Marine Geology 352 (2014) 89–110

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Carbonate mounds: From paradox to World Heritage

J.P. Henriet [a,*], N. Hamoumi [b], A.C. Da Silva [c], A. Foubert [d], B.W. Lauridsen [e], A. Rüggeberg [a,d,f], D. Van Rooij [a]

[a] Renard Centre of Marine Geology, Department of Geology & Soil Sciences, Ghent University, Belgium
[b] Faculty of Sciences, Mohammed V University-Agdal, Rabat, Morocco
[c] Sedimentary Petrology, Liège University, Belgium
[d] Department of Geosciences, University of Fribourg, Switzerland
[e] Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark
[f] GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany

ARTICLE INFO

Article history:
Received 29 January 2013
Received in revised form 12 January 2014
Accepted 15 January 2014
Available online 23 January 2014

Keywords:
carbonate mounds
North Atlantic Mound Basin
heterozoan carbonates
Paleo-Tethys
World Heritage

ABSTRACT

The recent marine carbonate world comprises two major compartments: (1) the surface domain of the photozoan carbonates, confined in space by water depth and by the penetration of light, and (2) a deep domain, where heterozoan mound-builder guilds directly forage on fluxes of nutrients, which primarily percolate from the photic zone and/or are generated by in situ benthic processes. Locally, giant cold-water coral mounds tower up to heights of 150 to 250 m above the sea floor, in general between 500 and 1300 m water depth and within sharply delineated provinces. Some 15 years of research on these giant mound provinces conveys a picture of their distribution in space and possibly sheds light on controls, acting in concert. Globally, there is no counterpart for the prolific North Atlantic Mound Basin (NAMB). A chemical control is seen by an overlay of the mound provinces on a map of the aragonite saturation horizon (ASH). An external physical control is inferred from the position of the mound provinces, girdling a vigorous North Atlantic subtropical gyre system and clustering close to the roof of the intermediate to deep water masses of a dynamically stratified ocean. On the eastern boundary of the NAMB, nutrient fluxes are enhanced by mixing processes, driven either by internal waves between Galicia and the Shetlands, or by the vast and heterogeneous Eastern Boundary Upwelling System along the Iberian/African margins down to 10°N. Early diagenesis by carbonate dissolution and re-precipitation driven by convecting or advecting internal fluids can contribute to stabilize such constructions, facilitating an exuberant vertical accretion. It is speculated that in the North Atlantic Ocean, the deep-water carbonate factory outclasses in size the shallow water coral reefs.

Giant mound formation is a recurrent play of Life since the dawn of the metazoans (Nama Group, Upper Neoproterozoic), however with actors and plots, varying from act to act. Remarkably, literature reports only three occurrences of deep-water mounds in the Phanerozoic: the modern ocean, possibly the Danian, and the Carboniferous. Some striking parallelisms in the development of the Atlantic and the Paleo-Tethys oceans, combined with the developing insights in the controls on deep-water mounds in the present ocean, invite for a comparative study. This has the potential to eventually shed light on the full circulation pattern of the Paleo-Tethys Ocean, surface and deep. Comparative studies will build upon (1) modeling of ocean circulation constrained by the record of deep-water carbonate systems and supported by advances in tracer and proxy tools, and (2) field studies on representative and accessible continental locations. The mound route that develops in Morocco under the auspices of IOC-UNESCO will provide to multi-disciplinary teams with marine and continental experience opportunities for confronting observations from the modern ocean and on key records of past oceanic basins. It has the potential to eventually qualify for a UNESCO recognition as World Heritage.

1. Introduction

In his foreword of the comprehensive source book "The History and Sedimentology of Ancient Reef Systems" edited by George D. Stanley in 2001, Noel P. James states that ever since Darwin reported on his investigations of far-flung reefs, these structures have held an unending fascination for Earth scientists. For James, the very word "reef" conjures up restful, tropical images wrapped in warmth and displayed in shimmering colors. A particular phrase from Stanley's volume however stuck in James's mind: "reefs are a plethora of paradoxes".

What James might have overlooked is that over half a century before Charles Darwin published "The structure and distribution of coral reefs" (1842), his grandfather Erasmus Darwin (1731–1802) had already commented on the hazardous "calcareous earth" in the additional notes to his opus "The botanic garden" (1791, Note XVI, p. 32): "… marine animals named coralloids raised walls and even mountains by the

* Corresponding author.
E-mail address: jeanpierre.henriet@ugent.be (J.P. Henriet).

0025-3227/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.margeo.2014.01.008

congeries of their calcareous habitations, these perpendicular coralline rocks make some parts of the Southern Ocean highly dangerous, as appears in the journals of Capt. Cook". The fascination of Earth scientists for tropical images in shimmering colors had clearly been preceded by concerns of navigators.

As a matter of fact, Stanley (2001) refers to two possible origins of the word reef, both related to navigation hazards: either an old German or Norse term ("rif") for a ridge of rock that lay as an obstruction near the surface of the water, or "Er Rif", an Arabic term given to "hills" found by traders in shallow waters between Tangier and Melilla. He furthermore endorses the requirement of warm, well-lighted, shallow marine conditions: "reefs are restricted to tropical and subtropical settings, primarily on western parts of oceans, ranging today between 20° and 30° north and south of the equator" (Stanley, 2001, p. 1–2). Understandably, when Hovland et al. (1994) reported carbonate build-ups in the cold and dark waters of Porcupine Seabight west of Ireland, about 52° north in the eastern North Atlantic, in depths ranging between 750 and 900 m, labeling them as "reefs" was not straightforward. Hovland et al. (1994) referred to "seabed mounds (carbonate knolls?)".

In the wake of the publication of Hovland et al. (1994), a vast momentum of European projects set off in 1997 to unveil thousands of giant deep-water carbonate mounds on the northwest European continental margin, buried or surfacing. They range in general between 30 and 250 m in height and sometimes coalesce to complex ridges (Henriet et al., 1998; De Mol et al., 2002; Huvenne et al., 2003; Wheeler et al., 2007). The surface mounds are commonly covered by thriving cold-water coral ecosystems rivaling in color and luxuriance anything tropical reefs can offer. That very same year, the seminal SEPM Special Publication No. 56 on cool-water carbonates was introduced with the statement "Cool-water carbonates have always been part of sedimentary geology, but never at the forefront" (James, 1997, p. 1). On the European margins, deprived of warm-water reefs, the vast provinces of cold-water coral ecosystems would soon move to the forefront, to get high visibility in particular at the 2nd International Symposium on Deep-Sea Corals held in Erlangen, September 2003 (Freiwald and Roberts, 2005). While the name cold-water coral "reefs" was still opportunistically used by scientists towards European policy to spur – not without success – the protection of those deep-water ecosystems in Irish waters which by miracle had escaped deep-water trawls, the term "cold-water coral mounds" soon gained widespread acceptance in scientific literature.

Biogenic deep-water mounds have also been reported on the western margin of the North Atlantic, from water depths of 1000–1300 m (Paull et al., 2000). "Modern deep-water coral mounds north of Little Bahama Bank: criteria for recognition of deep-water coral bioherms in the rock record" (Mullins et al., 1981) possibly set the stage for confronting the emerging insights in the world of deep carbonate mounds of the modern ocean with the vast fossil record of carbonate build-ups. This exercise is presently continued and amplified by the international network COCARDE ("Cold-water Carbonate Reservoir Systems in Deep Environments", Henriet et al., 2011) which, for the analysis of the fossil record, in particular draws from the vast Paleoreef data base developed in the comprehensive SEPM Special Publication No. 72 — "Phanerozoic Reef Patterns" (Kiessling et al., 2002).

In the introduction of that volume, reefs are defined as "laterally confined biogenic structures, developed by the growth or activity of sessile benthic organisms and exhibiting topographic relief and (inferred) rigidity" (Flügel and Kiessling, 2002, p. 3). This definition is quite close to that of Wood (1999, p. 5): "a reef is a discrete carbonate structure formed by in-situ or bound organic components that develop topographic relief upon the sea floor". Such broad and simple definitions allowed both Wood (1999) and Flügel and Kiessling (2002) to trace the evolution of reefs through Earth history, highlighting the ways in which reef communities can differ, and illuminating processes common to the formation of all reefs. Flügel and Kiessling (2002) acknowledge that some authors might use terms such as bioconstructions, buildups or bioherms, and consider these as synonymous with their reef definition. In the present review paper, mounds may be regarded as a subset of reefs sensu Flügel and Kiessling (2002), further individualized by a distinct context and significance.

The question of reefs and mounds indeed transcends semantics. The historical context of "reefs" as shallow water hazard, the longstanding fascination for the images of tropical reefs, and even a tenacious industrial bias for shallow water processes in the development of geomodels, reservoir models and porosity distribution in reef carbonates have long cast a shadow on the nature and significance of carbonate constructions in deeper water. Yet, ocean drilling on the Irish margin soon revealed the extraordinary significance of cold-water coral mounds, for instance as high-resolution environmental archive (IODP Exp. 307, Ferdelman et al., 2006; Foubert and Henriet, 2009; Thierens et al., 2010). As developed later, they may hold – far more than the shallow-water carbonate factory – a key to the dynamics of deep and intermediate water circulation, heartbeat of the Earth's climate machine. Furthermore, on a background of new discoveries of giant hydrocarbon accumulations in ancient mounds, the confrontation with the modern world of carbonate mound systems – in particular revealed by ocean drilling – becomes an eye opener and spurs new exploration insights and strategies (Philippe Lapointe, Total E&P, COCARDE Oviedo workshop 2009, in Henriet et al., 2011).

Such confrontation of ideas between the academic and industrial world in carbonate research, and between researchers of the modern systems and those of the fossil record calls for a forum, a broadband field laboratory which can be turned into a meeting place and a reference site. This paper narrates how a unique reference route is being developed for such purposes in Morocco, with the potential to qualify as a UNESCO World Heritage Route. In parallel, it invites for a ramble through some processes and possible controls on mound nature and origin, without any pretension to comprehensiveness, but with an avowed zest for the deeper realm of the carbonate world, in particular the Atlantic one. As regards the Mediterranean, the present paper will only evoke the cold-water coral mounds in the gateway region between the Atlantic and the Mediterranean, in relation to the proposed Moroccan mound Heritage Route. The specific nature of the Mediterranean as a confined basin justifies a stand-alone review of its deep carbonate world.

2. Cold-water coral reefs in canyons and on glacial margins

The world of cold-water coral habitats comprises build-ups which qualify for a definition of reefs, yet that we shall not discuss here. These are on one side the vast cold-water coral fields thriving in interglacial times on former glaciated shelves, such as the Norwegian Sula, Rost, Traena, Fugloy, Iver and Stjernsund reefs (Freiwald et al., 2004; Fosså et al., 2005; Rüggeberg et al., 2011), or the small and patchy reefs on rocky spurs off Scotland (Mingulay reef, Roberts et al., 2009). Though some of them feature an internal facies, comparable to that of deep-water coral mounds, the position of these shelf reefs within the reach of waxing ice sheets does not allow them to develop to the exceptional dimensions in space and time, such as observed in the mound provinces on the deeper slopes of northeastern Atlantic margins.

The other habitats not discussed in this paper are the deep cold-water coral colonies in canyons (De Mol et al., 2011; Huvenne et al., 2011, 2012). Perched under overhanging cliffs or high on rocky spurs in highly stressed environments, they form significant refuges, but again they are in general not in a position to develop to the giant build-ups further considered here. The development of a canyon head with its associated zones of sediment instability may however impact on mound provinces. On the western flank of Porcupine Bank, for instance, mounds are concentrated along the edges of a canyon head or are associated with a complex fault system, traced around the canyon head (Mazzini et al., 2011).