1 Coral Reefs at the Crossroads – An Introduction

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Abstract

Coral reefs are complex systems that are difficult to fully understand when viewed from a single perspective. As we have separated ourselves into increasingly smaller and more specific disciplines, we often lose sight of important connections between physical and biological factors and how they can change over different spatial and temporal scales. As stresses on these robust yet fragile systems broaden and deepen, it is becoming increasingly important that we break down artificial disciplinary barriers and ask questions that are difficult to frame from a single scientific perspective. This chapter provides a jumping-off point to examine coral reefs – sitting at both a disciplinary and a temporal crossroads.

Keywords

Interdisciplinary • Multidisciplinary • Scale • Perspective

Perhaps more than any other earth system, coral reefs sit at the crossroads of science. While organisms largely provide the raw materials, reef building responds to a wide range of non-biological processes. Water temperature confines today's scleractinean coral reefs to a narrow equatorial belt. Waves & currents control regional patterns of coral dispersal, dictate where larvae might or might not survive and create the critical linkages between reefs across individual ocean provinces. The underlying edifice provides a physical structure upon which wave energy, light intensity, sedimentation and chemical cues conspire to create zonation, the fundamental underpinning of reef characterization both today and in the geologic past.

The feedbacks among all these processes are myriad; spatial complexity is built by calcifying organisms that are in turn dependent on both surface topography and the vast network of environments on and in the reef for their success. More than 85 % of the reef's surface area exists within cryptic spaces that house roughly half of the fish species (Chap. 10) and similar proportions of other organisms living within the ecosystem boundaries. Understanding the nature and significance of these complex interactions is critical whether we are considering modern reefs (Chaps. 2, 4 and 5), their forebears throughout geologic time (Chaps. 3, 6, 7, 8, 9 and 10), or their descendants in an increasingly stressful world (Chaps. 9, 11 and 12).

Most recently, coral reefs have reached another crossroads. They evolved over the past 500 million years (Chap. 8) in response to large-scale changes in ocean processes (Chap. 9). While truly "pristine" reefs may not have existed for a very long time (Pauly 1995; Jackson 1997; Pandolfi et al. 2005), the past three decades have witnessed fundamental changes that have been far greater than anything documented over just the previous century (Wilkinson 2008; Jackson et al. 2014). Providing effective strategies for documenting and mitigating recent decline (Chap. 12) will require an approach that embraces a variety of disciplines that can transform scientific understanding into social will and political implementation. This volume will hopefully provide a starting point for reconnecting the different perspectives from which we view reef development.

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D.K. Hubbard et al. (eds.), *Coral Reefs at the Crossroads*,
Coral Reefs of the World 6, DOI 10.1007/978-94-017-7567-0_1

The persistence of this critical natural system may depend on our ability to tie together seemingly disparate views. In any event, this will certainly make our individual understanding richer.... and a lot more fun.

1.1 Coming Together

The proceedings of the first International Coral Reef Symposium in 1969 contained only 22 scientific papers. However, they covered 11 broad topics ranging from reef distribution and ecology to the geology of uplifted islands, research methods, and even the history of reef science – while spanning nine separate ocean regions. The number of papers from the second meeting increased fivefold and the topics were broadly distributed among biology, geology, chemistry, physical oceanography and management across an even wider geographic range. Presentations included some of our earliest discussions of coral biogeochemistry (Smith 1974), reef controls by sea-level rise (Hopeley 1974) and reef accretion in both the Atlantic (Land 1974) and the Pacific (Tracey and Ladd 1974).

Just as important was the consistent intersection of disciplines focusing on a single theme – coral reefs. The idea in the earlier meetings was to encourage the movement of participants freely and often from one topic or session to another. Their most unique element was that participants were drawn by a single interest in reefs and not the discipline that they occupied for the other 360 or so days of the year. More so than many that followed, the earlier ICRS meetings reminded us that we could learn more in a diverse group asking what we don't know than with close colleagues discussing what we think we do.

Our perceptions of coral reefs vary both spatially and temporally. Biologists can observe and manipulate complex processes in ways that are impossible for geologists to reproduce. However, these are generally limited to small areas and short intervals of time. Geologists have traditionally relied on biological models to understand the past, but are increasingly using their longer perspective to provide a view of reefs absent the stresses of climate change and other manifestations of human proliferation. Chemists can look at both minute and broad scales, providing what would be otherwise overlooked processes. Modelers can take seemingly disparate observations and combine them into simulations that can test existing ideas and generate new ones begging for field data. More recently, monitoring and management have increasingly relied on information generated from scientific studies to make wise decisions while, at the same time, asking questions that science has not yet realized are "important".

As we ponder the recent and dramatic changes on coral reefs, it is difficult to quantify factors beyond the scale of a single experiment or an individual researcher's career. Conversely, geologists consider broad expanses of time and space, but too often forget that this larger view is the cumulative result of small and short-lived events. The collective record was probably controlled more by these day-to-day factors than we acknowledge, and millennial scale processes alone cannot explain the time-averaged fossil record. Chemistry, physics, oceanography and a host of other related disciplines likewise contribute to the overall picture but, like biology and geology, each has its own unique perspectives, priorities and limitations. And, as short as the biological time-scale might seem to geologists, the election cycle of politicians and policy-makers can render coral reefs as little more than distractions. However, when all the perspectives of too-often disparate groups are combined effectively, they can provide insight that is impossible within any single discipline. This realization was at the core of the early reef symposia where much time was spent just talking about "how reefs work". This volume hopes to rekindle interests in viewing common problems from different perspectives.... together.

1.2 Our Changing View

On the morning of May 5th, 1961, Alan Shepard left Cape Canaveral on America's first manned flight into space, a journey that would last only 15 min and 22 s. Four minutes after launch, he deployed his periscope (windows were not added until two flights later) and reported, " What a beautiful view.... I can see Okeechobee.... identify Andros Island.... identify the reefs" (Hammack et al. 1961). Within a minute, he fired the first of three retro-rockets that would bring him back to the surface just 500 km from where he began.

Shepard's view from *Freedom 7* (Fig. 1.1) represents our earliest remote observation of Earth from space[1].... and what he saw were the reefs along Great Bahama Bank. Since then, we have seen photos of Earth from the moon ... and even farther as Voyager 1 departed the solar system in August of 2012. As a result, we have become accustomed to the spectacular images generated by manned spacecraft and orbiting satellites (e.g., Fig. 1.2). Students who have easy access to images on "Google Earth" and "Google Maps" on their cell phones take these for granted, failing to appreciate the limited perspective from low-flying aircraft in the latter twentieth century, just as we failed to appreciate challenges on the deck of the Beagle and other nineteenth

[1] Three weeks earlier (April 12, 1961), Yuri Gagarin had completed a single orbit around Earth. However, the small viewing port beneath his feet was configured to view Earth only for a final alignment during re-entry.

Fig. 1.1 Photograph taken by the automated camera system of *Freedom 7* on Alan Shepard's first US space flight in 1961 (Courtesy of NASA)

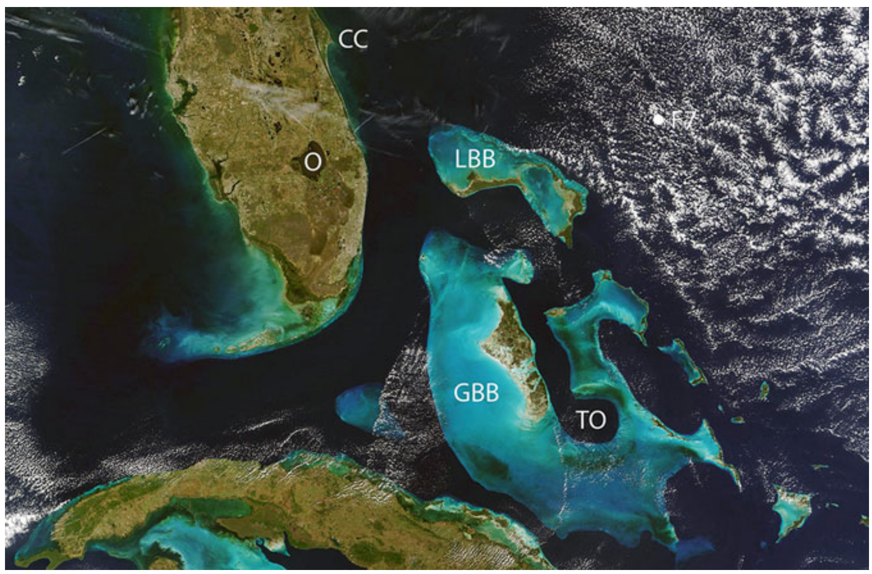

Fig. 1.2 NASA image of Florida and the northern Bahamas. The flight of *Freedom 7* lasted less than 16 min and covered only 500 km from Cape Canaveral (*CC*) to the "splashdown" site (F7) northeast of Little Bahama Bank (LBB). *O* Lake Okeechobee, *GBB* Great Bahama Bank, *TO* Tongue of the Ocean (Courtesy of NASA)

century sailing vessels. We have access to terabytes, petabytes, or even zettabytes of data and increasingly rely on satellite images, huge banks of remotely collected data and complex computer models of natural systems to conceptualize processes operating at scales ranging from microscopic to global.

However, this ever-broadening view has been accompanied by a narrowing of our individual focus. At the time of Darwin, natural philosophy blurred the boundaries between biology, geology, chemistry, physics and even the humanities. His seminal ideas on the role of subsidence in the evolution of Pacific reefs from narrow fringes along volcanic slopes to atolls were born not from the lofty perspective of orbiting satellites. Rather, they were the logical explanation for patterns revealed in early maps and the logs of observant seamen. According to Darwin, the solution was so obvious that "the whole theory was thought out on the west coast of S. America before I had seen a true coral reef".[2]

Today, the evolving scientific landscape has increasingly "organized" us into rigid disciplines or even sub-disciplines. Meaningful discussions still occur, but the goal is more often to seek validation or clarification of specific concepts than it is to question what we might be missing by staying in a familiar intellectual space. Even scientists working on large vessels that are funded by multi-disciplinary programs too often have separate research agendas and work on deck at

[2] Barlow N (1958) The autobiography of Charles Darwin 1809-1882, with the original omissions restored: http://darwinonline.org.uk/content/frameset?itemID=F1497&viewtype=text&pageseq=1, page 98.

different hours to maximize costly ship time. It is more common for different research groups to focus on their own piece of the larger puzzle than it is to look for questions that can only grow out of interactions within a broader group. There are exceptions, but they are too few.

Past attempts to bring different perspectives together in a single volume have still tended to focus largely on one discipline, perhaps adding a thoughtful contribution from another for context. For example, treatments of reefs through time have tended to use a description of modern reefs as a backdrop against which a primarily historical discussion of deep time can be set. Conversely, a volume might start with a broad-brush treatment of reef controls or evolutionary changes in reefs over time to introduce the largely biological themes that follow. Even the seminal *Biology and Geology of Coral Reefs* was organized in four volumes that tended to treat the two disciplines separately.

The goal in the following pages is to focus on a few broader themes, using contributions by different authors to highlight alternative ways of thinking about each. Obviously, this cannot be exhaustive either within or between topics. The main strategy is to group contributions that address a few important areas from different perspectives. Our hope is that readers drawn to chapters written by experts in their discipline will also examine related chapters that consider the same topic from a different viewpoint.... and that this will inspire them to look elsewhere in the volume and in the annals of reef studies with a new eye.

1.3 A Brief Look Back

In the nineteenth century, naturalists struggled to understand both the structure of coral reefs and the distribution of organisms that inhabited them. Much of the early understanding of coral zonation came from sounding leads and dredging. However, even with the crude methods available at the time, the depth limits for most modern corals were surprisingly well constrained to between 20 and 30 m, seemingly at odds with suggestions that reefs appeared to have built from significant depths.

The solution came from geologists in the form of subsidence. Charles Lyell (1832) suggested that atolls might have formed atop the rims of volcanic craters. As they sank, reef building offset subsidence, resulting in accumulations much thicker than the depth range across which corals were known to occur. Charles Darwin (1842) considered the specific tie to crater rims to be "a monstrous hypothesis"[3] and suggested instead that reefs evolved from fringes along the flanks of subsiding volcanic cones to barrier reefs and atolls as the central landmass sank beneath the waves. Darwin's (1842) answer for "the coral reef problem" spurred a heated debate that would last for over half a century.

Mojsisovic (1879) similarly argued that the well-developed coral reefs preserved in the Dolomites were the result of major tectonic uplift rather than a biblical deluge or any other upward excursion of sea level. His argument benefitted from the general acceptance of uplift as an important geologic process. However, the evidence for Darwin's subsidence hypothesis lay beneath the water, making his ideas just as problematic for empiricists like Alexander Aggasiz as they had been for biblical literalists like his father, Louis. The debate continued for over half a century until cores on Funifuti (Royal Society of London 1904) and Bikini Atolls (Emery et al. 1954; Tracey and Ladd 1974) revealed their volcanic ancestry.

The link between tectonic forces and carbonate island building remained the "important" question of the day... so much so that William Morris Davis (1928) characterized an overnight stay on the reef off Cairns as, "entirely fruitless as far as the origin of the reef is concerned".[4] But, the "age of reef ecology" would soon come. A host of marine biological labs can trace their roots back to at least the nineteenth century, but anything akin to modern coral-reef ecology had to wait for the development of the demand regulator (aka scuba) in 1943. This opened an era of intense exploration that allowed us to closely observe, measure and photograph marine systems. In the early 1950s, Tom Goreau visited Discovery Bay where he would eventually create a small marine lab in 1965. For decades, it grew and attracted scientists from different disciplines who repeatedly demonstrated the value of interdisciplinary study focusing on a specific natural system – the coral reef. Another notable Caribbean example was the West Indies Laboratory in the U.S. Virgin Islands, the brainchild of H. G. Multer and Fairleigh Dickinson Jr. Many marine scientists, some of them contributors to this volume, benefitted from the thoughtful discussions among mentors and peers brought together at these two facilities. Marine labs and field stations have come and gone, but the latter part of the twentieth century marked what was arguably an unparalleled growth of interdisciplinary, field-based, coral-reef studies, much of this owing to such places.

[3] Letter to Caroline S. Darwin dated 29 April, 1936: http://www.darwinproject.ac.uk/entry-301#mark-301.f2

[4] See the discussion of W.M. Davis' support of Darwin's subsidence theory by Hopley (1982).

1.4 Where Are We Now?

Until the 1980s, researchers spent most of their time documenting and explaining complex interactions among reef organisms and the edifice where they lived. The explosion of predators like *Acanthaster* on the Great Barrier Reef and the rapid decline of coral cover on Atlantic and Caribbean reefs suddenly expanded the "mundane" and underappreciated activity of coral-reef monitoring. The focus was more on decline than it was on function, and arguments over the relative importance of top-down (mostly overfishing) versus bottom-up stresses (e.g., nutrients) reflected a perception that impacts were to be found on this side of the horizon.

Arguments over methodology were often as heated as those over the dominant causes of decline and the solutions that might reverse it. What level of decline do we want to detect? Do we measure using fixed quadrats, rigid linear transects or irregular ones that take into account the spatial complexity of the reef surface? Direct measurement of coral abundance was the standard but required long and expensive hours spent underwater. Photographs and video were more efficient in the field but too often could not resolve small organisms, especially in hidden cryptic spaces. As field costs soared and image resolution improved, the scales gradually tipped toward photographic or video surveys. While we might think of this as a unique evolution of methods in response to new and specific needs, we should consider that the earliest practitioners had already had this discussion. While neither of the cameras in Fig. 1.3 enjoyed widespread use, the principles inherent to both underwater documentation and monitoring owe their origins to these and other early attempts.

Most recently, rising temperatures and changing ocean chemistry have broadened the discussion. The inadequacy of any single discipline to fully understand these and other problems we face should come as no surprise. Chemists and biologists have combined forces to address possible impacts of ocean acidification. Detailed genetic studies have revised our taxonomy and have provided unique ways to track evolutionary patterns of reef organisms and pathogens that threaten them. Remote sensing has evolved a complex alert system for bleaching and disease. Huge databases provide valuable repositories for information that can be combined to address critical problems, some never envisioned by their creators. And modeling can combine this information with new field and laboratory data to better constrain the controls of observed patterns and address future scenarios that we are yet to experience. Nevertheless, problems are growing faster than resources to study them and we need to figure out how to better triage the growing list of impacted species and systems. The answer is arguably the greater rigor and power of questions and protocols generated by groups of diverse investigators with related interests.

1.5 Where Are We Headed?

Wendell Berey (1987) reminded us that, "in order to understand what we are doing, we need to understand what nature would be doing if we were doing nothing." Observations and

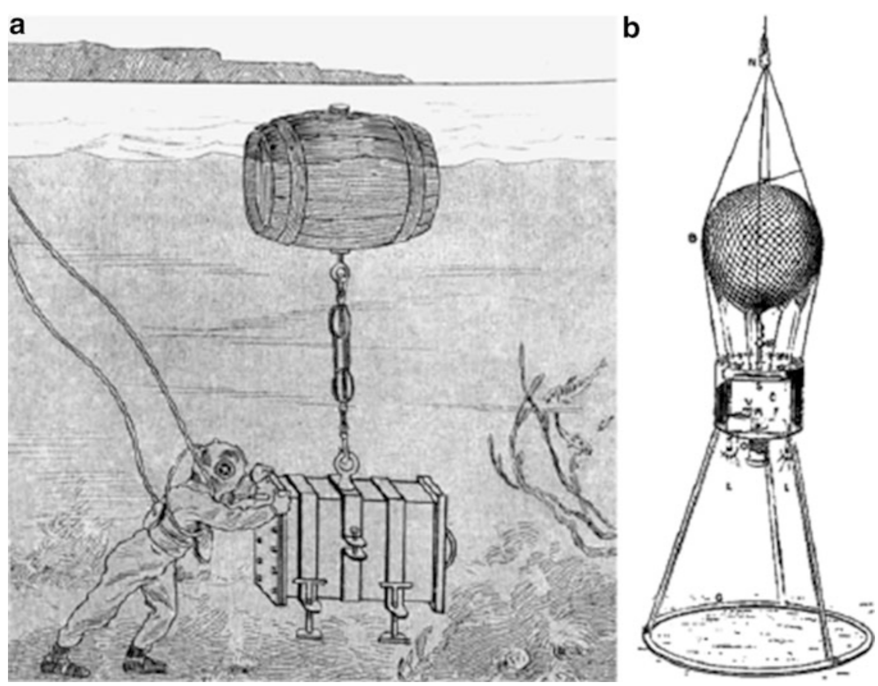

Fig. 1.3 Early underwater cameras. (**a**) Underwater camera system designed by Louis Boutan in the late nineteenth century for recording general underwater scenes. Low light levels and the insensitivity of early photographic plates required exposure times of up to 30 min (From Boutan 1900, p. 198). (**b**) Proposed camera for photographing the seabed. This apparatus, conceived by Regnard (1891, p. 72), was never put into practical use

measurements on modern reefs provide important information that allows us to better understand the nature and the magnitude of recent change. However, they have often been short-lived and all of them record changes that occurred long after the first human stresses were applied. Historical records predate our most ambitious monitoring efforts, the lifetime of a scientist, and especially the attention span of the political body. However, they still fail to accurately record the accumulated stresses that were already contributing to environmental instability – even if their impacts remained hidden until recently. The geological past provides an opportunity to more-realistically consider reefs when "we were doing nothing", but the record is both intermittent and incomplete due to selective preservation and time averaging. However insightful any approach might be by itself, when combined with others, it can help us with the triage we are currently undertaking – whether we are looking to the past, trying to predict the future, or just want to understand how a reef works.

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