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Excerpt
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Geomorphology and the Great Barrier Reef

1.1 Introduction

The Great Barrier Reef (GBR) is the largest coral reef system in the world. It extends from 24° 30′ S in the south to 9° 30′ S in the north, a distance of about 2300 km along the north-east shelf of Australia (Fig. 1.1). Accurate estimates of dimensions and other geographical data are available only for the Great Barrier Reef Marine Park (345 500 km^2) or the Great Barrier Reef World Heritage Area (348 000 km^2) which also includes islands excluded from the Park. Within this area are 2900 reefs occupying over 20 000 km^2 or 9% of the 224 000 km^2 shelf area (Hopley *et al.*, 1989). However, this administrative area does not include the contiguous shelf of Torres Strait, data for which are more scant. The Strait is 150 km wide and east of the line of high islands, which link Australia to Papua New Guinea, the shelf has a width of over 200 km. Estimated total shelf area here is about 37 000 km^2 and, relying on comparative data from the adjacent Great Barrier Reef Marine Park (which ends at 10° 42′ S) there may be a further 750 reefs and shoals with a total area of about 6000 km^2.

The GBR is also one of the best studied in the world. Although first described during James Cook's voyage of exploration in 1770, because of science's preoccupation with atolls, it did not become a major focus until after the establishment of the Great Barrier Reef Committee in 1922 and the ground-breaking year-long Royal Society Expedition to Low Isles near Cairns in 1928–29 (see below and Bowen and Bowen, 2002). Hopley (1982) summarized the geomorphological knowledge of the Reef as it stood at about 1980. Since then the amount of research has increased exponentially and this book is written with the intention of synthesizing this recent work to produce a new holistic picture of the evolution of the GBR.

There is much that can be learnt from the GBR which is also applicable to other reef systems of the world. Its size, extent, and variety of morphology

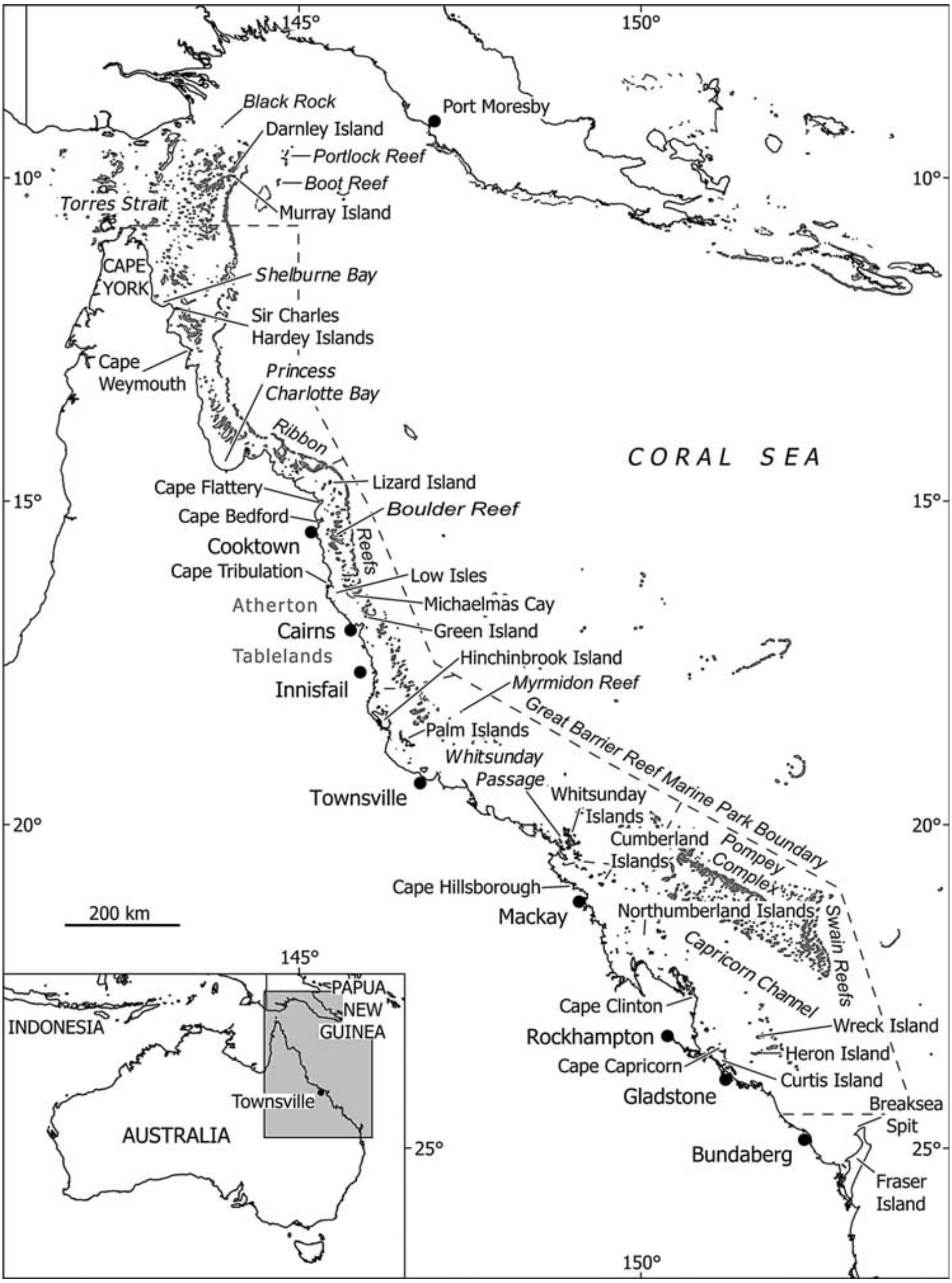

Figure 1.1 The Great Barrier Reef and major locations mentioned in Chapters 1 and 2.

together with its location close to the center of marine biodiversity (Briggs, 1992, 1999; Wallace, 2002) give it a range of reef morphology that cannot be matched elsewhere. It may not contain atolls but almost every other form of reef is found here. This reflects the latitudinal extent of 15° but even more important are the cross-shelf gradients with distances from mainland coastline to the edge of the continental shelf of up to 300 km (Hopley, 1989a). Thus, whilst the experience of Australia's largest reef may be most applicable to other shelf barriers such as those found in Papua New Guinea, Indonesia, Madagascar, New Caledonia, and Belize, it shares features with most reef systems elsewhere in the world.

With increasing global concern for coral reefs (Wilkinson, 2004), the GBR has importance from two other aspects. First, because of its size, distance offshore, and the absence of a subsistence economy dependent on reef resources living on its adjacent shoreline, there remain many parts of the Reef that may be regarded as pristine and against which other reefs may be compared. This condition has been aided by a large part of the Reef being under the management of the Great Barrier Reef Marine Park Authority (GBRMPA) for almost 30 years. In 2004 the area under complete no-take protection was increased from 4.5% to 33.3%. However, not every part of the GBR is unaffected by anthropogenic activities. The effects of mainland runoff are of major concern especially from the high-rainfall (>3000 mm) region south of Cairns where the GBR comes within 30 km of the coastline. Shipping movements, commercial fishing activities, and a marine tourism industry worth over A$2 billion annually also have impacts on the Reef and large areas of the Reef have been affected by coral bleaching especially in 1997–98 which was the hottest year on record. Thus strategies to tackle these problems including those associated with global warming may also be shared with most other coral reefs.

1.2 The role of geomorphology in the understanding of coral reefs

Coral reefs attract a wide range of disciplines as they are built and destroyed by living organisms, are subjected to many physical and chemical processes, and produce landforms which on a geoscientific scale are rapidly changing. Most of these disciplines have contributed to over 25 years of careful biophysical monitoring of the GBR and this has helped to identify natural variability in reef systems and in the environmental parameters affecting them (Done, 1992a). Disturbances have been identified as playing a major role in shaping the community structure of coral reefs but the synergistic effects of natural and new anthropogenic stresses on reef systems are considered as pushing reefs into disturbance regimes from which they cannot recover, a situation termed "turn-off" by Buddemeier and Hopley (1988).

To ecologists identifying decline in reef communities during the period of their monitoring programs, reefs have been interpreted as "fragile" ecosystems. In contrast, geologists, observing reefs surviving and evolving within ever-changing environments, perceived reefs as "robust." The debate polarized the two disciplines in the 1990s (e.g. Davies, 1988; Done, 1991, 1992b; Grigg, 1992, 1994a, b; Kinzie and Buddemeier, 1996). However, Done (1992b) also recognized that the paradox was largely a matter of scale and, quoting Buddemeier and Hopley (1988), pointed out "the importance of understanding ecological change over annual-to-decadal time scales in bridging the gap between geological and ecological perspectives" (Done, 1992b, p. 655). More recently, Grigg (2002) revisited the debate and concluded that both sides were correct, "depending on the scale of inquiry in space and time."

Whilst there is no demarcation line between areas of knowledge, there is clearly a space between ecology and geology which from the point of view of coral reefs may be filled by geomorphology which provides the continuum between the other two disciplines. An analogy may be made with atmospheric study. Ecology represents the day-to-day weather, monitoring of which can put together annual seasonal cycles. Geomorphology represents climate based on records which, for coral reefs, may go back beyond the period of instrumental monitoring. Widening the analogy, observations of tropical cyclones can provide sufficient data to provide risk assessment but the record may be far less than 100 years long. Geomorphological interpretation of storm deposits in beach ridges may allow a longer-term assessment (e.g., Chappell *et al.*, 1983; Nott, 2006) which can give greater confidence to the instrumental record. The climatic analogue may be extended further by relating geological investigation to major climatic changes in the past.

Spatially, geomorphology also bridges the gap. At one end of the scale, the study may be of single coral colonies, for example interpreting small-scale sea level changes from undulations in the surface of a microatoll (Smithers and Woodroffe, 2000). At the largest scale, it may provide global-scale comparisons, as for example for the effects of different relative sea level histories in the Holocene on reef development (Hopley, 1982, ch. 13). At and beyond this scale, geomorphology merges into geology.

In Australia and elsewhere, geomorphology has developed as part of geography, the essential spatial discipline. Spatial analysis is thus a fundamental part of geomorphology though more recently with the development of computer-based geographical information systems (GIS), other disciplines have encroached upon this area of study. The integrity of geomorphology, however, depends on other elements including study of both modern-day processes and historic evolution. When other non-related disciplines attempt what is essentially geoscientific research the results may be seriously misleading. For example, Pastorok and Bilyard (1985) published a table which estimated the degree of impact of sediment on coral reefs, with levels of more than 50 mg cm^{-2} d^{-1}considered as being severe to catastrophic. Their figures were widely quoted and suggestions made that they should be used as controls for assessing impacts on GBR waters. However, when the first measurements of sedimentation rates in inshore areas of the Reef were made (Mapstone *et al.*, 1989; Hopley *et al.*, 1990) sedimentation rates more than twice those quoted by Pastorok and Bilyard were found to be everyday occurrences. The cause of this misinterpretation was a lack of appreciation of the local adaptability of corals and even more so the geomorphological processes in the areas in which they obtained their data. These included the largely limestone islands of Barbados and Guam which have little surface runoff and thus naturally low sedimentation rates to which the local corals are adapted. The relationship between reefs and sedimentation rates is discussed in Chapter 13. As Risk (1992) noted: "a 'monitoring' program that does not include sedimentologists (geomorphologists?), chemists and oceanographers as well as biologists is in danger of being useless; without an integrated approach, biological monitoring is a sterile exercise incapable of identifying causes. Ecology is not, and should not be, the sole preserve of biologists."

A further example which indicates the degree of specialization that geomorphology brings to reef research is the impact of greenhouse induced sea level rise on coral reef islands. Without an understanding of the processes involved in island formation and erosion far too many commentators, including some scientists, merely raised the waterline against the atolls and cays, predicting that many may disappear altogether in the not-too-distant future (e.g., Falk and Brownlow, 1989; Wells and Edwards, 1989). However, where geomorphologists have taken into account the changes in sediment production on adjacent reef flats and more efficient delivery to the islands, results were very different with the possibility of some islands actually expanding (e.g., McLean, 1989; Parnell, 1989; Hopley, 1993, 1997a; Kench and Cowell, 2002). Other environmental changes may make the atolls uninhabitable but it is misleading to suggest that this ecological niche will not survive. This theme is also taken up in Chapter 13. Geomorphology can make important contributions to other environmental disciplines. It is also an essential ingredient to many management decisions.

1.3 A chronicle of geomorphology and reef research

Geomorphological observations of coral reefs are almost as old as the first modern scientific studies which accompanied the voyages of the early European explorers into tropical waters. The major objective of the early scientists or "naturalists" as they were then called was to observe and make collections of the botanical and zoological species that were so new to European eyes. However, they could not avoid seeing and commenting on the proliferation of coral reefs in the areas which they surveyed, especially in the Pacific Ocean. Thus, without the benefit of any underwater observation, many of the first accounts of coral reefs were of their shape, extent, and distribution, essential components of modern geomorphology, defined by Bloom (1978) as "the systematic description and analysis of landscapes and the processes that change them."

It was from the geomorphological observations of naturalists such as Banks, von Chamisso, Quoy, and Gaimard and of navigators such as Cook, Freycinet, and Beechey that the first great coral reef "problem" was identified (for greater discussion see Hopley, 1982, ch. 1; Bowen and Bowen, 2002). Extensive *geomorphological* data on the apparent simplicity and recurring pattern of the Pacific Ocean atolls was drawn together by Charles Lyell (1797–1875) in the second volume of his *Principles of Geology* (1832) which devoted the entire final chapter to a summary of all that was known of coral reefs, giving strong support to the idea that atolls had grown on the rims of submerged volcanic craters. The theory was further exemplified by Charles Darwin (1838) who highlighted the apparently anomalous thickness of reefs in relation to the depth at which reef-building organisms seemed to flourish (about 100 m). He reasoned that three main types of reef which had been identified by the early explorers and subsequently by scientific voyages such as that of the *Beagle* – fringing, barrier, and atoll – were genetically related and controlled by slow subsidence.

This geomorphological "problem" was to dominate coral reef research for the next 100 years with alternative hypotheses involving antecedent platforms cut by waves, rising depositional banks and sea level change postulated (for discussion see Hopley, 1982; Woodroffe, 2002a). Only deep drilling of an atoll could resolve the problem and in 1896–98 the Royal Society organized the Funafuti Coral Reef Boring Expedition under the leadership of T. Edgeworth David of Sydney University in Australia. Although extending down to 340 m with the upper 194 m in coral limestone, overlying dolomite, this drilling did not conclusively answer the questions regarding the origin of coral reefs as the lower section was interpreted by some as fore reef talus. Only the deep drilling associated with nuclear weapon testing on Bikini, Enewetak, and Mururoa atolls in the 1950s and later finally resolved the problem. Over 1000 m of shallow-water reef limestone was recovered, overlying basaltic (volcanic) foundations. Numerous unconformities marking periods of subaerial exposure also pointed to the major part played by sea level fluctuations in the evolution of modern reef morphology.

Whilst the concept of geomorphology was well established during the nineteenth century it was only during the first part of the twentieth century that it developed as a clearly defined and identified discipline. In the intervening period the evolving geomorphologist was a physiographer, physical geographer, or physical geologist, terms that endured until the mid twentieth century. W. M. Davis, regarded as the father of geomorphology, developed not a geomorphological cycle of landscape evolution but a geographical cycle (Davis, 1899). When Alfred Steers (the first British coastal geomorphologist) and his colleague Michael Spender mounted a geomorphological expedition to the GBR in 1928–29 as a companion program to the Royal Society's larger program on Low Isles (see, for example, Bowen and Bowen, 2002), it and its successor in 1936 were termed "Geographical Expeditions." Even later, one of the first holistic geomorphological texts was called *Principles of Physical Geology* (Holmes, 1944). Not surprisingly, the part played by geomorphology in the scientific study of the GBR has been obscure, to the extent that in a recent review of the history of science on the Reef (Bowen and Bowen, 2002) geomorphology does not rate a mention. At least in part it is the aim of this work to indicate that not only does geomorphology have a pivotal role to play in the modern understanding of coral reefs and the GBR in particular, but there is a lineage that can be traced back to the early voyages of exploration.

1.4 The history of geomorphological study of the Great Barrier Reef to 1982

1.4.1 The nineteenth century

The GBR contains no atolls and for this reason did not play a major role in the nineteenth-century debates on coral reefs. The *Beagle* sailed around the southern shores of Australia and Darwin never had the opportunity to view the GBR. His 1842 book makes only a brief mention of it with Darwin claiming that it supported the concept of subsidence. More than 70 years later in 1914 W. M. Davis, the leading physical geographer of the time, spent two weeks sailing up the Queensland coast but his interest in the detailed morphology of the Reef was very limited. Through some observation of coastal landforms but largely by deductive argument Davis tried to show that the Queensland coast and adjoining GBR had evolved through repeated patterns of continental uplift and shelf subsidence (Davis, 1917, 1928). He spent only one night actually on the Reef, at Green Island near Cairns which he found "was an entertaining experience but as might have been expected, entirely fruitless as far as the origin of the reef is concerned" (Davis, 1928, p. 347).

Until there was some concept of the magnitude and diversity of the coral reefs of the region, large-scale geomorphological interpretation remained speculative. Navigation through many parts of the Reef was limited and even as late as 1960 the best navigational charts showed huge tracts of reef completely blank and still with acknowledgements to the surveys of Flinders, King, Blackwood, Stanley, Yule, and Denham undertaken between 1802 and 1860. Holistic appreciation of the GBR came only when a complete aerial survey combined with the first satellite imagery became available in the 1960s and 1970s.

Nonetheless, from the mid nineteenth century onwards most researchers tried to link their field observations to one or other aspects of the "coral reef problem." Some (e.g., Jukes, 1847; MacGillivray, 1852; Rattray, 1869; Penck, 1896; Davis, 1917, 1928) including the early members of the Great Barrier Reef Committee (see below) supported Darwinian-style subsidence. Others such as Agassiz (1898), Gardiner (1898), and Andrews (1902) fitted their observations into various antecedent platform hypotheses (for fuller discussion, see Hopley, 1982, ch. 1). Finally, in the twentieth century Daly's (1915) glacial control theory involving sea level change affected observations and interpretations of workers such as Marshall *et al.* (1925) and Steers (1929, 1937).

However, retrospectively the greatest value of much of this early work relates to observation and description of individual features and conclusions relating to the more recent evolution of the GBR. It was these observations that were to be the focus of significant research in the second half of the twentieth century when radiocarbon dating provided a timescale for interpretation. Jukes (1847) for example was one of the first to note features along the Queensland coast which he attributed to "apparently recent elevation of the land." Scientific staff of other survey vessels did little to advance the ideas of Darwin, whom they supported, but they did describe many new features of the islands and mainland such as shingle ridges and cemented deposits.

One of the most observant of the early workers was the Harvard zoologist Alexander Agassiz (1898). In 1896, on a specially chartered vessel he spent two months on a reconnaissance survey of the GBR as far north as Lizard Island (14° 40′ S). His hypotheses on the origin of the Reef as a thin veneer over a wave-cut platform may be seen as extreme, and some of his interpretations such as storm-deposited reef blocks being the last remnants of a much higher reef are now completely untenable. However, his descriptions of many islands and the shapes of reefs, reef flat zonation (including the distribution of soft corals), and beach rock and conglomerate are highly accurate. He was the first to note the terrigenous sediment just behind the outer reef and Breaksea Spit as a northward encroachment of siliceous sand limiting the southern extent of the GBR.

1.4.2 The first part of the twentieth century, 1900–50

Building upon the work largely carried out on surveying voyages of the nineteenth century, the next boost for GBR geomorphological research came from the first deep drilling on a coral reef planned to endorse Darwin's subsidence, carried out not on the GBR, but on Funafuti Atoll. The drilling accomplished there between 1896 and 1898 was organized by the Royal Society but was led by Professor T. Edgeworth David of Sydney University and had other Australian interests. A tradition of coral reef research was established at Sydney University. E. C. Andrews, a student of David and a member of the Funafuti Expedition, formed a wide interest in coral reefs summarized most succinctly in his presidential address to the Royal Society of New South Wales many years later (Andrews, 1922). Charles Hedley was also a member of the Funafuti Expedition and in 1922 became the first Scientific Director of the Great Barrier Reef Committee.

As the GBR is located in Queensland, further impetus to geoscientific research was given with the appointment of H. C. Richards to the Foundation Chair of Geology and Mineralogy at Queensland University in 1919. In 1922 Richards presented an address to the Queensland branch of the Royal Geographical Society of Australasia on "The problems of the Great Barrier Reef" (Richards, 1922). Subsequently, the Governor of Queensland, Sir Matthew Nathan, supported an appeal to a wide array of scientific societies and educational institutions to nominate representatives on a Great Barrier Reef Committee of the Society. The Committee was set up in 1922 with members from 34 institutions. The initial chairman was Nathan, but Richards took over shortly afterwards, with Charles Hedley appointed Scientific Director. Hedley traveled widely along the Queensland coast using the steamer which serviced the lighthouses. Also, three Sydney University graduates were given scholarships to work on specific projects. Results of all this work, much of which was geomorphological in nature, were published in 1925 as the first volume of the *Transactions of the Royal Geographical Society (Queensland)*. However, shortly afterwards there was a major rift between the Committee and its parent Society. Bizarrely, the Great Barrier Reef Committee became a separate body without a parent institution.

However, the Committee did provide the stimulus for research and publication on the GBR, including the first drilling on Michaelmas Cay near Cairns to 183 m in 1926, one of the last projects of Charles Hedley. Eleven years later a second hole was sunk to 223 m on Heron Island at the southern end of the Reef. Both were intended to clarify the subsidence controversy and did provide valuable information on the development of the GBR.

Figure 1.2 Low Isles, a low wooded island near Cairns and site of the 1928–29 Royal Society Expedition.

Most importantly the Committee held talks with the British Association for the Advancement of Science the result of which was an expedition funded by the Commonwealth Government, the Great Barrier Reef Committee, and the Royal Society. The base was Low Isles (Fig. 1.2) near Cairns, with 23 scientists led by C. M. Yonge spending a year on the island between 1924 and 1929. The expedition is well covered by Bowen and Bowen (2002) except for the geomorphological work. Most of this was carried out by Alfred Steers from Cambridge University, the first true geomorphologist to spend time on the Reef (Fig. 1.3). He was accompanied by Michael Spender and E. C. Marchant, the party working for six weeks with the main expedition on Low Isles. As well as producing the first detailed map of a low wooded island the group also explored other parts of the GBR, mainly the islands, highlighting the usefulness of the islands in deciphering much of the recent geomorphological history of the Reef. Far from being the fiasco claimed by Bowen and Bowen (2002) the Steers-led expedition was the stimulus for much subsequent work, leading to the establishment of a strong continuing interest in coral reefs in the Geography Department of Cambridge University (as stated by Steers in talks with one of the authors (D. H.) in Townsville in 1967).

Publications of this purely geomorphological work and a second expedition to the GBR in 1936 refocused geoscientific research away from armchair-based