

Tsunami

The Underrated Hazard (Second Edition)



“The Hollow of the Deep-Sea Wave off Kanagawa” (*Kanagawa Oki Uranami*), a color woodcut, No. 20 from the series *Thirty-Six Views of Fuji*, circa 1831, by Katsushika Hokusai, a famous late 18th- and early 19th-century Japanese artist. Textbooks and many websites depict this wave as a tsunami wave, but in fact it is a wind-generated wave. It has a special shape called an *N*-wave, characterized by a deep leading trough and a very peaked crest. Some tsunami, such as the one that struck the Aitape coast of Papua New Guinea on July 17, 1998, emulate this form close to shore.

Edward Bryant

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Contents

Preface	xi
Acknowledgements	xv
List of figures	xxi
List of tables	xxvii
List of symbols	xxix
List of abbreviations and acronyms	xxxiii
PART I Tsunami as a known hazard	1
1 Introduction	3
Introduction	3
Five stories	4
1 An Aboriginal legend.	4
2 The Kwenaitchechat Legend, Pacific Northwest.	5
3 Krakatau, August 27, 1883	6
4 Burin Peninsula, Newfoundland, November 18, 1929	7
5 Papua New Guinea, July 17, 1998	9
Scientific fact or legends?	10
Causes of tsunami.	12
Distribution and fatalities	14
Mediterranean Sea.	15
Caribbean Sea	15

	Pacific Ocean Region (including Indonesia)	16
	New Zealand and Australia	22
	Bays, fjords, inland seas, and lakes	23
	Meteorological phenomena, freak waves, and storm surges	24
2	Tsunami dynamics	27
	Introduction	27
	Tsunami characteristics	27
	Tsunami wave theory	31
	Resonance	36
	Shallow-water, long-wave theory	37
	Run-up and inundation	40
	Run-up	40
	Inland penetration	45
	Depth and velocity at shore	46
	PART II Tsunami-formed landscapes	49
3	Signatures of tsunami in the coastal landscape	51
	Introduction	51
	Depositional signatures of tsunami	53
	Buried sand or anomalous sediment layers	53
	Foraminifera and diatoms	57
	Boulder floaters in sand	59
	Dump deposits	60
	Mounds and ridges	63
	Chevrons and dune bedforms	65
	Smear deposits	67
	Large boulders and piles of imbricated boulders	68
	Turbidites	75
	Erosional signatures of tsunami	77
	Small-scale features	77
	Large-scale features	83
	Flow dynamics	86
4	Coastal landscape evolution	91
	Introduction	91
	Catastrophism vs. uniformitarianism	91
	Tsunami vs. storms	94
	The nature of tsunami vs. storm deposits	95
	Movement of boulders	96

Types of coastal landscapes created by tsunami	98
Sandy barrier coasts	98
Deltas and alluvial plains	101
Rocky coasts	103
Atolls	104
Examples of tsunami-generated landscapes: Australia	106
South coast of New South Wales	106
Cairns Coast, Northeast Queensland	109
Northwest West Australia	112
Other examples of tsunami-generated landscapes	115
Grand Cayman	115
Bahamas	117
Chilean coast	119
PART III Causes of tsunami	125
5 Earthquake-generated tsunami	127
Introduction	127
Seismic waves	127
Magnitude scales for earthquakes and tsunami	129
Earthquake magnitude scales	129
Tsunami earthquakes	130
Tsunami magnitude scales	132
Seismic gaps and tsunami occurrence	134
Relationships between earthquakes and tsunami	135
How earthquakes generate tsunami	135
Linking tsunami run-up to earthquake magnitude	139
Large historical tsunamigenic earthquakes	140
Lisbon, November 1, 1755	140
Chile, May 22, 1960	143
Alaska, March 27, 1964	149
Events of the 1990s	154
Slow Nicaraguan tsunami earthquake of September 2, 1992	156
Flores, December 12, 1992	158
The Hokkaido Nansei–Oki tsunami of July 12, 1993	160
Papua New Guinea, July 17, 1998	163
The Indian Ocean tsunami, December 26, 2004	167
6 Great landslides	179
Introduction	179
Causes of submarine landslides	181

How submarine landslides generate tsunami	184
Historical tsunami attributable to landslides	186
The Lituya Bay landslide of July 9, 1958	187
Grand Banks tsunami, November 18, 1929	189
Geological events	193
Hawaiian landslides	193
The Canary Islands	196
The Storegga slide of 7950 BP	198
Bristol Channel, U.K., January 30, 1607	205
The risk in the world's oceans	213
Other volcanic islands	213
Other topography	215
7 Volcanic eruptions	217
Introduction	217
Causes of volcano-induced tsunami	217
Krakatau, August 26–27, 1883	222
Santorini, around 1470 BC	225
8 Comets and asteroids	231
Introduction	231
Near Earth objects (NEOs)	231
What are they?	231
How frequent have comet and asteroid impacts been?	234
How do extraterrestrial objects generate tsunami?	236
Mechanisms for generating tsunami	236
Size of tsunami	238
Geological events	245
Hypothesized frequency	245
Chicxulub, the Cretaceous–Tertiary (K/T) extinction event	247
Other events	251
<i>Deluge Comet</i> impact event 8,200 ± 200 years ago	251
The Mahuika Comet impact event and eastern Australia	253
Geological evidence for mega-tsunami	254
Maori legends supporting a cosmogenic event	257
Aboriginal legends supporting a cosmogenic event	258
Timing of Mahuika	260
Events in the Kimberley, Western Australia	263
Legends supporting cosmogenic tsunami	263
Field evidence	266

PART IV Modern risk of tsunami	271
9 Risk and avoidance	273
Introduction	273
What locations along a coast are at risk from tsunami?	277
Warning systems	280
The Pacific Tsunami Warning Center	280
Flaws in regional warning systems	285
Localized tsunami warning systems	286
How long have you got?	290
Where should you go if there is a tsunami warning?	291
What if it is an asteroid or comet?	294
Is it all that bad? The case of Sydney	295
10 Epilogue	299
Five stories	299
1 An unsuspected earthquake	299
2 An unassuming earthquake	302
3 A submarine landslide	303
4 A volcanic eruption	304
5 An asteroid impact with the ocean	305
Concluding comments	306
References	309
Index	325

Preface

Before 10 AM, March 18, 1989, I was a process geomorphologist who had dabbled into the coastal evolution of rock platforms and sand barriers along the New South Wales coastline of eastern Australia. I was aware of tsunamis, and indeed had written about them, but they were not my area of research expertise. No one had considered that tsunamis could be an important coastal process along the east coast of Australia. On that March morning in brilliant sunshine, with the hint of a freshening sea breeze, my life was about to change. I stood with my close colleague Bob Young, marveling at a section of collapsed cliff at the back of a rock platform, at Haycock Point south of Merimbula. We saw a series of angular, fresh boulders jammed into a crevice at the top of a rock platform that did not appear to be exposed to storm waves. Unlike many before us, we decided that we could no longer walk away from this deposit without coming up with a scientific reason for the field evidence that was staring us in the face. After agonizing for over an hour and exhausting all avenues, we were left with the preposterous hypothesis that one or two tsunami waves had impinged on the coast. These tsunamis were responsible, not only for jamming the rocks into the crevice, but also for the rockfall that had put the rocks on the platform in the first place. We did not need a big tsunami wave, just one of about 1 m–2 m depth running about 5 m–6 m above the highest limits of ocean swell on the platform. Over the next eight years that wave grew immensely until we finally found evidence for a mega-tsunami overwashing a headland 130 m above sea level at Jervis Bay along the same coastline. Subsequent discoveries revealed that more than one wave had struck the New South Wales coast in the last 7,000 years, that mega-tsunamis were also ubiquitous around the Australian coast, and that the magnitude of the field evidence was so large that only a comet or asteroid impact with the Earth could conceivably have generated such waves. From being a trendy process geomorphologist wrapped in the ambience of the 1960s, I had descended into the abyss of catastrophism dredged from the dark ages of geology when it was an infant discipline. Bob Young subsequently retired in 1996, but his clarity of thinking about the larger picture and his excellent eye for the landscape are

present in all of our publications and reflected in this textbook. There was not a day in the field with Bob that did not lead to excitement and discovery.

Since 1995, I have worked closely with Jon Nott from James Cook University in Cairns, Queensland. Bob Young trained Jon, so I have lost none of Bob's appreciation for landscape. Jon has enthusiastically continued field research with me in remote locations, and has uncanny luck for being able to obtain funding for a strange topic in an age where economic rationalism and blinkered adherence to the safe academe of the 1960s dominates. To stand with Jon at Point Samson, Western Australia, and both realize simultaneously that we were looking at a landscape where a mega-tsunami had washed inland 5 km—not only swamping hills 60 m high, but also cutting through them—was a privilege. Few geomorphologists who have twigged for the first time to a catastrophic event have been able to share that experience in the field with anyone else. Jon, Bob, and I formulated the signatures of tsunami described in Chapter 3, while Jon developed the equations for boulder transport also used in this chapter. David Wheeler did the fieldwork that first identified the dramatic tsunami chevron-shaped dunes at Steamers Beach, Jervis Bay. Since 2002, I have had the fortune of working with Simon Haslett of Bath Spa University in the U.K. By chance, a brief academic visit to the shores of the Bristol Channel in Wales with time to inspect medieval churches led us to stumble across what we believe was a tsunami on January 30, 1607. Much of the material about this event in the book is due to Simon's ability to search for, and interrelate, obscure manuscripts, and his dogged attention to detail in the field. All of us have withstood the rebuff of peers that goes with ideas on catastrophism in an age of "minimal astonishment". I hope that this book conveys to some the excitement of our discoveries about tsunami.

It is difficult to write a book on tsunami without using equations. The relationships among tsunami wave height, flow depth at shore, boulder size, and bedform dimensions were crucial in our conceptualization of mega-tsunami and their role in shaping coastal landscapes. In this second edition, the formulas have been either simplified further or kept to a minimum. Wherever I have used equations, I have tried to explain them by including a supporting figure or photograph. Terms used in equations are only defined once where they first occur in the text, unless there could be confusion about their meaning at a later point in the book. For reference, all terms and symbols are summarized at the beginning of the text. Many dates are only reported by year. Where ambiguity could exist, the prefix AD (Anno Domini) or the suffix BC (Before Christ) is used. If there is no ambiguity, then the affix is dropped and the year refers to AD. In some cases the term BP is used to measure time. This refers to years before present and is commonly used when reporting radiocarbon or thermoluminescence dates. Units of measurement follow the International System of Units except for the use of the terms kilotons and megatons. There are many definitions of the terms meteorite, asteroid, and comet. We have used the terminology favored by those studying the possibility of near Earth objects (NEOs) colliding with the Earth. A comet is any object consisting mostly of ice. An asteroid is any object consisting of rock and larger than 50 m in diameter. If it is less than 50 m in diameter, then the object is a meteoroid. If an asteroid impacts with the Earth, it is still an asteroid, whereas if a meteoroid impacts with the Earth, it is called a meteorite. In

order to convey viewpoints and arguments, unobstructed by copious referencing, strict adherence to formal, academic referencing has been relaxed. Usually, each section begins by listing the relevant journal articles or books that either have influenced my thinking or are central to the topic. Again, I apologize to anyone who feels that I have ignored their crucial work but the breadth of coverage precluded a complete review of the literature on many topics. All references to publications can be found at the end of the book. Some articles and data were acquired from the Internet. The Internet addresses in these cases are also referenced. Such material may not be readily available because the addresses have changed or because of the lack of an archival tradition for this new resource medium. Where material is not available in the literature or through these forums, it has been acknowledged at the beginning of the text.

Finally many researchers have published their field descriptions and interpretations without ever invoking mega-tsunami as an explanation. To find somebody re-interpreting their results may appear offensive. We publish our results not necessarily to duplicate the past, but to further knowledge. In many cases, I have found that tsunami explain the field evidence in publications better than the explanation given at the time.

Ted Bryant
August 2, 2007

Acknowledgments

A number of people and organizations should be acknowledged for their information about tsunamis. First is the U.S. government, which has a policy of putting all its information in the public domain. Many photographs used throughout this book and detailed information on events were obtained from U.S. government agencies and their employees. None of these accepts liability nor endorses material for any purpose. I have acknowledged these sources in this book, but mention here the National Geophysical Data Center (NGDC) at <http://www.ngdc.noaa.gov/seg/hazard/tsu.shtml> and the Pacific Marine Environmental Laboratory at <http://nctr.pmel.noaa.gov/> for their excellent sources. Many of the maps in the text are based upon Generic Mapping Tools (GMT), an online software package developed by Paul Wessel, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, and Walter H. F. Smith, Geoscience Laboratory, National Oceanic and Atmospheric Administration (NOAA). The package can be found at http://www.aquarius.ifm-geomar.de/omc/about_gmt.html

Background information on tsunami in Chapter 1, and reference to individual events throughout the book, were obtained through the Tsunami Laboratory run by Dr. Viacheslav Gusiakov at the Institute of Computational Mathematics and Mathematical Geophysics, Siberian Division Russian Academy of Sciences, Novosibirsk, Russia. His web address is <http://omzg.ssc.ru/tsulab/> I am also indebted to Slava for his comments on a cosmogenic source for the New South Wales mega-tsunami. Dr. Efim Pelinovsky, Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia, provided encouragement and information on Caspian Sea tsunami used in Chapter 1. Dr. Edelvays Spassov, formerly of the Bulgarian Academy of Sciences, provided information on Black Sea tsunami. Edelvays, thank you for making me aware that tsunamis are significant. Mr. Alan Rodda of Toowoomba, Queensland, provided the details of freak waves off the coast of Venus Bay east of Melbourne, Victoria. Mark Bryant provided the description of the freak wave at North Wollongong Beach in January 1994.

Figure 2.1, of a tsunami approaching the Scotch Cap lighthouse, Unimak Island, Alaska, was obtained from the website of Alan Yelvington at <http://www.semparpac.org/tsunami.jpg> These figures are the property of the U.S. Government and are in the public domain. Dr. Vasily Titov, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, Seattle, kindly permitted the computer-simulated tsunami wave train generated by the 1996 Andreanov earthquake to be reproduced in Figure 2.8. This simulation was downloaded from the Internet at <http://nctr.pmel.noaa.gov/Mov/andr1.mov> It is from the Maui High Performance Computing Center, Kihei, Hawaii, which is funded by the U.S. Department of Defense and the University of New Mexico. Dr. Steven Ward, Institute of Tectonics, University of California at Santa Cruz, kindly provided a preprint of a paper on tsunami that gave a novel view of the mathematical treatment of tsunami. Concepts from this paper, especially the term *tsunami window*, are included in the discussion of tsunami dynamics. Dr. Ward also gave his permission to use the time-lapse simulation of tsunami generated by an asteroid impact in a deep ocean in Figure 8.6 and provided information on the tsunami generated by the Nuananu Slide in Hawaii.

Prof. Toshio Kawana, Laboratory of Geography, College of Education, University of the Ryukyus, Nishihara, Okinawa, provided the photograph of boulders on the Ryukyu Islands used in Chapter 3. Prof. John Clague, Professor and Shrum Chair of Earth Sciences, Simon Fraser University, Burnaby, British Columbia, provided Figure 3.5, showing a sand layer deposited by a tsunami and sandwiched between peats. Susan Fyfe, a graduate of the School of Geosciences, University of Wollongong originally drew the outstanding sketches of *S*-forms and bedrock sculpturing used in Chapters 3 and 4. The *Journal of Geology* graciously allows these and other figures published in their journal to be used here. The photograph of the helical plug in Figure 3.1 was provided by John Meier, who is a landscape photographer working out of Melbourne.

Information on specific earthquake-generated tsunamis and the summary of warning systems presented in Chapters 5 and 9, respectively, originate from TSUNAMI!, the website of the Department of Geophysics, University of Washington, at <http://www.ess.washington.edu/tsunami/index.html> The names of individual authors for these pages are not published on the web and could not be properly referenced in the relevant sections. Information on the effects of the Alaskan tsunami of March 27, 1964 came from <http://wcatwc.arh.noaa.gov/about/64quake.htm> Details about the Papua New Guinea tsunami of July 17, 1998 were provided by Dr. Philip Watts, Department of Chemical Engineering, California University of Technology, Pasadena, and by Prof. Hugh Davies, Department of Geology, University of Papua New Guinea, Port Moresby. Prof. Davies also provided much of the background information for the story used in Chapter 1. This information is now available at <http://nctr.pmel.noaa.gov/PNG/Upng/Davies020411/> Sediment information on the Papua New Guinea event was taken from the U.S. Geological Survey Western Region Coastal and Marine Geology webpage at <http://walrus.wr.usgs.gov/tsunami/PNG/home.html>. Figure 5.22 of the sediment splay at Arop was prepared especially for this book by Dr. Bruce Jaffe and Dr. Guy Gelfenbaum, U.S. Geological Survey.

Additional information for tsunami generated by earthquakes, submarine landslides, and volcanoes originated from the webpages of Dr. George Pararas-Carayannis, retired director of the International Tsunami Information Center (ITIC), at <http://www.drgeorgepc.com/> Specific details about the Lituya Bay landslide of July 9, 1958 also originated here, at <http://www.drgeorgepc.com/Tsunami1958LituyaB.html> As well, details about the International Tsunami Warning System were gleaned from these pages, from the webpages of the International Tsunami Information Center at <http://www.tsunamiwave.info/> and from the National Oceanic and Atmospheric Administration (NOAA) at <http://www.noaa.gov/tsunamis.html> Additionally, particulars on the Alaskan Warning System were taken from the West Coast and Alaska Tsunami Warning Center Internet home page at <http://wcatwc.arh.noaa.gov/>

Dr. Simon Day of the Greig Fester Centre for Hazards Research, Department of Geological Sciences, University College, London, provided information on submarine landslides and their possible mega-tsunami—especially for the Canary Islands. Dr. Day also provided unpublished material and correspondence for Figure 6.9 and the descriptions of tsunami deposition on Fuerteventura and Gran Canaria. Dr. Barbara Keating, School of Ocean and Earth Science and Technology at the University of Hawaii, Manoa, provided the locations of landslides associated with volcanoes plotted in Figure 6.2 and detailed descriptions of historical tsunami in Hawaii related to landslides. Barbara also passed on her comments criticizing the tsunami origin of the boulder deposits on the island of Lanai referred to in Chapter 6. Figure 6.11 is taken from fig. 6 in Bondevik *et al.* (1997) and is used with the permission of Blackwell Science in the U.K. Figure 7.1 is copyrighted and provided by Lynette Cook, who is an astronomical artist/scientific illustrator living in San Francisco.

The following people gave information about near Earth objects (meteoroids, asteroids, and comets), the characteristics of these objects impacting with the Earth, and the effect of such impacts on human history: Prof. Mike Baillie, Palaeoecology Centre, School of Geosciences, Queen's University, Belfast; Dr. Andrew Glikson, Research School of Earth Science, Australian National University; Dr. Peter Snow, Tapanui, New Zealand; and Dr. Duncan Steel, Spaceguard Australia P/L, Adelaide, South Australia. Michael Paine's unofficial Spaceguard Australia webpage at <http://www1.tpgi.com.au/users/tps-seti/spacegd.html> provided information on comets, asteroids, and impact events. The Cambridge Conference Network (CCNet)—an electronic newsletter published by Dr. Benny Peiser, School of Human Sciences, Liverpool John Moores University, Liverpool, U.K. at <http://abob.libs.uga.edu/bobk/cccmenu.html>—also was a source of further information. Figure 8.1 appeared originally in Alvarez (1997) and is reprinted by permission of the original author, Ron Miller, Black Cat Studios, <http://www.black-cat-studios.com/> Dr. David Crawford of the Sandia National Laboratories kindly gave permission for the simulations of an asteroid hitting the ocean and the resulting splash used in Figure 8.4. Grahame Walsh of the TAKARAKKA Rock Art Research Centre, Queensland facilitated the fieldwork in the Kimberley, northwest Australia. This latter research was funded by the GeoQuEST Research Centre, University of Wollongong, and the Kimberley Foundation Australia. John Beal of Brushgrove in northern New South Wales provided aboriginal legends on tsunami for this part of Australia. Steve Hutcheon of Brisbane

identified comet X/1491 B1 as a prime candidate for the cause of the cosmogenic tsunami that struck the east coast of Australia in the 15th century, and diligently found all the publications relating to this object.

Finally, information about the 1886 Charleston earthquake and subsequent events in the region used in Chapter 10 were taken from the U.S. National Earthquake Information Center, World Data Center A for Seismology at http://earthquake.usgs.gov/regional/states/events/1886_09_01.php

*To the memory of
J Harlen Bretz*

Figures

Frontispiece	“The Hollow of the Deep-Sea Wave off Kanagawa”)	ii
1.1	“All the sheep!” Child’s impression of a large tsunami breaking on a rocky coast at night	8
1.2	Location of tsunami in the Pacific Ocean region	17
2.1	An artist’s impression of the tsunami of April 1, 1946 approaching the five-story high Scotch Cap lighthouse, Unimak Island, Alaska (<i>see</i> color section)	28
2.2	Various terms used in the text to express the wave height of a tsunami	28
2.3	Plots or marigrams of tsunami wave trains at various tidal gauges in the Pacific region.	29
2.4	Idealized forms characterizing the cross-section of a tsunami wave	30
2.5	Refraction of a tsunami wave crest as it approaches shore	33
2.6	Sequential photographs of the March 9, 1957 tsunami overriding the backshore at Laie Point on the Island of Oahu, Hawaii	35
2.7	Simple representation of gridded bathymetry	38
2.8	Computer simulation of the tsunami wave train generated by the June 10, 1996 Andrianov earthquake.	39
2.9	The remains of the Scotch Cap lighthouse, Unimak Island, Alaska, following the April 1, 1946 tsunami.	40
2.10	Run-up heights around the Hawaiian Islands for the Alaskan tsunami of April 1, 1946.	42
2.11	The American warship <i>Waterlee</i> in the foreground and the Peruvian warship <i>America</i> in the background	43
2.12	Run-up of a tsunami wave onto a beach modeled using shallow-water long-wave equations	44
2.13	Schematic diagram showing the cross-sectional area of coastline flooded and volume of inundation by a tsunami.	45
2.14	Tsunami run-up heights vs. landward limit of flooding on a flat coastal plain of varying roughness	46
3.1	The remnant plug at the center of a vortex, Cape Woolamai, Victoria (<i>see</i> color section).	52

3.2	Depositional and erosional signatures of tsunami.	52
3.3	Locations of coastline around Australia showing the most prominent signatures of paleo-tsunami	53
3.4	Grain size and sorting relationships associated with the Storegga tsunami	55
3.5	Sand layer, deposited by tsunami, sandwiched between peats at Cultus Bay, Washington State	58
3.6	Photograph of the coastal landscape on the island of Flores, Indonesia, following a tsunami.	59
3.7	A chaotically sorted dump deposit on Minnamurra Headland.	61
3.8	The chenier-like ridges in the Cullendulla Creek embayment at Batemans Bay	64
3.9	Fabric of sand and gravel deposited in a chevron-shaped dune by paleo-tsunami at Steamers Beach, Jervis Bay.	66
3.10	Schematic representation of the formation of a chevron due to tsunami.	67
3.11	Scattered boulders transported by tsunami across the reef at Agari-Hen'na Cape on the eastern side of Miyako Island, Japan	69
3.12	Boulders transported by tsunami down a ramp in the lee of the headland at Haycock Point	70
3.13	Dumped and imbricated sandstone boulders deposited 33 m above sea level along the cliffs at Mermaids Inlet, Jervis Bay.	71
3.14	Illustration of the forces necessary to entrain two boulders having the same length and width, but different thicknesses.	73
3.15	Boulder ripples deposited by tsunami at Jibbon	74
3.16	A Bouma turbidite sequence deposited on the seabed following the passage of a turbidity current	76
3.17	Various cavitation features and S-forms produced by high-velocity tsunami flow over headlands.	77
3.18	A star-shaped impact mark on the face of the raised platform at Bass Point	79
3.19	Sinuuous grooves on a ramp at Tura Point	80
3.20	Flutes developed on the crest of a ramp 14 m above sea level at Tura Point	81
3.21	Small dissected potholes at the top of a 15 m high headland at Atcheson Rock	82
3.22	The ramp at Bannisters Head on the New South Wales south coast	83
3.23	Canyon feature cut through the 20 m high headland at Atcheson Rock	84
3.24	Inverted keel-like forms at Cathedral Rocks	85
3.25	An arch at Narooma on the south coast of New South Wales.	85
3.26	Whirlpool bored into bedrock on the south side of Atcheson Rock	86
3.27	Types of vortices responsible for bedrock sculpturing by tsunami	88
3.28	Model for multiple-vortex formation in bedrock whirlpools	89
4.1	Model for irregular, large-scale, sculptured landscapes carved by tsunami	92
4.2	Section through the barrier beach at Bellambi	99
4.3	Model of the effect of tsunami upon a sandy barrier coastline.	100
4.4	Hypothesized tsunami overwashing of the Shoalhaven Delta, New South Wales	102
4.5	Model for smooth, small-scale, bedrock surfaces sculptured by tsunami	103
4.6	Model for the impact of tsunami upon coral atolls in the South Pacific Ocean	105
4.7	Flagstaff Point, Wollongong, eroded by the passage of a mega-tsunami	109
4.8	Kiama Headland lying 40 km south of Flagstaff Point and eroded by a mega-tsunami	110
4.9	Boulders stacked by tsunami on the platform at the south end of Oak Beach, north Queensland	111
4.10	The eroded headland at the north end of Oak Beach, north Queensland	112

4.11	Platform at Cape Leveque, West Australia	113
4.12	Raised beds of cockles on a hill at Point Samson, northwest Western Australia	114
4.13	Chiseled boulders deposited in bedded gravels 5 km inland of the coast at Point Samson, northwest Western Australia	115
4.14	Streamlined inverted keel-shaped ridge at Point Samson, northwest Western Australia	116
4.15	The Caribbean Region. (A) Grand Cayman Island. (B) The Bahamas	117
4.16	Location of historical tsunamigenic earthquakes since 1562 along the west coast of South America	119
4.17	Boulders deposited by a catastrophic tsunami near Coquimbo Bay, northern Chile, 200,000 years ago.	120
4.18	An elevated tsunami dump deposit at Michilla Bay, northern Chile	121
4.19	The ruins of Cobija in northern Chile	122
5.1	Artist's impression of tsunami smashing into the Alaska Railway terminus at Seward in Prince William Sound, March 27, 1964 (<i>see color plates</i>)	128
5.2	Comparison of the rate of seismic force between normal and slow tsunamigenic earthquakes	130
5.3	Types of faults giving rise to tsunami	136
5.4	Relationship between moment magnitude and the average slip distance of an earthquake	137
5.5	Relationship between the moment magnitude and tsunami wave height for the east coast of Japan and Tahiti	139
5.6	Location map for the Lisbon tsunami event of November 1, 1755	140
5.7	Wood engraving by Justine of the tsunami sweeping Lisbon, following the November 1, 1755 earthquake	141
5.8	Passage of the tsunami wave crest across the Pacific Ocean following the May 22, 1960 Chilean earthquake	144
5.9	Aerial view of Isla Chiloe, Chile, showing damage produced by the May 22, 1960 tsunami	145
5.10	Tide records or marigrams of the May 22, 1960 Chilean tsunami around the Pacific Ocean	147
5.11	Aftermath of the May 22, 1960 Chilean tsunami at Hilo, Hawaii	148
5.12	Earthquake and tsunami characteristics of the Great Alaskan Earthquake of March 27, 1964.	150
5.13	Limits of run-up of the tsunami that swept Valdez Harbor following the March 27, 1964 Great Alaskan Earthquake	152
5.14	Location of significant tsunami during the 1990s	155
5.15	Location and height of Nicaragua tsunami of September 2, 1992.	155
5.16	El Tránsito, Nicaragua, after the tsunami of September 2, 1992	158
5.17	Location and height of the Flores, Indonesia tsunami of December 12, 1992	159
5.18	Areas and epicenters of 20th century seismic activity in the Sea of Japan	161
5.19	Damage at Aonae, Okushiri Island, due to the Hokkaido Nansei-Oki tsunami of July 12, 1993.	162
5.20	Message issued by the Pacific Tsunami Warning Center following the Papua New Guinea earthquake of July 17, 1998	164
5.21	Location and height of the Aitape, Papua New Guinea tsunami of July 17, 1998	165
5.22	Overwash splay of sediment caused by the July 17, 1998 tsunami at Arop, Papua New Guinea	166

5.23	Map of the Indian Ocean tsunami of December 26, 2004 and its related characteristics	169
5.24	Total destruction at Banda Aceh	176
5.25	Erosion of landscape at Leupueung, north Sumatra	176
5.26	Sand layers deposited by tsunami at Lampuuk and Sri Lanka	177
6.1	Woodcut portraying the great flood of January 30, 1607 in the Bristol Channel	180
6.2	Location of major submarine slides and debris flows	182
6.3	Schematic representation of a coherent submarine slide	185
6.4	Location map of Lituya Bay, Alaska	188
6.5	524 m high run-up in Lituya Bay	189
6.6	Aerial photograph of the foreshores of Lituya Bay swept by the tsunami of July 9, 1958	190
6.7	Location of the Grand Banks earthquake of November 18, 1929 and the Burin Peninsula of Newfoundland affected by the resulting tsunami	192
6.8	Location of submarine slumps and debris flows on the Hawaiian Ridge.	193
6.9	The giant landslides of the Canary Islands.	197
6.10	Location of the Storegga slides near Norway and coastlines in the North Atlantic affected by the resulting tsunami	199
6.11	Alternating layers of sand and organic debris deposited by four successive tsunami waves of diminishing height in Kvennavatnet Lake basin near Bjugn, Norway, following the second Storegga slide	201
6.12	Raised rock drumlin or flute on the platform at St. Andrews, Scotland	203
6.13	Detached rock drumlins or flutes lying <i>en echelon</i> along the coastline at MacDuff, Scotland	204
6.14	Fluted stacks on the beach at Cullen, Scotland	205
6.15	The toothbrush-shaped headland at Logie Head	206
6.16	Location map of the Bristol Channel, U.K.	207
6.17	Fluting in bedrock at Ifracombe, Devon	209
6.18	Shallow vortex pool with central plug at Ogmere, Wales	209
6.19	Inverted toothbrush-shaped promontory at Ball Rock, South Wales	210
6.20	Imbricated boulder train at Dunraven Beach, South Wales.	213
7.1	An artist's impression of the tsunami from the eruption of Krakatau hitting the coast of Anjer Lor (<i>see color section</i>)	218
7.2	Location of volcanoes that have generated tsunami in recorded history	218
7.3	Coastline in the Sunda Strait affected by tsunami following the eruption of Krakatau on August 26–27, 1883	222
7.4	Coral boulder transported inland by the tsunami following the eruption of Krakatau in 1882	224
7.5	Eastern Mediterranean region affected by the Santorini eruption around 1470 BC.	226
8.1	An artist's impression of the Chicxulub impact tsunami as it crossed the coastal plain of the United States (<i>see color section</i>)	233
8.2	Probability of comets or asteroids of given diameter striking the Earth	235
8.3	Incidence of comets and asteroids, and related phenomena, between AD 0 and AD 1800	237
8.4	Computer simulation of the splash from an asteroid striking the ocean off the coast of Long Island	239
8.5	The size of tsunami generated by iron asteroids of various diameters striking the ocean	243

8.6	Modeled results of the initial development of a tsunami created by the impact of a 200 m diameter stony asteroid	244
8.7	Theoretical distribution of tsunami wave heights generated by iron asteroid impacts with the world's oceans over the last 225 million years	247
8.8	Location of the Chicxulub impact crater and stratigraphic sections of tsunami deposits surrounding the proto-Gulf of Mexico	248
8.9	Reconstruction of the impact sites of fragments of the <i>Deluge Comet</i> 8,200 ± 200 years ago.	252
8.10	Location map of southeast Australia and New Zealand showing evidence for tsunami	253
8.11	Giant flutes at Mason Bay, New Zealand related to the Mahuika Comet tsunami	255
8.12	Imbricated boulders stacked against a 30 m high cliff face on the south side of Gum Getters Inlet, Jervis Bay	256
8.13	Boulder pile blocking the mouth of Mermaids Inlet, Jervis Bay.	257
8.14	Schematic representation showing the steps in converting radiocarbon ages to calendar ones	261
8.15	The painting of a comet on Comet Rock, Kalumburu, Western Australia (<i>see color section</i>)	264
8.16	A typical Wandjina face painted on rock shelters throughout the Kimberley	265
8.17	Donati's Comet of 1858 (<i>see color section</i>)	266
8.18	The basalt headland at Cape Voltaire overridden by a mega-tsunami.	268
8.19	The chronology for mega-tsunami in northwestern Australia over the past two millennia	269
9.1	Drawing of a tsunami breaking on the Japanese coast (<i>see color section</i>).	274
9.2	The world's coastlines having historical records of tsunami in AD 1500 and AD 1750	275
9.3	Indicators of the world's coastline where tsunami will impact the most	276
9.4	People fleeing the tsunami at Hilo, Hawaii following the Alaskan earthquake of April 1, 1946.	278
9.5	Coral boulders deposited in the forest on Flores, Indonesia, following the tsunami of December 12, 1992	278
9.6	Location of seismic stations, tide gauges, and DART buoys making up the Pacific Tsunami Warning System and area of possible coverage of the THRUST satellite warning system	282
9.7	Logos used to warn the public of the threat of tsunami in the United States	283
9.8	Schema of DART I buoy system	288
9.9	Ryoishi on the Sanriku coast of Japan protected against tsunami by 4.5 m walls	288
9.10	Travel time for tsunami moving across a continental shelf	291
9.11	The degree of damage for different housing types produced by varying tsunami flow depths.	293
9.12	Probability of tsunami of various heights due to an asteroid affecting a selection of world cities.	295
9.13	A sampling of coastal areas in Sydney that could be affected by large tsunami	296
9.14	A boulder transported by tsunami at the front of cliffs at Little Bay, Sydney	297
10.1	The devastated landscape in Aceh, Indonesia following the Indian Ocean Tsunami of December 26, 2004.	300
10.2	Location map of scenarios for future tsunami events	301

Tables

1.1	Percentage distribution of tsunami in the world's oceans and seas	15
1.2	Origin of tsunami by region around the Pacific Ocean	18
1.3	Occurrence of significant tsunami in the Pacific region documented since 47 BC	19
1.4	Causes of tsunami in the Pacific Ocean region over the last 2,000 years	21
1.5	Largest death tolls from tsunami in the Pacific Ocean region over the last 2,000 years	21
3.1	Correspondence between the inferred age of anomalous sand layers and dated tsunami events on the Sanriku coast of Japan	57
3.2	Velocities and wave heights of tsunami determined from boulders on the New South Wales coast	72
4.1	Comparison of tsunami and storm-wave heights required to transport boulders	97
4.2	Comparison of tsunami and storm-wave heights required to transport boulders along the Queensland coast north of Cairns.	111
4.3	Comparison of tsunami and storm-wave heights required to transport boulders in the Bahamas	118
5.1	Disparity between seismic and moment magnitudes of recent earthquakes . .	131
5.2	Earthquake magnitude, tsunami magnitude, and tsunami run-up heights in Japan	132
5.3	Soloviev's scale of tsunami intensity	133
5.4	Statistics on the run-up heights of the May 22, 1960 Chilean tsunami around the Pacific Ocean	146
5.5	Statistics on the run-up heights of the March 27, 1964 Alaskan tsunami around the Pacific Ocean.	153
5.6	Major tsunami of the 1990s	156
5.7	Tsunami heights of the December 26, 2004 Indian Ocean tsunami	170
5.8	Maximum run-up heights of the December 26, 2004 Indian Ocean tsunami .	173
5.9	Maximum distance inland for the December 26, 2004 Indian Ocean tsunami	173
5.10	Death tolls for the December 26, 2004 Indian Ocean tsunami	174
6.1	Area and volume of large submarine slides and their associated tsunami . . .	181
6.2	Boulder dimensions and inferred tsunami characteristics, Bristol Channel. . .	211

6.3	Proportion of boulders showing tsunami-transport characteristics, Bristol Channel	212
7.1	Causes of historical tsunami induced by volcanoes	219
8.1	Tsunami heights generated at various distances from the impact site of iron or stony asteroids	242
8.2	Crater and tsunami characteristics modeled using analogs to nuclear explosions and the Shoemaker–Levy Comet impact into Jupiter	245
9.1	Estimated number of near Earth objects (NEOs) by size and return interval for impacts.	294

Symbols in formulas and Greek symbols

a	length of a boulder (m)
b	the intermediate axis or width of a boulder (m)
b_i	the distance between wave orthogonals at any shoreward point (m)
b_o	the distance between wave orthogonals at a source point (m)
b_I	intermediate diameter of largest boulders (m)
c	thickness of a boulder (m) or thickness of a submarine slide (m) or soil cohesion (kPa)
C	wave speed or velocity of a wave (m s^{-1})
C_d	the coefficient of drag (dimensionless)
C_i	wave speed at any shoreward point (m s^{-1})
C_l	the coefficient of lift (dimensionless)
C_m	the coefficient of mass (dimensionless)
C_o	wave speed at a source point (m s^{-1})
d	water depth below mean sea level (m) or the initial depth of a slide in the ocean (m) or the depth of water flow over land (m)
d_i	water depth at any shoreward point (m)
d_o	water depth at a source point (m)
D	diameter of an impact crater (m)
g	gravitational acceleration (9.81 m s^{-2})
H	crest-to-trough wave height (m)
H_b	wave height at the breaker point (m)
H_{max}	the maximum height of a tsunami wave above still water
H_o	crest-to-trough wave height at the source point (m)
H_r	tsunami run-up height above mean sea level (m)

\bar{H}_r	mean tsunami run-up height above mean sea level (m)
$H_{r\max}$	maximum tsunami run-up height above mean sea level (m)
H_t	wave height at shore or at the toe of a beach (m)
H_m	tsunami wave height above mean sea level (m)
$\bar{H}_{t\max}$	mean maximum tsunami wave height along a coast (m)
i_s	Soloviev's tsunami magnitude scale (dimensionless)
k	a constant (dimensionless)
K_r	refraction coefficient (dimensionless)
K_s	shoaling coefficient (dimensionless)
K_{sp}	coefficient of geometrical spreading on a sphere (dimensionless)
L	wavelength of a tsunami wave (m)
L_b	length of a bay, basin, or harbor (m)
L_s	bedform wavelength (m)
m	mass of an asteroid (kg)
m_{II}	tsunami magnitude, Imamura–Iida scale (dimensionless)
M_o	seismic moment measured (Nm)
M_t	tsunami magnitude (dimensionless)
M_w	moment magnitude scale (dimensionless)
n	Manning's roughness coefficient (dimensionless) or an exponential term
r	the radius of the crater made by an asteroid impact in the ocean (m)
r_a	radius of an asteroid (m)
R_e	the shortest distance from a location to the epicenter of an earthquake (km)
R_t	the distance a tsunami travels from the center of an asteroid impact (m)
S_p	density correction for an asteroid impact (g cm^{-3})
S_t	area of seabed generating a tsunami (m^2)
t	time(s)
T	wave period(s)
T_s	wave period of seiching in a bay, basin, or harbor(s)
\ddot{u}	instantaneous flow velocity (m s^{-1})
v	flow velocity (m s^{-1})
\bar{v}	mean flow velocity of water (m s^{-1})
v_a	impact velocity of an asteroid (m s^{-1})
v_{\min}	minimum flow velocity of water (m s^{-1})
v_r	velocity of tsunami run-up (m s^{-1})
W	kinetic energy of an asteroid impact (kilotons of TNT)
x_{\max}	limit of tsunami penetration landward (m)

GREEK SYMBOLS

α_i	the angle a wave crest makes to the bottom contours at any shoreward point (degrees)
α_o	the angle a wave crest makes to the bottom contours at a source point (degrees)
β	slope of the seabed (degrees)
β_w	slope of the water surface (degrees)
Δ	angle of spreading on a sphere relative to a wave's direction of travel
ΔC	a small correction on tsunami magnitude dependent on source region
ξ	pore water pressure (kPa)
ρ_a	density of an asteroid (g cm^{-3})
ρ_e	density of material ejected from an impact crater (g cm^{-3})
ρ_s	density of sediment (g cm^{-3})
ρ_w	density of seawater (g cm^{-3})
π	3.141592654
τ_s	the shear strength of the soil (kPa)
σ	the normal stress at right angles to the slope (kPa)
φ	the angle of internal friction or shearing resistance (degrees)

Abbreviations and acronyms

AMS	Accelerator-based Mass Spectrometry
AUD	AUstralian Dollar
CCNet	Cambridge Conference Network
CNES	Centre National d'Etudes Spatiales (French space agency)
K/T	Cretaceous–Tertiary
DART	Deep-Ocean Assessment and Reporting of Tsunami
DMSP	Defense Meteorological Satellite Program
EAS	Emergency Alert System
GMT	Generic Mapping Tools (software)
GEOS	GEOStationary satellite
GLORIA	Geologic LOng-Range Inclined Asdic)
GPS	Global Positioning System
HMR	Hawaii Mapping Research
IOC	Intergovernmental Oceanographic Commission
ITIC	International Tsunami Information Center
ITWS	International Tsunami Warning System
LADESS	Local Automatic Data Editing and Switching System
MF	Medium Frequency
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
NEA	Near Earth Asteroid
NEO	Near Earth Object
OLS	Operational Linescan System
PTWC	Pacific Tsunami Warning Center
PTWS	Pacific Tsunami Warning System
PNG	Papua New Guinea
SeaMARC	Sea Floor Mapping And Remote Characterization
SAWS	Simultaneous Announcement Wireless System

xxxiv **Abbreviations and acronyms**

SWAN	Shallow WAter Nonlinear
TL	ThermoLuminescence (dating method)
THRUST	Tsunami Hazards Reduction Utilizing Systems Technology
TOPES	TOPOgraphy Experiment Satellite
TOPEX	TOPOgraphy EXperiment (science project)
TREMORS	Tsunami Risk Evaluation through seismic MOment in a Real time System
UNESCO	U.N. Educational, Scientific and Cultural Organization
VHF	Very High Frequency
WRAH	Weather Radio All Hazards system
WC/ATWC	West Coast/Alaska Tsunami Warning Center