



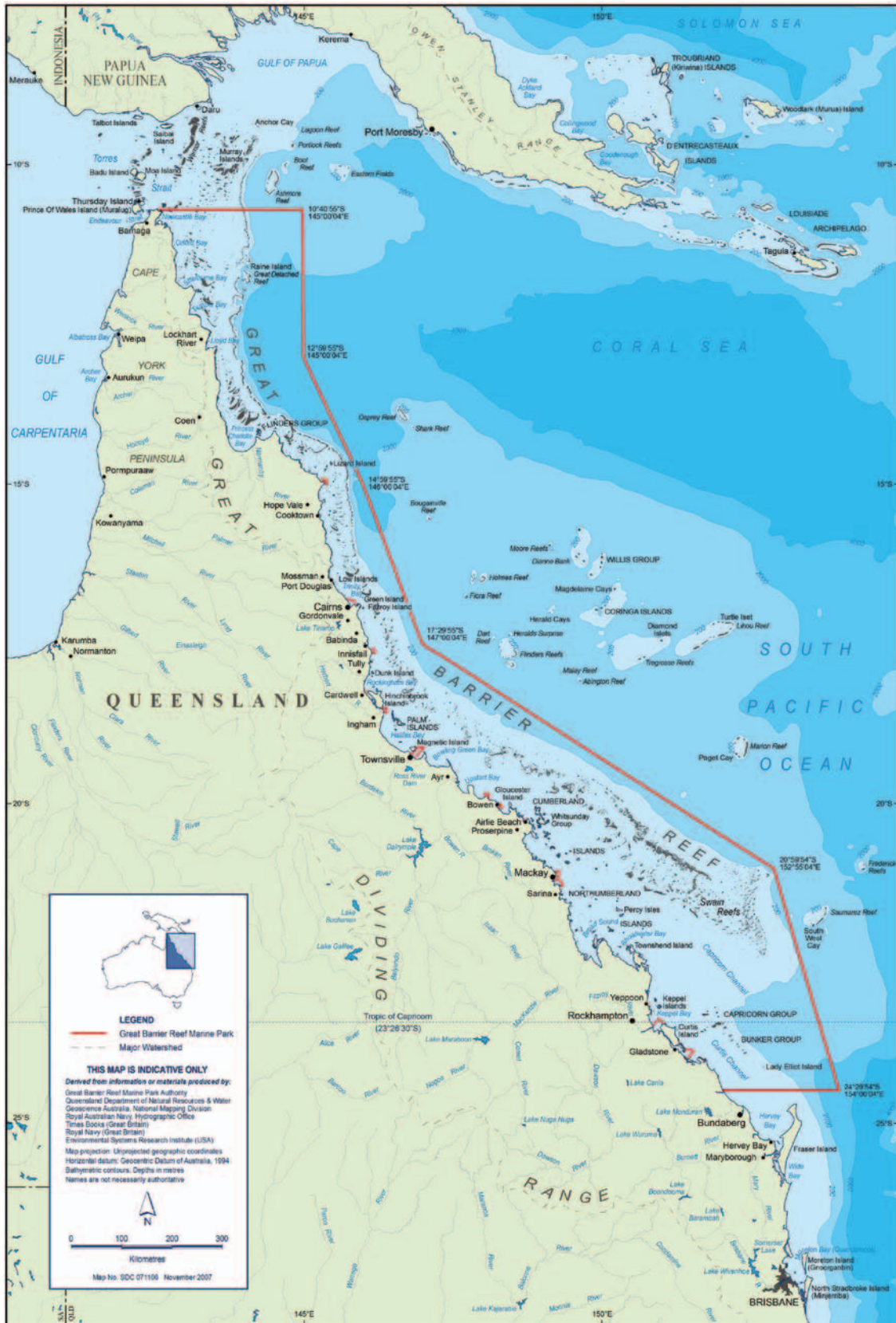
THE GREAT BARRIER REEF

Biology, Environment and Management

Second Edition

Editors: Pat Hutchings, Michael Kingsford and Ove Hoegh-Guldberg

THE
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Front cover: Great Barrier Reef (Photo: Tchami/Flickr, CC BY-SA 2.0)

Back cover: (left to right) crinoids (*Cenometra bella*) attached to a gorgonian, filtering the water current as it flows past; a stingray (*Taeniurops meyeri*) gliding through the water column; banded coral shrimp (*Stenopus hispidus*) cleaning a giant moray eel (*Gymnothorax javanicus*) (Photos by David Wachenfeld)

Map (p. ii): Great Barrier Reef (Courtesy of the Spatial Data Centre, Great Barrier Reef Marine Park Authority © Commonwealth of Australia (GBRMPA))

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Foreword

The Great Barrier Reef is one of the most spectacular examples of natural ecosystems anywhere, which easily justified its inclusion as a UNESCO World Heritage Area in 1981. Arguably, the Reef is also the best managed marine parks to be found anywhere. And for Australians going back thousands of years, it has been a central part of our identity, community and economy.

Preserving this magnificent piece of Australia's natural wealth has grown in importance as our understanding and knowledge of the system has increased. Developing a multi-use park system in 1975, Australia pioneered the idea that areas as large as the Great Barrier Reef Marine Park should not be shut away, but rather should be part of a harmonious balance between preservation and use.

This approach, however, has not always been easy. As the 1970s taught us, communities can see things in very different lights. At one end there were people who wanted to exploit the resources of the Reef without regard; at the other, people who wanted to simply lock it up. Fortunately, however, Australia chose the middle ground which requires us to understand and regulate the use of the park, while keeping it in good condition in perpetuity.

As a test of that dialogue and transparency of process, the Park underwent a systematic review of its zoning at the beginning of the Millennium, which resulted in extensive consultation with Australians and the international community. Led by the Hon Virginia Chadwick AO, who wrote the Preface to the first edition of this book, the review led to the largest and most comprehensive review of a Park system anywhere.

The results of the rezoning of the Park were spectacular. As a result of that consultation and process, the Park went from around 5% of its zones as 'no take' to no take areas comprising more than 33% of the total Park area. A key feature of these

modifications to the Great Barrier Reef was that they involved consultation with thousands, and that people discussed and owned the outcome. As a result of the changes, the *Great Barrier Reef Act* passed relatively easily through Federal Parliament in 2004.

This was a miraculous achievement in many minds, but heavily depended on having the necessary science in place to inform management decisions. And in this regard, it has been important that we have built our understanding and knowledge of the reef, so as to underpin the sorts of management decisions that were typical of re-zoning process.

The world's oceans, including the Great Barrier Reef, are being challenged at an unprecedented level. The ongoing challenges of dealing with climate change, overfishing and impacts from the land continue. Like coral reefs elsewhere, new methods of extraction are also posing additional challenges for the GBR, especially for lesser known areas such as the deep mesophotic reefs. These challenges, however, make it more, not less, important to base decisions relating to resource use and conservation on sound knowledge and understanding of the complex processes involved.

In its second edition, this book on the Reef builds on the tradition of the first edition and has expanded the already amazing array of authors and expertise to tackle a number of new and current issues to do with the Reef. Stretching from the geology, biology and oceanography of the Reef, to modern issues such as water quality, climate change and socio-economics of the Reef, this book enables the reader to get a total insight to how the world's largest coral reef functions. This is a book that will be useful for school students through to experts, and has relevance for people interested in coral reefs and related ecosystems worldwide.

For these reasons, I am extremely pleased to see the publication of the second edition of the book, the Great Barrier Reef. To put it bluntly, understanding how this vast system operates is in everyone's interest. This is why books such as *The Great Barrier Reef* are so important.

Honourable Robert Hill AC*
**Former Minister for the Environment and for
Defence**
Ambassador for Australia to the United Nations

* The Honourable Robert Hill was responsible for establishing the Commencement of Representative Areas Program (1998) that led to the rezoning of the GBR in 2004. He also initiated what would become the world's first national Oceans Policy just before that time, although he had moved on from Environment Department before it was implemented.

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Abbreviations

ABRS: Australian Biological Resources Study	MODIS: moderate resolution image spectroradiometer on the Terra and Aqua satellites (see http://modis.gsfc.nasa.gov/).
ACRS: Australian Coral Reef Society	MST: Marine Science and Technology (grant awarded by the federal government)
AIMS: Australian Institute of Marine Science	NASA National Aeronautics and Space Administration
ARC: Australian Research Council	NGOs: non-government organisations
AUV: autonomous underwater vehicle	NIWA: National Institute of Water and Atmospheric Research (New Zealand)
CFC: chlorofluorocarbon	NOAA: National Oceanic and Atmospheric Administration (USA)
COTS: crown-of-thorns starfish	NQAIF: North Queensland Algal Identification/Culturing Facility
CRC: Co-operative Research Centre	QDNR&M: Queensland Department of Natural Resources and Management
CSIRO: Commonwealth Scientific and Industrial Research Organisation	QDPI: Queensland Department of Primary Industries
DDM: day-to-day management program	QPWS: Queensland Parks and Wildlife Service
EAC: East Australian Current	OSCAR-NOAA: A NOAA project mapping, using satellite altimetry, the water surface elevation of the ocean, from which the near-surface water currents are calculated
ENCORE: Enrichment of Nutrients on Coral Reefs (project funded by ARC and GBRMPA)	RAP: Representative Areas Program
ENSO El Niño–Southern Oscillation	ROV: remote operated vehicle
EPICA: European Project for Ice Coring in Antarctica	RWQPP: Reef Water Quality Protection Plan
GBR: Great Barrier Reef	SeaWiFS: Sea-viewing Wide Field-of-view Sensor (see http://oceancolor.gsfc.nasa.gov/ SeaWiFS).
GBRCA: Great Barrier Reef Catchment Area	SOI: Southern Oscillation Index
GBRMP: Great Barrier Reef Marine Park	UQ: University of Queensland
GBRMPA: Great Barrier Reef Marine Park Authority	
GBRWHA: Great Barrier Reef World Heritage Area	
IPCC: Intergovernmental Panel on Climate Change	
IUCN: International Union for Conservation of Nature	
JCU: James Cook University	
MAGNT: Museum and Art Gallery of the Northern Territory	

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Author biographies

S. T. Ahyong

Shane Ahyong is a Principal Research Scientist and Manager of the Department of Marine Invertebrates at the Australian Museum, Sydney. He is an international authority on crustacean systematics, especially of decapods and stomatopods. Research interests include invertebrate taxonomy and phylogenetics, invasive species, biosecurity, and both freshwater and marine faunas. He has published more than 250 refereed articles and book chapters, and is a co-author of *The Biology of Squat Lobsters*, published by CSIRO Publishing.

P. Alderslade

Phil Alderslade has been researching the identification of octocorals since the early 1970s. Commencing in 1981 he spent 25 years as the Curator of Coelenterates at the Museum and Art Gallery of the Northern Territory in Darwin and during this time collaborated with Katharina Fabricius to co-author the book *Soft Corals and Sea Fans* – the only comprehensive field guide to the shallow water octocorals of the Red Sea, Indo-Pacific and central west Pacific regions of the world. Phil became semi-retired in 2006 and is now working as a research scientist (octocoral taxonomy) for CSIRO Oceans and Atmosphere in Hobart, Tasmania.

T. J. Anderson

Tara Anderson is a research scientist (benthic ecologist), at the National Institute of Water and Atmosphere in New Zealand. Her research over 25 years has focused primarily on the relationships between benthic habitats and biota, including bio-physical sea floor mapping and the role of biogenic habitat-formers in supporting fish assemblages, in a broad range of coastal and offshore marine ecosystems in New Zealand, Australia and along the west coast of the United States.

P. Bock

Philip Bock became fascinated by bryozoans while geological mapping in south-west Victoria, where the sediments are often packed with their skeletons. He took up study of the living bryozoans of southern Australia in order to gain an understanding of their environmental variation. After working at the Royal Melbourne Institute of Technology University for over 30 years, he retired in 1997, and maintains an active interest, including keeping the Bryozoa Home Page website available at <http://www.bryozoa.net/>. He also is a taxonomic editor for the World Register of Marine Species.

P. Bongaerts

Pim Bongaerts is Curator of Aquatic Biology at the California Academy of Sciences (USA). Before that, he held positions as ARC DECRA Research Fellow at the Global Change Institute (The University of Queensland) and as Lead Scientist for the deep-reef work of the 'XL Catlin Seaview Survey'. His research over the past 10 years has focused primarily on mesophotic coral ecosystems, using molecular techniques to study their biodiversity and connectivity with shallow-water reefs.

T. Bridge

Tom Bridge is Senior Curator of Corals at the Queensland Museum, based at the Museum of Tropical Queensland campus in Townsville, and at the Australian Research Council Centre of Excellence for Coral Reef Studies at James Cook University (JCU). He commenced his career with a BSc (Hons) at the University of Sydney, before moving to JCU to complete a PhD (2007–2011). From 2012 to 2016, he was a Postdoctoral Research Fellow at the ARC Centre of Excellence for Coral Reef Studies. Tom has worked on coral reefs across the Indo-Pacific. He has a particular interest in mesophotic

coral reef ecosystems and the application of remote imaging techniques such as autonomous underwater vehicles to survey habitats beyond the depths of conventional SCUBA diving.

J. Brodie

Jon Brodie is a Professorial Research Fellow with the ARC Centre of Excellence for Coral Reef Studies at James Cook University (JCU). He is also a Partner in C₂O Consulting. He has held positions as: Chief Research Scientist, Centre for Tropical Water and Aquatic Ecosystem Research, JCU; Director, Institute of Applied Science, University of the South Pacific, Fiji; and Director, Water Quality and Coastal Development Group, Great Barrier Reef Marine Park Authority (GBRMPA). Jon has collaborated with a wide range of research and environmental management colleagues from the Australian Institute of Marine Science, GBRMPA, CSIRO the Queensland Government, JCU and many Australian and international universities to establish the effects of changed terrestrial runoff and potential management solutions on Great Barrier Reef ecosystems and tropical marine environments globally.

M. Byrne

Maria Byrne is Professor of Marine and Developmental Biology at the University of Sydney. She received her BSc from the National University of Ireland Galway and PhD from University of Victoria, Canada. As a postdoctoral fellow at the Smithsonian Institution, she investigated Caribbean echinoderms and returned to Ireland working on sea urchin aquaculture and fisheries. Her research on marine invertebrate biology largely involves echinoderms and molluscs. In recent years her research has involved the quantification of the impacts of climate change stressors, ocean warming and ocean acidification on fundamental biological processes including growth, physiology, development and calcification. For 12 years Maria was the director of One Tree Island Research Station in the southern Great Barrier Reef. She has

produces over 300 peer reviewed scientific articles and recently co-edited and wrote the authoritative book on Australian Echinoderms.

D. Cameron

Darren Cameron is Director – Reef Interventions with the Great Barrier Reef Marine Park Authority in Townsville. He originally worked as a fisheries biologist and manager for the Queensland Government. He was part of the team that designed and implemented the 2004 rezoning of the Great Barrier Reef Marine Park. His main interests are in coral reef ecosystem and fisheries science and management. In particular, the effective design, implementation and adaptive management of multiple-use marine protected areas, which incorporate and contribute to ecologically sustainable fisheries management. He has over 30 years professional experience, having worked in over 16 countries, mostly in the Western and Central Pacific region.

A. Chin

Andrew Chin is a research fellow with the Centre for Sustainable Tropical Fisheries and Aquaculture at James Cook University. His research focuses on fisheries science and coastal systems, and he specialises in the biology, ecology and sustainable management of sharks and rays. He has worked on blacktip reef sharks, citizen science projects, hammerhead sharks and Indigenous fisheries, and he has specific interests in coastal fisheries and the diverse values of sharks in the Indo-Pacific. Before coming to James Cook University in 2008, Andrew worked at the Great Barrier Reef Marine Park Authority connecting research to priority management needs. Now in his current role, Andrew continues to focus on applied research that addresses end user needs.

J. H. Choat

Howard Choat is an Adjunct Professor of Marine Biology at James Cook University and has worked extensively on coral reef fishes over the Indian, Pacific and Atlantic Oceans.

B. C. Congdon

Brad Congdon is a 'Reader in Ecology' at James Cook University, Cairns. He is a field ecologist who applies ecological and evolutionary theory to the management and conservation of animal and plant species. He has a special interest in seabird conservation and has worked extensively with seabirds both in Australia and overseas. His current research is focused on understanding how changing ocean conditions impact seabird breeding success throughout the Great Barrier Reef and Coral Sea ecosystems. His research group was the first to demonstrate that seabirds are sensitive indicators of multiple climate-change impacts on top predators in these areas and have established rising sea-surface temperatures as a major conservation issue for seabirds of the Great Barrier Reef.

A. L. Crowther

Andrea Crowther is Senior Collection Manager, Marine Invertebrates at South Australian Museum. She completed her PhD at the University of Kansas, USA, where she studied shallow, tropical sea anemones. She has worked and published on sea anemones and other Cnidaria from around Australia with the Queensland Museum and she now works on sea anemones from the deep Southern Ocean.

J. C. Day

Jon Day was a terrestrial park planner and park ranger for the first 11 years of his professional career. In 1986, he joined GBRMPA, the agency responsible for the Great Barrier Reef (GBR). Over the following 28 years, Jon was involved in many aspects of planning and managing the GBR, including seven years in field management. In 1998, he was appointed as one of the Directors of GBRMPA, and for the next 16 years was variously responsible for conservation, planning, heritage (particularly World Heritage), Indigenous Partnerships, the GBR rezoning program and commencing the first 5-yearly Outlook Report. Jon retired from GBRMPA in 2014 to undertake a post-career PhD at the ARC Centre for Coral Reef Studies at JCU. He continues to publish widely on the GBR and World Heritage matters.

G. Diaz-Pulido

Guillermo Diaz-Pulido grew up in Colombia. He completed his BSc (Hons) in Marine Biology in Colombia in 1995 and his PhD in Marine Botany at James Cook University in 2002. He has done pioneering work on the ecology and diversity of reef algae from the Caribbean Sea and the Great Barrier Reef. His current research focuses on the ecology of coral-algal interactions, the impacts of ocean acidification and warming on macroalgae, and the potential of macroalgae to adapt to climate change. He is Associate Professor at the Griffith School of Environment at Griffith University.

P. J. Doherty

Peter Doherty is a post-retirement Fellow of the Australian Institute of Marine Science (AIMS), gained his PhD in 1980 by describing the population dynamics of damselfishes at One Tree Island. In 1989 he joined AIMS and led a research group in tropical fisheries ecology. In 1998, he joined the Co-operative Research Centre for the Great Barrier Reef World Heritage Area. One of his achievements was to facilitate the \$9 million research collaboration known as the GBR Seabed Biodiversity Project. His fondest memories are more than 100 days spent at sea on the *RV Lady Basten* working the back deck from midnight to midday.

S. Dove

Sophie Dove obtained an undergraduate degree in Mathematics and Philosophy from the University of Edinburgh, and a PhD in Biological Sciences from the University of Sydney. She is presently an Associate Professor within the School of Biological Sciences at the University of Queensland, as well as a Chief Investigator within the Australia Research Council Centre for Excellence in Coral Reef Studies. Her research interests predominantly lie in the area of coral reef dynamics under climate change and cover a range of organisms (e.g. macro-algae, sponges and corals) that contribute to the carbonate balance of reefs. The goal of this research is to gain a broader understanding of how different combinations of elevated sea surface temperature

and acidification may influence the coastal protective properties of shallow tropical reefs.

N. C. Duke

Norm Duke is a mangrove ecologist of more than 40 years standing, specialising in mangrove floristics, biogeography, genetics, climate change ecology, vegetation mapping, plant–animal relationships, pollution and habitat restoration. As Professorial Research Fellow, he currently leads an active research and teaching group on marine tidal wetlands at James Cook University TropWATER Centre. With his detailed knowledge and understanding of tidal wetland processes, he regularly advises on effective management and mitigation of disturbed and damaged ecosystems. He has published more than 230 peer-reviewed articles and technical reports, including his authoritative popular book *Australia's Mangroves*, and innovative smart device apps on Mangrove ID for all mangrove plant taxa in Australia and the World.

M. Ekins

Merrick Ekins was previously a plant pathologist but then decided he would rather go SCUBA diving for a living than walking through fields of sunflowers. He has been the Collection Manager of Sessile Marine Invertebrates at the Queensland Museum for the last 14 years and still loves discovering new species – one of the joys of science. His main research is describing new species of sponges, octocorals, ascidians and jellyfish. As well as taxonomic identification, Merrick has also explored the population genetics and connectivity of rock sponges on ocean deep seamounts.

K. Fabricius

Katharina Fabricius is a coral reef ecologist, and holds the position of a Senior Principal Research Scientist at the Australian Institute of Marine Science. Her main research interest is to better understand the roles of disturbances, including changing water quality, ocean acidification and the cumulative effects of multiple disturbances on the biodiversity and functions of coral reefs around the

world. Katharina was awarded a PhD in 1995 for her work on octocoral ecology. She has published over 140 journal articles, book chapters and a book on Indo-Pacific octocorals, jointly produced with Phil Alderslade.

L. Gershwin

Lisa-ann Gershwin is an international authority on medusae and ctenophores. Her research interests include taxonomy, systematics, biogeography, biodiversity, toxinology, bloom dynamics, marine stinger safety and prediction, and mesopelagic invertebrates. She has worked on medusae and ctenophores around the world since 1992, with particular focus on Australian species since 1998. While working in Australia, she has collected many thousands of specimens, with at least 212 species new to science, including numerous new genera, families and even a new suborder. She is the co-creator of *The Jellyfish App* and author of the best-selling books *Stung! On Jellyfish Blooms and the Future of the Ocean* and *Jellyfish: A Natural History*, both of which have been translated into multiple languages.

D. P. Gordon

Dennis Gordon FLS has been studying bryozoans for 50 years. He is a past President of the International Bryozoology Association and is currently an Emeritus Researcher at the National Institute of Water and Atmospheric Research, Wellington, New Zealand.

H. Heatwole

Harold Heatwole is an ecologist and herpetologist, who in the past 54 years successively held academic posts at the University of Puerto Rico, University of New England and North Carolina State University. His main research interests are sea snakes, island ecology, ants and tardigrades. He is the author of over 350 scientific articles and 11 books. He also produces videos for educational purposes. He holds a DSc and PhDs in Zoology and Botany, and Geography. The last two dealt respectively with vegetation dynamics on the small cays of the Great

Barrier Reef and the role of paleogeography in the evolution and dispersal of sea kraits. He is a Fellow of the Explorer's Club. Currently he is Professor Emeritus in biology at North Carolina State University, USA, and Adjunct Professor of Zoology at the University of New England, NSW, Australia.

O. Hoegh-Guldberg

Ove Hoegh-Guldberg is Professor of Marine Science and Director of the Global Change Institute (GCI) at the University of Queensland. After completing his BSc (Hons) Ove travelled to the United States to complete his PhD at the University of California at Los Angeles (UCLA). After postdoctoral work at the University of Southern California (USC) and a lectureship at UCLA, Ove, returned to University of Sydney in 1992 where he spent 8 years before taking the Chair at the University of Queensland. Here, he led the Centre for Marine Studies until 2010, when he became Director of the GCI. His research group focuses on the physiological ecology of corals and coral reefs, particularly regarding global warming and ocean acidification. In addition to his work producing published science (>300 articles), Ove was the coordinating lead author for Chapter 30, ('The Ocean') for the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC). He is currently also a Coordinating Lead Author for the Special IPCC Report on the implications of 1.5°C as a climate target. In 1999, he was awarded the Eureka Prize for his scientific research, and the Queensland Smart State Premier's Fellow (2008–2013). In 2012, he received a Thomson Reuters Citation Award in recognition of his contribution to research and an Australian Research Council Laureate Fellowship. He is member of the Australian Academy of Science, and received the Climate Change Prize from HSH Prince Albert II of Monaco in 2014 and the Banksia Foundational International Award in 2016.

M. O. Hoogenboom

Mia Hoogenboom received her PhD from James Cook University, Australia after which she conducted postdoctoral research at the Centre

Scientifique de Monaco and the University of Glasgow, Scotland. She currently teaches coral reef ecology in the College of Science and Engineering at James Cook University, and is also a Program Leader in the ARC Centre of Excellence for Coral Reef Studies. She is a coral physiologist and her research focuses on chronic and acute threats to coral health and coral community structure.

J. N. A. Hooper

John Hooper, Head of the Biodiversity & Geosciences Programs, Queensland Museum, is an international authority on sponges (Phylum Porifera) with specific research interests in taxonomy, systematics, biogeography, biodiversity and conservation biology, and collaborating with 'biodiscovery' agencies over the past three decades in the search for new therapeutic pharmaceutical compounds (and discovering thousands of new species along the way).

D. Hopley

David Hopley is a coastal geomorphologist, holding the position of Professor Emeritus in the College of Science and Engineering at James Cook University. He held a personal chair in marine science and has an association with the University exceeding 50 years. He worked on coral reef evolution, and changing sea levels, especially on the Great Barrier Reef. He has published more than 150 scientific papers on this and related topics along with two major books, *The Geomorphology of the Great Barrier Reef: Quaternary Evolution of Coral Reefs* (Wiley Interscience, 1982) and, with Scott Smithers and Kevin Parnell, *The Geomorphology of the Great Barrier Reef: Development, Diversity and Change* (Cambridge University Press, 2007).

P. A. Hutchings

Pat Hutchings is a Senior Fellow, Australian Museum Research Institute, having retired in 2016 as a Senior Principal Research Scientist at the Australian Museum. She has spent her research career working on the systematics and ecology of polychaetes. In addition, she has studied the process of

bioerosion, not only on the Great Barrier Reef but also in French Polynesia. More recently she has become interested in bioerosion on fossil reefs and how this process changed with major climatic changes affecting reefs and if this can be helpful in understanding the changes currently impacting on our modern day reefs. As well as publishing extensively, she has been active in the Australian Coral Reef Society, which was recognised by her being given honorary life membership. She has also been very active in commenting on management and zoning plans for Australian coral reefs.

G. P. Jones

Geoff Jones is one of the world's most influential authors in the fields of coral and temperate reef fish ecology, and marine conservation biology, with ~270 publications in peer-reviewed journals and books. Geoff graduated with a PhD from the University of Auckland in 1981 and has held postdoctoral fellowships at the University of Melbourne and Sydney. He is currently a Distinguished Professor in Marine Biology, College of Science and Engineering at James Cook University, and a Chief Investigator in the Australian Research Council Centre of Excellence for Coral Reef Studies. His special interests are in the processes determining the structure and dynamics of reef fish populations, and human impacts on and conservation of threatened marine habitats and species. He has worked extensively on the rocky reefs of New Zealand and Australia, and on the coral reefs around the world, including the Great Barrier Reef, Papua New Guinea and the Pacific. Geoff and collaborators were the first to tag and recapture marine fish larvae. He has since become a world leader in the field of marine population connectivity and its implications for the ecology, conservation and management of reef fish populations. He teaches in marine conservation biology at James Cook University and has supervised over 160 graduate research students.

R. Kelley

Russell Kelley is a science communication consultant, author of the Indo Pacific Coral Finder and the

Reef Finder, and manager of BYOGUIDES (www.byoguides.com; www.russellkelley.info). His outputs include scientific papers, book chapters, educational tools and international broadcast television productions.

M. J. Kingsford

Michael Kingsford is a Distinguished Professor in the Marine Biology and Aquaculture group of the College of Science and Engineering at James Cook University, Australia. The College is a recognised world leader in tropical marine biology and ecology. He has published extensively on the ecology of reef fishes, jellyfishes, biological oceanography and climate change. His projects have encompassed a range of latitudes and he has edited two books on tropical and temperate ecology. He is a Chief Investigator with the ARC Centre of Excellence for Innovative Coral Reef Studies. A major focus of his research has been on connectivity of reef fish populations, the utility of Marine Protected Areas, environmental records in corals and fishes and the ecology of deadly box jellyfishes. In addition to research and multiple senior leadership roles, he teaches undergraduate students and supervises many postgraduate students. He has over 30 years' research experience on the Great Barrier Reef.

A. W. D. Larkum

Anthony Larkum has worked in many fields – from molecules to ecosystems. His early interests were in the way plants absorb nutrients. However, an interest in SCUBA diving stimulated an interest in algae and in how algae are adapted to light fields underwater. This led to a lifelong interest in the physiology and ecology of algae and seagrasses. He has edited two books on the biology of seagrasses. He was instrumental in setting up the University of Sydney's One Tree Island Research Station and has been fascinated with the various roles of algae in the coral reef ecosystem. He initiated the ENCORE (Enrichment of Nutrients on Coral Reefs) Project at One Tree Island that looked at the effect of raising the local levels of nitrogen and phosphorus on coral reef organisms. He is also currently working on the potential effects of global

climate change, especially coral bleaching. His most recent interests are in the cyanobacteria of stromatolites and the role of chlorophyll-*d* and -*f* in these ecosystems.

V. Lukoschek

Vimoksalehi Lukoschek is a molecular ecologist whose overarching interest is the application of molecular genetic techniques to understand the ecology and evolution of marine vertebrates and invertebrates, and the application these findings to conservation and management. She has an ongoing research interest in sea snakes, which were the focus of her PhD at James Cook University (JCU) and a post-doctoral research fellowship at UC Irvine with Professor John Avise. She was the founding co-chair of the IUCN Sea Snake Specialist Group. Vimoksalehi has held a Research Fellowship with Professor Scott Baker at the University of Auckland working on cetacean genetics. Since 2010, Vimoksalehi has been a member of the ARC Centre of Excellence for Coral Reef Studies at JCU working on connectivity of broadcast spawning corals in collaboration with researchers at the Australian Institute of Marine Science, University of Melbourne and University of Queensland. Her research has been supported by a Queensland Government Smart Futures Fellowship, the Australian Academy of Science Endangered Species Fund, SeaWorld Research and Rescue Foundation, and Australia's Commonwealth Department of Environment. She currently holds an ARC Discovery Early Career Researcher Award.

H. Marsh

Helene Marsh is a marine conservation biologist based at James Cook University, with some 40 years' experience in research into species conservation, management and policy with particular reference to tropical coastal and riverine megafauna, especially marine mammals. She is a fellow of the Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering and her research has been recognised by awards from the Pew Foundation, the Society for

Conservation Biology and the American Society of Mammalogists. The policy outcomes of her research include significant contributions to the science base of the conservation of dugongs in Australia and internationally at a global scale (International Union for the Conservation of Nature, United Nations Environment Program, Convention for Migratory Species) and by providing advice to the governments of some 14 countries. Helene chairs the Australian Threatened Species Scientific Committee, a statutory committee that makes recommendations to the federal Minister for Environment and is a member of the Australian delegation to the World Heritage Committee. She is past President of the International Society of Marine Mammalogy, Co-chair of the IUCN Sirenia Specialist Group and is on the editorial boards of *Conservation Biology*, *Endangered Species Research* and *Oecologia*. Helene is proud of the accomplishments of the 55 PhD candidates that she has supervised to graduation, all of whom have taught her a lot. For further information see <https://research.jcu.edu.au/portfolio/helene.marsh>.

A.D. McKinnon

David McKinnon is an Associate Scientist at the Australian Institute of Marine Science (AIMS) and an adjunct Professor at James Cook University of North Queensland. Over a 40 year professional career, he published over 115 peer-reviewed scientific articles in several fields of marine science, including zooplankton ecology, coral reef trophodynamics and biological oceanography. David McKinnon has described over 70 copepod species, including three new genera. Since retiring from his position as a Principal Research Scientist at AIMS in 2015, he has continued to indulge his passion for marine science according to his whim.

J. M. Pandolfi

John Pandolfi is Professor in the School of Biological Sciences and the Centre for Marine Science at the University of Queensland, Australia. His research integrates paleoecological, ecological, historical and climate data to provide critical insights

into how marine communities are assembled and structured in the face of environmental variability and human impacts over extended periods of time.

C. R. Pitcher

Roland Pitcher is a Senior Principal Research Scientist at CSIRO Oceans & Atmosphere and was Principal Investigator of the Great Barrier Reef Seabed Biodiversity Project. His research over ~35 years on seabed habitats and biota, including distribution and abundance mapping, effects of prawn trawling, recovery and dynamics, and modelling provides an objective foundation to assist management in achieving sustainability of the seabed environment.

M. S. Pratchett

Morgan Pratchett is a Professorial Research fellow in the ARC Centre of Excellence for Coral Reef Studies at James Cook University (JCU). He also studied marine biology at JCU, but had several overseas postdoctoral appointments (University of Perpignan, Nova South-eastern University Oceanographic Centre and the University of Oxford) before taking up his current position. Morgan is a behavioural ecologist and conservation biologist working almost exclusively on coral reef systems and species. His current research focus is on major disturbances that impact coral reef ecosystems, including outbreaks of crown-of-thorns starfish and climate-induced coral bleaching.

B. C. Russell

Barry Russell is Curator Emeritus of Fishes at the Museum and Art Gallery of the Northern Territory in Darwin. He has over 45 years' research experience on the systematics, ecology and behaviour of tropical demersal fishes of the Indo-West Pacific. His current research interests include the taxonomy and phylogenetics of threadfin breams (Nemipteridae) and lizardfishes (Synodontidae). He is co-chair of the IUCN Species Survival Commission Snapper, Seabream and Grunt Specialist Group.

R. Saunders

Richard Saunders is a fish biologist whose current focus is on research that informs the sustainable management of Queensland's fisheries. Richard received a BSc (Hons) studying invertebrate ecology and PhD studying fish biology both from The University of Adelaide. He worked for 7 years in fisheries research at the South Australian Research and Development Institute and since 2012 has worked as a Senior Fisheries Biologist with the Queensland Department of Agriculture and Fisheries. Richard is also an adjunct Research Fellow with James Cook University in the Centre for Sustainable Tropical Fisheries and Aquaculture.

T. L. Sih

Tiffany Sih is a fish ecologist studying tropical fisheries and the deeper reefs of the Great Barrier Reef. Tiffany's research incorporates underwater video and advanced otolith chemistry to spatially refine fish populations at mesophotic depths. Tiffany received a BS in Biological Sciences from the University of Southern California, USA, and a Masters in Applied Science and PhD in Marine Biology from James Cook University, Australia, affiliated with the ARC Centre of Excellence for Coral Reef Studies and the Australian Institute of Marine Science.

S. Smithers

Scott Smithers is an Associate Professor in Tropical Geomorphology at James Cook University, Townsville. He has more than 25 years' experience of the geomorphology of coral reefs in the Pacific and Indian Oceans, as well as in the Caribbean Sea. Recent research on the Great Barrier Reef includes investigations of: Holocene sea-level change; the styles and rates of Holocene reef growth in different settings, with a particular focus on inshore turbid zone reefs; reef island evolution and morphodynamics; and reef carbonate budgets. Scott is a passionate advocate of the value of geomorphology to ecological understandings and management of the Great Barrier Reef (and other reefs). For

example, Scott's team delivered the geomorphological investigations that underpin recent sand movements on Raine Island undertaken to improve nesting and hatching outcomes for Endangered green sea turtles.

M. Srinivasan

Maya Srinivasan received her PhD from James Cook University (JCU), Australia in 2006. She is originally from Malaysia, and now lives in Australia, undertaking research and teaching at JCU. She has been conducting research on coral reef fishes for 20 years and has taught several marine biology subjects at JCU over the last 15 years. Her research focuses on population connectivity of coral reef fishes as well as conservation related questions, such as the impacts of climate change and the effectiveness of marine reserves. She has worked on coral reefs in many locations, including the Great Barrier Reef, Malaysia and Papua New Guinea. She has a voluntary role as board member and scientific advisor for Mahonia Na Dari Research and Conservation, a conservation and environmental education NGO in Papua New Guinea.

C. Syms

Craig Syms is a lecturer at the School of Marine and Tropical Biology at James Cook University. He has published a range of papers on the relationships between reef fishes and their habitats. His current research examines the role of different spatial and temporal scales of habitat variability in structuring communities. In addition to research, he has also advised extensively on marine resource management and evaluation of marine reserves in California. He teaches postgraduate sampling and experimental design and statistics, and supervises postgraduate students in a range of different marine projects.

C. C. Wallace

Carden Wallace is Principal Scientist Emeritus, Biodiversity and Geosciences Program, Queensland

Museum. She has researched biodiversity and evolution of staghorn corals on reefs around the world and is author of the monograph *Staghorn Corals of the World*. She was a member of the group from James Cook University who described the coral mass spawning phenomenon and has a particular interest in the corals and sea anemones of Moreton Bay. She now works on the fossil history and evolution of family Acroporidae with colleagues from many countries.

J. M. Webster

Jody Webster is Co-Coordinator of the Geocoastal Research Group in the School of Geosciences at The University of Sydney. His research in sedimentology and stratigraphy focuses on carbonate sedimentology, climate change, and tectonics around the world (e.g. the Great Barrier Reef, Tahiti, Hawaii, Papua New Guinea, Seychelles and Brazil). Jody is particularly interested in coral reef and carbonate platform systems, both modern and ancient, and their associated sedimentary systems (i.e. slopes and canyons) as tools to address fundamental questions in paleoclimate variability and tectonics, and in turn the influence of these factors on the geometry, composition and evolution of these sedimentary systems. Jody is also heavily involved in several large international research programs including the International Ocean Discovery Program, which is focused on recovering sediment cores from the sea bed to understand past sea level and climate changes.

R. C. Willan

Richard Willan is a molluscan taxonomist, presently Senior Curator of Molluscs at the Museum and Art Gallery of the Northern Territory in Darwin. Formerly he was on the staff of the Zoology Department at the University of Queensland in Brisbane, from where he studied the molluscs of the Great Barrier Reef. During that time he visited research stations on the reef, studying sea slugs and bivalves. He is the authority on invasive marine molluscs in Australia. As the result of many visits

to the Heron Island Research Station, he collaborated with Julie Marshall to write *Nudibranchs of Heron Island, Great Barrier Reef*.

E. Wolanski

Eric Wolanski is a coastal oceanographer and holds positions at James Cook University and the Australian Institute of Marine Science. He has 402 publications. He is a fellow of the Australian Academy of Technological Sciences and Engineering, the Institution of Engineers Australia (ret.), and l'Académie Royale des Sciences

d'Outre-Mer (Belgium). He was awarded an Australian Centenary medal, a Doctorate Honoris Causa from the Catholic University of Louvain and from Hull University, a Queensland Information Technology and Telecommunication award for excellence, and the 1st Lifetime Achievement Award from the Estuarine and Coastal Science Association. He is a member of the Scientific and Policy Committee of EMECS (Japan) and of the Scientific and Technical Advisory Board of Danubius-pp (Europe). He is an Erasmus Mundus scholar and is listed in Australia's *Who's Who*.

Introduction to the Great Barrier Reef

P. A. Hutchings, M. J. Kingsford and O. Hoegh-Guldberg

The Great Barrier Reef (GBR) is one of the world's most spectacular natural features and one of the few biological structures visible from space (Fig. 1.1). The sheer size of the GBR Marine Park (over 360 000 km²), as well as its beauty and biodiversity, draws people from all over the world. The reef stretches over 2200 km from subtropical waters (~27°S) to the tropical waters of Torres Strait (8°S) and as far as 400 km from the coast to the outer shelf slope. For Australians, the reef is a source of much pride and enjoyment. The GBR is one of the most prominent icons of Australia, with the majority of visitors coming specifically to Australia to see it. This drawcard for visitors underpins substantial income from industries such as tourism and commercial and recreational fisheries. What is perhaps surprising about the value generated by this extraordinary ecosystem for Australia is how little we know about the reefs that make up the GBR. We are still struggling to describe the myriad of species and processes that define the GBR – all with an urgency now that is heightened by the unprecedented local and global pressures that currently face it.

The frequency, and in some cases intensity, of major events affecting the GBR have increased in recent years. The first major recorded coral bleaching incident was in the early 1980s, followed by events in 1987, 1998, 2002, 2010, 2015 and 2016. The last two bleaching incidents resulted in an 80% loss of coral in northern regions of the GBR, while southern regions were largely unaffected. Although the number of cyclones affecting the reef has if

anything dropped, the intensity has increased. In the last 12 years the reef has been subjected to five category 5 cyclones, one of which (Cyclone Hamish) wreaked havoc to habitats on outer reefs of the GBR over ~1000 km. Threats from crown-of-thorns starfish, overfishing, run off from the land and a warming planet are impacts that organisms of the GBR have to deal with. Accordingly, these threats and challenges sharpen our resolve to understand how these factors can affect habitats and how a knowledge of pattern and process can provide the solutions that are so desperately needed if we are to avoid a heavily compromised GBR that is no longer a coral-dominated paradise.

Consequently, the underlying concept behind this book is to describe the patterns, processes, human interactions and organisms that underpin large reef ecosystems such as the GBR. Although much of the content of this book is focused on the GBR, we consider it highly relevant to coral reefs in other parts of Australia and the rest of the world. There has been no other comprehensive introduction to the biology, environment and management of the GBR, especially with regard to the major processes that underpin it or how issues such as deteriorating coastal water quality and climate change affect it. Extending our knowledge and understanding of these processes is vital if we are to sustainably manage the Reef, and reassure its future, especially during the coming century of rapid, anthropogenic climate change. Only by understanding and managing the GBR wisely do we have a chance of keeping the GBR 'great'.

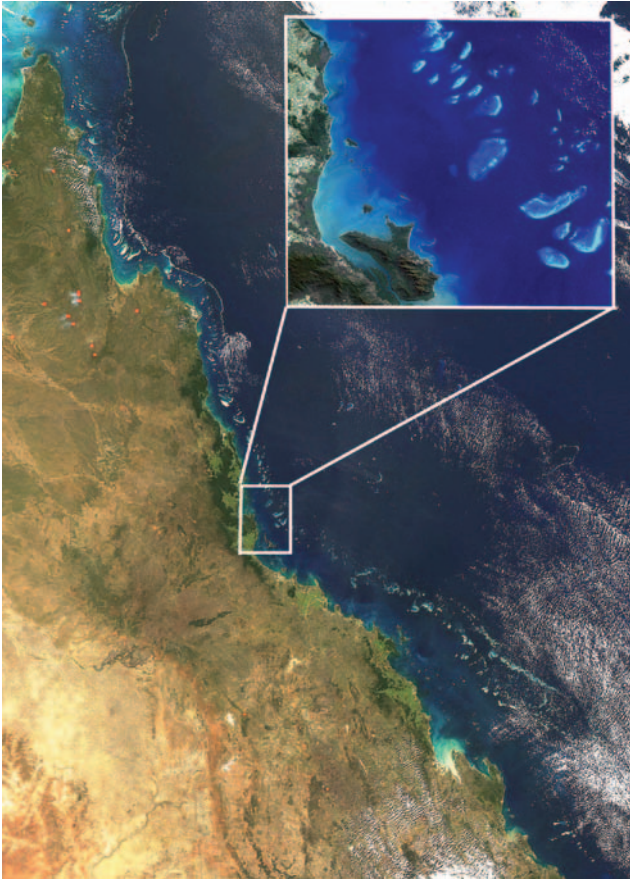


Fig. 1.1. Quasi-true colour image from space showing the Great Barrier Reef along the continental shelf of north-eastern Australia from Cape York to Gladstone (~2000 km). A mosaic of reefs can be seen parallel to the mainland and extending hundreds of kilometres across the GBR. (Source: Image generated from the Moderate Resolution Imaging Spectroradiometer (MODIS), data courtesy of NASA/GSFC, image courtesy of Dr Scarla Weeks, Centre for Marine Studies at The University of Queensland. Inset shows a closer cross-shelf view of the reefs out from Hinchinbrook, near Townsville).

This book is aimed at undergraduate and post-graduate students, the informed public, as well as researchers and managers who would like to familiarise themselves with the complexity of coral reefs such as the GBR. The project arose out of an advanced undergraduate course that has been held on the GBR for almost 20 years and which generated extensive discussions on the need for a book such as this at the Australian Coral Reef Society (ACRS). Through the Society and the course, we were able to invite the appropriate international

experts to contribute to this book. The ACRS (which started out as the Great Barrier Reef Committee) is the oldest coral reef society in the world and most of the authors are members and associates of this society. It was also intimately involved in the establishment of the world's largest marine park, the GBR Marine Park in 1975. This huge park, with some of the largest no-take areas in the global ocean, was enlarged and rezoned in 2004 based on our much increased scientific understanding of coral reefs and their challenges and solutions.

The book is divided into three sections. The first section focuses on the geomorphology, paleobiology and oceanography of the GBR. Here, various habitats of the GBR are discussed, not only from the point of view of coral-dominated ecosystems, but also with regard to the important associated inter-reefal areas (Chapters 2–9). These components of the GBR, along with catchments and offshore deeper waters, are highly interconnected (Fig. 1.2). The second section of the book focuses on the major processes that are affecting the reef and includes the description of organisms and processes that contribute to photosynthetic activity and primary production, as well as the flow of energy and nutrients within coral reef ecosystems. Other chapters deal with the major forces within and around the reef, illustrating its inherent dynamic nature. This section also reviews our current understanding of how local challenges (i.e. declining water quality and over exploitation of fisheries) as well as aspects of climate change (e.g. ocean warming, acidification and intensifying storms) have changed the circumstances under which coral reefs have otherwise prospered for thousands if not tens of millions of years (Chapters 10–14).

The third and final section of this book deals with the diversity of organisms that live in and around coral reefs (Fig. 1.3). In this section, the reader is introduced to broad categories of organisms (e.g. plankton) as well as the basic taxonomy of the major groups of organisms and their biology and ecology (Chapters 15–32). We believe that this provides the reader with a fascinating journey



Fig. 1.2. Crossing the Blue Highway. Designed and written by science communicator Russell Kelley and published by the ACRS, the Blue Highway poster portrays the reefs of the Great Barrier Reef as part of a larger supporting system that includes the coastal catchments and connects numerous interacting ecosystems from ridge to reef. The poster illustrates how natural nutrient loads from runoff and ocean upwelling fuel a connected mosaic of ecosystems and the role inter-reef habitats play in supporting migrating species as they move from inshore nursery grounds to the outer reefs. The model species of fish is *Lutjanus sebae* (red emperor snapper) that spawn near the shelf edge and recruit to estuaries as larvae. Juveniles move from recruitment habitat to reefs and inter-reefal habitats, before they mature. Printed copies of this poster are available from the GBRMPA (Artwork: G. Ryan).

through the unique and spectacular biodiversity of coral reefs. By weaving the basic taxonomy of these groups together with fascinating details of their lives, it is hoped that the interest of the reader will be inspired to explore this incredible diversity.

Throughout this book we come back to the major challenges that reefs face in our changing world. For this reason, our book is unique in that it reviews the past, current and future trajectories and possible management responses of the GBR. Globally, coral reefs are at risk and knowledge-based management is absolutely critical. The GBR is at the forefront of this, with a growing risk of

being severely degraded in the next few years if we don't understand the problems and apply evidence-based solutions.

It has been 11 years since the first edition of this book was published (2008). With a new decade, the pressures on the GBR have increased and trends such as increasing temperatures and ocean pH continue to warrant responses at a global and local level; you will find examples of this in all the chapters. We have added two extra chapters one on mesophotic reefs (Chapter 7) and another on fisheries of the GBR (Chapter 10). Chapter 7 reveals amazing diversity in habitats and associated fishes



Fig. 1.3. A rich diversity of coral species in shallow water on the GBR. A large aggregation of plankton-feeding fish hover close to the complex architecture of the reef that provides them with shelter (Photo: D. Wachenfeld).

on the shelf slopes of the GBR that have been largely unknown until now (Fig. 1.4). Fishing methods and markets have changed with time and Chapter 10 describes changes in time and new challenges that relate to managing GBR fisheries with methods other than zoning plans.

Impacts of coral reefs are a global issue and most, or all, of the impacts we describe for the GBR are also true of other reef systems of the world that include the Caribbean, Indo-Pacific and Red Sea. Furthermore, many of the habitat-forming organisms (e.g. corals), those that influence them, such as herbivorous fishes, starfish and bioeroders, as well as the organisms that simply use different habitats on the GBR are similar in other coral reef systems. Detailed accounts of other coral reef ecosystems include Riegl and Dodge on reefs of the USA and that of the Japanese Coral Reef Society (MEJCRS).

For most chapters, citations are not included in the text, but a list of helpful references is provided in 'Further reading' at the end of the chapter. However, for some chapters, citations are inserted within the text because they refer to specific (sometimes controversial) points.

Finally, it is our hope that this book will help develop a better understanding of coral reefs, engage the next generation of coral reef scientists, and assist in maintaining the ecological resilience of coral reefs such as the GBR, in order to allow them to survive the challenges of the future. This said, we hope that you will enjoy using this book to discover the intricacies of the world's most diverse marine ecosystem. As editors, we would like to thank the generous contributions from the many authors that have contributed to this book, the production of which would have not been possible otherwise.



Fig. 1.4. Deep reefs of tropical environments are a new frontier and our understanding of their uniqueness and connectedness with shallower environments is in its infancy. Deep Reef ~70 m at 'Deep Arcade' on the north-western wall of Osprey Reef (Image: Simon Mitchell).

Further reading

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SECTION 1

Nature of the reef

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Geomorphology of coral reefs with special reference to the Great Barrier Reef

D. Hopley and S. Smithers

Coral reef geomorphology is the study of the morphological development of coral reef structures and associated landforms across a range of temporal and spatial scales. It integrates ecological, physical and geological information to understand controls on coral reef formation, morphological diversity and change – past, present and future. Coral reefs are biogenic limestone structures built by corals and other carbonate-producing organisms in shallow tropical and subtropical marine settings, where they grow upwards or towards sea level as landforms able to resist wave action. Most coral reefs have long and punctuated histories of development, comprising episodes of reef growth when global sea levels are high during interglacials interspersed with periods of emergence and erosion during the ice ages when global sea levels were up to 125 m lower. As such, many coral reefs consist of sequences of carbonate materials deposited by former reefs, with successive units separated by solutional unconformities developed when low sea levels exposed them to subaerial erosion. These limestone structures form the substrates on which many modern coral reefs now grow as relatively thin living veneers of corals and other reef organisms. The distribution, size and shape of these substrates significantly influences the geomorphology of many modern reefs.

Coral reef landforms include both coral reefs as described earlier and geomorphic features

comprised of reefal sediments such as reef islands, sediment aprons and beaches. Unlike most other landforms, those on coral reefs are the result of interactions of ecological processes that influence the occurrence and productivity of calcium carbonate producers, and physical processes such as waves, currents and sea-level fluctuations that also influence ecological processes and can redistribute carbonate material across a reef system. Importantly, feedbacks occur between the ecological, physical and geological processes operating on coral reefs that are captured in geomorphological investigations. For example, as a coral reef grows towards the surface and into the wave base, the ecology of the reef may change to reflect increased hydrodynamic stresses. These ecological changes are recorded in a reef's geomorphology as changes in the composition of contributing organisms, reef accretion rates, and reef structure and fabric. However, as a reef grows upwards it also modifies waves and currents, influencing the distribution of carbonate-producing species and their products across it, evidence of which is also preserved geomorphologically and structurally. Coral reefs are thus 'living' and dynamic landforms that develop geomorphologies that both respond to and modify the environment in which they grow, all of which changes through time as growth proceeds.

Corals are the major reef-builders on most coral reefs (up to 10 kg CaCO₃/m²/year). However, many