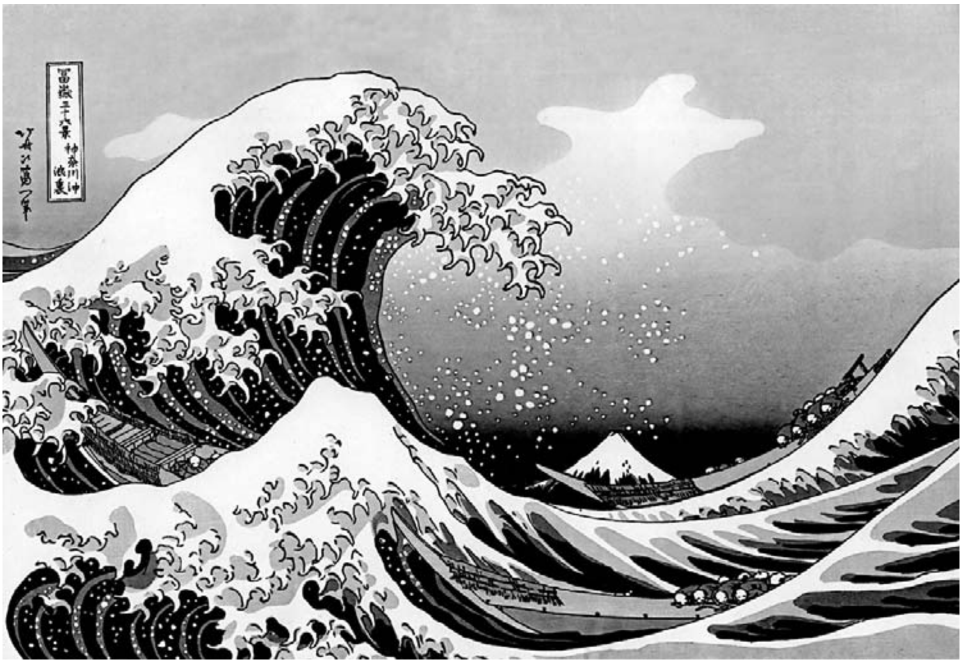
Tsunami

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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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 tsunami, and indeed had written about them, but they were not my area of research expertise. No one had considered that tsunami 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 tsunami 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-tsunami 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 tsunami. 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.sscc.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 tsunami 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 Nuuanu 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 tsunami 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

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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 ($9.81\,m\,s^{-1}$)
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 (N m)
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

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

Part I

Tsunami as a known hazard