Flooding caused by a rise in global mean sea level has the potential to affect the lives of more than 1 billion people in coastal areas worldwide. There have been significant changes in sea level over the past 2 million years, both at the local and global scales, and a complete understanding of natural cycles of change as well as anthropogenic effects is imperative for future global development.

This book reviews the history of research into these sea-level changes and summarises the methods and analytical approaches used to interpret evidence for sea-level changes. It provides an overview of the changing climates of the Quaternary, examines the processes responsible for global variability of sea-level records, and presents detailed reviews of sea-level changes for the Pleistocene and Holocene. The book concludes by discussing current trends in sea level and likely future sea-level changes.

This is an important and authoritative summary of evidence for sea-level changes in our most recent geological period, and provides a key resource for academic researchers, and graduate and advanced undergraduate students, working in tectonics, stratigraphy, geomorphology and physical geography, environmental science, and other aspects of Quaternary studies.

Colin V. Murray-Wallace is a Quaternary geologist and currently a Professor and Head of the School of Earth & Environmental Sciences in the University of Wollongong. His long-standing research interests have centred on Quaternary sea-level changes, neotectonics, carbonate depositional systems and amino acid racemisation dating, and he has undertaken coastal field investigations in southern Australia, Vietnam, Hawaii, and in South Africa. Professor Murray-Wallace was project leader of IGCP (International Geological Correlation Programme) project 437 (1999–2003) ‘Coastal environmental change during sea-level highstands’, and leader of the INQUA (International Union for Quaternary Research) Coastal and Marine Commission (2004–2007). He has served as Editor-in-Chief of the journal Quaternary Science Reviews since 2008.

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of both the IGCP project 274 ‘Coastal Evolution in the Quaternary’, and its follow-up project, and on the Scientific Steering Committee of the LOICZ (Land–Ocean Interactions in the Coastal Zone) project within IGBP. He was a lead author on the coastal chapter in the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment report. In 2012 he was awarded the R.J. Russell Award from the Coast and Marine Specialty Group of the Association of American Geographers.
QUATERNARY SEA-LEVEL CHANGES
A Global Perspective

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AND
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University of Wollongong, Australia

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To John Chappell
in appreciation of his truly outstanding contributions
to the study of Quaternary sea-level changes
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Preface

When the work of the geologist is finished and the final comprehensive report is written, the longest and most important chapter will be upon the latest and shortest of the geological periods.

(Grove Karl Gilbert, 1890, p. 1)

The investigation of relative sea-level changes has a rich intellectual lineage and has played a central role in development of the Earth Sciences. With the emergence of empirically based explanations for field observations of natural phenomena, an increasing appreciation that the ocean surface has not remained constant, relative to land, prompted several lines of geological inquiry. Myths and legends, as well as religious explanations for Earth surface events, such as flood legends, provided an early framework, examined by the emerging discipline of Earth Science. Extensive fieldwork in the nineteenth century, culminating in the Glacial Theory, and technological developments in geochemistry and geochronology in the latter twentieth century led to a geologically coherent explanation for fluctuations in relative sea level during the Quaternary, the past 2.59 Ma.

Responses of the Earth’s surface environments to Quaternary sea-level changes are complex and far-reaching. The effects of Quaternary sea-level changes extend from upper reaches of near-coastal drainage basins to the edge of continental shelves. Sea-level changes have amplified the effects of local climate changes, such as enhanced aridity due to increased continentality at times of lower sea level, and promoted marine abrasion along many bedrock-dominated coastlines. During the Quaternary, relative sea-level changes have exposed continental shelves and in places created land bridges which have acted as dispersal routes for a diverse range of biota, including early humans. Relative sea-level changes since the Last Glacial Maximum (LGM) 21,000 years ago, have resulted in the modern configuration of coastlines, and the coastal landforms we see today have developed in the past few millennia. The significance of sea-level changes in coastal landscape evolution is likely to have increased following the middle Pleistocene transition, approximately 1.2 Ma ago, when the amplitude of sea-level changes between glacial and interglacial, as well as the duration of glacial cycles, increased.
A paper by Rhodes Fairbridge, entitled 'Eustatic changes in sea level', published in *Physics and Chemistry of the Earth* in 1961, provided a stimulus for both of us. The earliest glimpses of this book began when one of us (CVM-W) was fossicking in the basement stacks of the Barr Smith Library in the University of Adelaide. There, he unearthed this paper which helped establish a nascent appreciation of the significance of relative sea-level changes in the geological record and represented a wonderful source for reflection, generating many questions. What were the causes of Quaternary sea-level changes? Why do different geographical regions appear to have contrasting relative sea-level histories? Were these seemingly contrasting records real or an illusory artefact of sampling? Could the contrasting records be explained within a coherent geohistorical framework? Would future technological improvements in aspects of geochemistry and geochronology begin to address many of the issues raised in the paper? Is the record of Quaternary sea-level changes relevant to an understanding of future sea-level changes?

The paper also focused the research and thinking behind the sea-level research that CDW undertook across the tropics, following his discovery of an original reprint of the paper hidden away in a cupboard in the Department of Geography at the University of Cambridge. In many respects the questions raised by Fairbridge's paper continue to be the focus of ongoing research, and are addressed in this book.

The paper by Fairbridge led to the realisation that Australian coastal landforms contributed significantly to a global perspective on Quaternary sea-level changes. Showing a high degree of tectonic stability due to several cratons, and located in the far-field of continental icesheets with minimal direct glaciation, Australia represents an ideal location to undertake palaeo-sea-level investigations. One person who seized on that opportunity, and has made an unparalleled contribution to the science of sea-level changes, is John Chappell, to whom we dedicate this book. Through meticulous research, John unravelled the complex series of changes in relative sea level from palaeo-sea-level evidence on the Huon Peninsula in Papua New Guinea, on the northern geological margin of the Australian continent, from the later middle Pleistocene through to the late Holocene. He complemented these studies with investigations more widely across the Australian continent. John has profoundly influenced our research, and the research of many other investigators around the world; it has been a pleasure and privilege to work alongside him, to learn from him, and to share our ideas with him.

Many people have influenced us over the years and we are particularly grateful for the lengthy and valuable discussions on aspects of Quaternary sea-level changes, as well as field excursions, with Tony Belperio, David Bowen, Robert Bourman, John Cann, Bill Carter, Peter Cowell, Patrick De Deckker, Robert Devoy, Charles Fletcher III, Don Forbes, Roland Gehrels, Victor Gostin, Nick Harvey, David Hopley, Kurt Lambeck, Antony Long, Roger McLean, Dan Muhs, Robert Nicholls, Richard Peltier, Paolo Pirazzoli, Peter Roy, Yoshi Saito, Ian Shennan, Andy Short, David Smith, Tom Spencer, David Stoddart, Bruce Thom, Sandy Tudhope,
Masatomo Umitsu, and the late Orson van de Plassche, amongst others. We have each pursued these interests through the activities, in particular, of successive projects of IGCP (the International Geological Correlation Programme, now called the International Geoscience Programme), through which we have met a wider sphere of sea-level researchers. In addition, numerous ‘Time Lords’ (geochronologists) have provided inspiration and support over the years, including Mike Barbetti, Steve Eggins, Stewart Fallon, David Fink, Rainer Grün, Quan Hua, David Price, Ulrich Radtke, John Wehmiller, Jian-xin Zhao, and the late John Prescott. Several colleagues read drafts of chapters, or responded to questions to assist our understanding, or clarify and supply data or illustrative material, including Robert Bourman, Allan Chivas, Tim Cohen, Zenobia Jacobs, Richard Roberts, and David Smith. We are grateful for their comments, but accept responsibility for any errors or omissions. Colleagues in the School of Earth & Environmental Sciences and the GeoQuest Research Centre at the University of Wollongong who have provided inspiration over the years include Ted Bryant, Allan Chivas, Lesley Head, Brian Jones, Gerald Nanson, David Price, and Bob Young. We have also had the privilege of supervising several gifted postgraduate students who are continuing the Australian academic tradition in sea-level research, including Brendan Brooke, Mack Dixon, David Kennedy, Craig Sloss, Scott Smithers, and Adam Switzer.

We would particularly like to thank Peter Johnson, cartographer par excellence, for preparing all the figures. We have a long working relationship with Peter and sincerely thank him for his dedication to this project. We also express our gratitude to the editors at Cambridge University Press; in particular, we thank Laura Clark, Susan Francis, Abigail Jones, Caroline Mowatt, and Sara Brunton for their help and encouragement. Finally, we thank our partners Gemma and Salwa for their forbearance during this project.
Abbreviations

AAR  amino acid racemisation
ABOX  acid–base–wet oxidation
AHD  Australian Height Datum
AMS  accelerator mass spectrometry
AOGCM  Atmosphere–Ocean General Circulation Model
APSL  above present sea level
AR4  Fourth Assessment Report
BAU  business as usual
BP  Before Present (radiocarbon terminology – before 1950 AD)
BPSL  below present sea level
cal. yr BP  calendar years before present (where present is 1950 AD)
CCD  carbonate compensation depth
CLIMAP  Climate: Long-Range Investigation, Mapping and Prediction
CMAT  current mean annual air temperature
De  equivalent dose
DORIS  Doppler Orbitography and Radiopositioning Integrated Satellite
DSDP  Deep Sea Drilling Project
EDT  effective diagenetic temperature
EMIC  Earth Models of Intermediate Complexity
ENSO  El Niño–Southern Oscillation
EPA  Environmental Protection Agency
EPICA  European Project for Ice Coring in Antarctica
EPILOG  Environmental Processes of the Ice-Age: Land, Oceans, Glaciers
ESA  European Space Agency
ESR  electron spin resonance
FAD  First Appearance Datum
FAR  First Assessment Report
FBI  fixed biological indicator
Ga  giga anna (billions of years; American billion)
GI  Greenland Interstadial
List of abbreviations

GIA  glacial isostatic adjustment
GNSS  Global Navigation Satellite System
GOCE  Gravity field and Ocean Circulation Explorer
GPR  ground-penetrating radar
GPS  Global Positioning System
GRACE  Gravity Recovery And Climate Experiment
GS  Greenland Stadial
Gt  gigatonnes
Gy  Gray (absorbed dose of ionising radiation equal to 1 J/kg)
HAT  highest astronomical tide
ICP-MS  inductively coupled plasma mass spectrometry
IGCP  International Geosciences Programme (was International Geological Correlation Programme)
INQUA  International Union for Quaternary Research
IODP  Integrated Ocean Drilling Program
IPCC  Intergovernmental Panel on Climate Change
IRD  Ice Rafted Debris
IRSL  infrared-stimulated luminescence
ITRF  International Terrestrial Reference Frame
ka  kilo anna (thousands of years)
kg  kilogram (1000 grams)
LA-ICP-MS  laser-ablation inductively coupled plasma mass spectrometry
LAT  lowest astronomical tide
LGM  Last Glacial Maximum
LOICZ  Land–Ocean Interactions in the Coastal Zone
m  metre
Ma  mega anna (millions of years)
MC-ICP-MS  multi-collector, inductively coupled plasma mass spectrometry
MHW  mean high water
MHWN  mean high water neaps
MIS  Marine Isotope Stage
MLWN  mean low water neap
MLWS  mean low water springs
mm  millimetre (one-thousandth of a metre)
MPT  middle Pleistocene Transition
MSL  mean sea level
MTL  mean tide level
NADW  North Atlantic Deep Water
NGA  National Geospatial-Intelligence Agency
NGMS  noble gas mass spectrometry
NGRIP  North Greenland Ice Core Project
List of abbreviations

NSW    New South Wales
ODP    ocean drilling project
OSL    optically stimulated luminescence
Pa     Pascal (unit of pressure equal to 1 N/m²; 1 newton per square metre)
PDB    Peedee Belemnite
PMS    palaeo-marsh surface
ppmv   parts per million by volume
PSMSL  Permanent Service for Mean Sea Level
RCP    representative concentration pathways
RMS    root-mean square
SAR    Second Assessment Report
SLE    sea-level equation
SLIP   sea-level index point
SMOW   Standard Mean Ocean Water
SRES   Special Report on Emissions Scenarios
SSH    sea-surface height
SST    sea-surface temperature
T/P    TOPEX/Poseidon
TAR    Third Assessment Report
TIMS   thermal ionisation mass-spectrometry
TL     thermoluminescence
TT-OSL thermally transferred optically stimulated luminescence
VLM    vertical land movement
WAIS   West Antarctic Icesheet
WOCE   World Ocean Circulation Experiment
XBT    expendable bathythermograph