Cool-water carbonate ramps: a review

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Abstract: This review of marine, cool-water carbonate ramps considers both their defining features and the key publications relating to them. Cool-water carbonate environments are dominated by open, skeletal debris-covered sea bottoms which support biological assemblages devoid of hermatypic coral reefs, calcified green algae and non-skeletal grains. The growing body of modern literature deals mainly with Neogene to Recent examples, particularly from the Australian, New Zealand and Mediterranean regions. Nevertheless, many ancient examples have been recognized and, without doubt, many more – currently described as ‘tropical carbonates’ – will also be found to be cool-water examples.

It is now becoming clear that a distinction must be made between those deposits associated with macrotidal regimes (i.e. world ocean sites) and those associated with land-locked water bodies such as the Mediterranean Sea. The principal difference between the two is not so much the diversity of biota but, more importantly, the minimal fair-weather reworking processes which characterize microtidal seas. This commonly allows colonization and sediment preservation in the inner-ramp zone. Biozones occupy much deeper-water sites on open ocean ramps, particularly where ramps are storm dominated. The correspondingly wider inner ramps in these world ocean sites generally become dominated by mass bioclastic reworking.

The past two decades have witnessed the development of alternative sedimentological models designed to cater for cool-water carbonate systems. These systems are dominated by open, skeletal debris-covered sea bottoms which support biological assemblages devoid of hermatypic corals, calcified green algae and non-skeletal grains (chlorozoan assemblages sensu Lees & Buller 1972). Recent examples, all distinctly different from tropical platform carbonates, have now been documented from cool-temperate to subtropical continental shelves, and even from the tropical zone. Ancient examples have also been reported in the literature, being variously designated as ‘temperate’, ‘non-tropical’ or, more frequently, as ‘cool-water’ limestones.

Although the pioneering works of Chave (1967), Lees & Buller (1972) and Lees (1975) undoubtedly set the pace for modern cool-water research, it must be remembered that Recent analogues of cool-water carbonates had also been described from the Mediterranean Sea in the pioneering works of Walther (1885, 1910) and over half a century later by Froidevaux (1976), Barbera et al. (1978), Carannante et al. (1981, 1988), Carannante & Simone (1988) and Bosence (1985).

Many modern works have concentrated on Tertiary (mainly Miocene) limestones in the peri-Mediterranean region (Barbera et al. 1978), in New Zealand (Nelson 1978) and in Poland (Studencki 1979). Nevertheless, there is a continuing interest in Recent examples, especially from the Brazilian (Milliman & Sumnerhayes 1975), New Zealand (Nelson et al. 1982) and Canadian (Nelson & Bornhold 1983) shelves.

Foremost in the post-1970s works that laid out a framework for future reference is the Non-Tropical Shelf Carbonates Ancient and Modern volume edited by Nelson (1988a). Collectively, these articles (and especially that of Nelson 1988b) defined the parameters of cool-water carbonate ramps. Later, SEPM Special Publication 56 (Cool-Water Carbonates edited by James & Clarke 1997) expanded the dataset considerably. Much of this work detailed modern and Neogene Southern Ocean carbonates, with the first article in the volume (James 1997) being dedicated to a consideration of the cool-water carbonate depositional realm. Here, the terms ‘photozoan’ (identifying tropical assemblages) and ‘heterozoan’ (encompassing cooler-water assemblages) were introduced. Many of the other papers in the volumes detailed modern and Tertiary Southern
Ocean carbonates; however, there were also significant contributions on Recent, Northern Ocean and on Palaeozoic and Mesozoic deposits. Such was the impact of these two collective volumes that many new researchers were attracted to the fast-growing field of cool-water carbonates.

During the early 1990s, studies effectively delineated new litho- and biofacies associations and depositional controls, especially around Australian and New Zealand shores. Since 1997 research has increasingly become concerned with synecological aspects of modern-day biota (e.g. James et al. 2001; Hageman et al. 2003; Smith & Nelson 2003; Amini et al. 2004; Halfar et al. 2004). There is also growing interest in extending these types of studies further back into older, Cenozoic deposits, with a view to better defining more ancient bio- and lithofacies (e.g. Lukasik et al. 2000; Nelson et al. 2003; Hendy & Kamp 2004). Equally fruitful are the studies interpreting cool-water deposits from both Cretaceous (e.g. Follmi et al. 1994; Carannante et al. 1995, 1997; Simone et al. 2003) and Palaeozoic successions (e.g. Samankassou 2002; Pope & Steffen 2003; Stemmerik & Worsley 2005).

Cool-water carbonate deposition is often controlled by relatively short-term eustatic changes so, inevitably, sequence stratigraphic considerations have become increasingly important (e.g. Brachert et al. 2003; Caron & Nelson 2003; Saxena & Betzler 2003; Caron et al. 2004). Much of this work has been directed towards developing models in the better known New Zealand and southern Australian sites. These sites also provided considerable information on non-tropical early carbonate diagenesis (see Nelson & Smith 1996; Brachert & Dullo 2000; Nelson & James 2000; Smith & Nelson 2003).

A new body of information has also developed during the past decade which deals with microtidal Quaternary and Neogene cool-water deposits from the Mediterranean region. Microtidal regimes are important because similar environments must have existed in the past whenever plate motion and orogenic activity conspired to create partly landlocked arms of former oceans. The Mediterranean region, the largest modern example, has remained microtidal at least since the early Miocene when its connection to the Indian Ocean was lost. Wave-driven processes and associated carbonate sediments in these water bodies appear to behave differently to their open ocean counterparts and the articles assembled in this volume are chosen to demonstrate this.

Although, early works provided a comparison between ancient and modern ‘temperate carbonates’ of the Mediterranean, it was not until Fornos & Ahr (1997) that modern Mediterranean ramp sediment distributions, in the Balearic region, enabled the first clear comparisons to be made between world ocean and microtidal sites.

Recently, Mediterranean cool-water Neogene carbonates have received much greater attention. Taphofacies studies have been carried out by Brachert et al. (1998) and Kourampas & Robertson (2000). Many of the Quaternary deposits contain well-developed eustatic signatures (the Mediterranean Sea remained connected to the Atlantic Ocean throughout the Quaternary). These glacio-eustatic changes have typically driven prograding clinoform foresets during regression (e.g. Hansen 1999) and back-stepping bioclastic wedges during transgression (e.g. Tesson et al. 2000). Other sandbody-focused studies include Massari et al. (2002) on Pliocene and Vecsei & Sanders (1999) on the Miocene sequences in Italy. Glaser & Betzler (2002) and Braga et al. (2001) have also worked on mixed carbonate–siliciclastic packages in the Miocene of southern Spain. Models of microtidal temperate carbonate sedimentation have been presented by Pomar & Tropeano (2001), Pedley et al. (2001) from Italian Quaternary examples and by Martin et al. (2004) for Spanish Pliocene deposits. Diagenetic studies of Mediterranean cool-water carbonates have also been carried out (e.g. Knoerich & Mutti 2003).

Cool-water carbonates

At present all marine carbonates are viewed as a continuum of depositional environments ranging between tropical and cold water. Biotial distributions and facies relationships appear clear in modern settings but can become misleadingly blurred in the ancient. Further difficulties arise from variable terminologies and a consensus has still to be reached on the precise definition of such terms as ‘cool-temperate’ and ‘warm-temperate’ marine carbonates (see discussions in Mutti & Hallock 2003). Consequently, all examples figured in this book are grouped under the cloak of ‘cool-water carbonates’. Many of these marine carbonates develop today in temperate latitudes, such as the Atlantic seaboard of Europe, Brazilian shelf, south coast of Australia, and New Zealand. Others form in warmer non-tropical regions, such as the Mediterranean Sea and the Caspian Sea. It must also be remembered that cool-water carbonates can also form within tropical climatic zones where cold coastal currents sweep shelf regions. They can also accumulate in aphotic depths.

Sea-water temperature, nutrient availability and light are principal controls on the type of carbonate forming in any region because they limit the diversity of skeleton-secreting organisms able to colonize substrates (see discussions in Pomar
2001; Mutti & Hallock 2003). Present-day ‘temperate’ environments are dominated by Foramol associations (sensu Lees & Buller 1972), dominated by benthic foraminifera, echinoids, molluscs and bryozoans. Coraline algae are the most important phototrophs contributing directly to the sediments. Colonial associations, however, typically lack hermatypic corals. Consequently, seafloor bioconstructions (frameworks) rarely exceed decimetre-scale relief, though these frameworks may be equally as robust in their tropical counterparts.

This absence of major reef barriers and baffles has major implications for sediment stability as commonly there is little to prevent wave and storm energy from penetrating directly to the shoreline (see discussions in Pomar 2001). Consequently, the majority of cool-water carbonates develop into carbonate ramp profiles. Nevertheless, isolated island sites, especially partly submerged volcanic seamounts, more typically develop narrow carbonate aprons or haloes associated with submerged wave-cut benches. High levels of sediment mobility are to be expected. The inner-ramp zone in particular is commonly also the site of very high bioclast attrition rates, with the development (though not always the preservation) of rounded shoreface packstones and grainstones. Only when bioclastic shoals are developed is there an opportunity for sheltered ‘lagoon’ and in situ invertebrate developments.

Cool-water carbonate ramps frequently are homoclinal in profile. Carbonate production and/or in situ preservation rates are much less than in their tropical counterparts and distal steepening is far less common. The general absence of reef frameworks within the mid-ramp zone ensures that any ‘aphanistic’ filters are small in comparison with tropical ramps. There are few sediment bafflers in cool-water sites, though inner and mid-ramp coralline algal biostromes and the delicate bryozoan ‘gardens’ of the outer ramp are important in controlling finer resedimentation patterns. Inevitably, storm activity is detrimental to the unprotected carbonate factory sites and partial dismantling is the norm. Line-sourced bioclasts and lime mud from the shallower ramp provide the principal ammunition carried by geostrophic flows, to be shot down-ramp into calciturbidite-dominated clinoform outer ramp sheets and/or into complex channel networks.

Rapid global sea-level change is a further factor controlling ramp profiles, especially during the Holocene. It is not surprising, therefore, that most cool-water carbonate ramps are trapped in catch-up mode with eustatic rise constantly threatening to outpace carbonate factory growth rate.

**Microtidal cool-water factories**

The considerable emphasis on microtidal ramps in this volume dictates that some generalized details should be given. Present-day carbonate production rates are never better than moderate; however, cool-water ramp biodiversity is generally high and communities are able to colonize into much shallower waters. To a large extent this is because the depth to fair-weather wave base is negligible compared with world ocean counterparts. The Mediterranean can, nevertheless, be an aggressive water body during violent winter storms. Such storms, however, are quite localized and last a matter of hours only. Seafloor communities appear to recover quickly and the principal effect of such storms is to relocate sand and finer-grade sediments further down-ramp. Only during prolonged stillstands does carbonate production ever outpace accommodation space.

The profile of a Pleistocene ramp from the Central Mediterranean (Fig. 1, modified from Pedley & Grasso 2002) serves to illustrate some of the biodiversity and depth control associated with microtidal Mediterranean ramps. Labelling of the transect zones generally follows that adopted by Reading & Collinson (1996), though it must be noted that some workers (e.g. Pomar & Tropeano 2001) merge the offshore transition and shoreface zones together and refer to everything between storm wave base and mean low water as the shoreface zone. Nevertheless, these ramp zones are tied closely to considerations of wave-base position rather than to predetermined water depths. Below storm wave base, where light and turbulence levels are lowest (offshore zone), delicate bryozoans produce a carpet-like open framework which acts as a filter, trapping muds and fine re sediments derived from the shallower ramp. Vinculariiform and Reteporiform growth-form strategies are successful during slow sedimentation phases, whereas mobile and flexible Cellariiform growth forms often dominate sites with moderate mud sedimentation rates (cf. Schopf 1969; Nelson et al. 1988).

In the shallower offshore margins and inner-ramp slope, light levels are sufficient for coralline algal phototrophs. Consequently, they produce a clearly definable biozone which is bounded by virtual darkness down-ramp and by recurrent damage by attrition in the up-ramp direction. Rhodolitic pavement facies dominate, especially where periodic overturning by turbulence occurs. In the deeper water, delicately branched growth forms dominate, whereas, smaller and more spherical rhodoliths dominate where agitation becomes frequent in the vicinity of storm-weather wave base.
Shorewards, in the area between storm- and fair-weather wave base (offshore transition zone), there is a progressive increase in bivalves, regular echinoids and benthonic foraminifera at the expense of planktonic foraminifera. Surprisingly, in the Mediterranean Sea it is common to find monospecific, hermatypic coral (Cladocora) patch-reefs within these mid-ramp areas. However, such bioherms are poorly cemented and contain few secondary framework elements for reinforcement. They offer virtually no resistance to waves and their survival is attributed mainly to the prevailing microtidal regime. Under catch-up regimes (e.g. Holocene) planar bioclastic facies extend up-ramp throughout this zone. They are often highly bioturbated and may even be nodular.

In contrast, constant reworking in the inner ramp (shoreface zone) makes it an unlikely place in which to find preserved in situ faunas. Generally, deposits consist of strongly reworked rudstone and grainstone-dominated bioclasts often built up into low-angle, tabular shoreface packages. A prime factor leading to the poor preservation potential of these inner-ramp carbonates in Holocene examples is sea-level rise, which inevitably focused storm and wave energy directly onto the beach zone. Where inner-ramp, highstand carbonates are preserved, the shoreface zone commonly terminates abruptly against a mollusc-bored, cobble and boulder zone lying proximal to an eroded cliff-edged coast.

An important variation in depositional style occurs where stillstands became well established (e.g. during the earlier Quaternary). During these times there is often a progressive local steepening of the ramp slope immediately seawards of the point where storm wave base intersects the ramp profile (often taken as the boundary between mid- and outer ramp (e.g. Pomar 2001; Pomar & Tropeano 2001). Here, it is common to find rudstone clinobeds (commonly rhodolitic in nature) which prograde basinswards and downlap onto finer outer ramp facies. These laterally extensive lithosomes represent avalanches of sediment swept out onto a depositional slope, below wave base by storm waves and wind-driven currents’ (Pomar & Tropeano 2001). This sediment, generally derived from the shoreface and offshore transition zone of the mid- and inner ramp, is apparently delivered on an infrequent basis, thus giving time for seabed invertebrate recolonization between events.

In Quaternary systems subjected to dynamic eustatic change, only the extreme-lowstand clinobed developments will be preserved. They correspond to the lowstand terraces of Chiocci & Orlando (1996) and to the shelf-perched and shelf-edge prograding sandbodies of Massari et al. (1999) and Pedley & Grasso (2002). In contrast, highstand clinobed lithosomes are commonly shaved or even totally dismantled during subsequent transgressive and highstand events.

In summary, the principal difference between Mediterranean ramps and carbonate ramps typical of world ocean sites is not so much the diversity of biota in the carbonate factory sites but, more importantly, the minimal fair-weather reworking process in microtidal seas. Any storm activity in such land-locked sea bodies usually is very localized but can be intense in the short term. By contrast, communities (biozones) inhabit much deeper sites on open ocean, storm-dominated
ramps, leaving the wide inner ramps mainly as sites for mass bioclastic reworking.

Articles in this volume

The book presents a large body of new research on Mediterranean-based cool-water carbonates. The microtidal, enclosed nature of the Mediterranean Sea potentially makes it more likely to preserve non-reworked inner-ramp facies, though this is not always apparent.

The first four articles deal with algal and cyanobacterial dominated substrates. Nalin, Basso & Massari provide an interesting example of the rigid framework associated with ‘coralligène de plateau’, which developed over a rhodolitic pavement in the Pleistocene Cutro terrace deposits of Calabria, Italy. The bioherm grew between fair-weather wave base and storm wave base (30–60 m) during a single transgressive–regressive event which terminated in burial by shoreline bioclastics. Basso, Morbioli & Corselli examine in detail the coralline algal component of ramps close to the Pontian Islands, Italy. The work shows how internal rhodolitic structure changes from laminar/concentric growth forms in unstable substrates to boxworks in stable sites with low sedimentation rates. The study also shows the increasing dominance of bryozoans in deepening biotopes. Bassi, Carannante, Murru, Simone & Toscano, make a detailed reconstruction of a Miocene temperate-type carbonate, deposited on a microtidal marginal setting. Ramp-top depths were controlled by storm wave base, the latter being responsible for intense turbulence and winnowing. Mobilized sediments were driven basinwards as gravity flows. Many current concepts are embodied in the article by Braga, Martin, Betzler & Aguirre, who present a well-considered cool-water carbonate model for the Tortonian to Zanclean (Miocene to Pliocene) of the Betic intermontane basins. Carbonate production took place mainly seaward of bioclastic shoals and below fair-weather wave base. In this example the lack of cementation encouraged particle mobilization both shorewards into the shoals, spits and beaches, and basinwards, where they were resedimented into outer-ramp channels, lobes and basin sites. Pedley & Grasso examine the general influence of eustatic change on accommodation space versus resedimentation and its implications for lime mud deposition. Reuter, Brachert & Kroeger illustrate details of a tropical to temperate carbonate transition from a late Miocene example in Crete, Greece.

Cool-water settings have now also been recognized in late Mesozoic successions within the Mediterranean realm. Ruberti, Toscano, Carannante & Simone provide an excellent example in connection with a rudist-rich succession from southern Italy. It must be remembered, however, that the Tethys was an open seaway during the Late Cretaceous, consequently tidal ranges were likely to have been closer to mesotidal rather than macrotidal at that time.

The section on world ocean sites is supported strongly by examples from New Zealand and
Australia, showing how recent studies have shifted towards investigations of skeletal taphonomies at both acoustic and conventional sample scales. The first example by Halfar, Strasser, Riegli & Godinez-Orta, however, demonstrates the expanding use of acoustic mapping in delineating bryomol carbonate factory sites in the northern Gulf of Mexico. The study showed that seafloor deposits can be subdivided into four acoustic facies on the basis of grain size and bryozoan growth morphologies. Significantly, the bryozoan associations grew in unusually warm conditions compared with other world ocean sites, largely because of the absence of faster-growing phototrophs caused by water turbidity. Work in Australia by Lukasik & James on a Miocene cool-water carbonate sequence shows how relatively small temperature changes caused a shift from heterozoan (echinoid and bryozoan) facies to bryozoan-rich, foraminifera and photozoan facies. These temperature shifts caused fluctuations in carbonate production rates which, in turn, affected the ability of the depositional system to record fluctuations in relative sea-level. Anastas, Dallymple, James & Nelson illustrate cool-water carbonate seaway deposits developed in mixed wave-dominated and current-dominated settings. These mixed energy conditions are most typical of wide seaways. Kindler, Ruchonnet & White provide an example of a temperate-water Pliocene platform, from ODP leg 194 in NE Australia, in which carbonate production was focused into the lowstand events but was shut off during highstands. Finally, Hendy, Kamp & Vonk provide a detailed analysis of condensed shell beds of New Zealand Miocene-Pliocene shelf sequences. These bivalve-dominated taphofacies, though otherwise siliciclastic successions, are used by the authors as palaeoenvironmental indicators. In addition, the variations in taphofacies appear to be environment specific, thereby providing considerable assistance in the recognition of transgressive, highstand and regressive systems tracts.

Diagenetic fabrics within cool-water carbonates are generally poorly known. Consequently, three interesting studies are included here in order to set the scene for future research. Mutti, John & Knoerich present a detailed review of the applications and limitations of chemostratigraphy in shallow-water heterozoan carbonates, using examples from the Marion Platform and from the Mediterranean. The study concludes that heterozoan systems relative to their tropical counterparts show good preservation of their marine signatures. Knoerich & Mutti provide a detailed consideration of epitaxial cements in Mediterranean Miocene carbonates. They show how aragonite, present among the invertebrate sediment contributors, was a driving force favouring the early diagenetic precipitation of epitaxial cements. The final article in the book, by Caron, Nelson & Kamp, examines the pathways and timing of cementation in Pliocene carbonates of New Zealand. In particular, they develop concepts of offlap and downlap cementation trends. A five-stage cement stratigraphic model is presented, based on petrographic criteria highlighted by cathodoluminescence and staining procedures. It is also worthwhile, from the diagenetic viewpoint, in returning to Pedley & Grasso (microtidal section). They record a range of non-luminescent vadose and marine phreatic cements which developed under the control of short-term eustatic change. These offer a means of recognizing eustatic processes at small outcrop scale and also shed light on the magnitude and relative pace of eustatic change within a complete glacio-eustatic cycle.

Overview

This increased attention of palaeontologists and sedimentologists on cool-water carbonate processes and environments prompted the editors to find ways to draw together these potentially diverse research strands into a collective publication. A number of articles in this book were presented originally at the 2004 International Geological Congress in Florence. This nucleus of articles, mainly on Mediterranean microtidal cool-water carbonates, stimulated considerable interest, particularly from other Mediterranean workers, and highlighted the need for a volume which gathered together a larger body of Mediterranean research on cool-water carbonates than had hitherto been possible. In addition, it was felt that because many of the original interpretations concerning cool-water carbonates were derived from studies in New Zealand and southern Australia, a significant part of the book should also include coverage of modern and ancient systems deposited in world ocean sites. It is hoped that this marriage of articles from the micro- and macrotidal domains will provide a useful reference source for all workers interested in entering the cool-water field. Above all, it is hoped that this book will provide a stimulus for all workers seeking to investigate modern and ancient microtidal carbonates associated with other land-locked water bodies. When added to the pre-existing database on Tertiary to Recent examples, a moderately comprehensive picture of modern cool-water systems emerges. This solid groundwork covers both palaeoecology and the associated sediment processes.

However, several formidable tasks still lie ahead. First, there is some way to go with respect
to understanding fully the preservation potential of these carbonates and particularly in unravelling their early diagenesis. The older sedimentary record also needs re-examination to ascertain better the relationships between cool-water and tropical successions, including re-examination and reinterpretation of successions hitherto considered to be wholly tropical. This will undoubtedly change the perception of how past global carbonate production rates were influenced by latitude and basin configuration. Finally, there is an urgent need to improve the dataset with respect to other microtidal cool-water bodies, both modern (e.g. Caspian Sea) and ancient. Interpreting ancient examples, of course, is no easy task. Biota generally belong to long-extinct phyla and their respective roles within ecosystems and as substrate stabilizers are often unclear.

Nevertheless, armed with modern concepts of functional morphology and sequence stratigraphy it is clear that the modelling of these dominantly bioclastic cool-water carbonates will offer new economic opportunities. Not the least of these is the potential of ancient examples to form regional aquifers and hydrocarbon reservoirs.

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