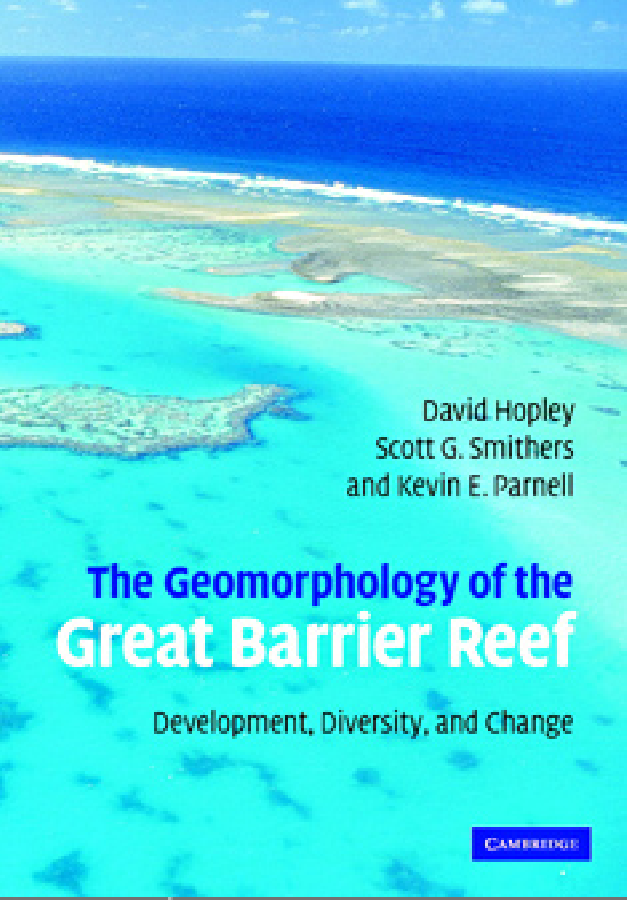

David Hopley
Scott G. Smithers
and Kevin E. Parnell

The Geomorphology of the Great Barrier Reef

Development, Diversity, and Change

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THE GEOMORPHOLOGY OF THE GREAT BARRIER REEF

Over the last 25 years considerable information on the geomorphological evolution of the world's largest coral reef system, the Great Barrier Reef, has become available. This book reviews the history of geomorphological studies of the Great Barrier Reef and assesses the influences of sea-level change and oceanographic processes on the development of reefs over the last 10 000 years. It presents analyses of recently attained data from the Great Barrier Reef and reconstructions of the sequence of events that have led to its current geomorphology. The authors emphasize the importance of the geomorphological time span and its relevance for present management applications. This is a valuable reference for academic researchers in geomorphology and oceanography, and will also appeal to graduate students in related fields.

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Development, Diversity, and Change

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Preface

In the preface to *The Geomorphology of the Great Barrier Reef: Quaternary Development of Coral Reefs* published by one of the present authors in 1982, the opportunity for a synthesis of ideas on the geomorphology of coral reefs was identified. Almost 25 years later and with a wealth of new research and publications, there is again the need for a holistic view of the evolution of the present geomorphological features of the world's largest coral reef system, which it is hoped this book will provide. However, it is very different from the 1982 publication which attempted to fill a wide area of coral reef science, using the Great Barrier Reef as an example. This volume is much more focused on the Great Barrier Reef (GBR) region and the way its features have evolved especially during the Holocene period of the last 10 000 years.

Much of the data for this period has come from programs of drilling into the reef to depths up to 25 m during the 1980s and 1990s, some of it for specific engineering or non-geomorphological purposes. By far the largest programs, however, were those headed by Professor Peter Davies (now Sydney University) of what was then the Bureau of Mineral Resources, Canberra, and one of the present authors (D. H.) and his postgraduate students. These and other drilling programs have created a data bank which could only be imagined in 1982 but it is not the only area in which the geosciences have added to the understanding of the development and processes which sustain the Reef. Studies of sedimentation patterns, hydrodynamics, and other geomorphological processes are integral areas of coastal geomorphology but over the last ten years in particular on the GBR such studies have often been undertaken by non-geoscientists. Whilst the quality of the data collected is unquestionable its use and interpretation has sometimes suffered from a lack of understanding of geomorphological processes, a theme that is taken up in the latter part of this book.

The geomorphological timescale is also a feature of the present work. In the past 15 years there has often been a division between geologists who see reefs as robust systems, surviving major climate and sea-level change over millions of years, and ecologists with a contrary view, monitoring the decline in reef systems over the last 50 years or more and interpreting them as fragile. The timescales used by each discipline are critical to the contradictory interpretations both of which are correct within their own dimensions. The boundary between the two is not sharp and is covered by the period considered basic to geomorphological understanding. Even since sea level reached its present position 6500 years ago, the GBR has changed enormously. It will be shown that maximum growth rates and maximum number of habitats occurred in early to mid-Holocene times. According to parameters by which ecologists may evaluate the health of a reef system, the GBR is already in a state of natural decline without any consideration of human impact. This needs to be acknowledged by management agencies that may only recognize the dynamic nature of the reef system at an ecological scale, for example, the importance of natural disturbances in creating biological diversity. However, these disturbances are superficial and changes, for example, to reef morphology and natural sediment build-up are measured at the geomorphological timescale and this provides the background trend upon which ecological periodicity is superimposed.

Thus the usefulness of geomorphology for reef management provides the theme for the final chapter in this book, drawing on the information provided earlier. The book moves from long- and short-term processes (sea-level change and oceanography) through an analysis of the GBR on a basic spatial division (inter-reefal areas, fringing reefs, mid-shelf reefs, outer shelf reefs, and reef islands). The final chapters provide a more holistic view of the data, describing the processes and rates of GBR evolution during the Holocene, and the way in which the Reef has changed dramatically over a relatively short period of 10 000 years, changes that were witnessed by the original Australians.

An enormous amount of new information has become available over the last 25 years and we have attempted the task of summarizing this and incorporating it into our ideas of how the GBR has evolved. Even as the manuscript was being written it was clear that the data flow is if anything increasing and it is our conclusion that, as in other disciplines, compilations that build on the foundations laid by earlier workers but incorporating the new data will be needed more frequently than the approximately 25 years since the publication of *The Geomorphology of the Great Barrier Reef* in 1982. Geomorphology is essential for the understanding of coral reefs and it is through compilations like this that professional geomorphologists can communicate their thoughts, ideas, and data to other disciplines.

Please note that SI units are used throughout this work except where taken from other works. Abbreviations include time units: millions of years (Ma) and thousands of years (ka). Many radiocarbon dates and other radiometric dates are as recorded in the quoted literature. Unpublished dates from the present authors are all reported as conventional radiocarbon years, without environmental correction.

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A number of individuals and organizations have provided photographs or have given permission to use diagrams, and these are acknowledged with the appropriate figures. Many of the figures produced for this book incorporate data which is © Commonwealth of Australia (Geoscience Australia) 2001–2004, and/or data provided courtesy of the Great Barrier Reef Marine Park Authority. The assistance of Paul Tudman of the Great Barrier Reef Marine Park Authority in accessing spatial data is gratefully acknowledged. We have endeavored to acknowledge the source of all diagrams used in the book that are not our own. We apologize for any inadvertent omissions.

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David Hopley
Scott G. Smithers
Kevin E. Parnell

1

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

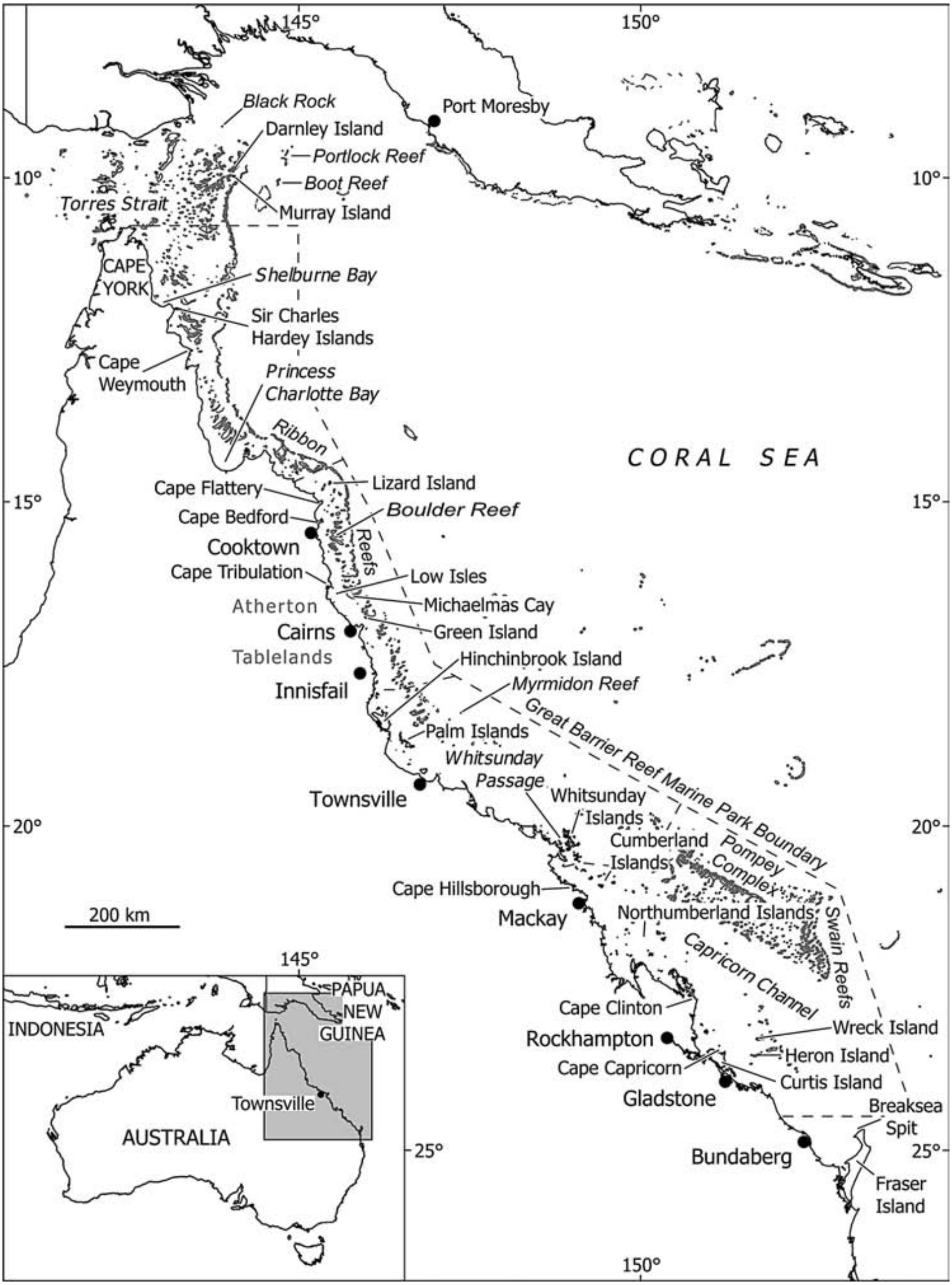

Figure 1.1 The Great Barrier Reef and major locations mentioned in Chapters 1 and 2.

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 $\mathrm{mg\,cm^{-2}\,d^{-1}}$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

Figure 1.3 Alfred Steers (left) a member of the 1928–29 Royal Society Expedition talking to David Stoddart (back to camera), leader of the 1973 Expedition and Richard Orme (second from left) a member of the Expedition and other participants of the 1973 Second International Coral Reef Symposium, during a field trip on the shingle ramparts of Low Isles during the 1973 Symposium.

hypotheses and towards field-based studies (Steers, 1929, 1937, 1938; Spender, 1930), as outlined by Hopley (1982, ch. 1). The carefully surveyed maps of the islands were of such quality as to allow quantitative comparison with surveys carried out in 1973 on the Royal Society–Universities of Queensland Expedition (see below). Whilst the work of the main party on Low Isles in 1928–29 was largely biological they did carry out research which could only be described as geomorphological and which also heralded the new era of careful field measurements. Most prominent was the experiment carried out by Sheina Marshall and A. P. Orr who deployed jars (whose dimensions were carefully given) at five positions on the Low Isles reef flat between December and June, with sediments being collected weekly (Marshall and Orr, 1931). Such an experiment was far beyond its time and was also carried out so carefully that it was possible to replicate it exactly some 63 years later (Johnston, 1996). The results are discussed in Chapter 13.

Of great help to the 1928–29 expedition was vertical aerial photography carried out by the Royal Australian Air Force. This was not the first aerial photography of the Reef as from 1924 there had been experiments using seaplanes to trial aerial survey of areas such as shipping passages (Bowen and Bowen, 2002, p. 303). Alfred Steers recognized the importance of this tool for geomorphological research (Steers, 1945) and during the Second World War further photographs of parts of the GBR and the adjacent coastline were taken. Partly instrumental in this were two geologists, Rhodes W. Fairbridge and Kurt Teichert, who persuaded the Royal Australian Air Force to undertake a project to improve the accuracy of the photo-interpretation of coral reefs (see Fairbridge and Teichert, 1948), Not surprisingly they concentrated on the well-studied Low Isles and produced a comparative analysis of this reef (Fairbridge and Teichert, 1947, 1948; Teichert and Fairbridge, 1950).

Traditional hydrographic survey of coral reefs can give but a generalized outline of these most complex of landforms (as seen on the naval hydrographic charts predating the 1920s). Fairbridge was possibly the first person with a geoscientific background to view the variety of reefs, the planimetric details of which had not been previously seen. Such a view gives new insight into the role of waves and currents in the formation of reefs whilst the appreciation of the range of morphology led for the first time to an evolutionary type of classification of modern reefs (Fairbridge, 1950).

1.4.3 New tools for research, 1950–82

From 1964 onwards the whole of the GBR was systematically photographed by the Australian Commonwealth Government at scales of between 1: 50 000 and 1: 80 000. Geomorphological research on the Reef after the Second World War had been almost non-existent, though with the establishment of a permanent research station by the Great Barrier Reef Committee on Heron Island in 1951 more systematic research at least on the southern end of the Reef had commenced. Most significant was the work of Graham Maxwell of the Geology Department, Sydney University who, with his students, set about mapping the surface sediments of the whole of the Great Barrier Reef Province (e.g., Maxwell *et al.*, 1961, 1964). He was therefore in an excellent position in the mid 1960s to combine his wide field knowledge with the new perspectives of almost the entire Reef from the aerial photography. The result was his magnificent *Atlas* published in 1968 which not only showed the distribution of surface sediments but illustrated the wide variations in reef size and morphology within the context of the latest bathymetric survey and ecological data. Like Fairbridge he envisaged an evolutionary classification of reefs through growth then dissolution, a process he termed "resorbtion." Whilst this scheme is no longer viable (see Hopley, 1982 for discussion) the work was at the forefront of a new wave of geomorphological research. Other geomorphological work of Maxwell remains highly relevant today (e.g., Maxwell, 1970, 1973a).

More or less contemporary with the publication of Maxwell's *Atlas* were a number of important events for further research on the GBR. Satellite imagery was available from 1972 and both the quality of the imagery and the techniques for processing them have improved greatly since then. Radiocarbon dating (and, later, other radiometric dating techniques) was coming into wide use in geomorphological study, providing an absolute chronology for evolutionary and process studies especially in the Holocene. Maxwell was himself one of the first to obtain radiocarbon dates for reefal sediments (Maxwell, 1969). Hopley also obtained many dates from a wide range of features which had been previously described for example by Steers, including emerged corals, cemented deposits, and other depositional materials, first from the high islands of North Queensland (e.g., Hopley, 1968, 1971) and later from the outer reefs (e.g., Hopley, 1977). A higher mid-Holocene relative sea level for the inner shelf of North Queensland was established from these studies.

Seismic reflection survey of inter-reefal areas was also being introduced into the GBR in 1973 (Orme *et al.*, 1978a, b) and shortly afterwards seismic refraction techniques allowed some insight into the internal structure of the reefs themselves (Harvey, 1977a, b; Harvey *et al.*, 1979). Also providing information on internal structure was a new wave of reef drilling, initially on the 1973 Royal Society–Universities of Queensland Expedition (see below) using land-based drills (Thom *et al.*, 1978), but shortly afterwards using hand-operated drills (Hopley, 1977) and more adaptable hydraulic rigs which could be deployed in a variety of positions on the reefs (Davies *et al.*, 1979) (Fig. 1.4).

All these tools were important in testing what was at the time a resurrected idea for the explanation of complex reef morphology. In 1974 E. G. Purdy published a paper which suggested that large- and small-scale reef forms were inherited from karst relief formed by subaerial weathering of earlier reefs during periods of glacially lowered sea level (Purdy, 1974). The idea was not entirely new having first been suggested by Japanese workers Yabe (1942), Asano (1942), and Tayama (1952) and exemplified by MacNeil (1954). Drilling into mid-Pacific atolls such as Enewetak, Bikini, Midway, and Mururoa in association with atomic weapon testing in the 20 years after the Second World War had

Figure 1.4 The James Cook University hydraulic drilling rig on Gable Reef typical of the equipment used during the 1970s onwards to obtain cores through the reef to about 30 m.

not only confirmed subsidence of mid-oceanic atolls but had also identified "solution unconformities" (Schlanger, 1963), buried surfaces which had been subjected to subaerial erosion. Reefs were shown to have a "layer cake" structure consisting of units approximately 20 m in thickness laid down over the previously exposed reef during high sea level periods. The last of the layers has been added during the Holocene. Purdy (1974) focused attention on the depth and relief of the unconformities especially that separating Holocene and Pleistocene reef. In Australia, Davies (1974) reinterpreted the core from the 1934 Heron Island drilling and established a depth of 20 m for the unconformity.

In 1973 after several years of planning with input from both Sir Maurice Yonge and Alfred Steers of the 1928–29 Royal Society Expedition, a second expedition led by David Stoddart of Cambridge University was mounted to research the northern GBR (Fig. 1.3). This Royal Society–Universities of Queensland Expedition had available the new tools of radiometric dating, drilling, and seismic survey and although much of the Expedition's work was focused on the reef islands, members were aware of both Purdy's and Davies' yet to be published work. Determination of the depth to Pleistocene below both reefs and inter-reefal areas was an important part of the work carried out. Results of the Expedition were published as both a monograph and in two volumes of the *Philosophical Transactions of the Royal Society* (Series A, vol. 291, pp. 1–194 and Series B, vol. 284, pp. 1–162).

1.4.4 The modern era, post-1982

At the end of the 1970s new innovative tools were opening up a whole new range of geomorphological research directions on the GBR, and first results from this work were starting to accumulate. Thus it seemed to one of the current authors an appropriate time for a review of coral reef processes and specifically to the formation of the GBR (Hopley, 1982). That monograph was much more comprehensive in its coverage than the current work as few monographs devoted entirely to coral reefs in general were available, and it was attempting to fill a perceived gap in the literature. Subsequently there have been many volumes devoted to many aspects of coral reefs including ecology (e.g., Dubinsky, 1990), geology (e.g., Birkeland, 1997; Wood, 1999), biogeography (Veron, 1995), and taxonomy (Veron, 2000), but, with the exception of the small book devoted mainly to the description and classification of coral reefs by Guilcher (1988), review of geomorphological work has been limited to single chapters in less specialized texts (e.g., Nunn, 1994; Woodroffe, 2002a).

On the GBR the amount of research has increased exponentially over the last 25 years. Probably the best known is the biological and ecological work which has been widely published but the increase of knowledge has expanded in all fields. For example in 1982 almost all of what was known about the oceanography of the GBR was contained in one 135-page monograph (Pickard *et al.*, 1977). In the last ten years three complete texts on oceanography have been published (Wolanski, 1994, 2001; Furnas, 2003). The increasing interest in coral reefs worldwide is illustrated by the attendance and the number of papers presented at the congresses of the International Society for Reef Studies held every four years (Salvat, 2002). In 1985 in Tahiti there were fewer than 600 participants presenting 424 papers. At the last two, in Bali (2000) and Okinawa (2004), numbers of both participants and papers exceeded 1500.

Perhaps not surprisingly, the geoscientific research carried out over this same period has been somewhat buried in the avalanche of biological, ecological, and management studies. Nonetheless, within this field too, there has been a similar increase in knowledge in evolutionary and process studies.

They include:

- increasing knowledge of the physiography and bathymetry of the GBR
- extensive data banks from shallow (~25 m) drilling and radiocarbon dating of cores from all areas of the reef (Fig. 1.4)
- an Ocean Drilling Program (ODP Leg 133) carried out just off the GBR in 1990
- drilling through the full extent of the northern GBR in 1995

- new paleoenvironmental analysis from coral cores
- measurement of processes operating on the Reef including rates of coral and reef growth, sediment movement, and rates of sedimentation.

These and many more studies carried out since 1982 form the foundation for the present work.

1.5 Outline of the following chapters

The organization of coasts into a series of overlapping temporal and spatial scales has been superbly exemplified by Woodroffe (2002a, ch. 1). This synthesis of recent work on the GBR is approached in a similar manner to explain how the present morphology has evolved. The basic premise is that most modern reefs, possibly excluding many fringing reefs, have grown over older Pleistocene reefal foundations which were drowned during the latter part of the Holocene transgression. How these Pleistocene reefs evolved and the earliest foundation of the GBR within the geological setting of north-east Australia is the subject of Chapter 2. Once it was established, the major large-scale influence on the evolution of the reef has been the oscillation of sea level within amplitudes of 100 m or more associated with the Pleistocene glaciation. Chapter 3 analyses the sea level history as it has affected the GBR, especially over the last 10 000 years. At the present time the major short-term driving forces are those associated with climate, oceanography, and water quality (Chapter 4).

Spatial patterns determine the organization of the next six chapters. Chapter 5 is an overall survey of GBR geography and geomorphology providing an analysis of the basic dimensions of the Reef. Chapter 6 is an introduction to the continental shelf of north-east Australia, describing the sediments and features of the inter-reefal areas. The next three chapters provide a cross-shelf analysis of the reefs: fringing and inner shelf reefs (Chapter 7), mid-shelf reefs (Chapter 8), and outer shelf reefs (Chapter 9). However, each has its own particular theme. Fringing reefs are examined in terms of the surface and deposits on which they have been built and their far from continuous growth history in the Holocene. Mid-shelf reefs are related to the evolutionary classification of Hopley (1982) and, with the information now available on rates of calcification and reef growth, tentative time-lines for evolution from one reef type to another are given. In Chapter 9, the regional differences in the reefs of the outer shelf are described and explained in terms of shelf edge morphology and possible tectonics.

Capping, and therefore younger than all these reefs, including the fringing reefs, are more than 400 reef islands (300 within the Marine Park, plus over 100 in Torres Strait). Chapter 10 goes beyond a simple classification to examine details of evolution and dynamics.

The final chapters provide a more holistic analysis of the data. Chapter 11 provides an overview of the data from all the reefs, especially from the shallow drilling programs, and provides some insight on rates of geomorphological processes through the Holocene. It also makes comparisons between the GBR and other reefs of the world. In Chapter 12 the rapidly changing paleogeography of the GBR region during the postglacial transgression is described, summarizing the evolutionary themes of earlier chapters.

The last chapter returns to the essence of geomorphology and its usefulness within the GBR to management and conservation processes. This is achieved through five themes: reefs and sedimentation, reefs and eutrophication, geomorphological input into conservation issues, reef islands, and finally global climate change and coral reefs. Given the speed with which new knowledge on the geomorphology of the GBR has accumulated over the last 20 years and as is illustrated by the following chapters, it is concluded that a synthesis of the data may be required more frequently than the 25-year interval since the last major review, Hopley (1982).

2

Foundations of the Great Barrier Reef

2.1 Introduction

For much of its length even the innermost reefs of the Great Barrier Reef (GBR) are beyond sight of the mainland. The main reef tract occupies the outer 30% to 50% of the shallow (<60 m) waters of the continental shelf which varies from about 250 km in width in the south central GBR to less than 40 km near Cape Weymouth. Whilst fringing reefs occur around many continental islands, some of which are located up to 70 km from the mainland shore, reefs attached to the mainland are rare, especially south of Cairns. Nonetheless, no study of the evolution of the GBR could ignore the geology and geomorphology of the adjacent mainland of north-east Australia. The continental shelf upon which it rests has formed from terrigenous sediments eroded from the Eastern Highlands (Symonds *et al.*, 1983), and as Lloyd (1977) noted, the geology of the shelf is closely related to the onshore geology of Queensland. For a large part of their history the GBR foundations have been part of the mainland as, during major glaciations of the Quaternary, sea level dropped to expose the shelf edge. Today, the direct influence of the mainland (including Papua New Guinea) in the form of runoff, sediment, and nutrients may be restricted to the Reef north of 18° S but along the entire coastline south to Fraser Island the sedimentary and geomorphological record of the last 8000 years or so greatly augments our understanding of the final phases in the evolution of the GBR which are the focus of this book. However, the fundamentals of the geological structure and physiological features of north-eastern Australia date back to the start of the Cainozoic about 65 Ma ago. Australia at this time was moving northwards at a rate of about 7 cm a year having separated from Antarctica and the other Gondwana continents 30 Ma earlier (Johnson, 2004). Eastern Australia had already commenced its own period of rifting with the Tasman Sea opening up over a 30 million year period between

84 and 54 Ma ago. The Coral Sea opened up much later, between 58 and 48 Ma ago, with uplift of the continental margins forming the Eastern Highlands and independent subsidence of a number of continental blocks producing the distinctive morphology of the Coral Sea including the Queensland, Marion, and Eastern Plateaux (Fig. 2.1). These events would eventually produce the conditions suitable for building the continental shelf upon which the GBR rests.

2.2 Geological and geomorphological development of the coast

As the Coral Sea opened up, uplift of eastern Queensland produced a drainage divide close to the east coast. Coastal streams cut back rapidly and the major rivers in particular were able to exploit the north-north-west–south-south-east structures of the older Tasman geosyncline and younger structures such as the Triassic Bowen Basin. The proto-Burdekin and Fitzroy Rivers were especially effective and moved the main drainage divide as much as 400 km inland. Working behind the coastal ranges these rivers were able to isolate large areas of westward sloping but eastward draining tablelands. Nearer to the coast the most resistant rocks (mainly granites) of what had been the initial and highest coastal divide remained as the highest peaks in Queensland overlooking a narrow coastal plain (Fig. 2.2). These include Mounts Bartle Frère (1611 m), Bellenden Ker (1593 m), Elliot (1234 m), and Dalrymple (1259 m). These mountains may not be especially high, but given their proximity to the coast and the coincident high annual rainfall totals for these areas (>3000 mm), they have the potential for very high sediment yields to the coastline. The Fitzroy (142 537 km^2) and Burdekin (130 126 km^2) Basins, though draining much drier inland areas, also have potential for high sediment yield into GBR waters (see Chapters 4 and 13).

Contemporaneous with the uplift of eastern Australia were a series of volcanic eruptions the products of which include older, eroded central volcanoes and younger shield volcanoes with long lava flows (Fig. 2.1). Central volcanoes are generally older in the north, believed to be the result of plate movement over a stationary mantle plume (Johnson, 2004). Behind the Queensland coast these range in age from 33 Ma at Cape Hillsborough to 24 Ma in the Glasshouse Mountains. However, even more extensive are the broad shield volcanoes located close to the Main Divide, dating from about 8 Ma to as young as 13 ka years. These include the Atherton Tableland (1800 km^2) behind Cairns where basalt flows between 3.9 and 1.6 Ma ago infilled the longitudinal valley between the coastal ranges and the Main Divide, with some flows extending down to the coast. The McBride (5500 km^2), Chudleigh (2000 km^2), Sturgeon (5200 km^2), and Nulla (7500 km^2) basalt provinces are of similar age with some lava flows

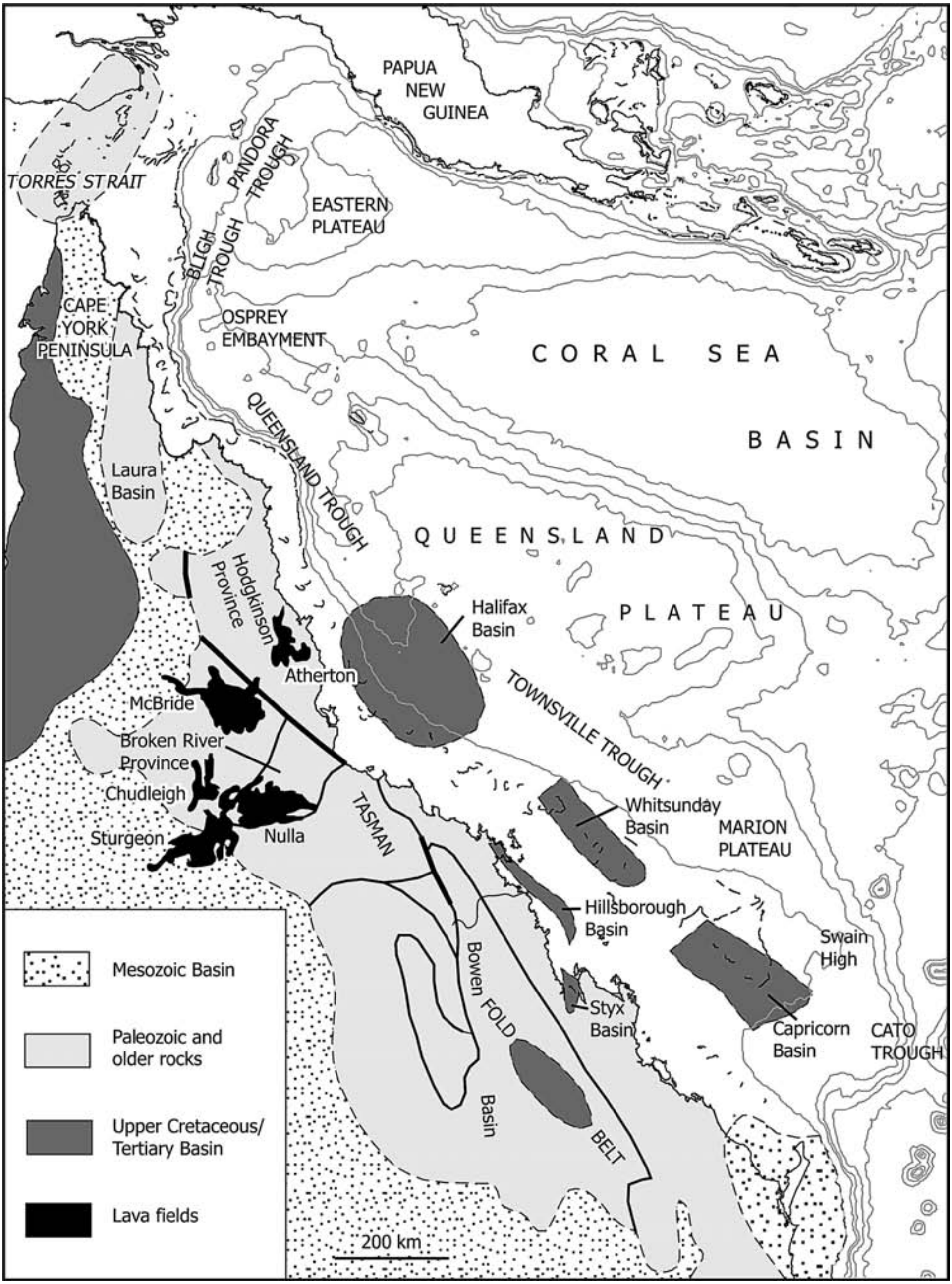

Figure 2.1 Major structural features of north-east Australia and the Coral Sea.

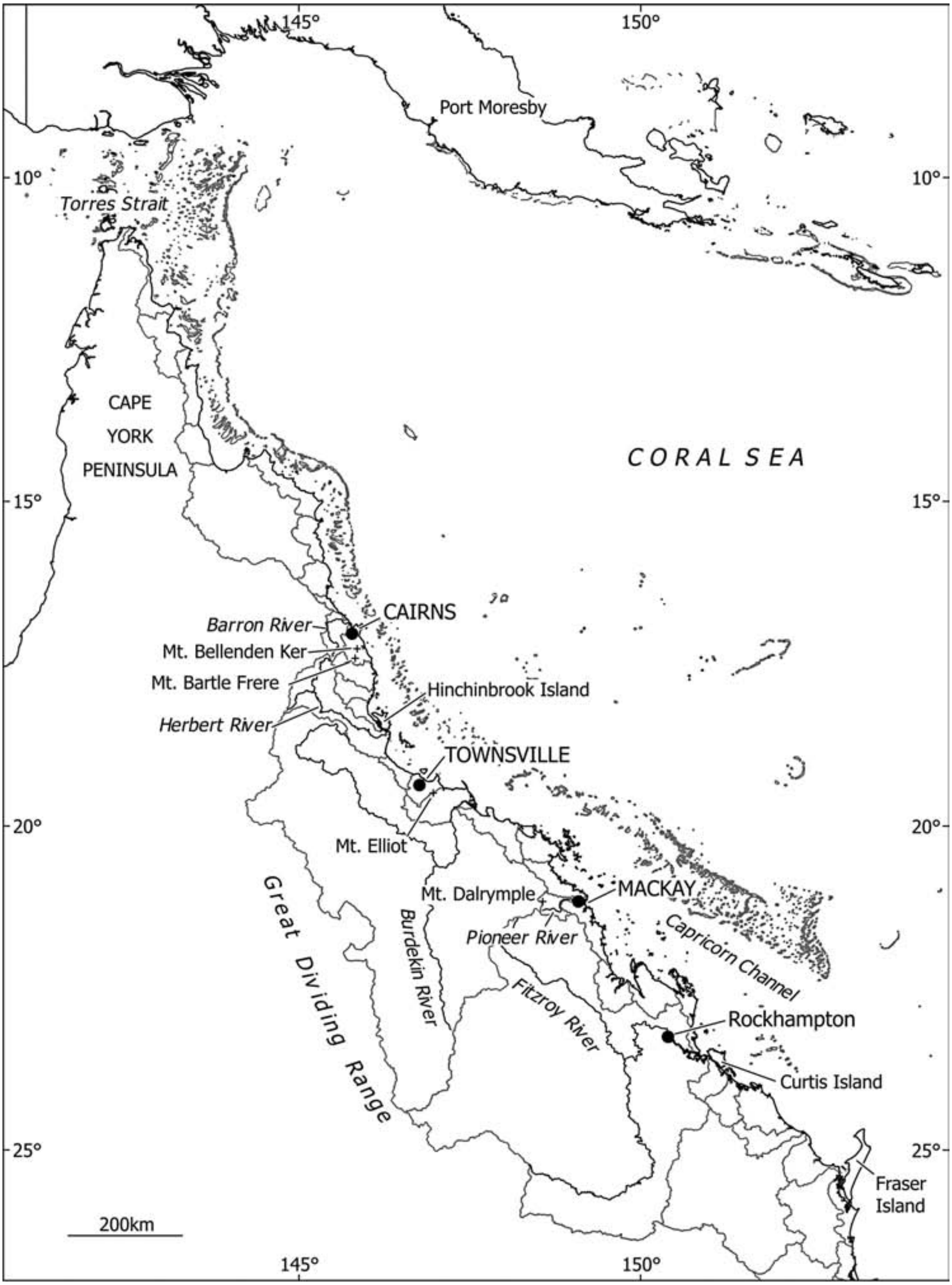

Figure 2.2 River basins and mountain peaks adjacent to the Great Barrier Reef.

Figure 2.3 The crater rim and surrounding coral reef of Waier Island in the Murray Islands, Torres Strait.

extending more than 150 km from their source craters (Stephenson *et al.*, 1980, 1998; Johnson, 2004). Volcanism on a more subdued scale has continued in eastern Queensland until the recent past. Numerous scoria cones remain from eruptions after 200 ka with some believed to be younger than 20 ka. Included in these are the pyroclastic cones and minor basalt flows of the Murray Islands blasted through the early GBR on the outer shelf in the far north (Fig. 2.3). These are almost certainly of Pleistocene age (Stephenson *et al.*, 1980).

Uplift and denudation of the Eastern Highlands over the last 50 million years has provided much of the material which has constructed the continental shelf upon which the GBR is established (Section 2.4). The present Holocene high sea level stand leaves visible only the uppermost section of this depositional province. Descriptions of the coastal plain have been made by Coventry *et al.* (1980) with the greatest detail available for the Townsville coastal plain (Hopley and Murtha, 1975). The sediments are mainly alluvial and colluvial including numerous abandoned river courses now marked by sandy rises crossing the coastal plain which is dominated by weathered clay soils. The unconsolidated deposits overlie bedrock typically by 30–150 m though numerous outcrops occur as coastal hills on the coastal plain, as headlands along the coast, and as islands offshore. Greatest depth of sediments on the coastal plain is associated with the lower reaches of the major streams. The Fitzroy River, for example, has an estuarine infill 3–18 km wide and at least 45 m thick. The deltaic deposits of the Pioneer River at Mackay are up to 30 m thick, the

Herbert River >93 m, and the Barron River at Cairns >40 m. Greatest detail is available for the Burdekin River delta (Hopley, 1970) where deltaic deposits are an average 70 m in thickness and reach a maximum of 150 m at the apex of the delta. As much as 38 m of Holocene sediments overlie a distinct weathered Pleistocene surface recognizable across the delta. The distributaries of the delta are highly dynamic and continue to prograde (e.g., Pringle, 2000). Both landforms and the monitoring of contemporary sediment loads in streams are indicative of large sediment yields to the mainland coastline inside the GBR (e.g., Pringle, 1991; Nott *et al.*, 2001; Thomas *et al.*, 2001), figures which are estimated to have increased by up to 900% since European settlement and land clearing (Great Barrier Reef Marine Park Authority, 2001). Flood plumes which historically may have limited inshore coral reef development are also considered to have proportionally increased their area of impact over the last 150 years extending to fringing reefs of the inshore islands and even mid-shelf reefs following major floods (Devlin *et al.*, 2001). A geomorphological assessment of the impact of increased sediment yield is made in Section 13.2.2.

The mainland coastline (most recently described by Hopley and Smithers, 2003) is mainly depositional, large sediment compartments separated by prominent headlands or by short stretches of hard rock coastline as for example near Cape Clinton (north of Rockhampton), adjacent to the Whitsunday Passage, between Innisfail and Cape Grafton (south of Cairns) and around Cape Tribulation. Fringing reefs are associated with only a few of these rocky coastlines, including Cape Tribulation and Hydeaway Bay south of Bowen (Fig. 2.4).

Figure 2.4 Emerged mid-Holocene fringing reef at Cape Tribulation.

Elsewhere the sediment compartments clearly reflect the south-to-north movement of sediments under the influence of the prevailing south-easterly trade winds. Typically, the coastline is made up of ten or more beach ridges up to 500 m wide but close to major rivers the sequence may widen to over 5 km (Fig. 2.5a). The majority of the ridges are Holocene in age, but a fragmentary Pleistocene series is found in some areas indicating at most only a marginally higher sea level than has been experienced in the Holocene (Section 3.3.1). However, there are large accumulations of dune materials of Pleistocene age in discrete locations along the coast. Dune cappings may raise Holocene beach ridges to a maximum of 10 m height at the exposed northern end of beaches but in a number of locations there are Pleistocene dunes rising to over 30 m height. Opposite the southernmost GBR this may not be surprising as the world's largest (and one of the highest) sand islands, Fraser Island, has dunes up to 240 m high. Formed of sediments swept by longshore drifts from the south, Fraser Island has accumulated over several phases of the Pleistocene and its continuation across the continental shelf as Breaksea Spit is a possible contributor to the termination of the GBR in this location (see Chapter 1).

Elsewhere along the coast the major dune sand masses are also considered to be Pleistocene in age, displaying spectacular colored variations as the result of weathering, and massive parabolic landforms (Fig. 2.5b). They include (from south to north): large dunes near Cape Capricorn on Curtis Island, and south of Cape Clinton; a large white silica sand complex on Whitsunday Island; at the northern end of Hinchinbrook Island where the Pleistocene sequence may extend at least 30 m below modern sea level (Pye, 1982a; Grindrod and Rhodes, 1984); the 700 km^2 silica sand complex of Cape Flattery and Cape Bedford and the 400 km^2 complex near Shelburne Bay in the far north. The dune fields appear to have been derived from high sediment yielding sedimentary or granitic rocks and to have formed at least in part during low sea levels via temporary storages of sand exposed on the continental shelf (Pye, 1982b; Pye and Bowman, 1984).

Within the lee of headlands, in all estuaries, and in channels between islands and the mainland, mangrove swamps predominate (Fig. 2.6). The most extensive system is found in the Hinchinbrook Channel and adjacent Missionary Bay where 31 species have been identified. On the wetter coastlines in favorable locations, mangroves extend right across the tidal flats but in drier areas and especially where the tidal range exceeds 4 m the mangroves are limited to the seaward margin and to drainage channels. Wide hypersaline mud flats dominate the coastline in these areas. They are particularly wide (<25 km) around the delta of the Fitzroy River and behind Princess Charlotte Bay (Chappell and Grindrod, 1984). Isolated chenier ridges may occur at irregular intervals across the flats.

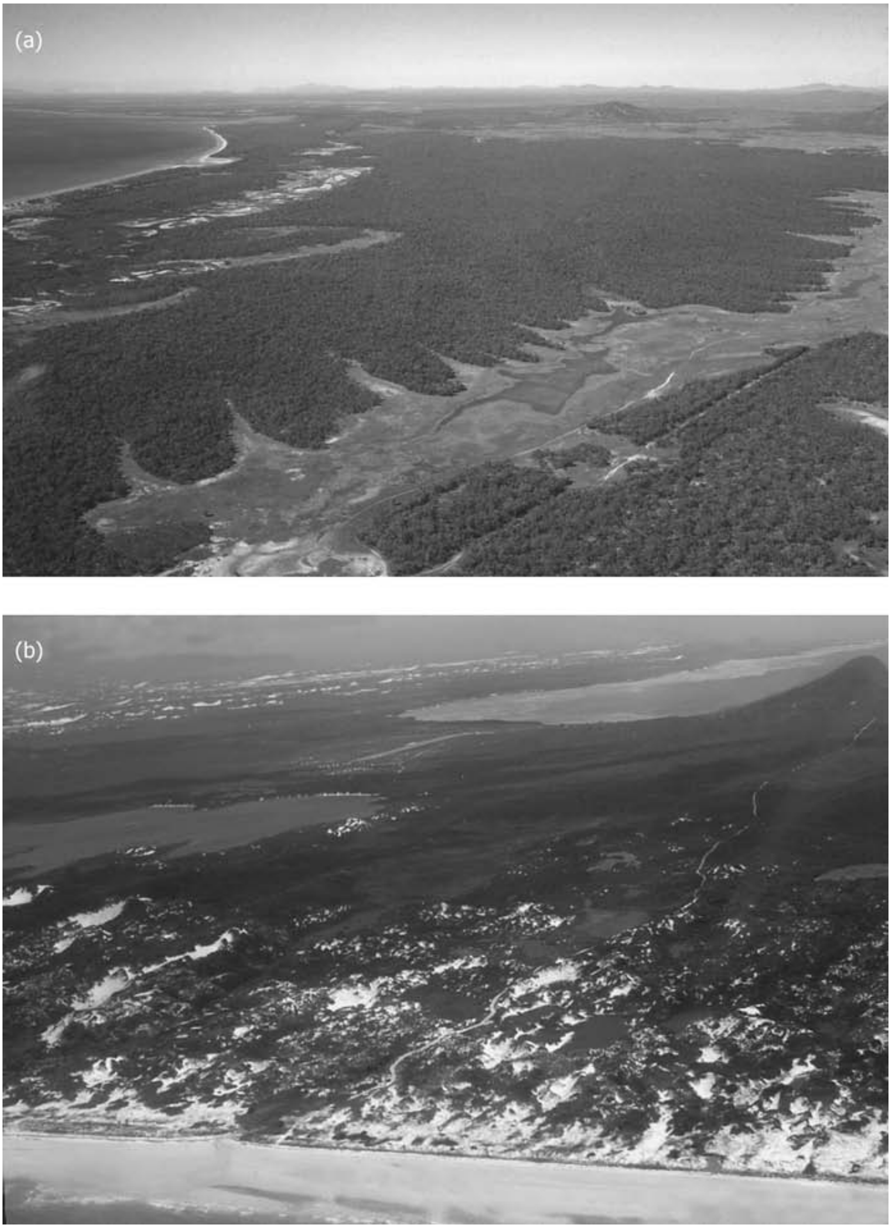

Figure 2.5 Depositional coastlines. (a) Wide beach ridge sequence north of the Burdekin River. Sand originated from offshore sources and brought ashore during the latter part of the transgression. (b) Large dune field south of Cape Flattery.

Figure 2.6 Mangroves at the northern end of Hinchinbrook Channel.

The geology of the mainland is extended seawards in the many islands which occur along the Queensland coastline. Hopley *et al.* (1989) estimated that there were 768 high islands in the Great Barrier Reef Marine Park with some kind of coral reef attached, but there are also others with no reef which were not incorporated into the calculation. There are also the many high islands of Torres Strait, which continue the geological structure and lithology of Cape York Peninsula. A number close to 1000 high islands may be a reasonable estimate for the whole GBR. By far the largest number occur between 20° and 22° S in the Whitsunday, Cumberland, and Northumberland Groups.

Most islands occur on the inner 30% of the continental shelf though as Hopley (1982) noted on the narrower shelf of the northern GBR in particular there may be significant outcrops of continental rocks within some of the mid-shelf reefs including the Sir Charles Hardy and Forbes Islands, Quoin Island, and Howick Island. Lizard and North and South Direction Islands have a similar mid-shelf location surrounded by reefs. In the south, where the shelf is much wider only Tern and Redbill Reefs have small granitic outcrops the probable *raison d'être* for their location in an otherwise reefless area. There is a strong possibility that other reefs have rocky foundations close to the surface. Pandora Reef 70 km north of Townsville and inside the Palm Islands has on its surface a large number of boulders of porphyritic granite similar to the rocks of adjacent islands. They are concentrated in two areas and have suggested (Hopley, 1982, figs. 10.13 and 11.2) that bedrock may be buried at very shallow depth between these two locations. The overall influence of basement rocks within the continental shelf on the GBR and its evolution can only be surmised but is likely to have been significant.

2.3 Evolution of the Coral Sea

The importance of the Coral Sea to the establishment and maintenance of the GBR cannot be overstated. Coral reefs existed here millions of years before the foundations of the GBR were laid and provided a gene pool for the GBR both in its initial establishment and subsequently after each major lowering of sea level when reef growth off the north-eastern Australia mainland was more or less annihilated (Davies *et al.*, 1989; McKenzie and Davies, 1993). Extensive seismic studies of the Coral Sea and especially the Queensland and Marion Plateaux in the 1980s (Davies *et al.*, 1989) have been supplemented with the new stratigraphic data which has come from Holes 811 to 826 drilled on Leg 133 of the Ocean Drilling Program in 1990 (McKenzie *et al.*, 1993). The GBR is but the youngest of a series of carbonate platforms which have existed in the region for more than 25 Ma.

When the Coral Sea had finished opening up about 50 Ma ago, it had produced the Coral Sea Basin >4600 m deep and underlain by oceanic crust, and a series of marginal plateaux underlain by modified continental crust (Davies *et al.*, 1989) (Fig. 2.1). The northernmost of these plateaux, adjacent to the GBR, is the Eastern Plateau, a complex fault-bounded block with an average depth of 1500 m and an area of 31 000 km^2. It is separated from the GBR by the Pandora and Bligh Troughs and separated from the Queensland Plateau to the south by the Osprey Embayment. The Queensland Plateau is one of the largest features of this type in the world, having an area of about 165 000 km^2 (Davies *et al.*, 1989). About half of the area is less than 1000 m deep, with living reefs found along its southern margin. The Queensland Plateau is separated from the GBR by the Queensland and Townsville Troughs. The Marion Plateau, 77 000 km^2, forms a deep-water extension of the Australian continental shelf. It is bounded on the east by the Cato Trough.

Within the Coral Sea it was on the plateaux that reef growth was first developed. However, for the first 25 Ma of their existence, Australia's position was far too far south for reef growth, but as the continent's position moved steadily northwards at about 7 cm yr^{-1} these shallow-water banks were moved from temperate to subtropical and tropical zones (Fig. 2.7). The studies carried out by the Ocean Drilling Program, Leg 133, have determined a complex

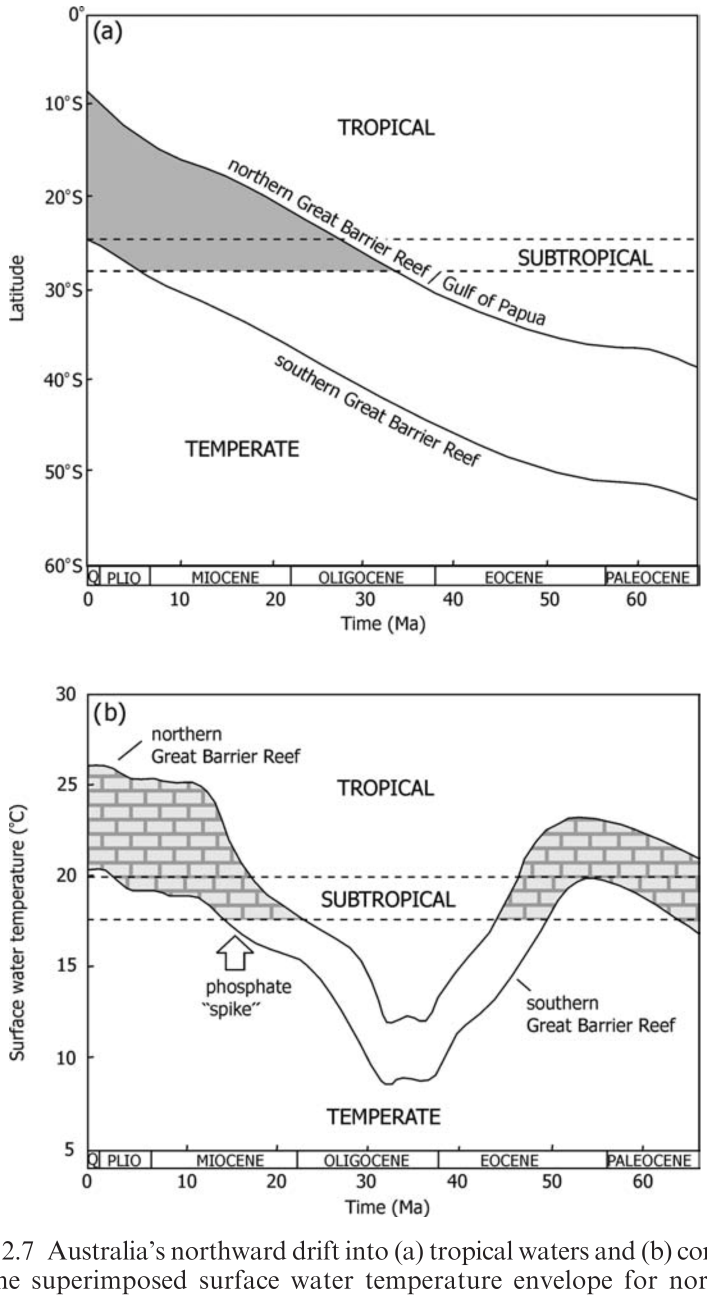

Figure 2.7 Australia's northward drift into (a) tropical waters and (b) combined with the superimposed surface water temperature envelope for north-east Australia and the Miocene "phosphate spike" which may have inhibited reef growth (after Davies, 1988).

subsequent history culminating in the development of the GBR (McKenzie *et al.*, 1993). Concentrating on the Queensland and Marion Plateaux these studies have indicated changing environmental conditions controlled by fluctuations in eustatic sea levels, pulses of subsidence of the plateaux not necessarily simultaneous (Katz and Miller, 1993), and changes in oceanographic conditions large enough to switch on and off the tropical reef systems which occupied the plateaux (Isern *et al.*, 1993).

The northernmost part of Australia first moved into the tropics about 24 Ma ago and bryozoan-rich sediments of temperate zones were replaced by tropical reef systems in suitably shallow waters (Fig. 2.7). However, the change was too rapid to be related to continental drift alone and the onset of tropical oceanographic convergence off north-eastern Australia is considered to have played a major part. Both the Queensland and Marion Plateaux remained within the photic zone (<100 m suitable for coral growth) for a considerable period of time. However, towards the late middle Miocene falls in eustatic sea level became more pronounced culminating in a major low about 10.4 Ma ago. The Marion Plateau, which was stable at this time, became emerged and remained so until about 5 Ma ago. In contrast the Queensland Plateau experienced subsidence about 13.7 Ma ago and was able to maintain carbonate productivity throughout the late middle Miocene.

A second subsidence pulse affected both plateaux between 7 and 6 Ma, drowning previously emerged reefs on the Marion Plateau. However, more or less simultaneously there was a change in oceanographic conditions with cooler waters not allowing reef growth on either platform (Isern *et al.*, 1993). The return of tropical conditions with warming of surface waters did not take place until 3.5 Ma ago (Isern *et al.*, 1993) unfortunately coinciding with the most recent period of subsidence 3–2 Ma ago which more than compensated for eustatic sea level lowering at about the same time. The Queensland Plateau sank beneath the photic zone apart from a few isolated areas, mainly on its southern margin where reefs still exist today (Holmes, Tregrosse, Flinders, Lihou, Willis Reefs, etc.). Whilst the Queensland Plateau became drowned, the previously emergent Marion Plateau did not renew reef growth during the sea level rise of the late Miocene as cool surface waters inhibited reef growth initially and, by late Pliocene/Pleistocene the platform, being attached to the Australian continent, had become the site of significant siliciclastic deposition, preventing coral growth in all but a few areas (e.g., Marion Reef) when surface temperature rose again. Thus before the GBR was even initiated the previously extensive coral reef growth on the Coral Sea plateaux had been very much reduced though still remaining significant for the establishment of the GBR.

2.4 The continental shelf of north-east Australia

Subsequent to the Coral Sea Basin opening up, the continental shelf of north-east Australia commenced its development (Mutter and Karner, 1980; Symonds *et al.*, 1983). The sequence developed by Symonds *et al.* (1983) remains a useful model though related specifically to the central GBR (Fig. 2.8). With some modification to its timing in view of more recent studies, five phases can be recognized:

(1) Post 50 Ma – opening of the Coral Sea Basin 50 Ma ago produced a fractured continental margin which had been the planated Tasman geosyncline. To seawards were the major rift basins which were to form the Pandora, Bligh, Queensland, and Townsville Troughs and, whilst what is now the inner part of the continental shelf remained a stable block beneath the coastal escarpment, the outer shelf was also formed from a series of rift basins which were filled initially with fluvial and colluvial sediment.

(2) 24–15 Ma – the major marine transgression of this time, together with marginal subsidence east of a hinge line identified on the inner shelf (see below) produced a transgressive onlap phase of sedimentation in the form of marginal marine fan deltas, through restricted shallow marine to open marine oozes and turbidites.

(3) 15–5 Ma – this was a period of lower sea levels with a major regression at about 10.4 Ma. It produced a dominantly offlap phase of fluvial and deltaic sedimentation with thin interbedded shallow-water sediments from short periods of high sea level. Sediment supply outstripped any subsidence and major progradation of the shelf took place, by approximately 10 km off Cairns and 40 km off Townsville.

(4) 5–<1 Ma – this phase coincided with the subsidence pulse of 3–2 Ma ago. This was balanced by massive shelf aggradation of more than 200 m formed of low sea level alluvial deposits in conjunction with thin high sea level clastic shallow-water onlapping sediments. Symonds *et al.* (1983) recognized wave and fluvial dominated deltaic deposits near the top of the sequence.

(5) The final reef-building phase – by 2.6 Ma ago the continental shelf was in place in appropriate neritic water depth for reef building (McKenzie and Davies, 1993; Watts *et al.*, 1993). Widespread reef building, however, does not appear to have commenced until after 700 ka for a number of reasons discussed below. Once initiated, the proto-reefs became preferential sites for future growth, especially after each glacial low sea level stand. Symonds *et al.* (1983) suggest that carbonate sediments from the reefs now became incorporated into the progradational facies of the shelf margin and that shelf edge reef growth channeled major low sea level sedimentation onto the slope, changing the style of sedimentation on the slope from mainly progradational to mounded submarine fans. The continental shelf has continued to develop since the first appearance of the GBR.

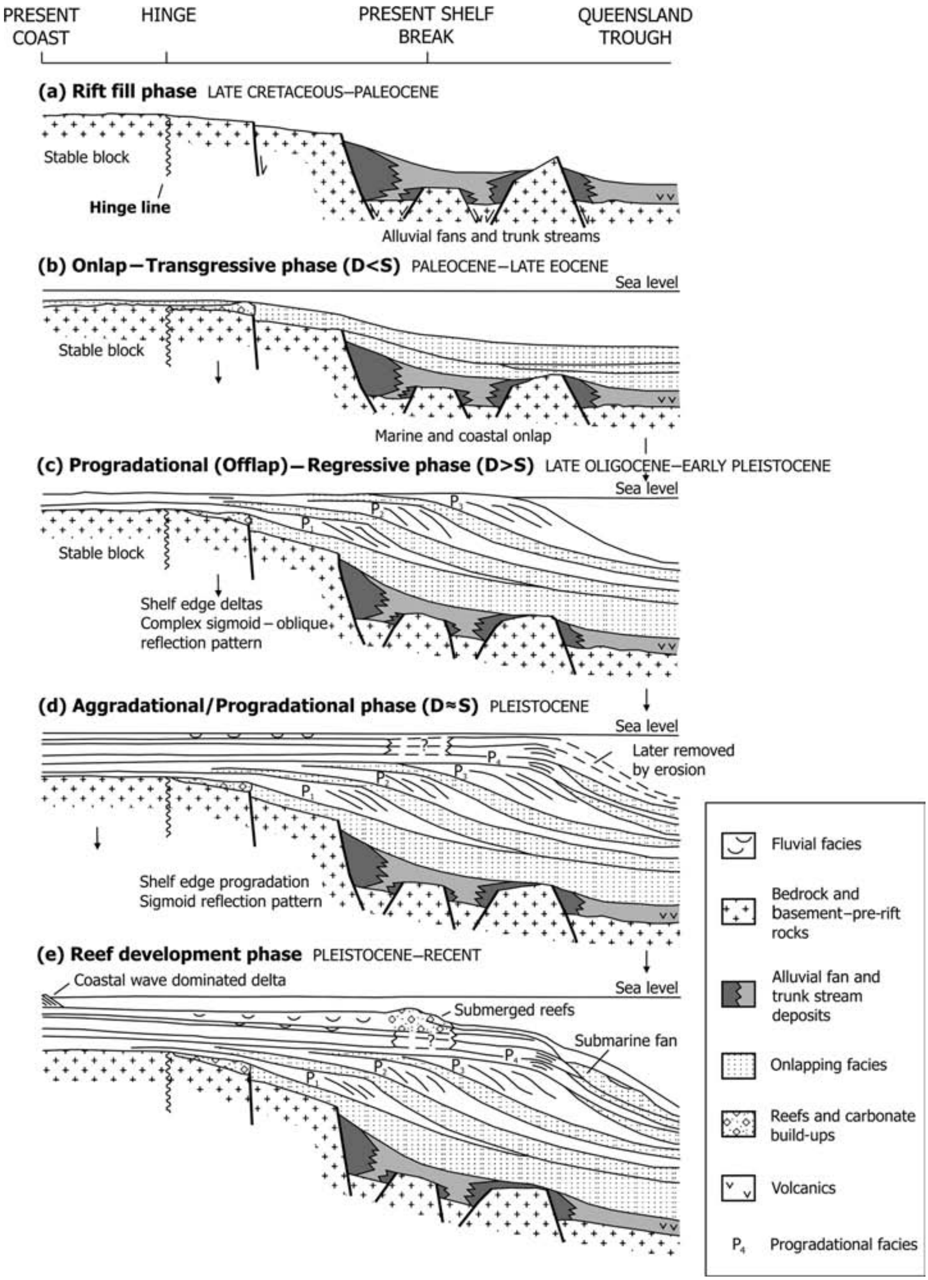

Figure 2.8 Evolution of the continental shelf of the central Great Barrier Reef (from Symonds *et al.*, 1983).

This continued development probably involves further tectonic activity. As noted by Lloyd (1977) the GBR shelf is related to the onshore structural features (Fig. 2.1) some of which may have continued activity well into the Cainozoic. Symonds *et al*. (1983) recognized a middle to inner shelf hinge line between Cairns and Townsville, paralleling the coastline and determining the western boundary of shelf subsidence. The southern extension of the hinge line can be extrapolated to the onshore Millaroo Fault Zone which forms the western boundary of the major Bowen Basin.

Elsewhere the general shape of the coastline can be closely linked to major structural features. Its general alignment is that of the ancient Tasman geosyncline whilst details such as the northern area of Princess Charlotte Bay are defined by older structures. The bay itself is the northern expression of the landward Laura Basin which is defined on its western side by the Palmerville Fault, the extension of which determines the alignment of northern Cape York. The Laura Basin is but one of a series of Tertiary basins (Benbow, 1980) which straddle the coastline or are imposed on the continental shelf including the Hillsborough Basin adjacent to the south central GBR, the Capricorn Basin of the southern GBR, which is defined on its western side by the Bunker Ridge and to the east by the Swain High, and the Halifax Basin impinging on the outermost shelf opposite Townsville (Grimes, 1980; Mutter and Karner, 1980). Volcanism appears to have been associated with the early foundation of several of the basins and subsidence has continued until at least the late Pliocene. Whilst this was prior to the foundation of the GBR, Grimes (1980) believes that some earth movements continued until the Quaternary. The Ocean Drilling Program showed that subsidence pulses on and adjacent to the GBR shelf were taking place until at least the late Pliocene (Katz and Miller, 1993).

Of particular importance is the Halifax Basin which underlies 800 km of the GBR opposite Townsville (Mutter and Karner, 1980, fig. 11). It contains up to 3000 m of mainly terrigenous sediments dating back to the opening up of the Coral Sea in the Cretaceous. However, more recent subsidence as late as the Pleistocene has been suggested (e.g., Benbow, 1980) and later in this work (Chapter 9) a case will be made for even more recent subsidence of the Halifax Basin affecting reef development on the outer shelf of the central GBR.

Whilst the GBR shelf is tectonically stable it does experience some earthquake activity (University of Queensland, 2005). Within the Coral Sea and GBR region locations have included (from north to south): in eastern Torres Strait near the Murray Islands, offshore from Cairns, offshore between Townsville and Mackay, and in the Capricorn Channel and Capricorn–Bunker Group of reefs in the southern GBR (Fig. 2.9). In November 1978 Heron Island

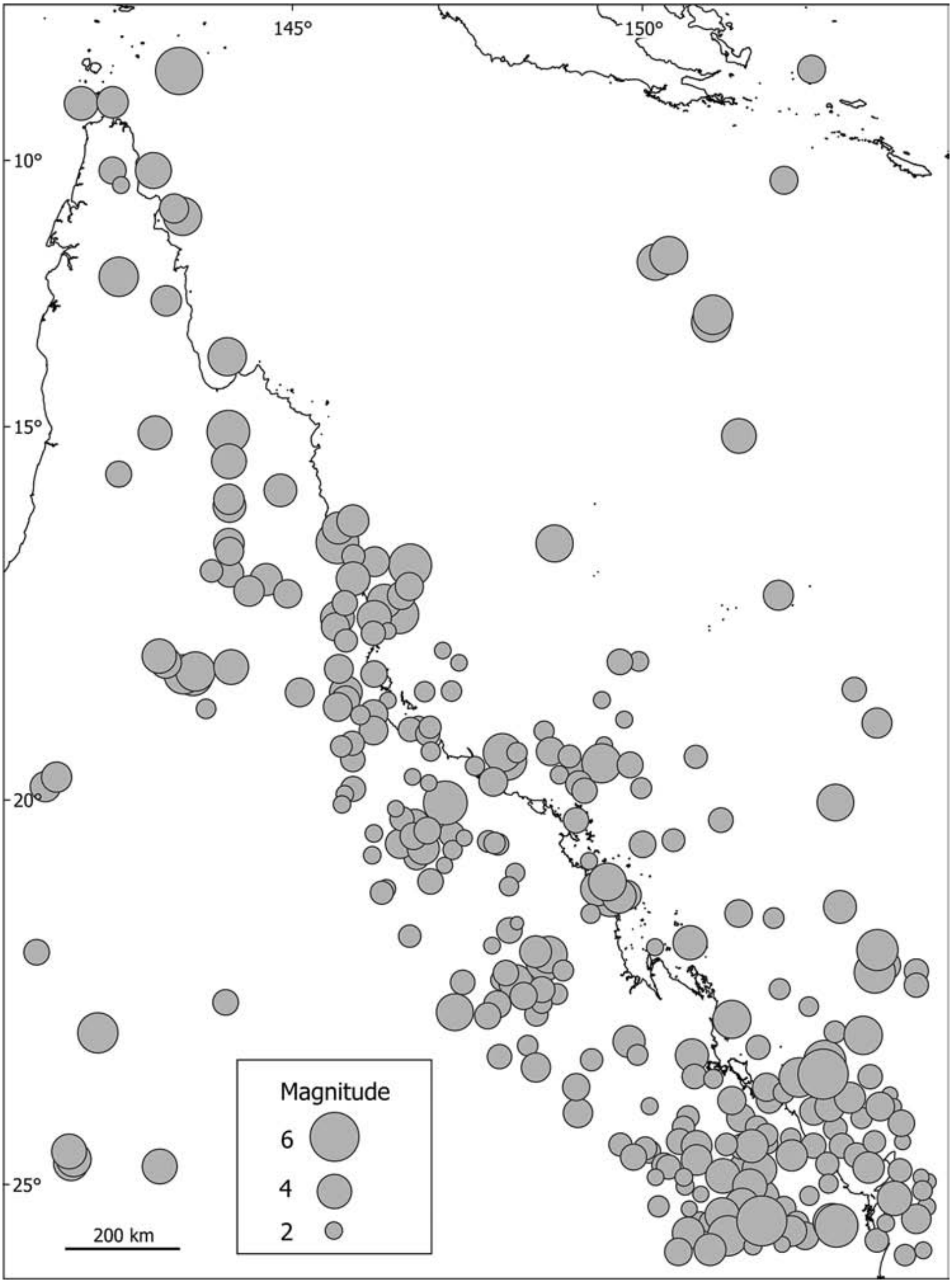

Figure 2.9 Seismic events recorded along the Queensland coast between 1866 and 2000 (from University of Queensland, 2005).

experienced a 5.2 magnitude earthquake located to the east of the island and in 1998 a 4.7 magnitude event centered to the west. In 2003 an earthquake 40 km east of Ingham was felt on the mainland between Cairns and Townsville and the Queensland record contains 493 tectonic events in the Townsville region, the largest having a magnitude of 5.5. Many of these have been out to sea. Also affecting the shelf has been volcanic activity sometime during the Pleistocene and subsequent to reef development. The area affected was the outer shelf of Torres Strait where six islands (Maer, Dauer, Waier, Darnley, and Stephens Islands, Black Rock and Bramble Cay) consisting of pyroclastic cones with some basaltic flows in varying degrees of erosion occur. The pyroclastic materials include reefal limestone indicating eruption through the previously established reef (Stephenson *et al.*, 1980) (Fig. 2.3).

2.5 The late establishment of the Great Barrier Reef

Whilst mid-oceanic atolls such as Enewetak, Midway, and Mururoa may have over 1000 m of reefal limestones representing almost continuous reef growth since the early Cainozoic, interrupted only by low sea level periods, the GBR is one of the youngest reef systems on earth. Only in the last 20 years has this young age been established. Previously from the four deep holes drilled on the reef, an age as great as the Miocene had been suggested for its foundation (Marshall, 1983a).

Drilling had commenced on the GBR in 1926 with the scientific borehole in Michaelmas Cay put down by the Great Barrier Reef Committee (Chapter 1). A further hole was drilled in 1937 in Heron Island and subsequently oil companies drilled exploratory wells in the Gulf of Papua (Anchor Cay, Borabi, and Pasca) and in the Capricorn Basin (Aquarius, Capricorn, and Wreck Island).

Unfortunately only three of these were actually located on a reef, Michaelmas, Heron and Wreck (Anchor Cay well was located just off the reef and did not penetrate reef framework above 225 m and even below this depth carbonate sediments are dominantly coralline algal rhodoliths: Marshall, 1983b). As Davies *et al.* (1989) noted, the boreholes on Michaelmas, Heron, and Wreck Islands had a remarkably similar stratigraphy with 100–150 m of what was presumed to be Plio–Pleistocene reef limestones overlying a thinner sequence of foraminiferal limestone and siliciclastics or mixed siliciclastics and carbonates. The Miocene or Pliocene age for the initiation of the GBR was based on poor recovery and extrapolation of evidence which was recognized as ambivalent even 40 years ago (Lloyd, 1973; Hill, 1974).

Figure 2.10 Ribbon 5 Reef site of deep drilling in 1995 and submersible reconnaissance of the outside of the reef in 1984 (photograph: Great Barrier Reef Marine Park Authority).

A much later age for all except the northernmost reefs in the Gulf of Papua was recognized once the relatively thin section of the reef was established from seismic interpretation. An age no greater than the Pleistocene was suggested (Marshall, 1983a; Symonds *et al.*, 1983). The 1990 Ocean Drilling Program confirmed this though the exact date of initiation was far from precise. Davies and McKenzie (1993) opted for an age of <500 ka, Feary *et al.* (1993) for as much as 1 Ma, and Montaggioni and Venec-Peyré (1993) for reef growth throughout the Pleistocene. The drilling in 1995 into Boulder and Ribbon 5 Reefs (Fig. 2.10) had hoped to provide a finite date, and has essentially done this (Fig. 2.11). The major reef-building turn-on event appears to have occurred between 452 and 365 ka ago though this was preceded by a transitional period of reef growth (International Consortium for Great Barrier Reef Drilling, 2001; Webster and Davies, 2003; Braithwaite *et al.*, 2004).

The question still remains as to why this turn-on was so late. At the largest chronological scale it required Australia to drift into tropical latitudes, which for the northern GBR was about 24 Ma ago, and for the southern Reef only in the last million years or so (Davies *et al.*, 1987, 1989) (Fig. 2.7). The start of this period is thought to coincide with early Miocene increased oceanic phosphate levels which would have inhibited the growth of coral reefs (Kinsey and Davies, 1979a). Subsequently even in some of the optimal coral reef areas of the Coral Sea plateaux, it has been shown that growth may not have been

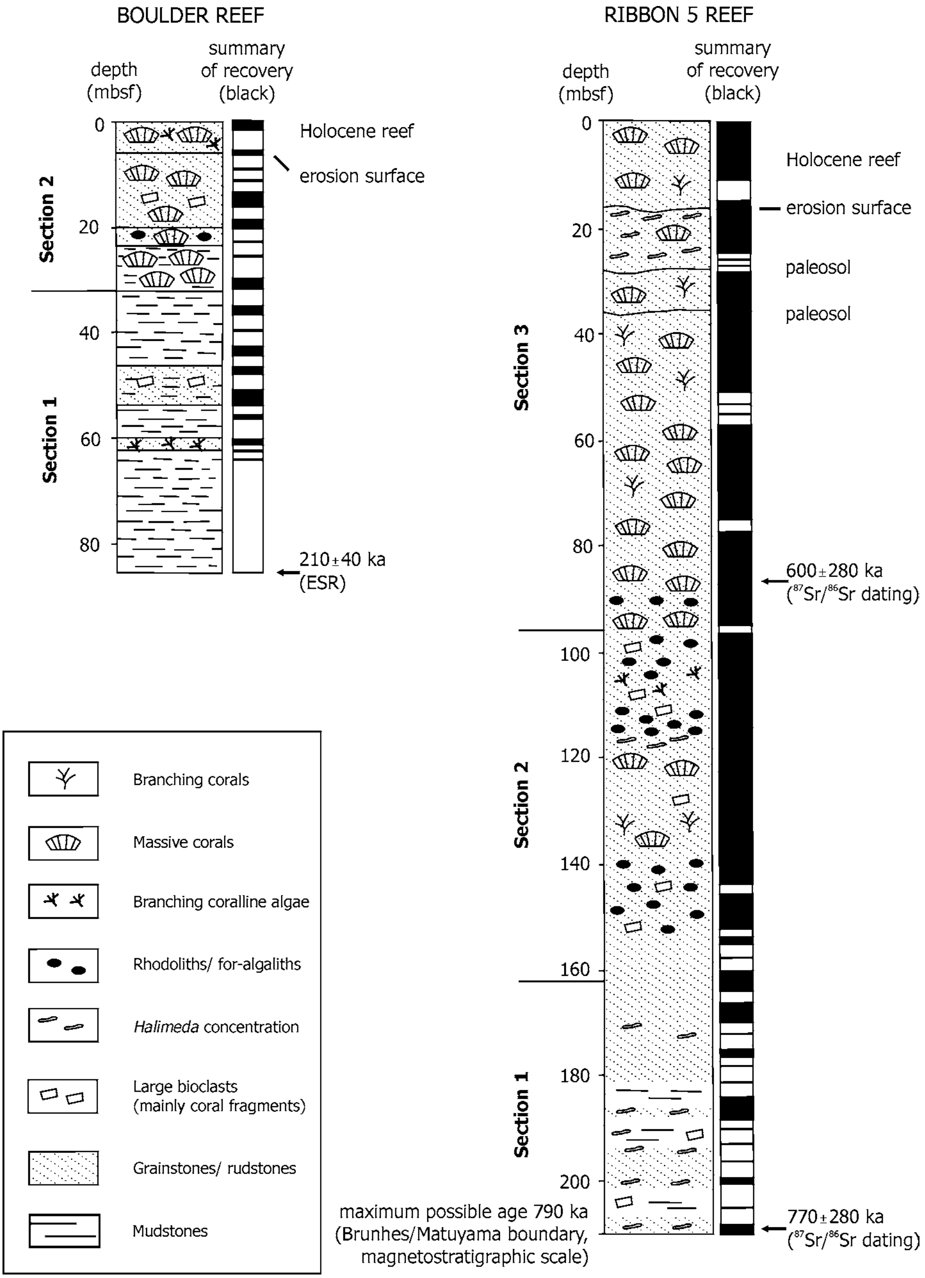

Figure 2.11 Core logs for the holes drilled through Boulder and Ribbon 5 Reefs (after Webster and Davies, 2003; Braga and Aguirre, 2004).

continuous. Reef growth declined on the Queensland Plateau in the late Miocene as surface water temperature dropped below 20° C, the result of reorganization of oceanic circulation in the Coral Sea (Isern *et al.*, 1993). Renewed warming took place only in the late Pliocene and early Pleistocene but apparently still before the GBR had been initiated. The massive lowering of sea level centered around 10 Ma ago, which aided the terrigenous progradation of the Queensland shelf, would also have prevented any reef build-up.

An examination of how the continental shelf off north-eastern Australia has been constructed clearly indicates two further features that would have provided constraints on reef development. The first was the massive amount of sediment which was being shed from the continental land mass since its uplift 50 Ma ago, providing what may have been very marginal conditions for reef turn-on (Perry and Larcombe, 2003). It may have been necessary for the shelf to have built out far enough from the continental land mass for the outer edge to have been sufficiently removed from extensive fluvial input during shelf flooding events. This would have been especially important for the area of the wet tropics centered on Cairns and opposite the two major rivers, the Fitzroy and the Burdekin.

Nonetheless, these conditions would have been achieved well before the commencement of the Pleistocene. The turn-on event (or events) would have required the Queensland shelf to have been seeded from other reefal areas with reefs of the Coral Sea identified as such nursery grounds (McKenzie and Davies, 1993). Also necessary would have been appropriate circulation patterns in the Western Coral Sea (Isern *et al.*, 1993), which seem to coincide with high sea level interglacials. Also suggested as a turn-on mechanism has been an up to 4° C increase in water temperature at about 400 ka ago. Webster and Davies (2003) note that Stage 11 at about 410 ka ago was the warmest interglacial in the last 450 ka and may have been the final trigger for extensive development. The event may also have been somewhat arbitrary once the general environment for reef growth was established. It was dependent on the coincidence of suitable oceanic temperature and circulation and an appropriate depth of water (between 30 and 80 m) on the outer shelf produced by a specific eustatic sea level high (see Section 3.2.2).

2.6 The Pleistocene Reef

In the far north of the GBR, especially within the Gulf of Papua, reef growth may have started soon after northern Australia entered tropical waters. Subsurface reefs of Miocene and Pliocene age have been identified in a number of places including the western margins of the Pandora Trough where such a reef 1.5 km thick occurs beneath Portlock and Boot Reefs. Buried reefs of similar age are found along the adjacent far northern GBR shelf (Davies *et al.*, 1989). Elsewhere a middle to late Pleistocene age is identified for the Reef and whilst the direct evidence comes only from Ribbon 5 and Boulder Reefs (International Consortium for Great Barrier Reef Drilling, 2001; Webster and Davies, 2003; Braithwaite *et al.*, 2004) similar relatively thin sequences of reefal framework seen in the boreholes on Michaelmas, Heron, and Wreck Reefs, and in seismic sections appear to corroborate this age for the Reef along its entire length.

The hole drilled to 210 m on Ribbon 5 Reef (Figs. 2.10 and 2.11) contains the more complete record. The reef is located on the edge of the continental slope (see Chapter 9) and especially in the lower section there is evidence for much downslope transport of material (International Consortium for Great Barrier Reef Drilling, 2001). Details of the core have been published by the International Consortium (2001), Webster and Davies (2003), Braithwaite *et al.* (2004), and Braga and Aguirre (2004). The lowest section from 210 to 158 m is composed of non-reefal grainstones and packstones interpreted as debris flows and turbidites. Some coral lithoclasts were recovered *(Seriatopora, Tubipora, Millepora)* but were considered to have originated from higher up the slope. Braithwaite *et al.* (2004) suggest that these may indicate older carbonates in the region than were recovered at Ribbon 5.

Between 158 and 96 m is a rhodolith-dominated section which was interpreted by Braithwaite *et al.* (2004) as representing gradual warming and shallowing of the environment. It also contains two *in situ* coral framework reef units, the oldest being between 138 and 130 m and containing robust, branching species of *Stylophora pistillata*, *Acropora humilis*, and *Pocillopora* sp. A sharp irregular surface with a change in $\delta^{18}O$ record separates this unit from the next coral framework section between 130 and 117 m. Basal grainstones are overlain by a 5 m *in situ* framework unit (Webster and Davies, 2003).

The upper section of the Ribbon 5 core is almost entirely reefal. It is composed predominantly of *in situ* coral framework in which six separate units were recognized by Webster and Davies (2003): 96–94 m, 94–85 m, 85–64 m, 64–25 m, 25–16 m, and 16–0 m. Similar assemblages of corals are found throughout including a robust branching community representing the shallow reef edge, a community dominated by massive *Porites* and faviids typical of lower-energy reef front or reef slope, and a similar assemblage which lacks encrusting forms and is interpreted as representing the leeward reef flat (Webster and Davies, 2003). The coralline algal sequences are in good agreement with these units and in this upper 96 m occur mainly as crusts on corals, also suggesting shallow reef settings (Braga and Aguirre, 2004). Each reef section appears to represent a sea level cycle with early flooding of a foundation in cool lower-energy conditions, progressing to shallow high-energy conditions later in the cycle.

The thickest framework unit between 64 and 25 m is very similar to some of the Holocene sections described in Chapters 8 and 9 with sections of up to 7 m of rubble. *Halimeda*, bryozoans, and encrusting foraminifera increase towards the top. The uppermost Pleistocene unit, between 25 and 16 m, is composed of a *Halimeda*-rich grainstone facies with minimal *in situ* coral. This may be similar to the uppermost Pleistocene in other reefs and is discussed further in Chapters 9 and 11.

The reef units are separated by distinct $\delta^{18}O$ changes and in at least one instance by an apparent marine erosion surface at ~130 m (International Consortium for Great Barrier Reef Drilling, 2001). Clear solution unconformities as are demonstrated for example in cores from Pacific atolls (e.g., Szabo *et al.*, 1985) are recognized only in the uppermost part of the core, at 16 m and 25 m (Webster and Davies, 2003) or 28 m according to International Consortium for Great Barrier Reef Drilling (2001) and Braithwaite *et al.* (2004). These latter authors also suggest a further “karst” surface with paleosols at 36 m. In a reinterpretation of the Heron Island bore, Davies (1974) identified solution unconformities at 20, 35, 75, 95, and 140 m, the upper two of which may equate with those seen in Ribbon 5.

Only Webster and Davies (2003) provide details of the 86 m core from inner shelf Boulder Reef (Fig. 2.11). The upper 34 m are carbonate dominated, consisting of four reef units between 0 and 11 m (Holocene), 11 and 20 m, 20 and 28 m, and 28 and 34 m. Poor recovery typified much of this part of the core and at the base of the 11–20 m section there was much rubble. The lower two sections contain or are set within siliciclastic muds. Muds, clay, and minor sands also dominate the core section between 34 and 86 m with only thin coral-bearing horizons at 47–56 m and 60–64 m.

Whilst sea level oscillation has been the major driving force in the deposition of the typical “layer cake” model of reef accretion, Webster and Davies believe that the changes in the coral assemblages within each unit also reflect the amount, or in some cases, the lack of accommodation space, wave energy, and sediment input. However, the same group of coral assemblages appear to be present throughout the construction of the GBR, tempting Webster and Davies to reiterate the geological robustness of reef systems (see Section 1.2).

The evidence of the Ribbon 5 and Boulder Reef cores suggests that the GBR was established after an early period of ephemeral reef development as represented in the thin reef layers below 96 m on Ribbon 5 and below 34 m on Boulder Reef. The latter in particular may equate to the turbid environment