (5); or assemblages, in which corals were accompanied by a diverse bivalve and gastropod fauna (*Pteria*–*Placophyllia* and *Epistreptophyllum typicum*–‘*Ampullospira*’ *suprajurensis* assemblages; 6, 7). Such coral meadows and other associations dominated by corals occasionally forming small patch reefs are particularly common in the lower part of the Consolação Member, but occur also in the other dominantly marine members (e.g. patch reefs or meadows dominated by the phaceloid coral *Calamophylliopsis*). A particularly diverse association is the *Comophyllia polymorpha*–*Crispispongia* cf. *expansa* association (4), which is represented by 131 taxa, of which half are corals and approximately 20% are small calcareous sponges (Fürsich and Werner 1991). Associated with them are bivalves, brachiopods, crinoids and gastropods and a rich encrusting and boring biota. In the Vestiaria Member, this association formed meadows and small patches on a mixed carbonate–siliciclastic sea floor. The respective horizon can be traced for more than 10 km west to east in the northern part of the study area, from Barrio via Vestiaria to Chiqueda (Fig. 3). Apart from this occurrence, calcareous sponges are rare in the benthic community relicts of the Alcobaça Formation. Several other marine assemblages are dominated by bivalves. These include the large semi-infaunal *Stegoconcha*, which provided the substrate for the encrusting oyster *Actinostreon gregareum* (8) or *Modiolus imbricatus* (11), both from the Salgado Member. Assemblages characterised by the deposit-feeding *Palaeonucula menkii* (9) occur in the Salgado and Vestiaria

members. The deep infaunal *Ceratomya* and epibyssate *Camptonectes* (10) typify an association restricted to the Columbeira Member at Sobral da Lagoa.

Another group of essentially marine associations/assemblages (12–17) appears to have been tolerant of slightly reduced/fluctuating salinity values and is mainly known from the Consolação and Vestiaria members. Assemblage (15) is dominated by corals, including *Amphiastrea piriformis*, and occurs in most sections of the São Martinho and Vestiaria members. The remaining associations are characterised by bivalves. Two species of the shallow infaunal *Myophorella* are the main components of assemblage (12). Association (13) is characterised by the semi-infaunal *Trichites* forming secondary hard substrates for the small oyster *Nanogyra nana*. Three associations are dominated by infaunal taxa: the shallow infaunal deposit-feeding *Mesosaccella* and the suspension-feeding infaunal *Corbulomima* (14), the suspension-feeding infaunal *Thracia* and *Corbulomina* (16) or the deeply burrowing *Laternula* (17). All six groupings occur in fine-grained siliciclastic or mixed substrates and occupied marine lagoons or protected bays.

Three other bivalve-dominated groupings (18–20) apparently occupied not only euhaline but also brachyhaline settings. They lived in partly marly bioclastic fine sand and are characterised by the epibyssate bivalve *Alaperna* (20), which co-occurs in some beds with either the cementing *Plicatula* (18) or the endobyssate *Isognomon* (19). The *Lycettia–Juranomia* association (21) had the widest salinity tolerance of all Alcobaca Formation associations, ranging from the euhaline to the upper oligohaline regime. Along this range, the composition of the accompanying taxa, mainly shallow burrowing bivalves, and the species diversity change accordingly. Associations (22) to (26) have a greater tendency to the brachyhaline regime, and some (25, 26) are restricted to it. Again, they are dominated by bivalves. Three of them are dominated by *Isognomon*, which serves as a substrate for either the eurytopic coral *Amphiastrea piriformis* (22) or the oyster *Praeexogyra pustulosa* (25) or else co-occurs with the shallow burrowing suspension-feeding bivalve *Eomiodon* (26). The infaunal *Mesosaccella–Protocardia* assemblage (23) and the *Thracia depressa* association (24) occur in fine-grained siliciclastic deposits of the low-energy nearshore shelf.

The bivalve-dominated associations (27–29) signify the brachyhaline to mesohaline regime. The low-diversity *Eomiodon securiformis* association (27) occurs in delta-front sandstone elsewhere in the Lusitanian Basin (e.g. at Santa Cruz; Fürsich 1981b), but in the Alcobaca Formation occupied protected bays and lagoons of the Arrinhada Member (São Martinho do Porto section). Together with a small corbulid, *Eomiodon* forms the infaunal *Jurassicorbula viriati–Eomiodon securiformis* association, typical of low-energy bays and lagoons. The brackish-water oyster *Praeexogyra*

pustulosa formed small patch reefs together with the small eurytopic oyster *Nanogyra nana* (28), again in lagoonal settings and protected embayments. Small-sized coral colonies occurring at some levels within the patch reefs point to strong salinity fluctuations. Similarly, *Nanogyra* might have replaced *Praeexogyra* as a reef constructor during times when salinity was at the upper brachyhaline end.

The mesohaline to oligohaline regime is represented by four associations (30–33), which are dominated by small, shallow-infaunal suspension-feeding bivalves and occur in fine-grained siliciclastic sediments (e.g. argillaceous silt), deposited in lagoons and protected bays. They all exhibit very low species diversities. The dominant species *Eomiodon astartoides* (30), *Myrene estremadurae* (30, 33), *Myrene hannoverana* (32) and *Jurassicorbula viriati* (31) belong to genera that have been well established as brackish endemic taxa elsewhere in the Jurassic (e.g. Hudson 1963a, b; Huckriede 1967; Mongin 1967; Fürsich 1994).

The freshwater regime is represented by two associations that consist of small gastropods: the *Valvata–Ptychostylus* association (34) and the *Anisopsis* association (35). They generally occur in fine-grained siliciclastic deposits but also in mixed sediments and in carbonate mudstones characterising freshwater lagoons and lakes of the coastal plain (CON, VES and ARR members). They have also been recorded from the Serra d'Arrábida and Cabo Espichel south of Lisbon. Unionid bivalves have not been found during our investigations but have been recorded by Choffat (1885–1888).

Additional associations and assemblages in the Alcobaca Formation certainly exist, but we lack statistical data on their composition. Worth mentioning are nerineid assemblages that occur in both high-energy carbonate and siliciclastic rocks (Fig. 18d). They represent transported and probably sorted relicts of one or several former gastropod-dominated communities. Some of the associations and assemblages listed above occur only in a single section. This may partly be an artefact, as statistically significant samples could not be obtained everywhere, but surely also reflects the great environmental heterogeneity represented by the Alcobaca Formation.

Palaeoecological analysis of benthic macrofauna, supported by an array of other palaeontological and sedimentological data, is a powerful tool to reconstruct palaeoenvironments. This is particularly well illustrated by the Alcobaca Formation, which records high-frequency changes between shallow-marine, near-shore and non-marine conditions in both time and space, and is here interpreted to document the salt tectonic evolution of the Lusitanian Basin during the Kimmeridgian time interval.

Microfossils

Foraminifera and ostracods are ubiquitous constituents of the Alcobaca Formation, occurring with assemblages of varying

compositions in different biofacies. Despite their widespread occurrence, taxonomic studies of these groups are rather scant. Foraminifera have been mentioned in several articles (e.g. Fatela 1990; Werner 1986; Fürsich and Werner 1991), but a detailed taxonomic treatment of this group from the Alcobaça Formation is still lacking. In contrast, the ostracods of the Alcobaça Formation have been the subject of several studies, largely focussing on the biostratigraphy of the mammalian-bearing Guimarota beds (e.g. Helmdach 1968, 1971a, b, 1974; Schudack 2000a, b). A more comprehensive study of the ostracods of this formation by the late F.-F. Helmdach remains unfinished (see above). Some legacy data from this study are incorporated here.

Among the foraminifera, litiolids taxa dominate in nearly all marine biofacies, where they are frequently abundant. They are represented by species that are globally characteristic of the Kimmeridgian at low to moderately high latitudes, but are generally not diagnostic at substage scale (e.g. *Alveosepta jaccardi*, *Everticyclammina virguliana*, *Rectocyclammina chouberti*, *Pseudocyclammina parvula*). Further common agglutinated foraminifera are *Ammobaculites* and *Nautiloculina*. As demonstrated in the Consolação section, litiolids decrease in diversity and abundance towards facies with strongly reduced salinity, where they are almost exclusively represented by *Pseudocyclammina parvula* (Werner 1986). Miliolids are also common constituents and generally occur in low-energy environments with reduced influx of siliciclastic material (e.g. wackestones), where they are often accompanied by Dasycladales (e.g. *Acicularia*). Apart from the free-living benthic foraminifera, fixo-sessile cementing foraminifera (e.g. *Placopsilina*, *Bullopore*, nubeculariids, *Tolypammina*) are common epibionts in euhaline to brachyhaline habitats, settling on various available surfaces, including corals, coralline sponges, molluscs or microbial crusts. Some of these taxa, e.g. *Placopsilina*, *Bullopore* and the questionable rotaliid foraminifer *Koskinobullina socialis* (e.g. Sánchez-Beristain and Reitner 2019), are also common epibionts on accretion layers of *Girvanella* oncoids in lagoonal settings.

Ostracods occur in a wide range of aquatic biofacies of the Alcobaça Formation. Apart from their stratigraphic value (see above), they are very useful as salinity indicators. The most common taxa of euhaline to brachyhaline bays and lagoons are *Schuleridea* (several different species, e.g. Fig. 6n), *Cytherella suprajurassica* (Fig. 6o) and *Cytherelloidea* aff. *weberi* (Fig. 6g). Additionally, Fürsich and Werner (1991) reported species of *Lophocythere*, *Terquemula* and *Protocythere* from the fully marine, widely distributed coralline sponge–coral meadows in the surroundings of Alcobaça. Several genera, such as *Theriosynoeum* (Fig. 6a, c, e), *Bisulcoypris* (Fig. 6k, l) and *Timiriasevia* (Fig. 6b), are considered indicative of freshwater environments. However, it should be noted that some of these taxa may also have coped with brackish conditions (Schudack 2000b). This is also true

of the species *Cetacella inermis* (Fig. 6m), *Cetacella striata* (Fig. 6f), *Poisia bicostata* (Fig. 6h), *Poisia clivosa* (Fig. 6q) and *Dicrorhygma* (*Orthorygma*) aff. *reticulata* (Fig. 6r), all of which occurred in brackish bays and lagoons within the Alcobaça Formation (e.g. in the Vestiaria and Consolação sections).

Ichnofauna

Bioturbation is ubiquitous in low-energy carbonate and siliciclastic facies within the Alcobaça Formation, because sufficient time was available for organisms to rework the substrate. The same is true of discrete trace fossils, whereby a few ichnogenera strongly dominate. Trace fossils from the Alcobaça Formation have been described and/or figured by Fürsich (1981a), Neto de Carvalho and Baucon (2010), Neto de Carvalho et al. (2010) and Neto de Carvalho (2016). In terrestrial red beds, particularly in fine-grained wet floodplain sediments, *Scoyenia*, a more or less horizontal burrow with scratch marks and a meniscate backfill, is very abundant (Fig. 23g). *Psilonichnus tubiformis*, several-cm-thick, mainly vertical shafts with short horizontal to oblique side branches, most likely produced by crabs, occur in low-energy coastal environments and may extend downwards for at least 2 m. They commonly start with a Y- or U-shaped tube (Fig. 23b) and may cross through layers representing alternations of non-marine and marginal marine (possibly tidal) conditions. From a similar environmental setting at Salgado, Neto de Carvalho et al. (2010) and Neto de Carvalho (2016) also recorded the banana-shaped crab burrow *Macanopsis plataniformis*, a curved lined burrow that starts as a subvertical shaft and turns horizontal, as well as other types of crab burrows (Fig. 23h). In deltaic coarse-grained to microconglomeratic sandstones of the Consolação section, *Polycladichnus irregularis* is common. This trace fossil is characterised by strongly lined shafts with Y-shaped bifurcations connecting to the bedding surface, and its maker may have been able to withstand salinity fluctuations. The vertical U-shaped spreiten burrow *Diplo craterion parallelum* is common in medium- to coarse-grained brackish-water tidal creek sandstones of the Consolação section. In low-energy carbonate and siliciclastic sediments of the shallow shelf, crustacean burrows, in particular the horizontal U-shaped spreiten burrow *Rhizocorallium commune* (Fig. 23d) and the network-forming *Thalassinoides suevicus* with Y-shaped branching burrows, are very common. The latter occurs in several size classes with the largest burrows reaching 4–5 cm in diameter (Fig. 23c). The former occurs associated with *Thalassinoides* or on its own. The fairly non-descript *Planolites* isp., a simple, unlined horizontal burrow, is widespread and occurs in a number of facies. A much rarer



◀ **Fig. 23** Typical ichnofossils of the Alcobaça Formation. **a** Dinosaur tracks; Salgado Mbr; São Martinho do Porto section, 565 m. **b** *Ptilonichnus tubiformis* Fürsich; Salgado Mbr; São Martinho do Porto section, 569 m; type locality and horizon of the ichnogenus and ichnospecies. **c** *Thalassinoides suevicus* (Rieth); Salgado Mbr; São Martinho do Porto section, fallen block, ~595 m. **d** *Rhizocorallium commune* Schmid; Salgado Mbr; São Martinho do Porto section, fallen block, ~593 m. **e** *Ptilonichnus* sp.; Gralha Mbr; São Martinho do Porto section, 509 m. **f** *Teichichnus rectus* Seilacher; Consolação Mbr; Consolação section, 23 m. **g** *Scoyenia* sp.; Gralha Mbr; São Martinho do Porto section, 415 m. **h** Crab burrow; Salgado Mbr; São Martinho do Porto section, 578 m. Scale bars: **d** = 50 mm; **g**, **h** = 10 mm

ichnospecies is *Teichichnus rectus*, an oblique cylindrical burrow with retrusive spreiten (Fig. 23f). Dinosaur tracks have been noted on several bedding planes in nearshore carbonate and mixed carbonate–siliciclastic strata (São Martinho do Porto section at Salgado, Fig. 23a; Salir do Porto, Sobral da Lagoa section, Fig. 7d). The trackways of Salgado have been identified as *Brontopodus* isp. and *Megalosauripus* isp. by Neto de Carvalho (2016) and are evidence of temporary (near-) emergence.

The ichnofauna can be accommodated in the classical ichnofacies scheme (e.g. Seilacher 1967; with subsequent additions, e.g. Bromley 1996), covering the non-marine Scoyenia ichnofacies, the high-energy marginal marine Skolithos ichnofacies, the low-energy marginal marine Ptilonichnus ichnofacies and the Cruziana ichnofacies of the shallow shelf. In general, the distribution of the ichnotaxa corresponds well with the environmental interpretation deduced from grain size, microfacies and sedimentary structures.

Discussion

Facies pattern and correlation

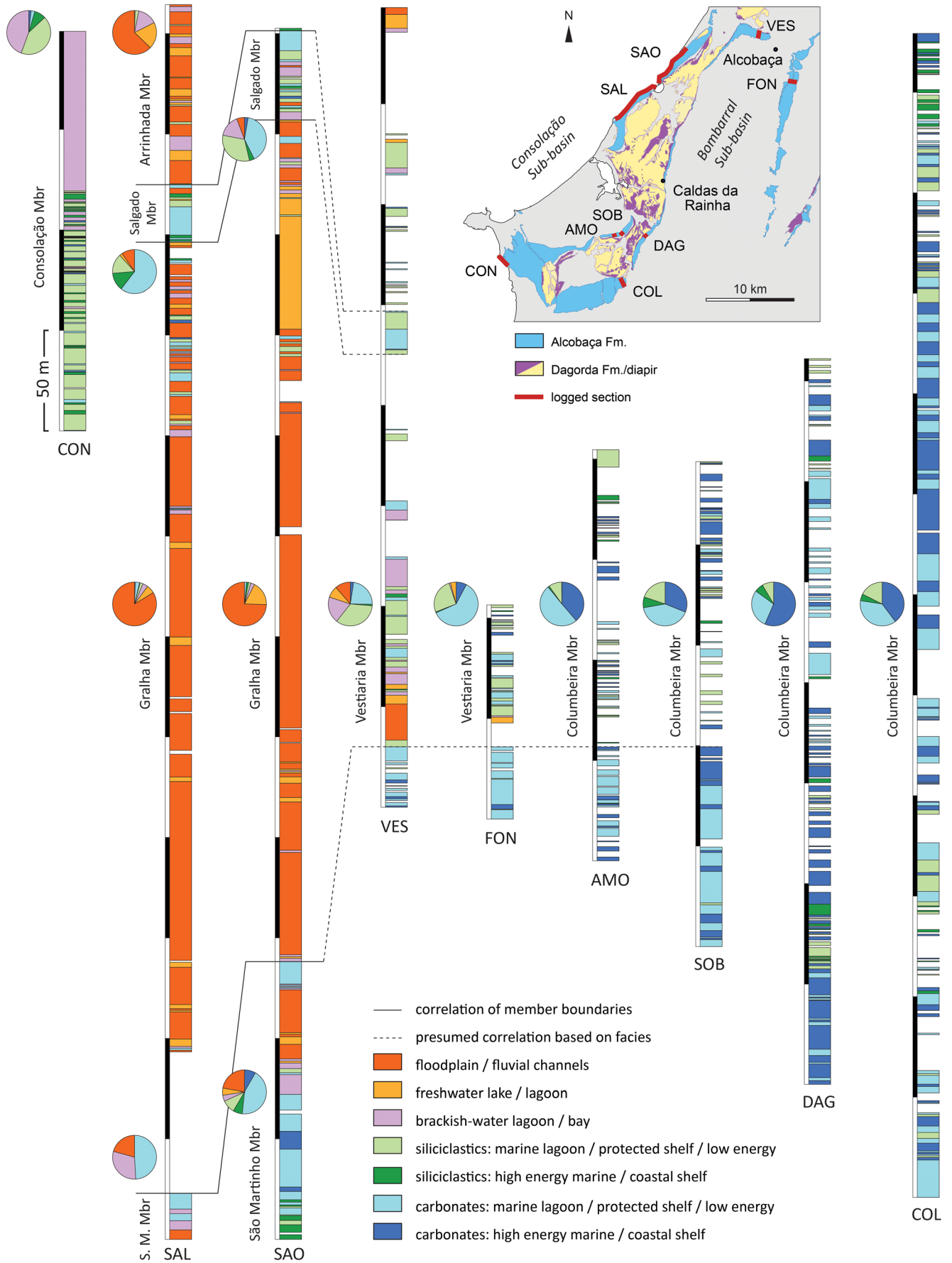
Comparing and correlating the various sections of the Alcobaça Formation is difficult, because in many of them, neither the base nor the top of the formation is seen, and none of the sections captures both. At outcrop, underlying strata commonly comprise dolostones or marls of the Upper Triassic to Hettangian Dagorda Formation, but this contact is invariably tectonic in nature, although most probably not involving major displacement. The undisturbed base of the Alcobaça Formation is only exposed in the Fonte Santa section, where the unit overlies clean, thick-bedded limestones of the middle Oxfordian Montejunto Formation. The contact is sharp, probably representing a paraconformity. The upper boundary has been defined as the onset of thick fluvial sandstones, which are assigned to the Lourinhã Formation. This boundary, seen for example at the top of the Vestiaria section,

is likely highly diachronous. Moreover, there are distinct lateral facies changes within the Alcobaça Formation between sections (Fig. 24). Although the four sections at Columbeira and Dagorda in the Bombarral Sub-basin, and at Amoreira and Sobral da Lagoa in the Consolação Sub-basin superficially look similar, the successions of marine siliciclastic and carbonate strata, and occasional brackish beds do not follow a clear vertical pattern and cannot be used for correlation (Fig. 24). Furthermore, all inland sections contain thick intervals of non-exposure, the nature (siliciclastic, mixed carbonate–siliciclastic) and environments of which (whether lake, lagoon, marine) cannot be reliably established. This makes lithostratigraphic correlation very difficult (see below). Unfortunately, due to the extreme scarcity of index fossils such as ammonites, it is impossible to place the tentative lithostratigraphic correlation shown in Fig. 24 on a sounder footing. Still, a distinct SE–NW zonation of the biofacies types introduced above becomes apparent, when comparing the different sections of the study area. The western sections, all situated in the Consolação Sub-basin (São Martinho do Porto, Salir do Porto and Consolação), are dominated by siliciclastic sediments. The comparatively short Consolação section shows a strong marine influence, especially in its lower part, while its upper third is characterised by brackish-water siliciclastic deposits. These are overlain conformably by thick grey to beige non-marine sandstones of the Lourinhã Formation. The brackish-water siliciclastic sediments at Consolação differ distinctly from the red beds of the Gralha Member at São Martinho and Salir do Porto, both with regard to colour and the thickness and abundance of sandstones. This suggests that the Gralha Member may have been deposited in a semi-arid climate, while the brackish succession at Consolação formed under a humid climate regime. For this reason, the Consolação Member is unlikely the equivalent of the Gralha Member but presumably corresponds to the Salgado and Arrinhada members of the upper São Martinho and Salir do Porto sections.

Further to the east, at Amoreira, Columbeira, Dagorda and Sobral da Lagoa, non-marine and brackish environments are absent and the successions are dominated by carbonate strata (Fig. 24). The Vestiaria and Fonte Santa sections occupy an intermediate position with minor red bed and lacustrine intercalations, common brackish-water intervals and a mixture of carbonate and siliciclastic sediments. The pattern of facies differentiation across the study area points to the presence of a topographic barrier and thus to distinct synsedimentary tectonic activity.

Control of diapirism on facies pattern and benthic communities

The most characteristic features of the Alcobaça Formation are the rapid vertical and lateral changes in facies and benthic



◀ **Fig. 24** Correlation of logged sections, based on depositional environments. Pie charts indicate the proportions of depositional environments in the exposed successions by member. Note that the dashed lines do not indicate member boundaries but rather the inferred laterally equivalent stratigraphic level. *AMO* Amoreira, *COL* Columbeira, *CON* Consolação, *DAG* Dagorda, *FON* Fonte Santa, *SAL* Salir do Porto, *SAO* São Martinho do Porto, *SOB* Sobral da Lagoa, *VES* Vestiaria

macrofauna. Typical are mixed carbonate and siliciclastic facies, which document the nearshore nature of many of the sediments. This is corroborated by the abundance of brackish-water faunas. However, there also exist thick packages of terrestrial red beds in the northern coastal sections (São Martinho and Salir do Porto) and of platform carbonate rocks in some of the eastern sections (e.g. Columbeira), recording the relative persistence of these general environmental settings (Fig. 24). A simplified depositional model of the Alcobaça Formation is displayed in a block diagram in Fig. 25 and in a schematic cross-section in Fig. 26.

The strongly varying facies pattern reflects, to some extent, climatic changes. Widespread brackish biota accompanied by abundant plant debris, such as in the upper part of the Consolação section and in the Vestiaria section, suggest increased freshwater influx into the basin and point to a humid climate. In contrast, the thick red beds of the coastal sections, with abundant caliche nodules and fluvial sandstones that rarely exceed 2–3 m in thickness, indicate a semi-arid climate and only limited freshwater input into the basin.

These climatic changes, however, cannot sufficiently explain the facies pattern, in particular the frequent minor fluctuations observed in all sections, which appear to have been decisively controlled by tectonic processes. The Alcobaça Formation occurs in three sub-basins, separated by the Caldas da Rainha Diapir and the Leiria, Porto de Mós and Rio Maior diapirs, respectively. Until recently, the prevailing view was that these diapirs are salt pillows, which started to form during the Early Jurassic, but did not prominently affect

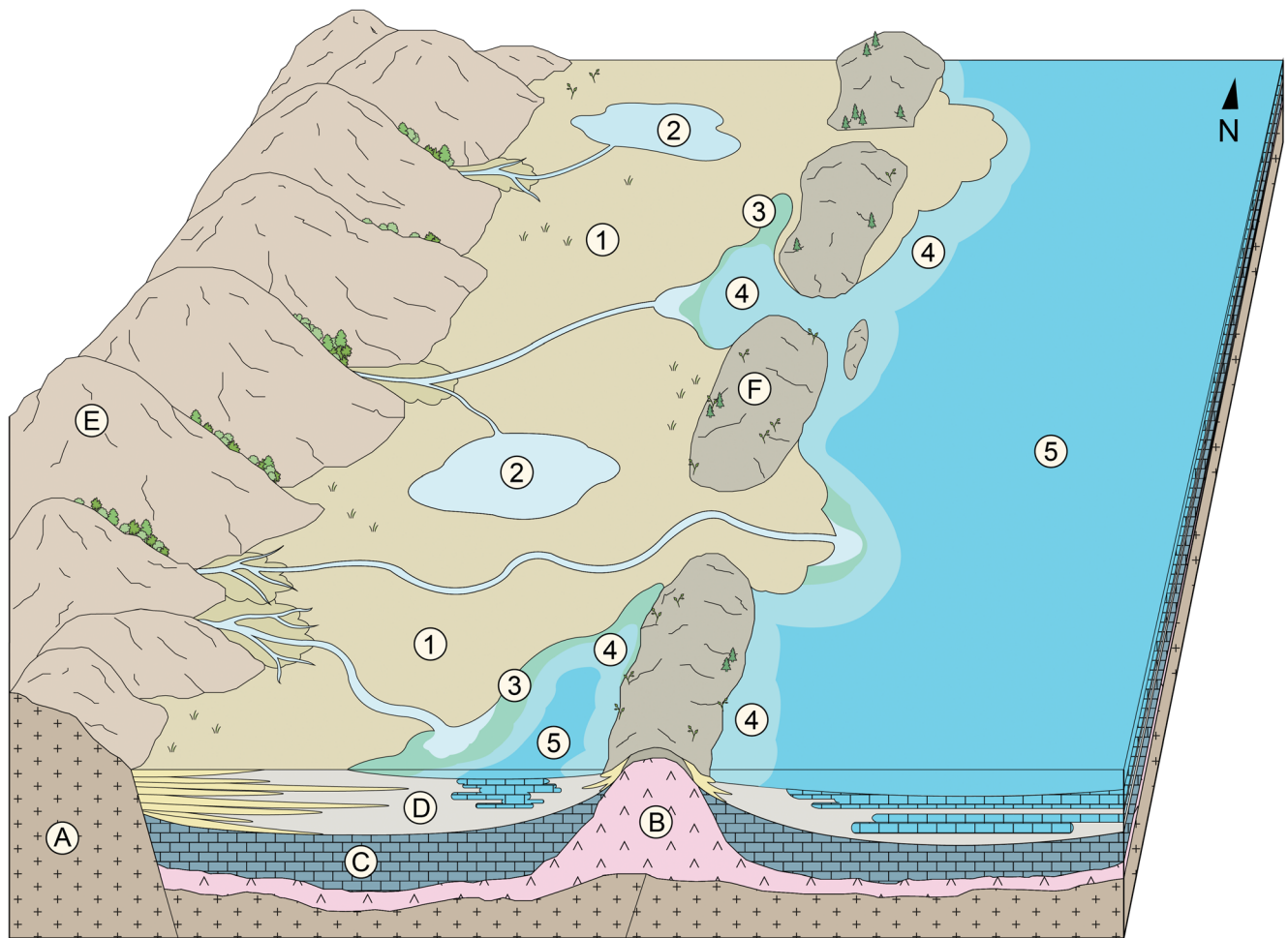


Fig. 25 Schematic depositional model of the Alcobaça Formation in the northern Consolação and western Bomarral sub-basins. *A* Variscan basement; *B* latest Triassic/earliest Jurassic salt (Dagorda Fm.); *C* Early Jurassic to Oxfordian carbonate rocks; *D* Alcobaça Fm.; *E* Berlenga Horst Block; *F* Caldas da Rainha Diapir (emergent passive diapir, with several saddles). Depositional environments/facies: 1 terrestrial, 2 lacustrine, 3 brackish water, 4 marine siliciclastic strata, 5 marine carbonate strata

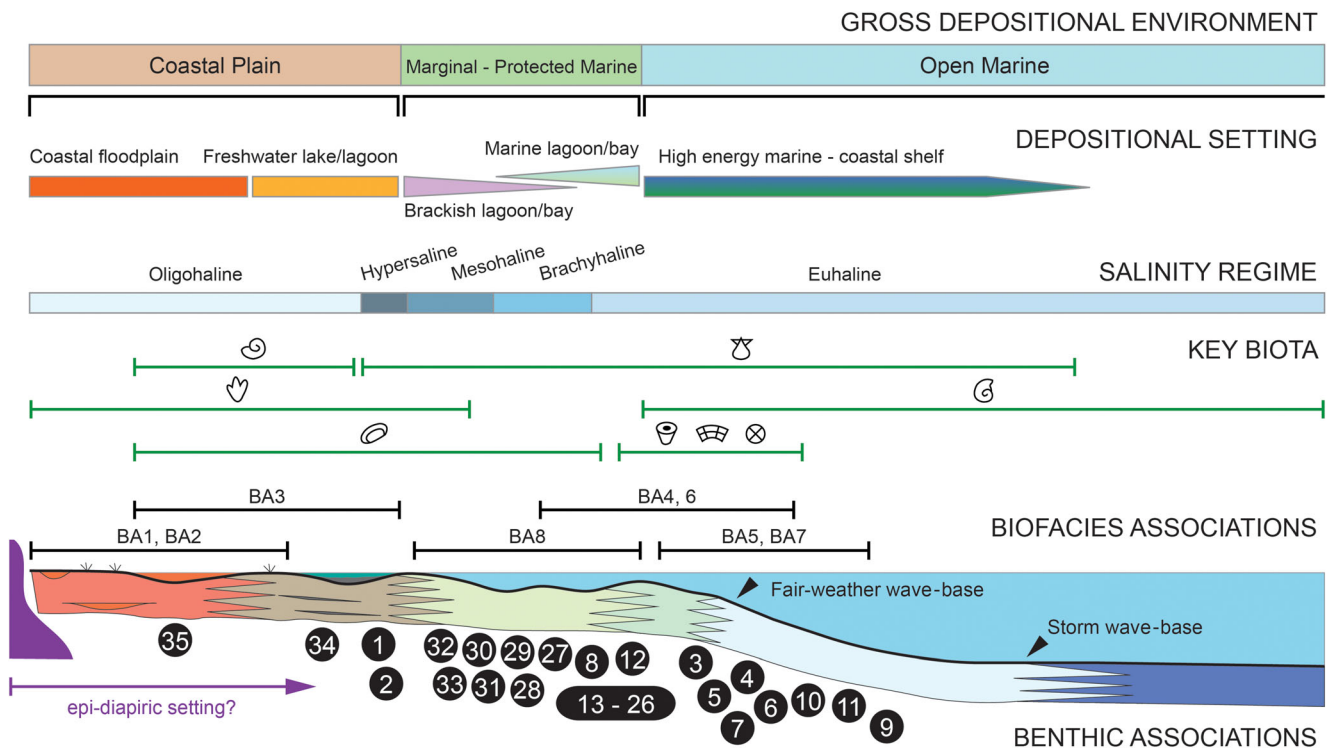


Fig. 26 Schematic cross section illustrating the distribution of gross depositional environments, depositional settings, salinity regimes, key biota (see Fig. 8 for the key of symbols), biofacies associations and benthic macrofaunal assemblages and associations (see Fig. 21 for numbers)

topography before the Late Jurassic, and only pierced the topographic surface during Late Cretaceous to Cenozoic shortening, related to Alpine deformation (e.g. Montenat and Guéry 1984; Guéry et al. 1986; Montenat et al. 1988; Wilson 1988; Ribeiro et al. 1990; Rasmussen et al. 1998; Alves et al. 2002, 2003; Kullberg et al. 2013). This model assumes that a more or less continuous Jurassic sedimentary succession was deposited on top of these pillows and was subsequently eroded (e.g. Wilson 1988; Rasmussen et al. 1998). An instructive example is the block diagram of Montenat et al. (1988: fig. 8), where the Kimmeridgian topography is quite accurately represented, but diapirs play a subordinate role in its interpretation. Recent studies, however, show that this scenario contradicts state-of-the-art models of salt tectonics and field evidence. It is now established that significant salt movement in the Lusitanian Basin initiated as early as the Early Jurassic, and passive diapirs started to pierce the overburden soon after (e.g. Lopez-Mir et al. 2019, 2020; Davison and Barreto 2020). This model implies that diapir growth kept abreast with sedimentation throughout the Jurassic, and deposition occurred only at the diapir flanks, but not on its crest, which was only covered by a thin veneer of roof strata (Fig. 25; see Hudec and Jackson (2007, 2011) and Giles and Rowan (2012) for concepts). This model further suggests that the basal contact of the Alcobça Formation with the Dagorda Formation, observed in several of the

studied sections, while being tectonic in nature, did not cause significant lateral displacement.

Thus, it is reasonable to assume that the Caldas da Rainha Diapir formed a topographic barrier during the Late Jurassic, separating the Consolação Sub-basin to the west from the Bombarral Sub-basin to the east (Figs. 25 and 26). The north-western part of the Consolação Sub-basin received siliciclastic sediments from the basement exposed on the Berlenga Horst, which formed, either as a chain of islands or as a continuous north-south elongated block, the western margin of the Lusitanian Basin. These fluvial sediments filled a shallow, subsiding graben adjacent to the diapir, which also received minor amounts of sediment shed from the diapir roof strata (Fig. 25). For much of the time, the diapir acted as a barrier so that only locally siliciclastic sediments reached the Bombarral Sub-basin in the east. At other times, marine waters from the Bombarral Sub-basin and the southern Consolação Sub-basin extended westward and northward, respectively, to the western flank of the diapir. The extent to which the diapir acted as a barrier apparently varied considerably throughout the Late Jurassic and was responsible for the frequent alternations and interfingering of non-marine, brackish-water and marine palaeoenvironments on both of its sides. The lower parts of the formation are represented by shallow-marine, high-energy siliciclastic to carbonate facies throughout the study area. They do not suggest a pronounced influence of the diapir on the facies pattern. The following thick package of lacustrine

and fluvial red beds in the northern coastal sections, which is not present on the eastern side of the diapir, except to a minor extent in the Vestiaria and Fonte Santa sections in the north, likely indicates the piercing of the diapir, which at that time acted as a pronounced barrier. In the upper part of the formation, repeated intercalations of brackish to marine sediments occur in the coastal sections. These document short-lived transgressions of marine waters, either advancing from the Bombarral Sub-basin, crossing the diapir via a saddle, or from the southern Consolação Sub-basin, using the foredeep flanking the diapir as a vector. Subsequently, the predominantly axial siliciclastic influx of the overlying Lourinhã Formation from the north terminated any marine influence in the area.

Evidence that the exposed diapir formed islands with adjacent intertidal to supratidal areas is also provided by the presence of common black pebbles, microkarst and dinosaur tracks in the Sobral da Lagoa and Amoreira sections. The dinosaurs must have crossed the coastal plains between the hills forming the western margin of the Lusitanian Basin and the emergent diapirs during periods of low water level and arid conditions and inhabited coastal areas while marine conditions prevailed. The exposed parts of the diapir also must have undergone erosion and supplied sediment to the Consolação and Bombarral sub-basins, but the quantity of this material is difficult to evaluate.

Marine to brackish-water areas on both sides of the diapir were populated by diverse macrobenthic communities (Fig. 26). In brackish lagoons and bays, bivalve-dominated communities lived, whose generally low diversity varied according to their salinity regime. These faunas were most prolific in the Consolação, Salir do Porto and São Martinho do Porto sections. Their dominance decreased in the Vestiaria and Fonte Santa sections, whereas in the remaining, carbonate-dominated sections, they are absent. The lowermost carbonate beds at Salir do Porto and São Martinho do Porto contain *Isognomon-Actinostreon*-dominated associations that most likely lived in slightly hypersaline environments (Fig. 26). This might reflect a relatively arid climate at that time. In the carbonate-dominated sections, corals and stromatoporoids are common elements. Corals and, in some cases, calcareous sponges, however, form patch reefs mainly in mixed carbonate–siliciclastic successions, settling on bioclastic detritus. This kind of substrate is also characteristic of the widespread coral meadows in the lower part of the Consolação section. The more pronounced marine influence in the southern sections seems to reflect a reduced influence of diapirism during the Kimmeridgian. This appears to have also been the case in the later part of the Kimmeridgian, when marine influence increased again throughout the study area.

Given that we did not study the succession in the Mamede Sub-basin in detail, it is unclear how much the Leiria, Porto de

Mós and Monte Real diapirs acted as a barrier. It should be noted, though, that both shallow-marine carbonate rocks and fine-grained freshwater to brackish-water siliciclastic strata were observed in the area of Abiul, signifying a range of lithofacies and biofacies similar to those observed in the other sub-basins.

The Alcobaça Formation as a model for biofacies analysis

Naturally, such detailed analysis of a single lithostratigraphic unit primarily advances the understanding of the conditions within the Lusitanian Basin. However, the Alcobaça Formation is particularly well exposed in several coastal sections and was so in the past at a number of localities inland. Furthermore, its fossil biota is remarkably well preserved over most of the succession. This made it possible to generate an outstanding dataset, which demonstrates the power of detailed biofacies analysis for disentangling a complex patchwork of palaeoenvironments. The observed interplay of sea-level fluctuations, climate changes and salt tectonics is not unique to the Lusitanian Basin. Units occupying a similar position at the interface of land and sea, thus showing a similar variability in biofacies, occur in numerous sedimentary basins, and the general approach applied to the Alcobaça Formation herein is transferrable.

Adjacent Atlantic basins, which are less well or not at all exposed, (presumably) show similar characteristics at a similar time, and biofacies of well materials, if available, could be directly compared. The Peniche Basin is situated directly to the west of the Lusitanian Basin, the Porto Basin to the north, the Galicia Basin to the northwest and the Alentejo Basin to the south. These basins are all part of the same continental margin, now entirely submerged, or almost so. Where available, scant evidence from wells and dredging documents lithologies and palaeoenvironments similar to those seen in the Lusitanian Basin (Boillot et al. 1973, 1974, 1975; Dupeuble et al. 1987). Moreover, seismic data, in particular from the Peniche Basin, suggest an evolutionary development comparable to that of the Lusitanian Basin, with salt tectonics playing an equally important role (Pinheiro et al. 1996; Alves et al. 2006, 2009; Pimentel and Pena dos Reis 2016; Walker et al. 2021).

Farther to the south, the Algarve Basin in southern Portugal and adjacent Spain is also influenced by diapirism but generally has a more marine, carbonate-dominated character (Terrinha et al. 2002; Borges et al. 2011; Matias et al. 2011; Fernandes et al. 2013). However, marginal marine environments with faunas similar to that of the Alcobaça Formation are represented in the basin (Pratsch 1958) but are probably understudied. In the Asturias Basin in northwestern Spain, a single comprehensive coastal outcrop of the late Oxfordian to early Tithonian Ribadasella Group exposes a number of biofacies similar to those observed in the Lusitanian Basin,

but seems to have a less intricate palaeoenvironmental development (Fürsich et al. 2012; González Fernández et al. 2014). Interestingly, significant thickness variations of Upper Jurassic strata in the subsurface (Boillot et al. 1979; Boillot and Malod 1988; Cadenas and Fernández-Viejo 2016) indicate a more complex development at the basin scale and suggest that tectonic processes, including diapirism, may have been neglected so far. At the conjugate western Atlantic margin, several basins offshore Newfoundland, including the Jeanne d'Arc, Flemish Pass, Orphan and Carson-Salar basins, have depositional histories similar to western Iberia (e.g. Stam 1986; Williamson 1987; McAlpine 1990). Being active hydrocarbon exploration areas, as increasing amounts of well materials become available from these basins, biofacies analysis may help to interpret their evolution.

The integrated approach documented here is limited only by the quality of the fossil record, not by geography or stratigraphy. It is thus globally applicable to constraining compartmentalisation in salt-floored basins.

Conclusions

1. The Alcobaça Formation is formally established as a lithostratigraphic unit of the central Lusitanian Basin. Its age is Kimmeridgian (late Bimammatum Zone to Beckeri Zone), based on ammonites, ostracods and strontium stable isotopes.
2. Seven members are established in the Bombarral and Consolação sub-basins (see Appendix), ranging across a spectrum from siliciclastic- to carbonate-dominated, whereby mixed carbonate–siliciclastic facies are characteristic.
3. The Alcobaça Formation captures a diverse range of depositional environments, from fluvial and coastal plain settings to marginal marine lagoons and embayments, and to the shallow-water shelf above storm wave-base.
4. Apart from common ostracods and foraminifera, the formation contains a rich benthic macrofauna dominated by bivalves, and an ichnofauna (including dinosaur tracks) representing the Scoyenia, Skolithos and Cruziana ichnofacies. Index fossils such as ammonites are very scarce.
5. Thirty-five benthic macrofaunal associations have been recognised, controlled mainly by water energy, substrate and salinity. Salinity-controlled associations occupied hypersaline to freshwater environments. The salinity regime of the associations has been determined based on sedimentological and ecological (species richness and evenness) parameters, species composition, comparison with modern relatives, the associated microfauna and microflora and morphological features such as shell thickness and shell size. Patch reefs and meadows mainly composed of corals, but locally also of calcareous sponges, or, in brackish environments, of oysters, occur at several levels.
6. To the west, in the northern Consolação Sub-basin, siliciclastic and often non-marine sediments dominate, whereas in the Bombarral Sub-basin farther to the east, thick carbonate successions prevail. Widespread terrestrial red beds with caliche and hypersaline carbonate facies in the lower part of the succession point to a semi-arid climate, which appears to have changed to more humid conditions near the top of the formation.
7. During Kimmeridgian times, the Caldas da Rainha Diapir, which started to rise as early as the Early Jurassic, formed an emergent topographic barrier, separating the northwestern part from the southeastern part of the basin. The western Consolação Sub-basin likely received siliciclastic sediments from Berlenga and adjacent basement horsts that formed the western margin of the Lusitanian Basin. These sediments only locally at times reached the areas east of the diapir, which were dominated by carbonate depositional systems. Brackish, marginal marine environments were common on both sides of the diapir.
8. The Alcobaça Formation, characterised by intricate facies patterns and varied biota, illustrates the impact of diapirism on the palaeogeography, facies and organisms of shallow-water basins such as the Lusitanian Basin. It forms an insightful analogue for adjacent Atlantic marginal basins and for elsewhere in the geological record. Detailed biofacies analysis of the unit is shown to be a powerful tool to analyse and disentangle the palaeoenvironmental development of such variable successions and, last not least, to subdivide them into meaningful lithostratigraphic units.

Appendix. Formal definition of the Alcobaça Formation

Derivation of name: From the city and municipality of Alcobaça, Oeste Subregion, Central Portugal.

Superior units: None. The proposed Estremadura Group of Witt (1977) and the Abadia Group of Leinfelder (1986) have never come into use.

First description: As Couches d'Alcobaça by Choffat (1885: 5, 18).

Chronostratigraphy: Earliest to latest Kimmeridgian (sensu Wierzbowski et al. 2016).

Synonyms: Couches d'Alcobaça = Camadas de Alcobaça = Alcobaça Beds (Choffat 1885; Zbyszewski and Moitinho de Almeida 1960; Ruget-Perrot 1961; Camarate França and Zbyszewski 1963, among others). Couches à *Lima alternicosta*, *pro parte* (Choffat 1885). Couches à *Lima*

pseudo-alternicosta = Camadas com *Lima pseudo-alternicosta*, *pro parte?* (Choffat 1901; Camarate França and Zbyszewski 1963, among others). Abadia Beds = Camadas de Abadia, *pro parte* (Camarate França et al. 1960; Manuppella et al. 1978; Wilson 1979). Camadas de Montejunto = Montejunto Formation, *pro parte* (Camarate França and Zbyszewski 1963; Mocho et al. 2017). Guimarota beds = Camadas de Guimarota = Guimarota-Schichten (Helmdach 1968, 1971a, b, among others). *Pholadomya protei* Beds = Camadas com *Pholadomya protei*, *pro parte* (Wilson 1975, 1979; Bernardes et al. 1991). Vale Verde Beds = Camadas de Vale Verde, *pro parte* (Wilson 1979; Bernardes et al. 1991). ‘Corallien/Sobral of Parant (1963)’ (Wilson 1979). Complexo de Vale de Lagares (Teixeira and Zbyszewski 1968). Formação Argilosa de S. Martinho do Porto (Bernardes et al. 1991). Reguengo Pequeno Subunit = Calcários calciclásticos com oóides, margas e grés de Reguengo Pequeno (Manuppella 1998; Manuppella et al. 1999). Moledo Subunit = Calcários de Moledo (Manuppella 1998; Manuppella et al. 1999). Consolação Member = Consolação Subunit = Grés, margas, calcários oolíticos e dolomites da Consolação = Consolação Formation (Leinfelder 1986; Manuppella 1998; Manuppella et al. 1999; Mocho et al. 2017; Castanera et al. 2020a, b). Calcários bioclásticos com corais e calcários oolíticos de Feteira (Manuppella et al. 1999). Margo-calcários de Abiúl = Formação de Abiúl = Membro de Abiúl (Almeida et al. 1990; Kullberg et al. 2013; Kullberg and Rocha 2014). **Lithology:** Characteristically highly variable. Carbonate rocks include marly, silty, sandy and rarely also pure mudstone; (mixed) (sandy) intraclastic, ooidal, oncoidal and bioclastic wackestone; (mixed) (sandy, silty or marly) intraclastic, oncoidal and bioclastic floatstone; silty ooidal wackestone; (mixed) sandy intraclastic, ooidal, oncoidal and bioclastic packstone; (mixed) (sandy) intraclastic, ooidal, oncoidal and bioclastic grainstone; (mixed) (sandy, marly) ooidal, oncoidal and bioclastic rudstone; oncolitic marlstone; coral boundstone; (silty, sandy, bioclastic) algal bindstone; and (sandy, silty) marl. Siliciclastic rocks include (silty, sandy) mudstone; (marly, argillaceous, sandy) (bioclastic, oolitic or oncolitic) siltstone; and (calcareous, marly, silty) (bioclastic, oolitic or oncolitic) fine- to coarse-grained sandstone. Rarely, coal layers and conglomerates consisting of caliche nodules occur.

Characteristic biota: Corals and coral meadows; marine and brackish-water bivalves, including abundant bivalviids, pteriids and neomiodontids, common shell concentrations of *Isognomon*, *Actinostreon* and *Trichites*, as well as *Praeoxgyra* patch reefs; marine and freshwater gastropods, including nerineids and valvatids; echinoids, predominantly abundant spines of *Pseudocidaris*; calcareous sponges, stromatoporoids, red algae and algal laminites; diverse

ichnofauna including *Psilonichnus*, *Rhizocorallium*, *Thalassinoides*, *Scoyenia* and dinosaur tracks.

Depositional environments: Marine: shallow, high- to low-energy open marine shelf, predominantly above fair-weather wave-base; shallow protected shelf below fair-weather wave-base; shoals, bars and channels; marine lagoons. Transitional: slightly hypersaline, brackish-water and freshwater lagoons and protected embayments. Freshwater: very shallow freshwater lakes and swampy areas; floodplain with overbank deposits; coastal plain; channels and levees of predominantly straight-headed streams.

Subunits: Seven members, which are defined below: the Consolação Member (proposed but not formalised by Leinfelder 1986), and the São Martinho, Gralha, Salgado, Arrinhada, Vestiaria and Columbeira members proposed here.

Two informal subunits introduced by Manuppella (1998) and Manuppella et al. (1999), i.e. the Reguengo Pequeno Subunit = Calcários calciclásticos com oóides, margas e grés de Reguengo Pequeno and the Moledo Subunit = Calcários de Moledo (Manuppella 1998; Manuppella et al. 1999) are poorly described and not supported by logs. The same applies to the Calcários bioclásticos com corais e calcários oolíticos de Feteira (Manuppella et al. 1999), which are referred to as the Alcobaca Formation herein, based on their lithology and fossil content. Outcrop in the respective area, at the southern slope of the Serra d’El Rei (Bombarral Sub-basin), is extremely poor, preventing a comprehensive log to be compiled (personal observation, June 2016).

The Margo-calcários de Abiúl = Formação de Abiúl = Membro de Abiúl (Almeida et al. 1990; Kullberg et al. 2013; Kullberg and Rocha 2014), which are restricted to a small area in the northwestern Mamede Sub-basin, east of Pombal, are similarly poorly described and exposed. The lithologies and biota observed conform to the general description of the Alcobaca Formation above (personal observation, June 2016). Whether the succession near Abiul has member status remains to be established. Farther to the south in the Mamede Sub-basin, the Complexo de Vale de Lagares of Teixeira and Zbyszewski (1968), cropping out in the area around the Vimeiro Diapir (Fig. 1: 6), conforms to the general description of the Alcobaca Formation but has not been studied by the present authors; its member status remains unassessed.

The ‘Praia da Amoreira-Porto Novo Subunit’ of Manuppella (1998) = ‘Grés margas e arenitos da Praia da Amoreira-Porto Novo’ of Manuppella et al. (1999) = ‘Praia da Amoreira-Porto Novo Formation’ of Mocho et al. (2017), which was assigned to the Alcobaca Formation by these authors, is considered part of the Lourinhã Formation herein.

Lower boundary: If undisturbed, the Alcobaca Formation overlies pure limestones of the Montejunto Formation. The contact is sharp and potentially represents a paraconformity.

The onset of the Alcobaça Formation is marked by the first level where siliciclastic influence becomes obvious, either as substantial admixtures of sand in the carbonate or in the form of siliciclastic horizons. In several sections, however, the Alcobaça Formation unconformably overlies clays, marls and anhydrites of the Dagorda Formation. The contact is tectonic but probably was so very early on, due to the diapiric activity.

Upper boundary: The Alcobaça Formation is overlain by fluvial–deltaic sandstones of the Lourinhã Formation. The contact is conformable and generally gradual. The upper boundary is defined as the level above which thick-bedded fluvial–deltaic sandstones, generally nested within stacked channel complexes, become dominant and euryhaline deposits are absent.

Thickness: Probably rather variable; minimum thickness approximately 400 m; maximum thickness greater than 600 m.

Type and reference sections, type region: The Vestiaria section, situated along the road from Fervença to Vestiaria, NW of the village (39.56882, –9.00305 to 39.56228, –9.00716; described in detail above), is selected as the stratotype of the Alcobaça Formation herein. The succession most closely conforms to the original Couches d’Alcobaça sensu Choffat (1885: 5, 18), which were described from near Fervença.

In the Vestiaria section, the top of the Alcobaça Formation is positioned at the base of a several-metres-thick fluvial sandstone bed, signalling the onset of the overlying Lourinhã Formation. However, the basal contact of the Alcobaça Formation with the underlying Dagorda Formation is tectonic in nature. The Fonte Santa section, just over 7 km to the southeast (road section near 39.52335, –8.95225), is the only comprehensive section exposing the paraconformable (?) basal contact of the Alcobaça Formation with the underlying Montejunto Formation and is thus selected as an additional reference section.

The western and eastern Bombarral Sub-basin and the eastern Consolação Sub-basin, where the sections studied herein are located, are considered the type region of the Alcobaça Formation. Owing to the heterogeneity of the unit, the type sections of the other six members defined below are all considered additional reference sections for the Alcobaça Formation.

Distribution: (A) Consolação Sub-basin, coastal exposures from south of Nazaré to Lagoa de Óbidos (sheets 26B Alcobaça, 26D Caldas da Rainha). (B) Consolação Sub-basin, coastal exposures at Consolação (sheet 26C Peniche). (C) Bombarral Sub-basin, western margin: eastern flank of Caldas da Rainha Diapir, between Rio Alcôa and Moledo (sheets 26B Alcobaça, 26D Caldas da Rainha, 30A Lourinhã, 30B Bombarral). (D) Bombarral Sub-basin, eastern margin: western flanks of Serra d’Aire, Serra de Porto de Mós and Serra dos Candeeiros, between Batalha and Rio Maior (sheets 26B Alcobaça, 26D Caldas da Rainha, 27A Vila

Nova de Ourém). (E) Mamede Sub-basin, western flank of Serra de Sico, between Pombal and Abiul (Carta geológica de Portugal, 1:50,000, sheet 23A Pombal). (F) Mamede Sub-basin, Vermoil and surroundings (sheet 23C Leiria). (G) Mamede Sub-basin, western flank of Serra d’Aire, Batalha and Porto de Mós (sheets 23C Leiria, 27A Vila Nova de Ourém). (H) Mamede Sub-basin, west of Ourém (sheet 27A Vila Nova de Ourém).

Time-equivalent units: Abadia Formation; Amaral Formation; Lourinhã Formation *pro parte*.

Age: Basal Kimmeridgian (late Bimammatum Zone; 156.9 ± 6 Ma) to latest Kimmeridgian (Beckeri Zone; 152.5 ± 5 Ma), based on strontium isotope stratigraphy (ages revised from Schneider et al. 2009, after Wierzbowski et al. 2017). Early Kimmeridgian (Planula/Platynota zones boundary interval) to earliest Tithonian (Hybonotum Zone), based on ammonite biostratigraphy (Werner 1986; Marques et al. 1992; Manuppella et al. 1999; herein). The earliest Tithonian age reported by Marques et al. (1992) for the highest part of the unit, which is deduced from the presence of *Hybonotoceras* sp., remains poorly supported and controversial. A basal to latest Kimmeridgian age is thus assumed herein (see “Revised age model”).

Members of the Alcobaça Formation

Due to its heterogeneity, the Alcobaça Formation is subdivided into seven lithologically and palaeoenvironmentally distinct members, which are defined in the following. For more detailed characterisations of the type sections, see “Section summaries”.

Consolação Member

Derivation of name: From the village of Consolação, south of Peniche.

First description: Section described in detail by Werner (1986); name proposed, but not formalised by Leinfelder (1986).

Synonyms: Consolação Subunit = Grés, margas, calcários oolíticos e dolomites da Consolação = Consolação Formation (Manuppella 1998; Manuppella et al. 1999; Mocho et al. 2017).

Type section: Coastal cliffs west and southwest of Consolação (39.32457, –9.36151 to 39.31232, –9.34679).

Lithology: Partly shelly calcareous sandstones and silty marl in the lower part; argillaceous silts, marly siltstones with intercalated fine- to coarse-grained sandstones in the upper part.

Lower boundary: Base of unit not exposed.

Upper boundary: Top of marly siltstones, overlain by thick fluvial sandstones of the Lourinhã Formation.

Thickness: 198 m.

Characteristic biota: Diverse coral meadows; benthic associations dominated by bivalve and pterioid bivalves; brackish-water softground associations; *Praeexogyra* patch reefs.

Depositional environment: Fully marine shallow shelf to nearshore salinity-controlled environments.

Distribution: Known from the type section only.

São Martinho Member

Derivation of name: From the parish of São Martinho do Porto.

First description: Logs published by Wilson (1979) and Bernardes et al. (1991).

Synonyms: Camadas de Montejunto, *pro parte* (Camarate França and Zbyszewski 1963). *Pholadomya protei* Beds = Camadas com *Pholadomya protei*, *pro parte* (Wilson 1975, 1979; Bernardes et al. 1991). Vale Verde Beds = Camadas de Vale Verde, *pro parte* (Wilson 1979; Bernardes et al. 1991).

Type section: Coastal cliffs at northern spur of Bay of São Martinho do Porto (39.51042, –9.14357 to approximately 39.51373, –9.14144).

Lithology: Basal 13 m fine- to medium-grained sandstones followed by fossil-rich wackestone to grainstone. After a 53-m-thick intercalation of fine-grained siliciclastic beds, the member concludes with a 12-m-thick sandy carbonate unit.

Lower boundary: The basal contact of the sandstones with the underlying Dagorda Formation is tectonic in nature; basal part of unit brecciated.

Upper boundary: Top of last carbonate bed of the second carbonate unit (Fig. 9 at 137 m), overlain by fine-grained siliciclastic beds of Gralha Member.

Thickness: 137 m (type section).

Characteristic biota: Shell concentrations dominated by *Isognomon*, *Actinostreon* and *Trichites*; algal laminites.

Depositional environment: Nearshore marine sandy shoals; brackish, marine to slightly hypersaline lagoons; coastal plain with fluvial channels.

Distribution: Known from the São Martinho do Porto and Salir do Porto sections.

Gralha Member

Derivation of name: From Praia da Gralha (Gralha Beach), north of São Martinho do Porto.

First description: Logs published by Wilson (1979) and Bernardes et al. (1991).

Synonyms: Abadia Beds, *pro parte* (Wilson 1979). Formação Argilosa de S. Martinho do Porto, originally proposed in an unpublished PhD thesis by Ellwood (1987), cited but not formalised by Bernardes et al. (1991).

Type section: Coastal cliffs north of São Martinho do Porto (approximately 39.51373, –9.14144 to 39.53606, –9.1252).

Lithology: Predominantly reddish argillaceous-marly silt with caliche nodules and with intercalated fine- to coarse-grained sandstones; some sandy limestone intercalations in the upper 120 m.

Lower boundary: Onset of fine-grained siliciclastic strata, following the last carbonate complex of the São Martinho Member (Fig. 9 at 137 m).

Upper boundary: Top of last thick red bed unit (Fig. 9 at 558 m), overlain by marlstones and limestones of the Salgado Member.

Thickness: 422 m (type section) to approximately 480 m.

Characteristic biota: Red beds unfossiliferous except *Scoyenia*; grey fine-grained siliciclastic strata with freshwater gastropods. Limestone intercalations with *Psilonichnus*, *Rhizocorallium* and *Thalassinoides* and a moderately diverse mollusc and coral fauna.

Depositional environment: Floodplain with fluvial channels; brackish-water lagoons; coastal lakes. Rare marine incursions.

Distribution: Known from the São Martinho do Porto and Salir do Porto sections.

Salgado Member

Derivation of name: From the village of Casal do Salgado, south of Nazaré, and the adjacent Praia do Salgado (Salgado Beach).

First description: Logs published by Wilson (1979) and Bernardes et al. (1991).

Synonyms: ‘Corallien/Sobral of Parant (1963)’ (Wilson 1979); this term incorrectly refers to an unpublished report of the Companhia Portuguesa dos Petróleos (CPP) by Parant (1963).

Type section: Coastal cliffs WSW of Casal do Salgado (approximately 39.539151, –9.121526).

Lithology: Mixed carbonate–siliciclastic strata, minor red bed intercalations; some fine-grained sandstones; common oncoidal floatstones to rudstones.

Lower boundary: Onset of marlstones and limestones following the last thick red bed unit of the Gralha Member (Fig. 9 at 558 m).

Upper boundary: Top of marine sandstone, overlain by non-marine siliciclastic beds of the Arrinhada Member (Fig. 9 at 605 m).

Thickness: 25 to 44 m (type section).

Characteristic biota: Scattered corals and stromatoporoids; marine bivalves and gastropods; diverse ichnofauna including dinosaur tracks.

Depositional environment: Very shallow, largely protected nearshore shelf, marine to brackish lagoons; coastal plain.

Distribution: Known from the São Martinho do Porto and Salir do Porto sections.

Arrinhada Member

Derivation of name: From the Miradouro da Arrinhada (= lookout of Arrinhada), halfway between Salir do Porto and Foz do Arelho.

First description: Herein.

Synonyms: None.

Type section: Coastal cliffs W of village of Boavista, SW of Salir do Porto (approximately 39.477073, -9.194230).

Lithology: Mainly reddish argillaceous/marly sandy silt with caliche nodules and intercalations of fine- to coarse-grained, partly cross-bedded sandstones; desiccation cracks and rootlets.

Lower boundary: Onset of siliciclastic strata on top of last carbonate bed of the carbonate-prone Salgado Member (Fig. 10 at 535 m).

Upper boundary: Top of fine-grained, relatively low-energy brackish-water siliciclastic strata, overlain by grey coarse-grained sandstone with abundant logs of fossilised wood of the Lourinhã Formation (Fig. 10 at 523 m).

Thickness: 88 m (type section).

Characteristic biota: Freshwater gastropods; *Scoyenia*, *Polycladichnus* and *Psilonichnus*.

Depositional environment: Mainly floodplain with fluvial channels; small lakes; brackish to freshwater lagoons.

Distribution: Known from the Salir do Porto and São Martinho do Porto sections; barely exposed in the latter.

Vestiaría Member

Derivation of name: From the parish of Vestiaría W of Alcobaça.

First description: Locality of Fervença mentioned by Choffat (1885: 5, 18). Position of the Vestiaría section of Marques et al. (1992) unclear; not identical with the section described herein.

Synonyms: None.

Type section: Road from Fervença to Vestiaría, N of village of Vestiaría (39.56882, -9.00305 to 39.56228, -9.00716).

Lithology: Reddish fine- to medium-grained sandstones, argillaceous/marly sandy silt, silty/sandy mudstone, marl; rare intraclastic grainstone; interlayered bedding.

Lower boundary: Onset of marine carbonate strata over reddish-purplish marls of the Dagorda Formation; contact tectonically distorted.

Upper Boundary: Top of fine-grained non-marine siliciclastic beds, overlain by coarse-grained fluvial sandstones of the Lourinhã Formation (Fig. 12, at 399 m).

Thickness: 399 m (type section; upper part poorly exposed).

Characteristic biota: Coral meadows, coral and coral-sponge patch reefs; freshwater gastropods; diverse marine benthic macrofauna.

Depositional environment: Fluvial channels; small lakes; brackish, partly tidal-influenced lagoons and fully marine coastal environments.

Distribution: Known from the Vestiaría and Fonte Santa sections and adjacent areas, including the localities of Barrio, Chiqueda and Carrascal.

Columbeira Member

Derivation of name: From the village of Columbeira, NW of Bombarral.

First description: Herein.

Synonyms: None.

Type section: Road from Azambujeiras dos Carros to Columbeira (approximately 39.29165, -9.19146 to 39.30282, -9.18704).

Lithology: Lower and upper part an alternation of sandy carbonate beds, marl and silty marl with minor sandstone intercalations and abundant lignite fragments; upper part in addition with common oncoids; middle part mainly intraclastic and ooidal wackestones to grainstones and oncoidal rudstones (Fig. 14). Several levels with dissolution cavities.

Boundaries: Base and top of member not seen.

Thickness: Greater than 576 m.

Characteristic biota: Red algae, stromatoporoids, corals, sponges, and echinoid fragments.

Depositional environment: Shallow to very shallow, occasionally emerged, marine carbonate platform composed of restricted and exposed areas.

Distribution: Known from the Columbeira, Dagorda, Amoreira and Sobral da Lagoa sections and adjacent areas.

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Declarations

Conflict of interest The authors declare no competing interests.

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