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Heterozoan carbonates: When, where and why? A synthesis on parameters controlling carbonate production and occurrences

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ABSTRACT

In modern and Phanerozoic times, heterozoan carbonates group a large array of depositional environments from the poles to the tropics. This global assessment reviews the critical parameters and controlling factors of heterozoan carbonates: (i) stratigraphic and global distributional trends, (ii) oceanographic and trophic relationships, and (iii) biological and sedimentary processes. Well-documented case studies ($n = 129$) have been investigated when facies and stratigraphic attributes were available, and when environmental settings, such as oceanography, climate and paleogeography were clearly identified. These case studies occur during specific periods of time in the sedimentary record, e.g. Late Ordovician, Early Carboniferous, Early Permian and Neogene, while they are absent during others, e.g. Triassic and Jurassic. Periods during greenhouse to icehouse transitions, and those with active thermohaline circulation, are particularly conducive for heterozoan carbonates. Based on global oceanographic patterns and existing ecological and hydrodynamic regime classifications (Hallock, 2001; Pedley and Carannante, 2006; James and Jones, 2015), a process-based classification scheme is proposed that distinguishes two main heterozoan carbonate systems: (i) a highly productive system characterized by suspension-feeding biota and (ii) an oligo-mesotrophic, warm-temperate system characterized by red algal and seagrass derived biota. Eight depositional models are proposed that combine (i) the source of energy for metabolic activities that allow the carbonate-producing biota to thrive and (ii) hydrodynamics and physiography of the depositional system that control the sediment accumulation. The local and platform scale based profiles can be used to complement the facies approach of James and Jones (2015).

1. Introduction

An important question that still is out in carbonate sedimentary system literature is what are the most critical driving parameters that control the production of cool-water (e.g. (Nelson, 1988b; Schlager, 2003)) or heterozoan carbonates (James, 1997)? Despite extended research on these particular carbonate sedimentary systems (James & Clarke, 1997; Nelson, 1988a; Pedley & Carannante, 2006a), there is no unequivocal answer to this question. The term “heterozoan carbonate” groups carbonate sediments that are dominated by skeletal grains of heterotrophic biota (i.e. feeding on organic matter) and phototrophic red algae (i.e. using light as source of energy; cf. (Hallock, 2001; Hallock, 2015)). In contrast to tropical, photozoan carbonates, such as coral reefs that are restricted to low latitudes, heterozoan carbonates occur within a wide spectrum of climatic zones (e.g. (Henrich et al., 1995; James & Jones, 2015; Nelson, 1988a)). In the modern world, examples of heterozoan carbonate deposits are found as red algal deposits in the Norwegian fjord region (Freiwald, 1998), as barnacle and

bivalve submarine dunes on Spitsbergen Bank (Henrich et al., 1997), as seagrass-derived and rhodoliths in the microtidal Mediterranean Sea (Betzler et al., 1997; Fornos & Ahr, 1997), as mollusc and barnacle sands on the Mauritanian Banc d'Arguin shelf facing the Sahara desert (Klicpera et al., 2015), and as extensive bryozoan accumulations on the distal part of the South Australian shelf facing the Southern Ocean (James et al., 2001). Hence, heterozoan carbonates are highly heterogeneous both in terms of sedimentary deposits and oceanographic realms. Beyond a case-to-case environmental interpretation, this heterogeneity obscures the establishment of a simple concept relating heterozoan carbonates and environmental processes and impedes the prediction of occurrences of heterozoan carbonates at a global scale in past sedimentary records. Such environmental drivers are potentially a combination of climate, oceanography, ecology and carbonate biogeochemistry.

The concept of heterozoan carbonate is a relevant tool to interpret sedimentary records in terms of grain associations and sedimentary facies (James, 1997; James & Jones, 2015; Kindler & Wilson, 2010). A

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limitation is, however, recognized for the Paleozoic during which heterozoan benthic organisms were fundamentally different (James & Jones, 2015). A set of causes was advocated to be responsible for the significant heterozoan carbonate production during the Paleozoic: “thermocline-stratified water column”, “climate change” and a “changing global current system” (James & Jones, 2015). As it was introduced above about the modern world, the lack of a conceptual scheme relating heterozoan carbonates and environmental processes at a global scale impedes the interpretation of distribution of heterozoan carbonates as a whole into a consistent framework of controlling parameters; besides water temperature, which was shown not to provide a fully satisfying model (Edinger et al., 2002; Halfar et al., 2004; Henrich et al., 1995; James, 1997; Lees & Buller, 1972; Michel et al., 2011; Pomar et al., 2004; Samankassou, 2002; Westphal et al., 2010).

Building a conceptual scheme relating carbonate sediments to environmental drivers implies to define carbonate factories that are controlled by discriminating parameters. For instance, phototrophic red algae and heterotrophic suspension feeders can be distinguished based on the energetic resources allowing the biota development, light or organic matter, respectively (cf. (Hallock, 2001; Hallock, 2015)). Such an approach could allow the prediction of specific carbonate-producing ecosystems in a given paleoceanographic setting (cf. (Lees & Buller, 1972); Lees, 1975; (Schlager, 2005), Chapter 1). In turn, the definition of platform-scale carbonate factories and associated carbonate grains allows the prediction of carbonate facies, depositional profiles and stratigraphic architectures (cf. (Schlager, 2005)). Such a process-based scheme relating carbonate platforms to environmental drivers at a global scale would allow interpreting changes of carbonate grain associations through space and/or time (e.g. (Pomar et al., 2004)).

An extensive bibliographic review was carried out to synthesize the occurrence of heterozoan carbonate platforms on a global scale throughout the Phanerozoic. These global occurrences were compared with oceanographic, climatic, eustatic, ecological and evolutionary data to determine whether stratigraphic trends exist that relate the global carbonate distributions to oceanographic patterns and climates throughout the Phanerozoic. By contrast to the general review of James and Jones (James & Jones, 2015), the present work is a process-based approach that specifically focuses on the global controlling parameters of carbonate production. In other words, we aim to answer the questions (i) whether or not ecological parameters drive the biota development of specific, platform-scale carbonate grain associations at a global scale and (ii) at a more local scale, whether or not the coupling between topography and hydrodynamics controls carbonate accumulation. This coupling is used to define eight depositional profiles that derived from the carbonate facies spectrum models of James and Jones (James & Jones, 2015). Based on global-scale, primary ecological and oceanographic principles and existing conceptual schemes, we attempt to decipher specific controlling parameters of different platform-scale carbonate factories that remain valid beyond evolutionary trends.

2. Methods and semantics

We analysed 129 case studies reaching from the Ordovician to the present (33 modern and late Pleistocene case studies and 96 outcrop and subsurface examples, cf. Appendix) to obtain a detailed overview of the distribution of heterozoan carbonate platforms through space and time. While we aimed at defining the distributional patterns of carbonate deposits, we first determined (a) the facies characteristics of the deposits to differentiate different types of heterozoan carbonate platforms, and (b) the environmental controls of carbonate production to interpret their geographic occurrences at a global scale. We therefore focused on the analysis of (i) the grain association, (ii) the trophic relationship, (iii) the locus of production, (iv) the overall sediment composition, (v) the type of carbonate platform and the (vi) oceanographic, (vii) climatic and (viii) paleogeographic setting.

The bibliographic search was primarily driven by case studies in

which the authors described the platform-scale deposits as *cool-water carbonates*. The study was undertaken in 2014 and 2015; therefore, only a few later published case studies were implemented into the database. We realize that we may have missed out on some case studies despite our intensive literature search, but nevertheless estimate that we obtained a representative data set of the diversity of platform-scale heterozoan carbonates through space and time, well suited to our purpose. It needs to be mentioned that in terms of grain association we consider *foramol* (Lees & Buller, 1972), non-tropical (Nelson, 1988b; Rao, 1996) and cool-water carbonates or C-factory (Schlager, 2003; Schlager, 2005) as equivalent names of heterozoan carbonates (cf. (Kindler & Wilson, 2010) for a detailed discussion). To classify the deposits as being part of the heterozoan carbonate entity, we followed the definition of James (James, 1997) in which suspension-feeding organisms and/or red algae characterize the carbonate or mixed siliciclastic-carbonate system at the platform scale. Large foraminifers as photosymbiotic organisms are considered to be typical grains of the photozoan association, and thus carbonate platforms dominated by these foraminifers are not taken into account. By contrast, light-dependent seagrass ecosystems leading to heterotrophic and/or red algal grain-dominated carbonate platforms are included in the study. We only considered the shallow-water marine carbonates, i.e. platforms: ramp and shelf settings; deep-water coral mounds and seep carbonates are excluded from the review. Specific case studies, in which proximal settings display photozoan carbonates, while other parts of the platform show a characteristic sedimentation of heterozoan carbonates (e.g. Paleozoic North American cratonic ramps; cf. (James, 1997), Fig. 13), are considered as heterozoan case studies at a platform scale.

2.1. Notes on semantics

Semantics is a critical issue in applying and discussing carbonate factory concepts (James, 1997; Schlager, 2005) leading to different understandings and confusion especially in terms of environmental interpretation, paleogeography and paleoceanography (e.g. (Kindler & Wilson, 2010)). For example, rudist and large photosymbiotic benthic foraminifer grains are considered either as a photozoan/tropical (this study, following (James, 1997)) or a heterozoan/cool-water carbonate association depending on authors (e.g. (Brandano et al., 2009; Carannante et al., 1997; Schlager, 2005)). Also, heterozoan grain associations occur in the distal, oligophotic and aphotic parts of almost every photozoan carbonate platforms (James, 1997). Following an oceanographic process-based approach at a platform-scale, sediment bodies that are characterized by a heterozoan grain association but are parts of either a photozoan carbonate platform (e.g. rhodolith beds of the Brazilian Abrolhos Shelf; (Amado-Filho et al., 2012)) or a siliciclastic shelf (e.g. reefs off the Amazon River mouth; (Moura et al., 2016)) are not included in the study. Even though it remains difficult to interpret incomplete records of platform depositional profiles and to attribute a single oceanographic driver to a platform-scale grain association, case studies of photozoan vs. heterozoan carbonates are considered here at the platform scale (following in this respect the carbonate factory approach of (Schlager, 2005)).

3. Overview of case studies

3.1. Phanerozoic overview

Most sedimentary deposits of heterozoan carbonates are accumulations of loose grains, whose locus of deposition differs from the locus of production (cf. (James & Jones, 2015)). Depositional profiles vary between homoclinal ramps, distally-steepened ramps, open shelves and uneven shelves, which include topographic highs, escarpments and fjords.

The preservation of heterozoan carbonates is apparently not uniform through geological time (Fig. 1). They occur during specific

Fig. 1. Stratigraphic distribution of heterozoan carbonate case studies with characteristic biota and depositional settings (global temperature curve from the PALEOMAP Project, 2015).

periods in the sedimentary record, e.g. Late Ordovician, Early Carboniferous and Early Permian, while they are absent during others, e.g. Triassic and Jurassic (Fig. 1). A larger number of case studies occur in more recent times (Oligocene to recent; 76 out of 129 case studies including 33 modern case studies). A geological preservation bias could not be ruled out for the latter increase of case studies. Another reason, which could justify this observation, is that many biota characterizing heterozoan carbonates such as barnacles, infaunal bivalves and red algae evolved during the Neogene (e.g. (Crame, 2002), about infaunal bivalves, and (Aguirre et al., 2000), about red algae).

3.2. Paleozoic era

Specific ramp profiles occur during the Paleozoic that are generally very wide (hundreds of kilometers) and include skeletal shoals and mounds of bryozoans, crinoids and brachiopods. Most occurrences are found in North America (21 out of 40 case studies, Figs. 2A, B, 3). Other cases occur in Northern and Western Europe ($n = 12$), Northern Africa ($n = 2$), Australia ($n = 3$), Bolivia ($n = 1$) and China ($n = 1$). Heterozoan carbonates typically occur in the paleo-tropics ($n = 22$) along cratonic and foreland margins influenced by open-ocean waters, i.e. the Sebré Trough during the Late Ordovician ((Kolata et al., 2001; Pope, 2004); Fig. 3) and the Ouachita Trough during the Early Carboniferous (Fransen, 2006). Upwelling of nutrient-rich waters was interpreted as the driving mechanism for the development of heterozoan carbonates at these low paleolatitudes (Fransen, 2006; Pope, 2004; Whalen, 1995). Other Paleozoic occurrences are found at mid-paleolatitudes during the Permian ($n = 4$; cf. (Beauchamp & Desrochers, 1997; Bensing et al., 2008; Stemmerik, 1997)) and in high paleolatitudes during the Late Ordovician (northern Gondwana; $n = 7$), Early Silurian (western

Gondwana; $n = 1$) and Permian (northern and southeastern Pangea; $n = 6$; Fig. 2).

While accumulations of characteristic heterotrophic biota occur in most parts of the Paleozoic case studies, inner ramps show a clear latitudinal pattern. In the paleo-tropics to paleo-subtropics, proximal settings might show sabkha environments, ooid shoals and skeletal grains that are characteristic of the photozoan association such as corals and large benthic foraminifers (Ordovician, Devonian, Carboniferous and Permian; e.g. (Beauchamp & Desrochers, 1997; Bensing et al., 2008; Martindale & Boreen, 1997)). At higher paleolatitudes, the inner-ramp deposits typically show terrigenous-dominated facies (Ordovician, Silurian and Permian; e.g. (Beauchamp & Desrochers, 1997; Blomeier et al., 2013; Jafarian et al., 2017a; Jafarian et al., 2017b; James et al., 2009a; James et al., 2009b; Rogala et al., 2007; Vennin et al., 1998)). The inner ramp of mid-paleolatitude case studies during the Permian shows an intermediate character with varying terrigenous deposits and biota typical of a subtropical climate (i.e. large benthic foraminifers; cf. (Bensing et al., 2008)). Paleozoic heterozoan carbonates are often associated with phosphate-rich deposits and cherts in more distal environments (cf. (Beauchamp & Desrochers, 1997; Fransen, 2006)).

Such large depositional systems and accumulations of heterozoan grains are restricted to the Paleozoic period and refer to the “upwelling” and “thermocline ramp models” of James (James, 1997). The topographically-controlled sedimentation of heterozoan carbonates on Permian horst blocks of Australia differs from other Paleozoic depositional models and corresponds to the “cold-water carbonate facies model” of (James & Jones, 2015); case study 33; cf. (James et al., 2009a; James et al., 2009b)).

Fig. 2. Overviews of the global distributions of heterozoan carbonate case studies (circles and numbers). Each map shows case studies of a given stratigraphic interval (cf. Appendix) that are displayed on a given time period paleogeography (modified paleogeographic maps of (Kießling et al., 2003), including carbonate platforms in black).

3.3. Cretaceous period

During the Mesozoic, heterozoan carbonates mostly occur at low paleolatitudes (8 out of 9 cases; Fig. 2C). They display a wide distribution covering Western Europe (Denmark, Spain and France), West Africa (Gabon and Republic of Congo), South America (Peru and Brazil) and India. While most occurrences show mixed carbonate-siliciclastic sediments in which tropical grains are present (e.g. ooids, oncoids,

green algae, rudists and large benthic foraminifers; n = 6), abundant bryozoans, molluscs, echinoderms and small benthic foraminifers characterize the grain associations. Carbonates are produced and deposited from the innermost part of the platform to the mid-ramp. Cretaceous heterozoan carbonates show much more limited deposit widths and thicknesses compared to the very wide homoclinal ramps of the Paleozoic.

While platform profiles of Cretaceous heterozoan carbonates are

Fig. 3. Late Ordovician heterozoan carbonates (18 dots, 454–445 Ma period; cf. Appendix). Main continental (black lines) and platform areas (dashed lines) are shown and paleo-upwelling prediction (hatched zones) is highlighted (430 Ma). Note the correspondence to heterozoan carbonates and predicted upwelling zones (redrawn from (Parrish, 1995)).

similar, specific grain associations allow to distinguish two marine realms, (i) a mixture of diverse phototrophic and heterotrophic biota in small, oceanographically restricted basins of the Tethyan region ($n = 5$; e.g. Basco-Cantabrian Basin) and (ii) suspension-feeding biota in more open-ocean-influenced platforms of the South Atlantic, which is opening during the Cretaceous ($n = 3$). Such ramp profiles fit into the hydrodynamic model of “interior basin margin ramp” of James and Jones (James & Jones, 2015); no corresponding profile, however, was found among the facies spectrum models of (James, 1997; James & Jones, 2015; James & Lukasik, 2010). The only case study of Cretaceous heterozoan carbonate occurring at a relatively high paleolatitude comes from the Danish Basin. This very wide ramp shows a depositional profile that is similar to the high-latitude ramp of the Paleozoic (cf. previous Section 3.2; case study 49; cf. (Surlyk, 1997)).

3.4. Cenozoic era (excluding the late Pleistocene-Holocene)

While few case studies cover the Paleogene up to the end of the Eocene ($n = 4$), many case studies occur during the Oligocene and Miocene time interval ($n = 43$ up to the Early Pleistocene). Cenozoic heterozoan carbonates are found at mid-paleolatitudes, while they are not recorded at very low and very high latitudes (Fig. 2D, E, F). Numerous case studies occur in the Mediterranean, Tethys and Paratethys realms and include red algal, large benthic foraminifer and seagrass meadow deposits that are typical of subtropical and warm-temperate paleolatitudes (21 out of 47 case studies, cf. (Betzler et al., 1997; James & Bone, 2011)). Only carbonate systems characterized by seagrass and red algal deposits with secondary large benthic foraminifer grains lacking corals (apart from few *Porites*) are counted as proper case studies. Other occurrences of heterozoan carbonates that are characterized by heterotrophic biota are recorded in Australia and New Zealand ($n = 17$). A minority of occurrences comes from Pacific Islands, the east coast of the USA (North Carolina), Alaska, southern Argentina, northern Morocco and NW India ($n = 9$). Two types of depositional environments can be distinguished (also cf. (Betzler et al., 1997; James & Jones, 2015; Pedley & Carannante, 2006b)); (i) ramps of semi-enclosed basins (i.e. relatively low hydrodynamics; e.g. Mediterranean Sea, semi-enclosed gulfs and bays) and (ii) exposed open shelves and distally-steeped ramps (i.e. relatively strong hydrodynamics; e.g. Southern Ocean).

The large array of initial topographies and oceanographic settings (i.e. hydrodynamic regimes) leads to very diverse depositional profiles. These depositional profiles can be grouped into different types of sedimentary systems. The Eocene case study from Morocco (case study 50) shows a ramp with heterozoan biota and mounds that relates to the high-latitude homoclinal ramp depositional model that is described for the Paleozoic (cf. Section 3.2). Several case studies show ramps with well-developed rhodalgal sedimentation in distal parts of the ramp (i.e. red algal-dominated facies, cf. (Carannante et al., 1988; Pomar, 2001a); case studies 73, 77, 86, 89, 90 and 95). These ramps refer to the “warm temperate lower energy facies model” of James and Jones (James & Jones, 2015). Other case studies display well-developed sedimentation in proximal settings that often includes tropical biota (e.g. corals and large benthic foraminifers; case studies 51, 56, 57, 61, 64, 65, 67, 69, 70, 71, 78, 79, 80 and 81). Five case studies show a warm-temperate deposition type (cf. (Betzler et al., 1997)) that is strongly controlled by sediment transport (case studies 66, 68, 74, 75 and 87). These case studies often show an active tectonic setting as either faulting or strong subsidence (e.g. inherited escarpment on ramp, very narrow platform and channelized deposition). Numerous case studies display sedimentary systems that are dominated by strong hydrodynamics. Deposition within a seaway or a paleo-valley shows a wave-, tide- and/or current-dominated sedimentation (e.g. cross bedding) and corresponds to the “carbonate seaway model” of James and Lukasik (James & Lukasik, 2010) and James and Jones (James & Jones, 2015). Several case studies show great volume of sedimentation along distal parts of open shelves

(i.e. outer-shelf deposits and slope clinoforms), where bioclastic grains are derived from a highly energetic open shelves (i.e. Australian case studies; cf. “shaved shelf model” of (James & Lukasik, 2010), and “warm temperate high energy facies model” of (James & Jones, 2015); case studies 54, 58, 59, 63 and 82). Other highly hydrodynamic systems include segmented shelves, where carbonate production and accumulation are largely controlled by antecedent topography (e.g. fjords, volcanic substratum and topographic highs; case studies 52, 53, 60, 62, 85, 88, 92, 93, 94 and 96). These segmented shelf settings refer to both the “cool temperate” and “cold water carbonate” facies models of James and Jones (James & Jones, 2015). Two case studies were not classified because of the lack of information about their depositional setting (case studies 76 and 83).

3.5. Modern times

Like most sedimentary carbonates, heterozoan carbonates preferentially occur outside terrigenous-dominated settings (e.g. Chave, 1967). Nevertheless, heterozoan carbonates are commonly found in mixed siliciclastic-carbonate sedimentary systems (19 of 33 case studies). Moreover, carbonate deposits do not occur in major anoxic and poorly saturated carbonate regions (e.g. the Humbolt and Benguela Current regions and most parts of the Southern Ocean). Modern heterozoan occurrences display a worldwide distribution from the poles to the tropics including the Mediterranean Sea ($n = 6$), Australia and New Zealand ($n = 8$) and the northern North Atlantic ($n = 10$) among others (Fig. 4). Types of carbonate deposits are warm, high-nutrient (e.g. Mauritania, Panama, Galapagos; (Michel et al., 2011; Reijmer et al., 2012; Reymond et al., 2015); cf. (Allmon, 2007), and (Westphal et al., 2010)), warm-temperate (e.g. Mediterranean Sea, South Australian gulfs; (Betzler et al., 1997)), cool-water (e.g. South Australia, New Zealand; (James & Lukasik, 2010; Nelson, 1988b)) and cold-water carbonates (northern North Atlantic; (Henrich et al., 1995; James & Jones, 2015)), the latter deposits including relict sediments with very low (e.g. western Canada) to no production (e.g. Antarctica). Most deposits consist of thin, grainy sediment covers dating back to the last transgression (maximum 18 ka BP; e.g. (James & Lukasik, 2010)).

As for the Cenozoic period, modern deposits of heterozoan carbonates display a large array of depositional profiles at a platform scale. Six case studies show ramps with well-developed seagrass-derived and rhodalgal sedimentation, which corresponds to the Mediterranean, warm-temperate carbonate model (cf. (Betzler et al., 1997; Fornos & Ahr, 1997; Pérès & Picard, 1964); case studies 99, 100, 101, 105, 122 and 124). These ramps also refer to the “warm temperate lower energy facies model” of James and Jones (James & Jones, 2015). Several case studies display a well-developed sedimentation in proximal settings that often includes tropical to subtropical biota (e.g. corals and large benthic foraminifers) and a varying amount of phototrophic biota depending on the intensity of upwelling and/or terrigenous input (case studies 98, 108, 118, 120, 123, 127 and 128). End members of such depositional profiles are on the one hand, the Mauritanian shelf which is influenced by a major Eastern Boundary Upwelling system and desert dust input. In this Mauritanian setting, phototrophic grains are restricted to few red algae in few meters water depth, while a large production of suspension-feeding bivalves and barnacles occurs (Klicpera et al., 2015). On the other hand, a rhodalgal-dominated sedimentation which includes few corals in proximal settings and bioclastic deposits in distal settings arise in the well-illuminated, subtropical environment of the Abrolhos Shelf and the middle part of the Gulf of California ((Collins et al., 1997), and (Halfar et al., 2006), respectively).

Few case studies show the typical high-energy, “shaved shelf” depositional profile of the Great Australian Bight (cf. (James & Bone, 1994; James & Lukasik, 2010); case studies 125 and 126). Such an open shelf shows a relict-dominated inner shelf where little sedimentation occurs, while most production is shed towards the distal parts of the

Fig. 4. Map showing recent occurrences of heterozoan carbonates: 33 referenced occurrences (dots and circles; cf. Appendix) and 14 non-referenced occurrences (stars) from Lokier et al. (Lokier et al., 2009), Nelson (Nelson, 1988b), Rao (Rao, 1996). Isothermal lines of 18 °C and 24 °C during the warmest time (summer) of each hemisphere are shown. Map modified from www.outline-world-map.com.

platform and the slope (cf. “warm temperate high energy facies model” of (James & Jones, 2015)). Finally, numerous heterozoan carbonate deposits accumulate on topographic highs (coarser-grained) or lows (finer grains) or as localized bioclastic beds. Sedimentation is directly controlled by relatively high hydrodynamics and corresponds to the “cool temperate” and “cold water carbonate” facies model of James and Jones (James & Jones, 2015).

4. Stratigraphic distribution of heterozoan carbonates

4.1. Paleozoic records of heterozoan carbonates

Photozoan carbonates that are characterized by non-skeletal grains and carbonate-producing biota such as corals, microbes, algae and stromatoporoids (Brookfield, 1988; Kiessling et al., 2003; Kolata et al., 2001), are known from tropical, oceanographically-restricted cratonic basins. Seawater of these paleoenvironments is thought to have been supersaturated with respect to carbonate (cf. (Gattuso et al., 1998; James, 1997; Opdyke & Wilkinson, 1993; Riding, 2005)). By contrast, Late Ordovician and Carboniferous heterozoan carbonates are found in zones along cratons that are marked by open-ocean, highly productive waters (Fig. 3; (Franseen, 2006; Pope, 2004)). These occurrences relate to predicted zones of paleo-upwelling (cf. (Parrish, 1982; Parrish, 1995; Whalen, 1995)). At higher paleolatitudes, the location of heterozoan carbonate deposits along the northern Gondwana margin during the Late Ordovician corresponds to a highly productive zone in which the formation of deep waters within a thermohaline circulation model is predicted (cf. (Pohl et al., 2017), and personal communication) – which implies the absence of a perennial oceanic stratification as observed in the modern, highly productive northernmost Atlantic (cf. Fig. 3, n = 10 modern case studies of heterotrophic carbonate-secreting biota in NE Atlantic).

The oceanic driver of the heterotrophic carbonate production (i.e. bryozoans, crinoids and brachiopods) is a high marine productivity. This paleoecological relationship was highlighted in several well-documented paleoenvironmental studies (e.g. (Franseen, 2006; Kolata et al., 2001; Martindale & Boreen, 1997; Pope, 2004; Samankassou, 2002; Zhou et al., 2015)). The occurrence of phosphate and chert

deposits agrees with this interpretation (e.g. (Franseen, 2006)). Following Whalen (Whalen, 1995) and James (James, 1997), an analogue of such carbonates in terms of oceanographic processes and grain association (i.e. ooids and suspension-feeding biota) is the upwelling-influenced, modern Mauritanian shelf (Klicpera et al., 2015; Michel et al., 2011). The very wide homoclinal ramps of the Paleozoic imply that hydrodynamics were moderate and hence they can neither be compared to the Mauritanian shelf nor to the modern South Australian setting facing the Southern Ocean (cf. (James et al., 2001)). Insights into moderate hydrodynamic processes might be gained in the modern from sedimentary processes of the Persian Gulf, which shows a unique modern example of an extensive ramp system (cf. (Riegl et al., 2010)).

During Icehouse periods, cool to cold oceanic waters restrict the occurrence of photozoan carbonates to a narrow tropical belt and hence open up large regions for heterozoan carbonates to flourish. A shift in carbonate association from photozoan to heterozoan is observed in relation with the northward drift of Permian continents that brought northern Pangea into higher paleolatitudes (cf. (Beauchamp & Desrochers, 1997; Bensing et al., 2008; Jafarian et al., 2017a; Jafarian et al., 2017b; James & Lukasik, 2010; Reid et al., 2007)). Carbonate deposits at sub-polar paleolatitudes occur within siliciclastic settings in zones where topography or currents restrict terrigenous input and where waters are highly productive (i.e. upwelling occurrences; (Frank et al., 2012; James et al., 2009a; James et al., 2009b; Reid et al., 2007)). Modern analogues of such oceanographic settings that are characterized by cool- to cold-water, suspension-feeding biota are found in Spitsbergen (case study 107; (Henrich et al., 1997)) and around Tasmania (case study 129; (James & Bone, 2011)). At mid-paleolatitudes during the Permian, lower productivity levels (i.e. low- to high-mesotrophic) allow photosymbiotic biota (i.e. large benthic foraminifers) to develop along with suspension-feeding biota (cf. (Bensing et al., 2008)). Modern analogues of such warm- to cool-temperate, mesotrophic marine realms include the Rottneft Shelf system described by James et al. (James et al., 1999) and transitional photozoan-heterozoan carbonate associations (cf. (Halfar et al., 2006)).

Overall, apart from mid-paleolatitude Permian case studies, the paleoceanographic analysis of Paleozoic heterozoan carbonates shows that their occurrence is associated with highly productive areas,

particularly those with upwelling waters. As functional ecology implies, high marine productivity thus appears to be the steering parameter to produce a large amount of suspension-feeding biota (i.e. brachiopods, crinoids and bryozoans).

4.2. Mesozoic records of heterozoan carbonates

As a greenhouse period, the Mid-Cretaceous displays very wide tropical and subtropical climate belts. The Mesozoic limestones are largely dominated by muddy, microbial (Triassic–Jurassic) and rudist-rich (Jurassic–Cretaceous) carbonates (Kiessling et al., 2003; Pomar & Hallock, 2008). High-paleolatitude shelves record terrigenous deposits (J.-P. Masse, personal communication). Heterozoan carbonates are found at places where terrigenous input and/or increased nutrient levels inhibit photozoan and especially rudist development and promote suspension-feeding biota (e.g. bryozoans) under warm-water conditions (Allmon, 2007; Carannante et al., 1997; Philip & Gari, 2005). This is particularly the case in the Tethyan region. In the southern hemisphere, the accumulation of heterozoan carbonates coincides with the South Atlantic opening that promotes the influence of open-ocean waters. In terms of environmental processes, the modern Indo-Pacific setting provides a good regional analogue in which highly diverse photozoan carbonates thrive and some heterozoan carbonates develop under disturbed environmental conditions (i.e. terrigenous input and/or nutrient influx; cf. (Wilson & Vecsei, 2005)). Light competition appears to control the development of grain associations under mesotrophic to eutrophic conditions (cf. (Hallock, 2001; James, 1997; James & Lukasik, 2010; Mutti & Hallock, 2003)). Light-dependent grains including photozoan grains can occur in the proximal part of the ramp, while heterotrophic, aphotic carbonate-secreting biota characterize the platform-scale sedimentation.

4.3. Cenozoic records of heterozoan carbonates

During the Paleocene and Eocene, high global temperatures lead to low latitudinal and bathymetric gradients and a weak oceanic circulation (Pomar et al., 2017). Heterozoan carbonates thrive after a series of dramatic changes in oceanic circulation and climate, which take place after 40 Ma and include a global climatic cooling, the disruption of the Tethyan circumtropical seaway, the opening of the circumpolar Southern Ocean, the rapid expansion of Antarctic continental ice sheets and the onset of the thermohaline circulation ((Cramer et al., 2009), and (Zachos et al., 2001), for paleoclimatic trends; (Pomar & Hallock, 2008) for carbonate sedimentary trends). On the one hand, the establishment of a more active global circulation leads to upwelling of nutrient-rich deep waters, which, in turn, promotes a higher marine productivity (e.g. (Read, 1998)). On the other hand, increasing oceanic gradients are thought to increase wave energy (Pomar et al., 2017).

Biotic evolution and the occurrence of wide, shallow platform areas (e.g. Central Mediterranean; (Esteban, 1996; Gatt & Gluyas, 2012)) lead to the extensive colonization of oligo-mesotrophic, warm to warm-temperate provinces by red algae (cf. (Braga, 2017; Pomar & Hallock, 2008); Fig. 2E, F). Most oligotrophic, tropical platforms are colonized by tropical carbonates such as the Rupelian–Burdigalian Malampaya buildup (e.g. large photosymbiotic foraminifer deposits and coralline reef systems including reefal red algal species; (Fournier et al., 2005; Kiessling et al., 2003; Perrin, 2002; Qing Sun & Esteban, 1994)). Heterotrophic-dominated assemblages are promoted by nutrient-rich environmental conditions including local terrigenous input that are typical for the ocean margins of Australia and New Zealand (e.g. (Hayton et al., 1995)). The microtidal, oligo-mesotrophic Mediterranean realm (i.e. mid-latitude) hosts red algal-large foraminifer-seagrass, large benthic foraminifer and coralline carbonates (Buxton & Pedley, 1989; Esteban, 1996; Mutti et al., 2010; Pedley & Carannante, 2006b; Pomar et al., 2017).

Climatic and oceanographic changes are considered to be the major

parameters controlling carbonate factory development and evolution (Bourrouilh-Le Jan & Hottinger, 1988; Braga et al., 2010; Edinger & Risk, 1994; Halfar & Mutti, 2005; Johnson et al., 2008; McCall et al., 1994). Halfar and Mutti (Halfar & Mutti, 2005) and Pomar et al. (Pomar et al., 2017) demonstrated that oceanographic changes are responsible for the red algal vs. coral biotic change in the Tethys ($\delta^{13}\text{C}$ -based interpretation) and invoked productivity as the driving parameter. However, because light is the energy source in both factories, i.e. red algae-seagrass-photosymbiotic foraminifer and coralline, eutrophication cannot be a direct driver of the red algal-seagrass-large foraminifer factory development. A large increase in nutrient input favours an increase in large planktonic blooms and associated benthic heterotrophic biota (e.g. bryozoans and molluscs) against seagrass and red algal carbonate systems (cf. (Brandano, 2017; Halfar et al., 2006; Hallock, 2001; Jaramillo-Vogel et al., 2016)). The latter factory nevertheless might be more resilient against such disturbance (Halfar & Mutti, 2005). However, the carbonate production should be pushed by other, still poorly constrained, environmental controls (e.g. seasonal variability, turbidity range, substrate colonization, hydrodynamics, platform physiography, seawater carbonate saturation; cf. above cited references for a discussion about the Cenozoic and (Bosence, 1983; Bosence & Pedley, 1982; Freiwald, 1998), pp. 772–773; (Hallock, 2001), p. 407; (Henrich et al., 1995; O'Connell et al., 2016), for a discussion about red algal controlling parameters).

Modern warm-temperate carbonates that show seagrass and rhodolith dominated environments (Betzler et al., 1997; Carannante et al., 1988; Riosmena-Rodríguez et al., 2017) can represent an analogue for Oligo-Miocene carbonate grain associations from the Tethys and Paratethys. Oligo-Miocene carbonates, however, show extensive accumulations (10s of meters thick deposits) that do not agree with the carbonate production patterns of the modern Mediterranean Sea (i.e. thin sediment veneers and low accumulation potentials; cf. (Betzler et al., 1997)). The contribution of corals (i.e. *Porites* and others) to Oligo-Miocene carbonate sediments is far beyond the modern contribution of *Cladocora* corals ((Buxton & Pedley, 1989; Esteban, 1996; Perrin, 2002; Pomar et al., 2017; Riosmena-Rodríguez et al., 2017) for Oligo-Miocene; (Özalp & Alparslan, 2011; Peirano, 2001), for Modern). Main environmental differences include a warmer Oligo-Miocene climate (e.g. (Zachos et al., 2001)) and temporary open Tethyan seaways (e.g. (Harzhauser & Piller, 2007)). Thus, warmer water temperatures and potentially increased oceanic circulation could explain the apparent higher carbonate production within the Tethys realm during the Oligo-Miocene in comparison to the modern Mediterranean Sea (see (Brandano, 2017; Carannante et al., 1988; Pomar et al., 2017), for further discussions about analogues). By contrast, the extensive development of rhodolith-rich platforms could be explained by the tectonic evolution of the Mediterranean region that gave rise to numerous shallow-water platforms around relatively small islands (Braga, 2017).

More productive rhodolith carbonates of modern tropical and subtropical shelves are found along the Brazilian coast, the Gulf of California and the Australian Abrolhos shelf (n°123, 120 and 108; (Carannante et al., 1988; Collins et al., 1997; Halfar et al., 2006), respectively). In terms of facies description, such grain associations are defined as the transitional photozoan-heterozoan association (see (Halfar et al., 2006)) and represent relevant analogues for red algal-dominated, Oligo-Miocene Tethyan carbonates. Furthermore, calmer oceanographic settings of semi-enclosed gulfs host subtropical to warm-temperate, transitional photozoan-heterozoan associations (e.g. Oligo-Miocene Murray Basin; (Lukasik et al., 2000), case study 64; and modern analogues of South Australian gulfs, (James & Bone, 2011), case studies 127 & 128; also cf. (Betzler et al., 1997)). These gulfs are influenced by various terrigenous input.

More nutrient-enriched settings show a stronger heterotrophic biota signature and photic biota, if present at all, which are restricted to innermost platform settings (e.g. (Coffey & Read, 2007), case study 51; (Jaramillo-Vogel et al., 2016), case study 56). Present-day

oceanographic analogues with upwelling can be found along the southern Brazilian Coast, the Gulf of Panama and the northern Gulf of California ((Carannante et al., 1988; Reijmer et al., 2012), and (Halfar et al., 2006), respectively). Nutrient-enriched, high-energy shelves host bioclastic accumulations the occurrence of which is controlled by sea-bottom topography and hydrodynamics (e.g. (James et al., 2011), case studies 52, 53, 92; (Hendy et al., 2006), case study 88). A large array of heterozoan carbonate deposits exists within these highly hydrodynamic settings but modern analogues of such sedimentary processes can be grouped into (i) upwelling systems such as the NW African shelf (case study 121), (ii) localized bioclastic bodies such as sand dunes off the coast of Scotland (case study 114), (iii) shell beds within terrigenous systems such as the Wanganui Shelf (case study 106) and (iv) “shaved shelves” and distal accumulations of the famous Great Australian Bight (case study 126).

4.4. Phanerozoic trends

Biota evolution leads to changing deposition and composition of carbonate grain associations through time (e.g. (Insalaco et al., 2000)). However, the energetic pathways used by organisms to develop and precipitate carbonate remains constant due to the consistency of physical and chemical principles (cf. (Hallock, 2015)). Organo-mineralization (sensu (Dupraz et al., 2009)) and biomineralization by phototrophic and heterotrophic organisms have been controlled by the same parameters through time (i.e. seawater carbonate saturation, light and nutrient cycles; cf. (Pomar & Hallock, 2008)). Hence, from the Paleozoic to the present day, the development of suspension-feeding molluscs, brachiopods, crinoids and bryozoans depends upon a sufficient amount of marine plankton productivity ((Allmon, 2007; Birkeland, 1987; Hallock, 2001; Hallock & Schlager, 1986; Margalef, 1968; (Mutti & Hallock, 2003; Wilson, 1975; Wood, 1993)). The global distribution of carbonate platforms characterized by such heterotrophic biota was controlled by marine productivity that, in turn, is controlled by paleoceanographic circulation (e.g. (Whalen, 1995)).

Heterozoan carbonate platforms started to develop during the early Paleozoic with the evolution of suspension-feeding metazoans such as bryozoans, echinoderms and brachiopods (Hallock, 2015; James & Jones, 2015). Most deposits are found along relatively enclosed basins and cratonic troughs (e.g. North American craton, Seabee Trough, Ouachita Trough and Sverdrup Basin). The apparent peaks in the occurrence of heterozoan carbonate systems during the Phanerozoic do not correlate with fluctuations in the areal extent of the carbonate platforms (Kiessling et al., 2003), the areal extent of flooded continents (Kidwell & Brenchley, 1996), CO₂/O₂ (Bernier, 2006), “calcite/aragonite seas” (Stanley & Hardie, 1998), nor extinction events (Wood, 1993). In terms of climatic conditions, however, a striking number of heterozoan case studies deal with Greenhouse to Icehouse transition periods, i.e. Late Ordovician, Early Carboniferous and Oligo-Miocene (Fig. 1); as pointed out earlier by Read (Read, 1998). The transitional periods towards glaciations are characterized by: (i) a high sea level before the development of a full ice cap relating to extensive areas with submerged shallow platforms; (ii) an enhanced thermohaline circulation leading to stronger open-ocean influences on platform settings that, in turn, result in increased upwelling and oceanic productivity; and (iii) moderate eustatic fluctuations (50–75 m) leading to widespread grainy deposits (cf. (Read, 1998)). The second scenario is considered to be the main mechanism constraining the distributions of heterozoan carbonates at a global scale (cf. (Johnson et al., 2008; Pomar et al., 2017) for Cenozoic oceanic change and productivity).

During the Late Ordovician and Mississippian periods, heterozoan carbonates occur in regions with deep-water formation and low-latitude upwelling. During the Cenozoic and past Icehouse periods, the global imprint of the thermohaline circulation (e.g. low-latitude upwelling and high-latitude deep-water formation) is not straightforward. The Permian and Cenozoic periods rather show a latitudinal distribution

with photozoan carbonates within the paleo-tropics and heterozoan carbonates at higher paleolatitudes (i.e. subtropical to polar; Fig. 2B, D, E, F; (Kiessling et al., 2003), Table 2, and references therein; (Beauchamp & Desrochers, 1997; Bensing et al., 2008; James & Lukasik, 2010); for a specific discussion about the Permian period). During the Cenozoic, the formation of temperate seagrass and coralline algal ecosystems led to the colonization of warm-temperate heterozoan carbonates in mid-latitude environments, especially within the Tethys/Mediterranean and in Australia and New Zealand (Fig. 2D, E, F).

The Mid-Cretaceous period represents the greenhouse exception during which no global signal is captured (Fig. 2C). This period with high water temperatures, salinities and carbonate saturation (Riding, 2005) during which the shallow-water carbonate areas are one of the largest of all times (Kiessling et al., 2000) favoured carbonate platform development in general. The heterozoan occurrences correspond to local environmental disturbances (high terrigenous and/or nutrient influx) in otherwise photozoan carbonate zones. The main components of photozoan carbonates of the Cretaceous calcite seas are rudists (Scott, 1988; (Simo et al., 1993; Stanley & Hardie, 1998; Stanley & Hardie, 1999)). Following the Late Ordovician and Carboniferous pattern of heterozoan carbonates which occur along troughs near cratons influenced by open-ocean waters, the Cretaceous occurrences of heterozoan carbonates in the South Atlantic could also be driven by open-ocean impacts due to the opening of the Atlantic. However, so far no such an interpretation was made about the Cretaceous heterozoan carbonates (poorly-studied sedimentary deposits), although the paleoceanographic setting is strikingly similar to the ones described for the Paleozoic troughs (Franseen, 2006; Pope, 2004).

Thus, at a global scale and outside areas where carbonate production is inhibited by terrigenous input, peak occurrences of heterozoan carbonate platforms appear to relate to specific paleoceanographic circulation patterns rather than a cold or icehouse climate promoting “cool-water carbonates” (also cf. (Read, 1998)). The global oceanic circulation controls the regional patterns of water parameters such as water temperature and nutrient concentration (e.g. (Pomar et al., 2017; Schlager, 2005), Chapter 1). In turn, nutrient concentrations control planktonic productivity that drives the development of benthic heterotrophic biota (Hallock, 2001; Hallock & Schlager, 1986). Following modern oceanographic observations (e.g. (Schlager, 2005), Chapter 1) and interpretations of sedimentary records of planktonic and shallow-water carbonates (Hallock & Pomar, 2008; Hallock et al., 1991; Pearson et al., 2008; Pomar et al., 2017; Read, 1998), we interpret that an active thermohaline circulation constitutes a major link between global paleoceanographic circulation, paleoclimatic changes and carbonate distribution. An absence of carbonates at high paleolatitudes during greenhouse times could then be associated with a weak thermohaline circulation. During the Cretaceous period, the formation of deep waters is thought to have been limited, thus restricting the strength of the global oceanic circulation (e.g. (Hay, 2008)).

Consistently and apart from dramatic extinctions events, photozoan carbonates occur at low latitudes throughout the Phanerozoic and their distribution is extended during warm greenhouse periods (e.g. (Kiessling, 2001)). A stronger thermohaline circulation during transitional greenhouse-icehouse times and icehouse periods would constrict the latitudinal distribution of photozoan carbonates (e.g. (Kiessling, 2001)). During times of reduced equatorial seawater throughflow, this stronger circulation would restrict the distribution of photozoan carbonates along the western continental margins that are affected by Eastern Boundary Upwellings (cf. (James et al., 1999; Whalen, 1995)).

The above discussed hypothesis for the control of global carbonate production by thermohaline circulation provides a consistent scheme that allows interpreting the stratigraphic and global distribution of heterozoan carbonates. Following the Late Ordovician period example and the organic-rich rock prediction approach of Parrish (Parrish, 1995), the thermohaline circulation appears to offer a predictive paleoceanographic tool to interpret carbonate distribution (cf. (Pohl et al.,

2017), for a model approach).

Apart from light-related heterozoan carbonate platforms, which occurred at subtropical and warm-temperate paleolatitudes (e.g. (Bensing et al., 2008; Betzler et al., 1997)), regions of high marine productivity appear to host large accumulations of heterozoan carbonates. Eastern Boundary Upwellings that occur along western continental margins, thus correspond to potential regions for the development of extensive heterozoan carbonate deposits (e.g. (James et al., 1994; Whalen, 1995)). However, only a few records are available that confirm this interpretation due to the limited preservation and exposure of western continental margins. For example, the eastern Panthalassa margins and terranes show narrow shelves that are influenced by terrigenous input in general. Triassic and Liassic bivalve reefs could nevertheless correspond to such global paleoceanographic process-driven carbonate production (e.g. (Leinfelder et al., 2002; Martindale et al., 2015)).

5. Interpretation of controlling parameters

5.1. Modern oceanographic environments

Recent deposits consist of thin accumulations as lag sediments, which most likely will have low preservation potential. Thus, such occurrences only count in the recent, while there are few records in the fossil. Modern heterozoan carbonates are subsequently more abundant than fossil heterozoan carbonates at a global scale.

By contrast to photozoan carbonates, typically restricted to warm, saline, well-illuminated (euphotic) and nutrient-poor (oligotrophic) marine environments, heterozoan carbonate sedimentation is much less constrained by temperatures or insolation rates. Heterozoan carbonates occur all over the world without restriction of light penetration; except for red algal and seagrass-derived bioclastic sediments. Two major specific environmental conditions host the heterozoan carbonate deposits, whose first-order controlling parameters are (1) planktonic-rich waters ($n = 24$) and (2) a subtle combination of light penetration and hydrodynamic levels ($n = 9$; Fig. 4; Appendix 1, column “Environmental energy”). In terms of hydrodynamics, these groups parallel the classifications of depositional settings of (1) open shelves and (2) protected gulfs (e.g. (Betzler et al., 1997)); (1) macrotidal and (2) microtidal regimes (e.g. (Pedley & Carannante, 2006b)); (1) deep, high-energy cool-water carbonate shelves and (2) shallow, moderate-energy, cool-water temperate to subtropical carbonate shelves (James, 1997); and (1) open-ocean shelves and seaways and (2) interior basins (James & Jones, 2015).

- (1) Highly productive oceanic zones include (i) upwelling zones except for strongly oxygen deficient, narrow continental platforms such as those influenced by the Arabian, Benguela and Humboldt upwelling systems, (ii) oceanic mixing zones (e.g. North Atlantic) and (iii) fronts (e.g. the polar front such as the one occurring along Spitsbergen Bank; (Henrich et al., 1997). Heterotrophic heterozoan carbonates are mainly produced by suspension-feeding biota (e.g. bryozoans, molluscs and barnacles) occurring in shallow waters. Kelp forests form a specific carbonate factory within hard-bottom areas within high hydrodynamic settings (Freiwald, 1998; James et al., 2013).
- (2) Oligo-mesotrophic, subtropical or warm-temperate seas (typically the Mediterranean Sea) in which the characteristic carbonate sediments are red algae and seagrass-derived bioclastic grains (Betzler et al., 1997; Fornos & Ahr, 1997; James et al., 2009a; O'Connell et al., 2016; Perry & Beavington-Penney, 2005). The warm-temperate carbonates are controlled by light penetration that allows for photosynthesis (seagrass and algae; (Bosence, 1985), about coralline algae), and thus has the same primary driver as photozoan carbonates. These light-related heterozoan carbonates are found in settings in which temperature, salinity (Jones et al.,

2015; Wasserman, 2011) and/or light penetration (Muir et al., 2015) are not high enough over the entire year to accommodate the development of photozoan carbonates. Red algal sediments can develop under lower light conditions (distal, oligophotic platform; (Pérès & Picard, 1964; Pomar, 2001a)) than modern coral reefs. Secondary parameters controlling these warm-temperate carbonates are bioerosion and grazing affecting red algal production in shallow waters (< 20 mwd; (Ballesteros, 2006; Henrich et al., 1995)). As revealed by the fact that the occurrence of extensive warm-temperate carbonates are restricted to semi-enclosed basins or gulfs (i.e. the Mediterranean Sea and South Australian gulfs; (Betzler et al., 1997; James & Bone, 2011; O'Connell et al., 2016)), hydrodynamics should have an intermediate strength, high enough to winnow terrigenous input and fines away from the depositional realm ((Birkett et al., 1998), p. 25), but not too much to develop extensive deposits ((Betzler et al., 1997; Bosence, 1985; Henrich et al., 1995); Hottinger, 1983). By contrast, red algal ridges and crusts, which are resistant to high hydraulic regimes and are part of the coral reef ecosystem (cf. (Bosence, 1983; Cabioch et al., 1999)), pertain to photozoan carbonates.

In terms of classification, it is important to note that localized maerl deposits (i.e. rhodoliths beds of branching corallines) from the NE Atlantic (cf. (Bosence & Wilson, 2003)) are part of shelfal carbonate sediments which are mostly composed of heterotrophic, carbonate-producing organisms (e.g. bivalves, echinoderms and bryozoans; cf. (Freiwald, 1998); B. Caline, personal communication). Hence, at the platform scale, these deposits are considered to be part of the heterozoan carbonates of the highly productive marine environment model (see above (1)).

End-members and categories are convenient concepts to deal with the complexity of natural ecosystems. In reality, however, heterozoan carbonates seem to express more gradual changes and transitional trends in terms of depositional settings and local environmental conditions. For instance, variable terrigenous and nutrient input under low to moderate hydrodynamics can result in carbonate associations more typical of the highly productive model (e.g. mollusc- and bryozoan-dominated carbonate facies of the Wanganui shelf; (Gillespie & Nelson, 1997); case study 106).

Interestingly, the most classical modern examples of heterozoan carbonates, those that occur in the Great Australian Bight, show an intermediate character between both heterozoan end members ((James & Bone, 2011; James et al., 2001); case study 126). Parts of the proximal platform that are relatively protected from the Southern Ocean swell (e.g. coastline is oriented parallel to the swell direction) are colonized by seagrass meadows and extensive red algal deposits (e.g. ~200 km-long coralline gravel facies; ((James & Bone, 2011), Fig. 8.9). Only a weak seasonal upwelling (mesotrophic conditions) promotes a fair carbonate production of suspension-feeding biota (bivalves) over most part of the inner and mid shelf showing many intraclasts. An abundant carbonate production of suspension-feeding bryozoans and molluscs occurs on the outer shelf and upper slope that is correlated with seasonal upwelling (James & Bone, 2011; James et al., 2001). The first peculiarity of this passive margin rarely seen in heterozoan carbonate settings is the nearly complete absence of terrigenous input because of the very dry and very flat hinterland (James & Bone, 2011). The second peculiarity is that this platform faces the Southern Ocean, the most energetic swell experienced by a carbonate system on Earth (e.g. (Porter-Smith et al., 2004)). These outstanding wave-energy conditions promote biota and facies that are more typical of the highly productive setting model.

5.2. Consistent principles and controlling parameters of carbonate production throughout the Phanerozoic

At a global scale, heterozoan carbonates include two systems that

Table 1

Main global-scale oceanographic parameters and principles (lines) driving different platform-scale carbonate factory (columns) development. Heterozoan carbonates sensu James (James, 1997) are split into two carbonate factories; photozoan carbonates sensu James (James, 1997) are splitted into three carbonate factories. Seep and continental carbonates are considered separately. Different platform-scale carbonate factories are thus related to specific global-scale oceanographic conditions (cf. text for more details).

Oceanographic parameters	Heterozoan 1 heterotrophic biota (bryozoans, echinoderms, molluscs, barnacles...) & in some cases help environment	Heterozoan 2 red algae & seagrass platform	Skeletal photozoan 1 (rudists, symbiotic large foraminifers, green algae)	Skeletal photozoan 2 (coral reefs)	Evaporites & non-skeletal photozoan (stromatolite-producing microbes, peloids, ooids, algal mats) & in some cases proximal evaporites	Continental (travertine, tufa) & seep (microbes, chemosymbiotic bivalves and worms) factory
Salinity	Open ocean	Open ocean	Open ocean to restricted	Open ocean	Restricted	Restricted
Water temperature	Normal to slightly hypersaline	Normal	Normal to slightly hypersaline	Normal	Hypersaline	Independent
Carbonate saturation	Independent	Independent	Tropical to warm-temperate	Tropical	Tropical	Independent
	Undersaturated to highly saturated	Poorly to highly saturated	Highly saturated	Highly saturated	Supersaturated	Seep-derived elements and alkalinity
Trophic conditions	Eu- to mesotrophic	Oligo- to mesotrophic	Oligo- to mesotrophic	Oligotrophic	Independent	Independent
Light conditions	Independent	Oligophotic	Meso- to euphotic	Euphotic	Independent	Independent
Energetic source for biota growth & calcification	Organic matter	Light	Light	Light	"Passive": Water chemistry (carbonate supersaturation)	Chemical seep
Steering factors of carbonate precipitation	Food supply	Water transparency, moderate hydrodynamics	Temperature, water transparency	Temperature, water transparency	Temperature, salinity, marine restriction	Water chemistry (pore water or seep source)
Carbonate precipitation mode (Schlager, 2005)	Biologically controlled Heterotrophic	Biologically controlled Autotrophic	Biologically controlled Autotrophic (except rudists)	Biologically controlled Autotrophic	Abiotic & biotically induced	Every mode

are driven by two different sources of energy needed by the carbonate-producing biota for their metabolic activities including biomineralization (cf. also (Hallock, 2015), p. 27):

- (1) An ecosystem that is structured by heterotrophic biota (e.g. suspension-feeding bryozoans and bivalves), and that is driven by organic matter, i.e. energy is derived from ingested food, and.
- (2) An ecosystem that is structured by seagrass/red algae and that is driven by light, i.e. energy is derived from photosynthesis.

These two ecosystems are found in opposite oceanographic settings, restricted versus open ocean respectively, even though the systems may overlap, e.g. the Great Australian Bight (e.g. (James et al., 2001)). Once these two systems (seagrass/red algae and heterotrophic biota) are recognized, heterozoan carbonates can be set into a consistent conceptual scheme of paleoceanographic controlling parameters of carbonate factories (Table 1, Fig. 5). Thus, different carbonate factories are related to specific paleoceanographic conditions and their spatial distributions are theoretically predictable at a global scale.

An efficient way to characterize carbonate production and the corresponding depositional environments is to refer to the source of energy used by the ecosystem to produce and accumulate carbonate sediments (cf. also (Hallock, 2015), p. 27) (Table 1, Fig. 5). This scheme allows categorizing carbonate factories according to a gradient of carbonate saturation of the waters (also cf. (Gattuso et al., 1998; Hallock, 2001; Kleypas et al., 1999), p. 407; (Opdyke & Wilkinson, 1993)):

- Heterozoan carbonates (i.e. heterotrophs excluding the seagrass/red algal factory) and deep-water coral mounds appear to be able to produce carbonate deposits in poorly saturated marine waters using a large amount of organic matter as source of energy.
- Seagrass-derived and red algal carbonate platforms occur right outside the latitudes of the photozoan association, i.e. the warm-temperate carbonate province sensu (Betzler et al., 1997); also cf. (James et al., 2013)), which shows lower carbonate and aragonite saturation than the tropics (cf. (Hallock, 2001), p. 407). Seagrass and red algal ecosystems thrive better in clear, oligotrophic waters but flourish also in mesotrophic waters (e.g. (Ballesteros, 2006; O'Connell et al., 2016)). In addition, red algae bloom in oligophotic environments.
- Photozoan carbonates (excluding non-skeletal deposits) are considered to develop best in highly carbonate saturated tropical waters under oligotrophic (=low-nutrient) and euphotic conditions (particularly for photosymbiotic organisms; cf. (Hallock, 2001)).
- Non-skeletal grains, algal mats, microbes (e.g. the ones precipitating stromatolites) and other components of peritidal environments accumulate in carbonate super-saturated waters (e.g. very warm and salty, shallow waters of the Bahamas bank top, Shark Bay and the Trucial Coast; cf. (Riegl et al., 2010); also cf. (Schlager, 2005), p. 14, for ooids, aragonitic seafloor cements and whittings).
- Locally, occurrences of specific seeps allow for carbonate production by chemosymbiotic organisms, e.g. bivalves and worms, and microbes below the carbonate compensation depth (CCD) or in continental settings (e.g. Alonso-Zarza and Tanner, 2010; (Case et al., 2015)).

Hence as a simple general rule it can be stated that marine carbonates are preferentially found in tropical seas (high water temperatures and salinities), while the amount of production and accumulation decreases towards the poles (also cf. (Kleypas et al., 1999)). Nevertheless, carbonates can potentially occur anywhere (even in poorly saturated settings and siliciclastic successions) where carbonate-secreting biota find a source of energy to survive and to build their skeletons. Such source of energy includes chemically super-saturated waters (typically deep seep carbonates) and organic matter (e.g. highly productive Spitsbergen polar front). Heterozoan carbonates that are composed of

Fig. 5. Main global-scale environmental parameters driving the platform-scale carbonate factory (“Carbonate production” and “Schlager” nomenclature; cf. (Schlager, 2005)) development. Parameters from top to bottom are “terrigenous deposits”, “carbonate saturation” as an environmental gradient from higher “++” (left hand side) to lower – (right hand side) that promotes different carbonate productions (also cf. (Kleypas et al., 1999)), “energetic sources” for biota growth and calcification (also cf. (Hallock, 2015)), and the oceanographic “controlling parameters” that characterize the marine environments. Heterotrophic rudists and Paleozoic corals (e.g. rugose corals) are placed into the “photozoan *sensu stricto*” association in the carbonate precipitation gradient due to their restricted occurrences in shallow, warm, highly saturated waters (cf. text for more details).

heterotrophic biota are able to occur in plankton-rich (i.e. organic-rich) settings throughout geological times. The proposed model thus appears to be valid in terms of ecology throughout the Phanerozoic.

The energy fuelling the development of biota and abiotic chemical reactions is considered the first-order parameter of carbonate production (also cf. (Hallock, 2015), p. 27). For instance, a heterotrophic association will never be able to thrive without a sufficient amount of marine productivity to feed on (Hallock, 2001). The first-order parameter driving seagrass/red algal ecosystems is light (i.e. availability of photosynthetically active radiation PAR). Competition is then governing the success of the light-driven carbonate factory at a given location, either the coral reef, the green algal or seagrass-derived/red algal association (cf. (Hallock, 2001; James & Lukasik, 2010; Mutti & Hallock, 2003)). In addition, various ecological parameters, which are considered here as second-order parameters, can inhibit the development of any carbonate factory. These parameters may include water temperature as lethal temperature threshold for specific species (e.g. coral species), substrate type (e.g. biota specialized to live either in mud or on a hardground) and hydrodynamics (e.g. species living in either calm or agitated waters). At a global scale, the energy fuelling carbonate production (light or organic matter) allows to link global oceanic circulation and carbonate distribution by using paleoclimate models. Solar insolation determines the distribution of light and heat reaching the Earth surface; oceanic circulation then drives the distribution of water temperatures, carbonate saturation and marine productivity by heat transfer (e.g. (Schlager, 2005), chapter 1). In turn, these oceanographic parameters control the distribution of carbonate production, which then appears predictable at a global scale. At a local scale, however, this global-scale pattern is overprinted by local environmental parameters (e.g. riverine discharge) and accumulation processes that define depositional models.

5.3. Depositional profiles of heterozoan carbonates

5.3.1. General comments

Because we were not able to fit every case study in the facies spectrum models of James and Jones (James & Jones, 2015) and James and Lukasik (James & Lukasik, 2010), we implemented the scheme using a process-based approach. The facies spectrum models of James and Jones (James & Jones, 2015) and James and Lukasik (James & Lukasik, 2010) imply a direct paleoclimatic and paleobathymetric interpretation from field-based sedimentary facies studies. The proposed scheme follows our global model and implements a downscaling for the prediction of the local sedimentary systems. The scheme is funded upon a process-based stepwise approach, implying that individual models correspond to specific paleoenvironmental conditions interpreted from paleo-ecological data. Paleoenvironmental conditions include the source of energy (i.e. light and organic matter, the latter being related to nutrient input) provided to the carbonate factory to prosper (cf. Section 5) and can be related to paleoceanographic and paleoclimatic contexts. This means that the deterministic approach used relates paleoecological data to physico-chemical processes that can be simulated by paleoceanographic and paleoclimate numerical models (e.g. (Pohl et al., 2017)). By contrast, James and Jones (James & Jones, 2015) combine both global and local scales by imposing a climatic framework of warm-, cool- and cold-temperate when interpreting facies data; main facies spectrum systems thus correspond to platform types and paleo-geographic contexts. Therefore, both approaches are complementary and overlapping (Table 2). The novel output of the proposed scheme is that it includes processes controlling carbonate production (e.g. nutrient and terrigenous input) into the model definition beyond the oceanic setting (“depositional setting” sensu (James & Jones, 2015)) and paleoclimatic system (“facies spectrum system” sensu (James & Jones, 2015)). The proposed scheme thus provides a predictive tool for the occurrence of sedimentary systems given specific environmental conditions.

Table 2

Relationships between the depositional models of the present study and the models of James and Jones (James & Jones, 2015).

Depositional model (present work)	Depositional setting (James & Jones, 2015)	Facies spectrum system (James & Jones, 2015)
(1) Low-latitude, eutrophic, homoclinal ramp	Interior basin	Thermocline-stratified ramp
(2) High-latitude, eutrophic homoclinal ramp	Interior basin	Thermocline-stratified ramp
(3) Low-latitude, eutrophic and/or terrigenous-influenced, distally-steepened ramp	? Both interior basin & open ocean shelf	- Warm-temperate lower energy - Warm-temperate high energy
(4) Warm-temperate, transport-dominated accumulation	Both interior basin & open ocean shelf	- Warm-temperate lower energy - Warm-temperate high energy
(5) Warm-temperate, oligotrophic, distally-steepened ramp	Both interior basin & open ocean shelf	Warm-temperate lower energy
(6) Seaway	Seaway	- Warm-temperate lower energy - Warm-temperate high energy
(7) Segmented platform	Open ocean shelf	Cool- & cold-temperate
(8) Shaved shelf	Open ocean shelf	Warm-temperate high energy

Each depositional profile refers to a global-scale energetic model that controls the type of carbonate production (cf. Section 5.1). Our database includes 92 heterotrophic carbonate factories and 26 seagrass/red algal carbonate factories, the latter only occurring during the Cenozoic (cf. Appendix). While seven case studies show a mixed character with biota characteristic of both factories, four sedimentary systems could not be assigned to a specific factory because of partial preservation of the platform and undefined paleoceanographic conditions. The source of energy for carbonate production is, however, not controlling the sedimentary system and the facies partitioning. At a local scale, the coupling between sea-bottom topography and hydrodynamics (waves, tides and currents) controls sediment transport and sediment accumulation. Thus, few categories of depositional profiles are specific to neither the heterotrophic nor the seagrass/red algal carbonate environments, which apply to carbonate production at a global scale (cf. Section 5.1). At the platform scale, sediment accumulation processes are the critical mechanisms that differentiate the depositional profiles. Carbonate accumulations controlled for example by transport processes (e.g. seaway) can be produced by either a light- or a nutrient-driven carbonate factory ((James et al., 2014), case study 72, and (Nelson et al., 2003), case study 91, respectively).

In contrast to other carbonate factories in which carbonate production allows the construction of sediment build-ups and very fast in situ cementation, heterozoan carbonates sensu James (James, 1997) and/or C-factory sediments sensu Schlager (Schlager, 2005) are characterized by sediment dispersion; grain production is spread out and syn-sedimentary cementation is not frequent (e.g. (Nelson, 1988b; Opdyke & Wilkinson, 1993; Reijmer, 2014)). Thus, an environment of reduced sediment transport, topographic sediment trapping and/or a high carbonate production led by organic-rich waters or light is required for the accumulation of heterozoan carbonates. A coupling is proposed of hydrodynamics and initial topography (e.g. breaks, highs and depressions) as well as coastline orientation in relation to swell orientation. This combination of processes steers heterozoan carbonate sedimentation, i.e. the “leeward” (protected) vs. “windward” (exposed) platform areas and the development of facies mosaics.

Proximal settings can be characterized by environmental conditions decoupled from the offshore setting (cf. (James & Jones, 2015)). For instance, warmer and saltier settings such as peritidal evaporative systems or clearer coastal waters that contrast with offshore productive waters can occur in upwelling zones, e.g. modern Mauritania (Michel et al., 2011) and the Mississippian Western Canadian Sedimentary Basin (Martindale & Boreen, 1997). Thus, facies and producers will vary with distance to the coast in many cases. As a result, the allocation of a platform-scale carbonate factory to a specific carbonate system of the present described scheme implies a deterministic approach; interpretation is driven by the choice of steering environmental controls that lead to the specific depositional profile. If not possible, the attempt to assign a sedimentary record to such a category will guide the paleoenvironmental and paleoclimatic interpretation. The same applies

for the facies distribution and the geometries of the models; as shown by Williams et al. (Williams et al., 2011), a continuum of architectures occurs in carbonate platforms, thus the choice of a single model for ambiguous case studies might be challenging. The deterministic approach based on driving parameters of the carbonate sedimentation (= process-based) will allow for better-constrained interpretations to be made.

James and Jones (James & Jones, 2015) and James and Lukasik (James & Lukasik, 2010) provide detailed depositional models of the carbonate facies spectrum. In this study, because of a different focus, different depositional models are obtained even though overlap exists (Table 2). In both models, the facies spectrum of (James & Lukasik, 2010) and the process-based scheme presented in this study, the large number of depositional models highlights the diversity of heterozoan carbonate systems. This diversity of deposits comes from a set of local environmental parameters controlling on one side the biota (e.g. temperature, salinity, etc.) and on the other side sediment transport (i.e. the coupling between hydrodynamics and topography); the parameters controlling the latter also influence the former (e.g. substrate type).

5.3.2. Main sedimentary profiles of heterozoan carbonates

Sedimentary profiles of heterozoan carbonate are carbonate ramps or mixed carbonate-siliciclastic ramps. Topographic breaks related to an initial topography (e.g. fjords) could occur along platform profiles. Hydraulic energy is the primary controlling factor of sediment accumulation that separates two groups of profiles, (1) high hydrodynamics ($n = 40$; Open ocean shelf and Seaway of (James & Jones, 2015)) and (2) low to moderate hydrodynamics ($n = 87$; Interior basin margin ramps of (James & Jones, 2015)); two case studies remain undefined because of the lack of data (case studies 76 and 83). These two groups were then divided into eight depositional profiles based on the loci of production and loci of sediment accumulations that refer to the local scale (Fig. 6; cf. Appendix for the allocation of models of each case study).

Profile names are given following a mixed ecological and sedimentological approach:

- Either low or high latitude is mentioned when characteristic grains (e.g. tropical/subtropical photosymbiotic fossils) and/or facies (e.g. inner-platform glacial deposits) occur. In general, low paleolatitudes host the greatest accumulations and most diverse biotic associations.
- Trophic conditions follow the classification of Hallock (Hallock, 2001). Eutrophic conditions are assigned to heterotrophic grain associations and nutrient-rich environments such as upwelling. Oligotrophic to mesotrophic waters correspond to environments of photosynthetic and photosymbiotic biota including seagrass environments.
- Topographic terminology follows the classifications of Burchette and Wright (Burchette & Wright, 1992) and James and Jones (James & Jones, 2015). In addition, and focusing on the coupling of

Fig. 6. Heterozoan carbonate depositional profiles. Characteristic width (km) and depth (m) of platforms are given at the top-right corner of each profile.

topography and hydrodynamics, we describe a segmented platform model (type 7) and a transport-dominated model (type 4).

5.3.2.1. Low to moderate hydrodynamics

5.3.2.1.1. Type 1. Low-latitude, eutrophic, homoclinal ramp ($n = 23$; Appendix). The first model is the homoclinal ramp showing wave-driven interfingering facies belts that are composed of oolitic and/or bryozoan-crinoidal shoals, a bryozoan-crinoidal mid-ramp, deep-ramp bryozoan-crinoidal mounds and organic-rich (or phosphate-rich or cherty) fine-grained basinal deposits. A coastal zone including “photozoan components” such as non-skeletal grains, stromatolites, stromatoporoids, green algae and corals can occur. Such hundreds-of-kilometers-wide carbonate ramps are typical of the Paleozoic and cratonic platforms, over which moderate hydrodynamics allow for autochthonous and para-autochthonous accumulations.

In terms of facies distribution, the sedimentary profile models of “upwelling ramp” (James, 1997) and “thermocline-stratified ramp” (James & Jones, 2015) apply. These sedimentary profiles are restricted to the Paleozoic periods given the unique, extensive homoclinal ramp geometry of the cratonic margins and the very specific sediment bodies

such as the large ooid shoals, crinoidal accumulations and bryozoan mounds. In terms of carbonate production processes, eutrophic waters drive the large heterotrophic production (Hallock, 2001). Upwelling brings cooler waters onto the platform but cool to cold waters per se cannot drive the carbonate production. Modern Mauritania (case study 98) shows an example of an oceanographically decoupled proximal and distal setting without any shallow-water thermocline (Giraud et al., 2000). The 80-km-wide inner shelf includes ooidal and sabkha deposits, while the distal part of the platform is influenced by upwelling waters and covered by grains of heterotrophic biota (i.e. bivalves and barnacles; (Klicpera et al., 2015; Michel et al., 2011)).

5.3.2.1.2. Type 2. High-latitude, eutrophic, homoclinal ramp ($n = 18$; Appendix). This type shows a homoclinal ramp with wave-driven interfingering facies belts. It displays a terrigenous inner ramp (e.g. glacial deposits), a bryozoan-crinoidal mid-ramp, bryozoan-crinoidal mounds on the deep-ramp and organic-rich, fine-grained basinal deposits. Sponges can occur in the two deepest sedimentary settings. Such extensive cool-water carbonate ramp geometries are typical of the Paleozoic; the Danian Danish Basin shows the only post-Paleozoic example of such a sedimentary profile (Bjerrager & Surlyk, 1997).

Eutrophic conditions are thought to drive the production of large heterotrophic deposits. Terrigenous deposits such as glacial deposits within the proximal setting indicate the high-latitude paleoenvironment (James & Lukasik, 2010).

5.3.2.1.3. Type 3. Low-latitude, eutrophic and/or terrigenous-influenced, distally-steepened ramp ($n = 29$; Appendix). This distally steepened ramp shows wave-driven interfingering facies belts that comprise a diverse and highly productive bioclastic inner ramp and a bioclastic mid- and outer-ramp (mixed in situ and transported sediments). Tropical components, e.g. rudists, and subtropical grains, e.g. large benthic foraminifers, can occur within the inner ramp. A less diverse biotic association is expected in eutrophic settings. This ramp type may show relatively high terrigenous and/or nutrient input that explains the inhibition of a photozoan carbonate platform in these low-latitude settings.

Grain associations vary between heterotrophic biota in eutrophic marine paleo-environments to a light-related seagrass and red algal carbonate production in mesotrophic waters and terrigenous-influenced settings. Such grain associations correspond to disturbed tropical to subtropical marine paleo-environments. Carbonate production is thought to be facilitated within oversaturated, warm, low-latitude waters. Paleoceanographic patterns of eutrophic settings can be similar to the Paleozoic sedimentary profile type 1 but the platform extent is much narrower. This sedimentary profile typically occurs during the Cretaceous but is also commonly found during the Cenozoic and in the Modern.

5.3.2.1.4. Type 4. Warm-temperate, transport-dominated accumulation ($n = 5$; Appendix). No typical depositional profile could be recognized for accumulations that are strongly controlled by their initial topography (e.g. steep volcanic basement) or substratum movements (i.e. faulting or subsidence), while hydraulic energy is not interpreted to be very strong. Therefore, a transport-dominated depositional model is proposed in which hydraulic energy is not interpreted as the major transport agent; by contrast to the high hydraulic energy sedimentary profile types 6 to 8. These type 4 platforms show a diverse bioclastic inner ramp, possibly with seagrass and/or subtropical components, e.g. large foraminifers, and a bioclastic mid- and outer-ramp with mixed in situ and transported sediments. Terrigenous input can be high. The grain association is comparable to either the type 3 or type 5 sedimentary profile but the stratigraphic architecture or inherited topography is different. Accommodation and thus sediment transport and accumulation are largely controlled by tectonics or initial topography (i.e. escarpment and high slope angle). Only Oligo-Miocene case studies were included in this model; however, this sedimentary profile type should not be restricted to any geological period.

5.3.2.1.5. Type 5. Warm-temperate, oligotrophic, distally steepened ramp ($n = 12$; Appendix). This distally-steepened ramp shows wave-controlled facies belts and includes a diverse bioclastic inner ramp with seagrass and possibly subtropical components, e.g. large foraminifers, and a red algal middle and/or outer ramp. Terrigenous input can occur and can be abundant in the proximal setting. This model is equivalent to the modern Mediterranean scheme of Pérès and Picard (Pérès & Picard, 1964); (“maërl”, “faciès à pralines”, “détritique côtier et du large”; also cf. (Betzler et al., 1997; Fornos & Ahr, 1997)) and the distally-steepened ramp characterized by a high rate of red algal, coarse-grained production in the distal, oligophotic zone (cf. (Pomar, 2001a)). The facies model corresponds to the “warm-temperate lower energy” sketch of James and Jones (James & Jones, 2015).

Oligotrophic conditions are assigned to such carbonate production based on the comparison with modern Mediterranean trophic conditions and the light-related biota from the inner (seagrass and large benthic foraminifers) to the mid and outer ramp (red algae). Sedimentary facies that are characterized by heterotrophic biota are mostly restricted to nearshore, mollusc-rich facies and distal bryozoan-rich sediments occupying the aphotic zone sensu Pomar (Pomar,

2001b). This sedimentary profile model is only relevant as of the Early Miocene period due to the evolution of red algae that as of that period in time were able to colonize entire temperate platforms (e.g. (Braga, 2017; Pomar et al., 2017)).

5.3.2.2. High hydrodynamics

5.3.2.2.1. Type 6. Seaway ($n = 4$; Appendix). This system is characterized by hydrodynamic (wave, tide and/or current) controlled bioclastic deposits that contain wave-related sedimentary structures (e.g. cross bedding). Terrigenous input is high. Seagrass and oolitic/bioclastic shoals (topographic high) can be present on the inner ramp and feed the bioclastic bodies. Modern seaway-type systems (i.e. Hecate Strait; (Carey et al., 1995)) in which sediments do not accumulate are not considered; they rather correspond to a topographically controlled dispersal system (cf. type 7, Segmented platform). The seaway sedimentary profile is considered as a topographically accumulating sedimentary system and strictly corresponds to the “seaway model” of James and Jones (James & Jones, 2015). Carbonate production might correspond to either light-related or heterotrophic biota. Only Cenozoic case studies were included in this model; however, this sedimentary profile type should not be restricted to any geological period.

5.3.2.2.2. Type 7. Segmented platform ($n = 29$; Appendix). This system includes wave-abraded (“shaved”) shelves showing topographic-induced trapping mechanisms for terrigenous input (fjords, troughs, shelf islets) and/or effective winnowing of terrigenous components (e.g. fluvial systems). Carbonate deposits are localized reworked sand bodies (typically coarse-grained subaqueous dunes). High-frequency eustatic sea-level cycles, especially the last glacial and last transgressive sedimentation, have a strong imprint on this sedimentary system. Kelp forest is a common carbonate factory. Glacial deposits can occur in proximal settings.

Facies models correspond to the “cool temperate” and “cold-water carbonate facies” of James and Jones (James & Jones, 2015). Most case studies are found in high-latitude settings in which swell and storm waves are strong and carbonate production is driven by a high marine productivity. Such sedimentary profiles can occur throughout the Phanerozoic; most case studies that are included in this model, however, are found in the most recent period ($n = 18$) because of a low-preservation potential of the deposits (relatively small, reworked deposits in cool waters).

5.3.2.2.3. Type 8. Shaved shelf ($n = 7$; Appendix). The last profile shows wave-abraded (“shaved”) shelves in which most sediment deposition occurs on the outer shelf and slope. Terrigenous input is absent. Hardgrounds and reworked intraclasts are widespread on the shelf throughout the succession. Seagrass and/or red algal deposits can occur in proximal settings. The facies model corresponds to the “warm-temperate high energy” model of James and Jones (James & Jones, 2015). Most of the carbonate production shows heterotrophic biota that is driven by a fairly high trophic marine environment, at least seasonally. The records of this sedimentary profile model are restricted to the Cenozoic period and the Australian shelves.

5.3.3. Implications of depositional profiles

The proposed models combine depositional profiles with the distribution of biota characterizing the heterozoan grain association or C-factory depositional environment. In addition, the new classification scheme associates paleoceanographic scenarios with depositional styles allowing predicting which specific biota may develop within these environments. Prediction of heterozoan carbonates through space and time could have significant impact on the exploration and development of analogue reservoirs hosting hydrocarbon, water and hence geothermal fluids (Taranaki fields, (Hood et al., 2003); North American Paleozoic fields, cf. Appendix).

6. Summary and concluding remarks

During the Phanerozoic, specific time intervals host a significant number of heterozoan carbonate platforms. These occurrences are related to either terrigenous input or paleoceanographic conditions, especially glaciation periods during which thermohaline circulation is strong (e.g. Late Ordovician, Carboniferous, Permian and late Cenozoic). Late Ordovician and Carboniferous case studies are found at either low or high paleolatitudes and correspond to regions of upwelling and deep-water formation, respectively. Most heterozoan carbonates of the Permian and Cenozoic periods occur from mid to high paleolatitudes (subtropical to polar). Greenhouse periods (e.g. Cretaceous) show only limited occurrences that are associated with local environmental disturbance (e.g. terrigenous and nutrient influx). Heterozoan carbonates made of heterotrophic biota accumulate in settings of high marine productivity, as such a process is needed to sustain the production of suspension feeders. Seagrass and coralline red algal platform systems develop outside the ecological zones in which photozoan carbonates thrive (i.e. the tropics). This zone corresponds first to the warm-temperate province (cf. (Betzler et al., 1997)). Because light provides the energy allowing seagrass and red algae to flourish, these carbonate systems occur in marine environments of low to moderate productivity. Thus, a better understanding of heterozoan carbonates can be gained using a deterministic environmental approach based on the energy needed for the carbonate-producing biota to produce and accumulate sediments.

A model is proposed separating the phototrophic seagrass/red algal and the heterotrophic platform systems. This model is consistent with the definition of other platform-scale carbonate factories and valid throughout the Phanerozoic in terms of functional ecology at a global oceanographic scale. The scheme allows predicting and modelling the global paleoceanographic trends of carbonate distribution. High marine productivity regions show favourable oceanographic conditions for carbonate production of heterotrophic biota, while intermediate latitudes are susceptible to host carbonate platforms of subtropical and warm-temperate, light-related ecosystems (e.g. rhodalgic platforms). Hence, on a global scale it is theoretically possible to predict a platform-scale carbonate factory for a given oceanic region. Because carbonate sedimentology remains a conundrum, i.e. multiple environmental parameters control the production and sedimentation of carbonates, local parameters such as terrigenous input and hydrodynamics can overprint the global-scale oceanographic signal. On a local sedimentological scale and using a process-based approach, eight depositional profiles are proposed that are derived from the facies spectrum models of James and Jones (James & Jones, 2015). These profiles are based on the energy driving the carbonate production and the coupling between hydrodynamics and topography, which controls the transport and the preservation of sediments. Both global and local scales are linked by paleoceanographic conditions, which are related to paleogeography and paleoclimate.

The present approach is an attempt to assess the role of controlling parameters of carbonate production, and thus holds large uncertainties and unanswered questions. In practice, the global-scale, paleoceanographic approach is limited because of the limits to detailed paleogeographic reconstructions and the associated paleoceanographic circulation patterns. Although no straightforward relationship is drawn with the stratigraphic distribution of heterozoan carbonates, the role of oceanic geochemistry also remains uncertain (CO_2 atmospheric concentrations and Mg:Ca ratio; cf. e.g. (Hallock, 2015)). Heterotrophic carbonate-secreting biota, which depend on organic matter concentration to thrive, correspond to opportunist organisms and appear to be able to precipitate carbonates under low carbonate saturation states. This ability makes these carbonate producers relatively independent from seawater chemistry to a certain extent. Light-related heterozoan carbonates, i.e. seagrass and red algal sedimentary systems at the platform scale, which are restricted at relatively low latitudes, do not

show the same ability.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earscirev.2018.05.003>.

References

- Aguirre, J., Riding, R., Braga, J.C., 2000. Diversity of coralline red algae: origination and extinction patterns from the Early Cretaceous to the Pleistocene. *Paleobiology* 26, 651–667.
- Allmon, W.D., 2007. Cretaceous marine nutrients, greenhouse carbonates, and the abundance of Turrilline gastropods. *J. Geol.* 115, 509–523. <http://dx.doi.org/10.1086/519775>.
- Alonso-Zarza, A.M., Tanner, L.H., 2010. Carbonates in Continental Settings: Facies, Environments, and Processes. In: *Developments in Sedimentology*. 61. Elsevier, pp. 377.
- Amado-Filho, G.M., Moura, R.L., Bastos, A.C., Salgado, L.T., Sumida, P.Y., et al., 2012. Rhodolith beds are major CaCO_3 bi-factories in the tropical South West Atlantic. *Plos One* 7 (4), e35171. <http://dx.doi.org/10.1371/journal.pone.0035171>.
- Ballesteros, E., 2006. Mediterranean coralligenous assemblages: a synthesis of present knowledge. *Oceanogr. Mar. Biol.* 44, 123–195.
- Beauchamp, B., Desrochers, A., 1997. Permian warm- to very cold-water carbonates and cherts in Northwest Pangea. In: James, N.P., Clarke, J.A.D. (Eds.), *Cool-water Carbonates*. SEPM Special Publication 56, pp. 327–347.
- Bensing, J.P., James, N.P., Beauchamp, B., 2008. Carbonate deposition during a time of mid-latitude ocean cooling: early Permian subtropical sedimentation in the Sverdrup Basin, Arctic Canada. *J. Sediment. Res.* 78, 2–15. <http://dx.doi.org/10.2110/jsr.2008.004>.
- Berner, R.A., 2006. GEOCARBSULF: a combined model for Phanerozoic atmospheric O_2 and CO_2 . *Geochim. Cosmochim. Acta* 70, 5653–5664. <http://dx.doi.org/10.1016/j.gca.2005.11.032>.
- Betzler, C., Bracht, T., Nebelsick, J., 1997. The warm temperate carbonate province - a review of the facies, zonations, and delimitations. In: *Cour. Forschungs-Institut Senckenb.* vol. 201. pp. 83–99.
- Birkeland, C., 1987. Nutrient availability as a major determinant of differences among coastal hard-substratum communities in different regions of the tropics. In: Birkeland, C. (Ed.), *Differences between Atlantic and Pacific Tropical Marine Ecosystems: Community Structure, Ecological Processes, and Productivity*. UNESCO, Paris, pp. 45–90.
- Birkett, D.A., Maggs, C., Dring, M.J., 1998. Maerl - An Overview of Dynamics and Sensitivity Characteristics for Conservation Management of Marine SACs.
- Bjerager, M., Surlyk, F., 1997. Benthic palaeoecology of Danian deep-shelf bryozoan mounds in the Danish Basin. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 250, 184–215.
- Blomeier, D., Dustira, A.M., Forke, H., Scheibner, C., 2013. Facies analysis and depositional environments of a storm-dominated, temperate to cold, mixed siliceous-carbonate ramp: the Permian Kapp Starostin Formation in NE Svalbard. *Nor. Geol. Tidsskr.* 93, 75–93.
- Bosence, D.W.J., 1983. Coralline algal reef frameworks. *J. Geol. Soc. Lond.* 140, 365–376.
- Bosence, D.W.J., 1985. The “coralligène” of the Mediterranean - a recent analog for tertiary coralline algal limestones. In: Toomey, D.F., Nitecki, M.H. (Eds.), *Paleoalgology*. Springer, Berlin Heidelberg, pp. 216–225.
- Bosence, D.W.J., Pedley, H.M., 1982. Sedimentology and palaeoecology of a Miocene coralline algal biostrome from the Maltese Islands. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 38, 9–43.
- Bosence, D.W.J., Wilson, J., 2003. Maerl growth, carbonate production rates and accumulation rates in the northeast Atlantic. *Aquat. Conserv.* 31, S21–S31. <http://dx.doi.org/10.1002/aqc.565>.
- Bourrouilh-Le Jan, F.G., Hottinger, L.C., 1988. Occurrence of rhodoliths in the tropical Pacific - a consequence of Mid-Miocene paleo-oceanographic change. *Sediment. Geol.*

- 60, 355–367.
- Braga, J.C., 2017. Neogene rhodoliths in the mediterranean basins. In: Riosmena-Rodríguez, R., Nelson, W., Aguirre, J. (Eds.), *Rhodolith/Maërl Beds: A Global Perspective*. Vol. 15. Springer, Coastal Research Library, pp. 169–193.
- Braga, J.C., Bassi, D., Piller, W.E., 2010. Paleoenvironmental significance of oligocene-miocene coralline red algae - a review. In: Mutti, M., Piller, W.E., Betzler, C. (Eds.), *Carbonate Systems during the Oligocene-Miocene Climatic Transition*. vol. 42. Wiley-Blackwell, IAS Special Publication, pp. 165–182.
- Brandano, M., 2017. Oligocene Rhodolith Beds in the Central Mediterranean. In: Riosmena-Rodríguez, R., Nelson, W., Aguirre, J. (Eds.), *Rhodolith/Maërl Beds: A Global Perspective*. vol. 15. Springer, Coastal Research Library, pp. 195–219.
- Brandano, M., Frezza, V., Tomassetti, L., Cuffaro, M., 2009. Heterozoan carbonates in oligotrophic tropical waters: the Attard member of the lower coralline limestone formation (Upper Oligocene, Malta). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 274, 54–63. <http://dx.doi.org/10.1016/j.palaeo.2008.12.018>.
- Brookfield, M.E., 1988. A mid-Ordovician temperate carbonate shelf-the black river and Trenton limestone groups of southern Ontario, Canada. *Sediment. Geol.* 60, 137–153. [http://dx.doi.org/10.1016/0037-0738\(88\)90115-7](http://dx.doi.org/10.1016/0037-0738(88)90115-7).
- Burchette, T.P., Wright, V.P., 1992. Carbonate ramp depositional systems. *Sediment. Geol.* 79, 3–57.
- Buxton, M.W.N., Pedley, H.M., 1989. Short Paper: A standardized model for Tethyan Tertiary carbonate ramps. *J. Geol. Soc. Lond.* 146, 746–748. <http://dx.doi.org/10.1144/gsjgs.146.5.0746>.
- Cabioch, G., Montaggioni, L.F., Faure, G., Ribaud-Laurenti, A., 1999. Reef coral assemblages as recorders of paleobathymetry and sea level changes in the Indo-Pacific province. *Quat. Sci. Rev.* 18, 1681–1695. [http://dx.doi.org/10.1016/S0277-3791\(99\)00014-1](http://dx.doi.org/10.1016/S0277-3791(99)00014-1).
- Carannante, G., Esteban, M., Milliman, J.D., Simone, L., 1988. Carbonate lithofacies as paleolatitude indicators: problems and limitations. *Sediment. Geol.* 60, 333–346. [http://dx.doi.org/10.1016/0037-0738\(88\)90128-5](http://dx.doi.org/10.1016/0037-0738(88)90128-5).
- Carannante, G., Graziano, R., Ruberti, D., Simone, L., 1997. Upper cretaceous temperate-type open shelves from northern (sardinia) and southern (apennines-apulia) mesozoic tethyan margins. In: James, N.P., Clarke, J.A.D. (Eds.), *Cool-Water Carbonates*. vol. 56. SEPM Special Publication, pp. 309–325.
- Carey, J., Moslow, T.F., Barrip, J.V., 1995. Origin and distribution of Holocene temperate carbonates, Hecate Strait, Western Canada continental shelf. *J. Sediment. Res.* A65, 185–194.
- Case, D.H., Pasulka, A.L., Marlow, J.J., Grupe, B.M., Levin, L.A., Orphan, V.J., 2015. Methane seep carbonates host distinct, diverse, and dynamic microbial assemblages. *MBio* 6. <http://dx.doi.org/10.1128/mBio.01348-15>.
- Chave, K.E., 1967. Recent carbonate sediments - an unconventional view. *J. Geol. Edu.* 15, 200–204.
- Coffey, B.P., Read, J.F., 2007. Subtropical to temperate facies from a transition zone, mixed carbonate-siliciclastic system, Palaeogeogr. North Carolina, USA. *Sedimentology* 54, 339–365. <http://dx.doi.org/10.1111/j.1365-3091.2006.00839.x>.
- Collins, L.B., France, R.E., Zhu, Z.R., Wyrwoll, K.-H., 1997. Warm-water platform and cool-water shelf carbonates of the Abrolhos Shelf, Southwest Australia. In: James, N.P., Clarke, J.A.D. (Eds.), *Cool-Water Carbonates*. vol. 56. SEPM Special Publication, pp. 23–36.
- Crame, J.A., 2002. Evolution of taxonomic diversity gradients in the marine realm: a comparison of late Jurassic and recent bivalve faunas. *Paleobiology* 28, 184–207.
- Cramer, B.S., Toggweiler, J.R., Wright, J.D., Katz, M.E., Miller, K.G., 2009. Ocean overturning since the Late Cretaceous: inferences from a new benthic foraminiferal isotope compilation. *Paleoceanography* 24. <http://dx.doi.org/10.1029/2008PA001683>.
- Dupraz, C., Reid, R.P., Braissant, O., Decho, A.W., Norman, R.S., Visscher, P.T., 2009. Processes of carbonate precipitation in modern microbial mats. *Earth Sci. Rev.* 96, 141–162. <http://dx.doi.org/10.1016/j.earscirev.2008.10.005>.
- Edinger, E.N., Risk, M.J., 1994. Oligocene-Miocene extinction geographic restriction of Caribbean corals: roles of turbidity, nutrients and temperature. *Palaios* 9, 576–598.
- Edinger, E.N., Copper, P., Risk, M.J., Atmojo, W., 2002. Oceanography and reefs of recent and Paleozoic tropical Epeiric seas. *Facies* 47, 127–150.
- Esteban, M., 1996. An overview of Miocene reefs from Mediterranean areas: general trends and facies models. In: Franseen, E.K., Esteban, M., Ward, W.C., Rouchy, J. (Eds.), *Models for Carbonate Stratigraphy from Miocene Reef Complexes of Mediterranean Regions*. SEPM Special Publication, Concepts in Sedimentology and Paleontology. Vol. 5. pp. 3–53.
- Fornos, J.J., Ahr, W.M., 1997. Temperate carbonates on a modern, low-energy, isolated ramp: the Balearic platform, Spain. *J. Sediment. Res.* 67, 364–373.
- Fournier, F., Borgomano, J., Montaggioni, L., 2005. Development patterns and controlling factors of tertiary carbonate buildups: insights from high-resolution 3D seismic and well data in the Malampaya gas field (offshore Palawan, Philippines). *Sediment. Geol.* 175, 189–215. <http://dx.doi.org/10.1016/j.sedgeo.2005.01.009>.
- Frank, T.D., Pritchard, J.M., Fielding, C.R., Mory, A.J., 2012. Cold-water carbonate deposition in a high-latitude, glacially influenced perian seaway (southern carnavon basin, Western Australia). *Aust. J. Earth Sci.* 59, 479–494. <http://dx.doi.org/10.1080/08120099.2012.672932>.
- Franseen, E.K., 2006. Mississippian (Osagean) Shallow-water, mid-latitude siliceous sponge spicule and heterozoan carbonate facies: an example from Kansas with implications for regional controls and distribution of potential reservoir facies. In: *Current Research in Earth Sciences*. Kansas Geological Survey Bulletin 252, part 1.
- Freiwald, A., 1998. Modern nearshore cold-temperate calcareous sediments in the Troms District, northern Norway. *J. Sediment. Res.* 68, 763–776 (1073-130X/98/068-763/\$03.00).
- Gatt, P.A., Gluyas, J.G., 2012. Climatic controls on facies in Palaeogene Mediterranean subtropical carbonate platforms. *Pet. Geosci.* 18, 355–367. <http://dx.doi.org/10.1144/1354-079311-032.1354-0793/12/>.
- Gattuso, J., Frankignoulle, M., Bourge, I., Romaine, S., Buddemeier, R.W., 1998. Effect of calcium carbonate saturation of seawater on coral calcification. *Glob. Planet. Chang.* 18, 37–46.
- Gillespie, J.L., Nelson, C.S., 1997. Mixed siliciclastic-skeletal carbonate facies on wanganui shelf, New Zealand: a contribution to the temperate carbonate model. In: James, N.P., Clarke, J.A.D. (Eds.), *Cool-water Carbonates*. SEPM Special Publication. vol. 56. pp. 127–140.
- Giraud, X., Bertrand, P., Garçon, V., Dadou, I., 2000. Modeling of 15 N evolution: first palaeoceanographic applications in a coastal upwelling system. *J. Mar. Res.* 58, 609–630.
- Halfar, J., Mutti, M., 2005. Global dominance of coralline red-algal facies: a response to Miocene oceanographic events. *Geology* 33, 481–484. <http://dx.doi.org/10.1130/G21462.1>.
- Halfar, J., Godínez-Orta, L., Mutti, M., Valdez-Holguín, J.E., Borges, J.M., 2004. Nutrient and temperature controls on modern carbonate production: an example from the Gulf of California, Mexico. *Geology* 32, 213–216. <http://dx.doi.org/10.1130/G20298.1>.
- Halfar, J., Godínez-Orta, L., Mutti, M., Valdez-Holguín, J.E., Borges, J.M., 2006. Carbonates calibrated against oceanographic parameters along a latitudinal transect in the Gulf of California, Mexico. *Sedimentology* 53, 297–320. <http://dx.doi.org/10.1111/j.1365-3091.2005.00766.x>.
- Hallock, P., 2001. Coral reefs, carbonate sediments, nutrients, and global change. In: Stanley, G.D. (Ed.), *The History and Sedimentology of Ancient Reef Systems*. Springer, Boston, MA, pp. 387–427. http://dx.doi.org/10.1007/978-1-4615-1219-6_11.
- Hallock, P., 2015. Changing influences between life and limestones in earth history. In: Birkeland, C. (Ed.), *Coral Reefs in the Anthropocene*. Springer, Dordrecht, pp. 17–42. <http://dx.doi.org/10.1007/978-94-017-7249-5>.
- Hallock, P., Pomar, L., 2008. Cenozoic evolution of larger benthic foraminifera: paleoceanographic evidence for changing habitats. In: *Proceedings of the 11th International Coral Reef Symposium*, pp. 7–11 (Ft. Lauderdale, Florida).
- Hallock, P., Schlager, W., 1986. Nutrient excess and the demise of coral reefs and carbonate platforms. *Palaios* 1, 389–398. <http://dx.doi.org/10.2307/3514476>.
- Hallock, P., Premoli Silva, I., Boersma, A., 1991. Similarities between planktonic and larger foraminiferal evolutionary trends through Paleogene paleoceanographic changes. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 83, 49–64. [http://dx.doi.org/10.1016/0031-0182\(91\)90075-3](http://dx.doi.org/10.1016/0031-0182(91)90075-3).
- Harzhauser, M., Piller, W.E., 2007. Benchmark data of a changing sea — Palaeogeography, Palaeobiogeography and events in the Central Paratethys during the Miocene. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 253, 8–31. <http://dx.doi.org/10.1016/j.palaeo.2007.03.031>.
- Hay, W.W., 2008. Evolving ideas about the Cretaceous climate and ocean circulation. *Cretac. Res.* 29, 725–753. <http://dx.doi.org/10.1016/j.cretres.2008.05.025>.
- Hayton, S., Nelson, C.S., Hood, S.D., 1995. A skeletal assemblage classification system for non-tropical carbonate deposits based on New Zealand Cenozoic limestones. *Sediment. Geol.* 100, 123–141.
- Hendy, A.J.W., Kamp, P.J.J., Vonk, A.J., 2006. Cool-water shell bed taphofacies from miocene-pliocene shelf sequences in New Zealand: utility of taphofacies in sequence stratigraphic analysis. In: Pedley, H.M., Carannante, G. (Eds.), *Cool-Water Carbonates: Depositional Systems and Palaeoenvironmental Controls*. vol. 255. Geological Society, London, Special Publications, pp. 283–305. <http://dx.doi.org/10.1144/GSL.SP.2006.255.01.17>.
- Henrich, R., Freiwald, A., Betzler, C., Bader, B., Schiller, P., Samtleben, C., Brachert, T.C., Wehrmann, A., Zankl, H., Khlmann, D.H.H., 1995. Controls on modern carbonate sedimentation on warm-temperate to Arctic coasts, shelves and seamounts in the northern hemisphere: implications for fossil counterparts. *Facies* 32, 71–108.
- Henrich, R., Freiwald, A., Birkett, T., Schäfer, P., 1997. Evolution of an arctic open-shelf carbonate platform, spitsbergen bank (barents sea). In: James, N.P., Clarke, J.A.D. (Eds.), *Cool-Water Carbonates*. vol. 56. SEPM Society for Sedimentary Geology Special Publication, pp. 163–181.
- Hood, S.D., Nelson, C.S., Kamp, J.J., 2003. Modification of fracture porosity by multi-phase vein mineralization in an Oligocene nontropical carbonate reservoir, Taranaki Basin, New Zealand. *AAPG Bull.* 87, 1575–1597.
- Insalaco, E., Skelton, P., Palmer, T.J., 2000. Carbonate platform systems: components and interactions — an introduction. In: Insalaco, E., Skelton, P.W., Palmer, T.J. (Eds.), *Carbonate Platform Systems: Components and Interactions*. vol. 178. Geological Society, London, Special Publications, pp. 1–8. <http://dx.doi.org/10.1144/GSL.SP.2000.178.01.01>.
- Jafarian, E., Kleipool, L.M., Scheibner, C., Blomeier, D.P.G., Reijmer, J.J.G., 2017a. Variations in petrophysical properties of Upper Palaeozoic mixed carbonate and non-carbonate deposits, Spitsbergen, Svalbard Archipelago. *J. Pet. Geol.* 40, 59–83.
- Jafarian, E., Groen, R.D., Nootgedacht, C.W., Scheibner, C., Blomeier, D.P.G., Reijmer, J.J.G., 2017b. Facies arrangement and cyclostratigraphic architecture of the Templet Member and the Kapp Starostin Formation (Permian) on Spitsbergen, Svalbard. *Norw. J. Geol.* 97, 213–231.
- James, N.P., 1997. The cool-water carbonate depositional realm. In: James, N.P., Clarke, J.A.D. (Eds.), *Cool-water Carbonates*. Vol. 56. SEPM Special Publication, pp. 1–20.
- James, N.P., Bone, Y., 1994. Paleogeology of cool-water, subtidal cycles in mid-Cenozoic limestones, Eucla platform, southern Australia. *Palaios* 9, 457–476.
- James, N.P., Bone, Y., 2011. *Neritic Carbonate Sediments in a Temperate Realm - South Australia*. Springer, Dordrecht Heidelberg London New York (254 pp.).
- James, N.P., Clarke, J.A.D., 1997. *Cool-water Carbonates*. 56. SEPM Society for Sedimentary Geology Special Publication, pp. 440.
- James, N.P., Jones, B.G., 2015. The cool-water neritic realm. In: James, N.P., Jones, B. (Eds.), *Origin of Carbonate Rocks*. AGU, John Wiley & Sons, pp. 135–149.
- James, N.P., Lukasik, J.J., 2010. In: *Cool- and cold-water carbonates*, James, N.P., Dalrymple, R.W. (Eds.), *Facies Models 4*. Geological Association of Canada, St John's,

- Newfoundland, pp. 371–399.
- James, N.P., Boreen, T.D., Bone, Y., Feary, D.A., 1994. Holocene carbonate sedimentation on the west Eucla Shelf, Great Australian bight: a shaved shelf. *Sediment. Geol.* 90, 161–177. [http://dx.doi.org/10.1016/0037-0738\(94\)90037-X](http://dx.doi.org/10.1016/0037-0738(94)90037-X).
- James, N.P., Collins, L.B., Bone, Y., Hallcock, P., 1999. Subtropical carbonates in a temperate realm: modern sediments on the Southwest Australian shelf. *J. Sediment. Res.* 69, 1297–1321.
- James, N.P., Bone, Y., Collins, L.B., Kyser, T.K., 2001. Surficial sediments of the Great Australian Bight: facies dynamics and oceanography on a vast cool-water carbonate shelf. *J. Sediment. Res.* 71, 549–567.
- James, N.P., Bone, Y., Brown, K.M., Cheshire, A., 2009a. Calcareous epiphyte production in cool-water carbonate seagrass depositional environments; Southern Australia. In: Swart, P.K., Eberli, G.P., McKenzie, J.A. (Eds.), *Perspectives in Carbonate Geology: A Tribute to the Career of Robert Nathan Ginsburg*. vol. 41. Wiley-Blackwell, IAS Special Publication, pp. 123–148.
- James, N.P., Frank, T.D., Fielding, C.R., 2009b. Carbonate sedimentation in a Permian high-latitude, subpolar depositional realm: Queensland, Australia. *J. Sediment. Res.* 79, 125–143. <http://dx.doi.org/10.2110/jsr.2009.021>.
- James, N.P., Jones, B.G., Nelson, C.S., Campbell, H.J., Titjen, J., 2011. Cenozoic temperate and sub-tropical carbonate sedimentation on an oceanic volcano – Chatham Islands, New Zealand. *Sedimentology* 58, 1007–1029. <http://dx.doi.org/10.1111/j.1365-3091.2010.01193.x>.
- James, N.P., Reid, C.M., Bone, Y., Levings, A., Malcolm, I., 2013. The macroalgal carbonate factory at a cool-to-warm temperate marine transition, Southern Australia. *Sediment. Geol.* 291, 1–26. <http://dx.doi.org/10.1016/j.sedgeo.2013.03.007>.
- James, N.P., Seibel, M.J., Dalrymple, R.W., Besson, D., Parize, O., 2014. Warm-temperate, marine, carbonate sedimentation in an Early Miocene, tide-influenced, incised valley; Provence, south-east France. *Sedimentology* 61, 497–534. <http://dx.doi.org/10.1111/sed.12063>.
- Jaramillo-Vogel, D., Bover-Arnal, T., Strasser, A., 2016. Bryozoan beds in northern Italy as a shallow-water expression of environmental changes during the Oligocene isotope event 1. *Sediment. Geol.* 331, 148–161. <http://dx.doi.org/10.1016/j.sedgeo.2015.10.006>.
- Johnson, K.G., Jackson, J.B.C., Budd, A.F., 2008. Caribbean reef development was independent of coral diversity over 28 million years. *Science* 319, 1521–1523.
- Jones, N.S., Ridgwell, A., Hendy, E.J., 2015. Evaluation of coral reef carbonate production models at a global scale. *Biogeosciences* 12, 1339–1356. <http://dx.doi.org/10.5194/bg-12-1339-2015>.
- Hottinger, L., 1983. Neritic Macrodictyon Genesis, an Ecological Approach. In: Peryt, T. (Ed.), *Coated Grains*. Springer, pp. 38–55.
- Kidwell, S.M., Brenchley, P.J., 1996. Evolution of the fossil record: thickness trends in marine skeletal accumulations and their implications. In: Jablonski, D., Erwin, D.H., Lipps, J.H. (Eds.), *Evolutionary Paleobiology*. University of Chicago Press, pp. 290–336.
- Kiessling, W., 2001. Paleoclimatic significance of Phanerozoic reefs. *Geology* 29, 751–754.
- Kiessling, W., Flügel, E., Golonka, J., 2000. Fluctuations in the carbonate production of Phanerozoic reefs. In: Insalaco, E., Skelton, P.W., Palmer, T.J. (Eds.), *Carbonate Platform Systems: Components and Interactions*. Vol. 178. pp. 191–215. Geological Society, London, Special Publications. <https://doi.org/10.1144/GSL.SP.2000.178.01.13>.
- Kiessling, W., Flügel, E., Golonka, J., 2003. Patterns of Phanerozoic carbonate platform sedimentation. *Lethaia* 36, 195–226. <http://dx.doi.org/10.1080/00241160310004648>.
- Kindler, P., Wilson, M.E.J., 2010. Carbonate grain associations: their use and environmental significance, a brief review. In: Mutti, M., Piller, W.E., Betzler, C. (Eds.), *Carbonate Systems During the Oligocene-Miocene Climatic Transition*. Vol. 42. pp. 35–48 Blackwell Publishing Ltd, IAS Special Publication.
- Kleypas, J.A., McManus, J.W., Menez, L.A.B., 1999. Environmental limits to coral reef development: where do we draw the line? *Am. Zool.* 39, 146–159.
- Klicpera, A., Michel, J., Westphal, H., 2015. Facies patterns of a tropical heterozoan carbonate platform under eutrophic conditions: the Banc d'Arguin, Mauritania. *Facies* 61, 421. <http://dx.doi.org/10.1007/s10347-014-0421-5>.
- Kolata, D.R., Huff, W.D., Bergström, S.M., 2001. The Ordovician Sebrer Trough: an oceanic passage to the Midcontinent United States. *GSA Bull.* 113, 1067–1078.
- Lees, A., 1975. Possible influence of salinity and temperature on modern shelf carbonate sedimentation. *Mar. Geol.* 19, 159–198.
- Lees, A., Buller, A.T., 1972. Modern temperate-water and warm-water shelf carbonate sediments contrasted. *Mar. Geol.* 13, M67–M73.
- Leinfelder, R.R., Schmid, D.U., Nose, M., Werner, W., 2002. Jurassic reef patterns - the expression of a changing globe. In: Kiessling, W., Flügel, E., Golonka, J. (Eds.), *Phanerozoic Reef Patterns*. Vol. 72. pp. 465–520 SEPM Special Publication.
- Lokier, S.W., Wilson, M.E.J., Burton, L.M., 2009. Marine biota response to clastic sediment influx: a quantitative approach. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 281, 25–42. <http://dx.doi.org/10.1016/j.palaeo.2009.07.007>.
- Lukas, J.J., James, N.P., McGowan, B., Bone, Y., 2000. An epeiric ramp: low-energy, cool-water carbonate facies in a Tertiary inland sea, Murray Basin, South Australia. *Sedimentology* 47, 851–881.
- Margalef, R., 1968. The Pelagic Ecosystem of the Caribbean Sea. In: *Symposium on Investigations and Resources of the Caribbean Sea and Adjacent Regions*. UNESCO, Paris, pp. 484–498.
- Martindale, W., Boreen, T.D., 1997. Temperature-stratified Mississippian carbonates as hydrocarbon reservoirs - examples from the Foothills of the Canadian Rockies. In: James, N.P., Clarke, J.A.D. (Eds.), *Cool-water Carbonates*. Vol. 56. pp. 391–409 SEPM Special Publication.
- Martindale, R.C., Corsetti, F.A., James, N.P., Bottjer, D.J., 2015. Paleogeographic trends in Late Triassic reef ecology from northeastern Panthalassa. *Earth Sci. Rev.* 142, 18–37. <http://dx.doi.org/10.1016/j.earscirev.2014.12.004>.
- McCall, J., Rosen, B., Darrell, J., 1994. Carbonate deposition in accretionary prism settings: early miocene coral limestones and corals of the Makran mountain range in Southern Iran. *Facies* 31, 141–178.
- Michel, J., Vicens, G.M., Westphal, H., 2011. Modern heterozoan carbonates from a eutrophic tropical shelf (Mauritania). *J. Sediment. Res.* 81, 641–655. <http://dx.doi.org/10.2110/jsr.2011.53>.
- Moura, R.L., Amado-Filho, G.M., Moraes, F.C., Brasileiro, P.S., Salomon, P.S., et al., 2016. An extensive reef system at the Amazon River mouth. *Sci. Adv.* 2, e1501252. <http://dx.doi.org/10.1126/sciadv.1501252>.
- Muir, P.R., Wallace, C.C., Done, T., Aguirre, J.D., 2015. Limited scope for latitudinal extension of reef corals. *Science* 348, 1135–1138. <http://dx.doi.org/10.1126/science.1259911>.
- Mutti, M., Hallock, P., 2003. Carbonate systems along nutrient and temperature gradients: some sedimentological and geochemical constraints. *Int. J. Earth Sci.* 92, 465–475. <http://dx.doi.org/10.1007/s00531-003-0350-y>.
- Mutti, M., Betzler, C., Stevens, T., 2010. *Carbonate Systems During the Oligocene-miocene Climatic Transition*. Wiley-Blackwell (IAS Special Publication 42).
- Nelson, C.S., 1988a. Non-tropical shelf carbonates - modern and ancient. *Sediment. Geol.* 60, 367 pp. [https://doi.org/10.1016/0037-0738\(88\)90108-X](https://doi.org/10.1016/0037-0738(88)90108-X).
- Nelson, C.S., 1988b. An introductory perspective on non-tropical shelf carbonates. *Sediment. Geol.* 60, 3–12. [http://dx.doi.org/10.1016/0037-0738\(88\)90108-X](http://dx.doi.org/10.1016/0037-0738(88)90108-X).
- Nelson, C.S., Winefield, P.R., Hood, S.D., Caron, V., Pallentin, A., Kamp, P.J.J., 2003. Pliocene Te Aute limestones, New Zealand: expanding concepts for cool-water shelf carbonates. *New Zeal. J. Geol. Geophys.* 46, 407–424.
- O'Connell, L.G., James, N.P., Doubell, M., John, F., 2016. Oceanographic controls on shallow-water temperate carbonate sedimentation: Spencer Gulf, South Australia. *Sedimentology* 63, 105–135. <http://dx.doi.org/10.1111/sed.12226>.
- Opdyke, B.N., Wilkinson, B.H., 1993. Carbonate mineral saturation state and cratonic limestone accumulation. *Am. J. Sci.* 293, 217–234.
- Özalp, H.B., Alparslan, M., 2011. The first record of *Cladocora caespitosa* (Linnaeus, 1767) (Anthozoa, Scleractinia) from the Marmara Sea. *Turkish J. Zool.* 35, 701–705. <http://dx.doi.org/10.3906/zoo-0907-80>.
- Parrish, J.T., 1982. Upwelling and petroleum source beds, with reference to Paleozoic. *Am. Assoc. Pet. Geol. Bull.* 66, 750–774.
- Parrish, J.T., 1995. Paleogeography of Cord-rich rocks and the preservation versus production controversy. In: Huc, A.-Y. (Ed.), *Paleogeography, Paleoclimate, and Source Rocks*. AAPG Special Volume, *Studies in Geology* 40, Chapter 1, pp. 1–20.
- Pearson, P.N., McMillan, I.K., Wade, B.S., Jones, T.D., Coxall, H.K., Bown, P.R., Lear, C.H., 2008. Extinction and environmental change across the Eocene-Oligocene boundary in Tanzania. *Geology* 36, 179–182. <http://dx.doi.org/10.1130/G24308A.1>.
- Pedley, H.M., Carannante, G., 2006a. Cool-water carbonates: depositional systems and palaeoenvironmental controls. *Geol. Soc. Lond., Spec. Publ.* 255 (322 pp.).
- Pedley, H.M., Carannante, G., 2006b. Cool-water carbonate ramps: a review. In: Pedley, H.M., Carannante, G. (Eds.), *Cool-water Carbonates: Depositional Systems and Palaeoenvironmental Controls*. Vol. 255. pp. 1–9. Geological Society, London, Special Publications. <https://doi.org/10.1144/GSL.SP.2006.255.01.01>.
- Peirano, A., 2001. Biomass, carbonate standing stock and production of the Mediterranean coral *Cladocora caespitosa* (L.). *Facies* 44, 75–80. <http://dx.doi.org/10.1007/BF02668168>.
- Péres, J.M., Picard, J., 1964. *Nouveau manuel de bionomie benthique de la Mer Méditerranée*. In: *Recueil de la Station Marine d'Endoume*. vol. 31. pp. 1–137. <http://paleopolis.rediris.es/BrachNet/REF/Download/Manuel.html> (viewed on 12.06.2016).
- Perrin, C., 2002. Tertiary: the emergence of modern reef ecosystems. In: Kiessling, W., Flügel, E., Golonka, J. (Eds.), *Phanerozoic Reef Patterns*. Vol. 72. pp. 567–621 SEPM Special Publication.
- Perry, C.T., Beavington-Penney, S.J., 2005. Epiphytic calcium carbonate production and facies development within sub-tropical seagrass beds, Inhaca Island, Mozambique. *Sediment. Geol.* 174, 161–176. <http://dx.doi.org/10.1016/j.sedgeo.2004.12.003>.
- Philip, J.M., Gari, J., 2005. Late Cretaceous heterozoan carbonates: Palaeoenvironmental setting, relationships with rudist carbonates (Provence, south-east France). *Sediment. Geol.* 175, 315–337. <http://dx.doi.org/10.1016/j.sedgeo.2004.11.006>.
- Pohl, A., Donnadiou, Y., Le Hir, G., Ferreira, D., 2017. The climatic significance of Late Ordovician-early Silurian black shales. *Paleoceanography* 32. <http://dx.doi.org/10.1002/2016PA003064>.
- Pomar, L., 2001a. Ecological control of sedimentary accommodation: evolution from a carbonate ramp to rimmed shelf, Upper Miocene, Balearic Islands. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 175, 249–272.
- Pomar, L., 2001b. Types of carbonate platforms: a genetic approach. *Basin Res.* 13, 313–334.
- Pomar, L., Hallock, P., 2008. Carbonate factories: a conundrum in sedimentary geology. *Earth Sci. Rev.* 87, 134–169. <http://dx.doi.org/10.1016/j.earscirev.2007.12.002>.
- Pomar, L., Brandano, M., Westphal, H., 2004. Environmental factors influencing skeletal grain sediment associations: a critical review of Miocene examples from the western Mediterranean. *Sedimentology* 51, 627–651. <http://dx.doi.org/10.1111/j.1365-3091.2004.00640.x>.
- Pomar, L., Baceta, J.I., Hallock, P., Mateu-vicens, G., Basso, D., 2017. Reef building and carbonate production modes in the west-central Tethys during the Cenozoic. *Mar. Pet. Geol.* <http://dx.doi.org/10.1016/j.marpetgeo.2017.03.015>.
- Pope, M.C., 2004. Cherty carbonate facies of the Montoya Group, southern New Mexico and western Texas and its regional correlatives: a record of Late Ordovician paleoceanography on southern Laurentia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 210, 367–384. <http://dx.doi.org/10.1016/j.palaeo.2004.02.035>.

- Porter-Smith, R., Harris, P.T., Andersen, O.B., Coleman, R., Greenslade, D., Jenkins, C.J., 2004. Classification of the Australian continental shelf based on predicted sediment threshold exceedance from tidal currents and swell waves. *Mar. Geol.* 211, 1–20. <http://dx.doi.org/10.1016/j.margeo.2004.05.031>.
- Qing Sun, S., Esteban, M., 1994. Paleoclimatic controls on sedimentation, diagenesis, and reservoir quality: lessons from Miocene carbonates. *Am. Assoc. Pet. Geol. Bull.* 78, 519–543. <http://dx.doi.org/10.1306/BDF924E-1718-11D7-8645000102C1865D>.
- Rao, C.P., 1996. *Modern Carbonates: Tropical, Temperate, Polar - Introduction to Sedimentology and Geochemistry*. University of Tasmania, Hobbart, Tasmania (206 pp.).
- Read, J.F., 1998. Phanerozoic carbonate ramps from greenhouse, transitional and ice-house worlds: clues from field and modelling studies. In: Wright, V.P., Burchette, T.P. (Eds.), *Carbonate Ramps*. Vol. 149. Geological Society, London, Special Publications, pp. 107–135. <http://dx.doi.org/10.1144/GSL.SP.1999.149.01.07>.
- Reid, C.M., James, N.P., Beauchamp, B., Kyser, T.K., 2007. Faunal turnover and changing oceanography: late Palaeozoic warm-to-cool water carbonates, Sverdrup Basin, Canadian Arctic Archipelago. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 249, 128–159. <http://dx.doi.org/10.1016/j.palaeo.2007.01.007>.
- Reijmer, J.J.G., 2014. Carbonate factories. In: Harff, J., Meschede, M., Petersen, S., Thiede, J. (Eds.), *Encyclopedia of Marine Geosciences*. Springer Science+Business Media, Dordrecht, pp. 80–84. <http://dx.doi.org/10.1007/978-94-007-6644-0>.
- Reijmer, J.J.G., Bauch, T., Schäfer, P., 2012. Carbonate facies patterns in surface sediments of upwelling and non-upwelling shelf environments (Panama, East Pacific). *Sedimentology* 59, 32–56. <http://dx.doi.org/10.1111/j.1365-3091.2010.01214.x>.
- Reymond, C.E., Zihlul, K.-S., Halfar, J., Riegl, B., Humphreys, A., Westphal, H., 2015. Heterozoan carbonates from the equatorial rocky reefs of the Galápagos Archipelago. *Sedimentology* 63, 940–958. <http://dx.doi.org/10.1111/sed.12244>.
- Riding, R., 2005. Phanerozoic reefal microbial carbonate abundance: comparisons with metazoan diversity, mass extinction events, and seawater saturation state. *Rev. Esp. Micropaleontol.* 37, 23–39.
- Riegl, B., Poiriez, A., Janson, X., Bergman, K.L., 2010. The Gulf: Facies belts, physical, chemical, and biological parameters of sedimentation on a carbonate ramp. In: Westphal, H., Riegl, B., Eberli, G.P. (Eds.), *Carbonate Depositional Systems: Assessing Dimensions and Controlling Parameters - The Bahamas, Belize and the Persian/Arabian Gulf*. Springer, Dordrecht Heidelberg London New York, pp. 145–213.
- Riosmena-Rodríguez, R., Nelson, W., Aguirre, J., 2017. . Springer, Coastal Research Library vol. 15.
- Rogala, B., James, N.P., Reid, C.M., 2007. Deposition of polar carbonates during interglacial highstands on an Early Permian shelf, Tasmania. *J. Sediment. Res.* 77, 587–606. <http://dx.doi.org/10.2110/jsr.2007.060>.
- Samankassou, E., 2002. Cool-water carbonates in a paleoequatorial shallow-water environment: the paradox of the Auernig cyclic sediments (Upper Pennsylvanian, Carnic Alps, Austria-Italy) and its implications. *Geology* 30, 655–658.
- Schlager, W., 2003. Benthic carbonate factories of the Phanerozoic. *Int. J. Earth Sci.* 92, 445–464. <http://dx.doi.org/10.1007/s00531-003-0327-x>.
- Schlager, W., 2005. Carbonate Sedimentology and Sequence Stratigraphy. In: *SEPM Concepts in Sedimentology and Paleontology* No. 8, Tulsa, Oklahoma, (200 pp.).
- Scott, R.W., 1988. Evolution of late jassic and early cretaceous reef biotas. *Palaio* 3, 184–193.
- Simo, J.A.T., Scott, R.W., Masse, J., 1993. Cretaceous carbonate platforms: an overview. In: Simo, J.A.T., Scott, R.W., Masse, J. (Eds.), *Cretaceous Carbonate Platforms*. Vol. 56. AAPG Memoire, pp. 1–14.
- Stanley, S.M., Hardie, L.A., 1998. Secular oscillations in the carbonate mineralogy of reef-building and sediment-producing organisms driven by tectonically forced shifts in seawater chemistry. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 144, 3–19.
- Stanley, S.M., Hardie, L.A., 1999. Hypercalcification: paleontology links plate tectonics and geochemistry to sedimentology. *GSA Today* 9, 2–7.
- Stemmerik, L., 1997. Permian (Artinskian-Kazanian) cool-water carbonates in North Greenland, Svalbard and the western Barents Sea. In: James, N.P., Clarke, J.A.D. (Eds.), *Cool-water Carbonates*. Vol. 56. pp. 349–364 SEPM Special Publication.
- Surlyk, F., 1997. A cool-water carbonate ramp with bryozoan mounds: Late Cretaceous-Danian of the Danish Basin. In: James, N.P., Clarke, J.A.D. (Eds.), *Cool-water Carbonates*. Vol. 56. pp. 293–307 SEPM Special Publication.
- Vennin, E., Alvaro, J.J., Villas, E., 1998. High-latitude pelmatozoan ± bryozoan mud-mounds from the late Ordovician northern Gondwana platform. *Geol. J.* 33, 121–140.
- Wasserman, H.N., 2011. A Global View of Coral Reef Cementation as a Function of Seawater Aragonite Saturation States. http://scholar.colorado.edu/honr_theses/722/ (viewed on 12.06.2016).
- Westphal, H., Halfar, J., Freiwald, A., 2010. Heterozoan carbonates in subtropical to tropical settings in the present and past. *Int. J. Earth Sci.* 99, S153–S169. <http://dx.doi.org/10.1007/s00531-010-0563-9>.
- Whalen, M.T., 1995. Barred basins: a model for eastern ocean basin carbonate platforms. *Geology* 23, 625–628.
- Williams, H.D., Burgess, P.M., Wright, V.P., Porta, G., Della, Granjeon, D., 2011. Investigating carbonate platform types: multiple controls and a continuum of geometries. *J. Sediment. Res.* 81, 18–37. <http://dx.doi.org/10.2110/jsr.2011.6>.
- Wilson, J.L., 1975. *Carbonate Facies in Geologic History*. Springer-Verlag, Berlin Heidelberg New York (471 pp.).
- Wilson, M.E.J., Vecsei, A., 2005. The apparent paradox of abundant foramol facies in low latitudes: their environmental significance and effect on platform development. *Earth Sci. Rev.* 69, 133–168. <http://dx.doi.org/10.1016/j.earscirev.2004.08.003>.
- Wood, R., 1993. Nutrients, predation and the history of reef-building. *Palaio* 8, 526–543.
- Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 ma to present. *Science* 292, 686–693. <http://dx.doi.org/10.1126/science.1059412>.
- Zhou, L., Algeo, T.J., Shen, J., Hu, Z., Gong, H., Xie, S., Huang, J., Gao, S., 2015. Changes in marine productivity and redox conditions during the late Ordovician Hirnantian glaciation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 420, 223–234. <http://dx.doi.org/10.1016/j.palaeo.2014.12.012>.