QUATERNARY SEA-LEVEL CHANGES

A Global Perspective

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.

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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.

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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 glacials and interglacials, 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

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

NSW	New South Wales
ODP	ocean drilling project
OSL	optically stimulated luminescence
Pa	Pascal (unit of pressure equal to 1 N/m^2; 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