Active Faults of the World

There is an ever-increasing need for a better understanding of regional seismic hazards, particularly in developing parts of the world where major building projects are planned and there is a huge migration of people to large cities that are at risk from earthquakes. Disasters in recent times, such as the earthquakes in Japan and Haiti, are chilling proof of the dangers of building in active fault zones.

This book provides the first worldwide survey of active earthquake faults, with a focus on those described as "seismic time bombs", with the potential to destroy large cities in the developing world such as Port-au-Prince, Kabul, Tehran, and Caracas. Leading international earthquake expert, Robert Yeats, explores both the regional and plate-tectonic context of active faults around the world, providing the background for seismic hazard evaluation in planning large-scale projects such as nuclear power plants or hydroelectric dams. He also highlights work done in more advanced seismogenic countries such as Japan, the United States, Italy, New Zealand, and China as helpful examples for developing nations, providing an important basis for upgrading building standards and other laws.

In addition to providing a valuable technical summary of active fault zones worldwide, the book presents the human side of earthquake science, exploring the impact of major quakes on social development through history, such as the effect of the 1755 Lisbon earthquake on the Age of Enlightenment. It will form an accessible reference for analysts and consulting firms, and a convenient overview for academics and students of geoscience, geotechnical engineering and civil engineering, and land-use planning.

Robert Yeats is a Fellow of the American Association for the Advancement of Science and the Geological Society of America. He is senior consultant and partner in Earth Consultants International, an international firm focusing on earthquake hazards, and also an Emeritus professor at Oregon State University. He has decades of experience in earthquake geology worldwide, including acting as chair of the International Lithosphere Project on active faults for several years, and authoring three previous books: *The Geology of Earthquakes* (with Kerry Sieh and Clarence R. Allen), *Living with Earthquakes in California*, and *Living with Earthquakes in the Pacific Northwest.* An endowed professorship at Oregon State University has been named in his honor, and the AAPG have recognized his work by awarding him the Michel T. Halbouty Human Needs Award.

Praise for this book:

"This book is an astonishing achievement. It is extraordinarily comprehensive and well illustrated with seismological and geodetic data. It is an up-to-date starting point for anyone who wants a quick introduction to the earthquake faulting of a specific region, and will remain a reliable introduction to the context of advances in the field, and how to use them."

James Jackson, Department of Earth Sciences, Cambridge University

"This ambitious compilation of all that is known of the surface faults of our planet will be a reference work for many years to come. The text is audacious in scope, with myriad maps and their associated geodetic velocity fields. Yeats encapsulates discussion and controversies surrounding faults, providing a guide to the next generation of future geologists, and presents his summaries of fault zones with easy authority."

Roger Bilham, Department of Geological Sciences, University of Colorado at Boulder

"This clearly written and highly illustrated book is the first to augment seismic hazards assessments with data on the precise locations of active faults, their slip-rates and earthquake recurrence intervals, and the elapsed time since the last earthquake on that fault. It is essential reading for anyone tasked with protecting at-risk populations or infrastructure prone to earthquakes".

Gerald Roberts, Department of Earth and Planetary Sciences, Birbeck, University of London

"Robert Yeats has compiled the results of several decades of international effort, producing a comprehensive geographical coverage, which remains accessible by providing context throughout. It is an impressive achievement and will be an essential reference not only for academics and students, but also for practitioners in engineering geology, civil engineering, and planning."

Ken McCaffrey, Department of Earth Sciences, Durham University

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Preface: Introduction and historical perspective

The construction of nuclear power plants, large dams, and other critical facilities in the United States and Europe during the 1970s led to a requirement that the sites for these structures be evaluated for seismic hazards. A necessary new approach to the evaluation of seismic hazards included the study of active faults, which led to the recognition in fault zones of earthquakes that pre-dated a written historical record. *Paleoseismology*, the study of ancient earthquakes based on their geological expression, became a primary tool in the siting and evaluation of critical facilities. However, virtually all of these studies were site-specific, without a broader understanding of the significance of active-fault features in the study of earthquakes. There seemed to be a barrier between the study of faults by the structural field geologist and the analysis of faulting in real time, which includes geomorphic expression of surface rupture accompanying earthquakes, and the study of how faulting is part of the natural evolution of landscapes, despite early attempts to do this by Charles Lyell (1875).

Analysis of active faults built on the work of nineteenth-century pioneers, including Charles Lyell of England (as part of his *Principles of Geology*), G.K. Gilbert of the United States (Owens Valley and San Andreas faults, California, and Wasatch fault, Utah), Alexander McKay of New Zealand (Hope fault), José Aguilera of México (faulting accompanying the 1887 Sonoran earthquake), and Bunjiro Koto of Japan (faulting accompanying the 1891 Mino-Owari earthquake).

A worldwide analysis of the tectonic setting of active faults and their Quaternary history did not begin until after World War II, when Robert E. Wallace of the US Geological Survey (USGS) established his scientific reputation with a careful description of active features of the San Andreas fault (Wallace, 1949) and the surface rupture of the 1915 Pleasant Valley, Nevada, earthquake (Wallace, 1984). Bob Wallace recognized that a thorough understanding of active-fault features around the world required an international effort to look for common properties and to take advantage of a larger worldwide data set of historical earthquake surface ruptures. Wallace's first compilation, in large part limited to the United States, was sponsored by the Geophysics Study Committee of the National Academy of Sciences and published in 1986 as *Active Tectonics: Studies in Geophysics*. This was more than an academic exercise. In his "anonymous" overview paper at the beginning of that volume, Wallace pointed out the importance to society of studies of active faults as indicators of earthquake hazards, and he indicated the importance of current geological research as a guide to policymakers in decisions on societal problems related to earthquakes.

By the time that volume appeared, Wallace was already comparing American active faults with surface ruptures from earthquakes overseas. These included the 1966 Varto, Turkey, earthquake (M 6.8) on the North Anatolian fault, with implications for the San Andreas fault (Wallace, 1968), and the 1739 Pinglu, China, earthquake (M 8) on the Helanshan fault in the

Yinchuan Graben, a fault that offset the Great Wall of China (Zhang *et al*., 1986). This earthquake provided lessons for an understanding of faulting in the Central Nevada Seismic Zone, including the 1915 Pleasant Valley and 1954 Dixie Valley and Fairview Peak surface ruptures.

In 1983, inspired by Wallace and his Chinese colleagues in their study of the 1739 earthquake, an international project, *A Worldwide Comparison of the Characteristics of Major Active Faults*, was begun as Project 206 of the International Geological Correlation Programme (IGCP) through UNESCO. The leaders of this project were Robert C. Bucknam of the USGS and Ding Guoyu and Zhang Yuming of the State Seismological Bureau of China, although Bob Wallace was clearly the *éminence grise* for this project. In that same year, Wallace, together with Bill Bull, a geomorphologist at the University of Arizona, organized an international meeting at Winnemucca, Nevada, followed by a field trip through the 1915 Pleasant Valley and 1954 Dixie Valley surface ruptures that permitted his Chinese collaborators in the Pinglu earthquake study to compare the Chinese normal fault with the normal fault ruptures of central Nevada. The first meeting of the IGCP project was held in June, 1984, at Kobe, Japan, at the end of a project I undertook with Kelvin Berryman of the New Zealand Geological Survey (later the Institute of Geological and Nuclear Sciences, or GNS Science), comparing reverse faults affecting the design of proposed hydroelectric dams in Central Otago with those in the California Transverse Ranges.

The objective of the IGCP project, discussed at Kobe, was "to synthesize current knowledge of the characteristics and tectonic histories of selected major active faults." Members of the project were to compile their findings in an atlas "illustrating the seismological, geological, and geomorphic attributes of the selected faults in a variety of continental tectonic settings." The scientists who assembled at Kobe from around the world became colleagues and fast friends in this effort, and collaboration continues today, augmented by younger workers and scientists from other countries. We were taken on a field trip to the Rokko Mountains by Professor Kazuo Huzita, who warned that faults in the Kobe area were very likely to produce a major earthquake in the near future. Professor Huzita's warning went unheeded by the Japanese government. Less than 11 years later, the 17 January 1995, Kobe earthquake of M 6.9 struck this fault system, taking the lives of several thousand people and destroying Professor Huzita's lovely classical Japanese home near Kobe.

Although publications would be the official products of our collaboration, we decided to meet at different places to see various faults for ourselves and not be required to learn about them only through the lenses of scientific publications from different countries and cultures. We met in Beijing, China, in 1985 and took a field trip along the Tan-Lu fault of eastern China (Li and Zheng, 1985). A meeting in 1987, at Franz Josef, New Zealand, was accompanied by a detailed look at New Zealand's plate-boundary Alpine fault (Beanland, 1987). In 1989, the year of the International Geological Congress in Washington, DC, we met at Mammoth Lakes in the eastern Sierra Nevada of California and examined the San Andreas fault and normal faults in the Great Basin, including the Wasatch fault, first reported on by Gilbert in 1883. Our collaboration was realized in two special volumes: Hancock *et al*. (1991) in the *Journal of Structural Geology* and Bucknam and Hancock (1992) in *Annales Tectonicae*. The Chinese, Japanese, and New Zealand atlases were compiled (for example, Research Group for Active Faults of Japan, 1991), and Wallace contributed his San Andreas fault atlas in the form of a

USGS professional paper (Wallace, 1990). Other atlases were either not published or appeared in different formats, such as fault compilations for probabilistic earthquake hazard analysis. The two volumes that completed the project described faults in China, Greece, India, Japan, Nepal, New Zealand, Pakistan, the Soviet Union, Turkey, the United States, and Venezuela.

In 1987, Ray Price, then the president of the Inter-Union Commission on the Lithosphere, invited me to lead Working Group 1 of the International Lithosphere Program (ILP), *Recent Plate Movements and Deformation*, taking the place of its recently deceased distinguished chairman, K. Nakamura. I invited several of my colleagues from IGCP Project 206 to become members because we were convinced that we had left a lot of work undone in our study of active faults: not enough known to achieve a synthesis, too few countries involved, and too few scientists from underdeveloped seismogenic nations studying faults that endangered their societies. Our opportunity came in 1990, when ILP restructured its study committees from Working Groups to focused Task Groups.

The year 1990 was the beginning of the International Decade of Natural Disaster Reduction (IDNDR), which was fully embraced by ILP by establishing its Global Seismic Hazards Assessment Project (GSHAP), which became Task Group II-1. Task Group II-2, headed by Vladimir Trifonov of the Soviet (later Russian) Academy of Sciences, was charged with making a worldwide compilation of active faults. Trifonov organized a field excursion in the summer of 1990 to major active faults in the Soviet Union, including the surface rupture of the Armenian earthquake of 1988 and other active faults in Soviet Central Asia, including the Talas–Fergana fault. My wife became seriously ill, and I had to cancel, so Trifonov simply deferred the trip until the following summer. But international events intervened: the Soviet Union collapsed and was restructured into separate republics, so that all of the field trip stops Trifonov had planned for the Task Group were now in foreign countries!

The chaotic conditions in Moscow caused the leadership of ILP to seek help from the USGS, and at the American Geophysical Union meeting in San Francisco in December, 1991, Task Group II-2 was divided into an Eastern Hemisphere group headed by Trifonov and a Western Hemisphere group headed by Michael Machette of the USGS. A status report on the reorganization and its implications for GSHAP was published by Trifonov and Machette (1993).

The Western Hemisphere portion of Task Group II-2, which had as its objective the characterization of earthquake source faults, began in 1994 with a compilation of a national database documenting seismogenic Quaternary faults and folds in the United States. The first version of the database was completed in 2004 and contained about 10 000 pages of documentation on more than 2000 faults in the United States (http://earthquake.usgs.gov/regional/qfaults/). This compilation supports the National Probabilistic Seismic Hazard maps and is revised every 5 years to update the probabilistic strong-ground motion hazard used in the International Building Code. The second version of the maps using the fault database was published by Petersen *et al*. (2008).

The American database became the model for compiling fault maps for the Western Hemisphere, focusing on Latin America. ILP project meetings were conducted in Mérida, Venezuela, in January, 1992, Quito, Ecuador and Guatemala City, Guatemala in February, 1993, and Caracas, Venezuela, in March, 1997, as well as meetings at the International

Geological Congress in 1992 (Kyoto) and 2000 (Rio de Janeiro). The Western Hemisphere portion was completed in 2004 with the publication of fault maps and data for ten countries and the establishment of an internet database for the Quaternary faults and folds of Latin America under the leadership of Carlos Costa and Hector Cisneros of the Universidad Nacional de San Luis, Argentina, with assistance from Hugh Cowan of New Zealand. This work is available as pdfs on the internet; it was also summarized in a volume edited by Costa (2006).

Another result of the reorganization of ILP was the formation in 1990 of Task Group II-3, *Great Earthquakes of the Late Holocene*, another contribution to the International Decade of Natural Disaster Reduction that focused on paleoseismology. I was the chair, and the vice-chairman was Yoshihiro Kinugasa of the Geological Survey of Japan (later with the Tokyo Institute of Technology), and the membership included several veterans of IGCP 206. Our objectives were to summarize worldwide knowledge in paleoseismology through interaction among specialists around the world and to encourage paleoseismological investigations in developing seismogenic countries by technology transfer. We organized technical sessions and field trips that were part of the 1992 International Geological Congress in Kyoto, Japan, in 1992.

The next venture was a workshop on paleoseismology at Marshall, California, on 18–22 September 1994, sponsored by ILP and USGS, with additional support from IGCP 206 and the US Nuclear Regulatory Commission. This workshop was attended by 89 paleoseismologists from 15 countries, with 35 participants from outside the United States. Countries not previously represented included Argentina, Canada, Ecuador, France, Italy, Iran, Israel, the Philippines, and Sweden. Short summaries of 93 presentations were published by Prentice *et al*. (1994), and 27 papers were published in a special section on paleoseismology in the *Journal of Geophysical Research* (Yeats and Prentice, 1996).

The task group also contributed technical sessions and field trips to the International Geological Congress in Beijing, China, in 1996. A short course in paleoseismology was conducted in Beijing during the IGC, and another one took place at the Wadia Institute of Himalayan Geology in Dehra Dun, India, that same year, co-sponsored by ILP, the US National Science Foundation, and the Indian Department of Science and Technology. A trench excavated for that short course was the first paleoseismic trench in the Himalaya (Oatney *et al*., 2001). At about the same time, two books appeared: *Paleoseismology*, edited by James McCalpin, now in its second edition, and a textbook, *The Geology of Earthquakes* by Robert Yeats, Kerry Sieh, and Clarence Allen. These books incorporated many of the findings of IGCP Project 206 and ILP Task Group II-3, including examples from around the world.

After the Beijing IGC, a follow-up proposal, *Earthquake Recurrence Through Time*, was accepted by ILP in 1998 as Task Group II-5, chaired by Daniela Pantosti of Istituto Nazionale di Geofisica e Vulcanologia of Italy, with Alan Hull of the Institute of Geological and Nuclear Sciences of New Zealand as vice-chairman. Hull took a consulting position in the United States, and he was replaced by Kelvin Berryman of GNS Science. Results of this task group were summarized at a meeting in Kaikoura, New Zealand, in 2001 and published in a volume edited by Pantosti *et al*. (2003). New countries were represented: Spain, Thailand, Korea, and Australia.

Other workshops and special volumes have followed, too many to be summarized here. A Central American workshop in paleoseismology was convened in Managua, Nicaragua, in March 1998, in which the participants excavated three trenches and compared trenching results with two high-stand shorelines of Lake Managua (Cowan *et al*., 2002). Two specialized topics covered by individual workshops and special volumes include archaeoseismology (Stiros and Jones, 1996; Dunne *et al*., 2001) and earthquake engineering geology (Krinitzsky and Slemmons, 1990; Serva and Slemmons, 1995).

In 2008, the Global Earthquake Model (GEM) 5-year initiative was launched (http://www.globalquakemodel.org) to "provide an independent standard to calculate and communicate earthquake risk, raise risk awareness, promote mitigation and insurance use, and stimulate risk transfer." In the following year, a GEM project, *Faulted Earth*, led by Kelvin Berryman (New Zealand), Carlos Costa (Argentina), Kerry Sieh (Singapore), and Ross Stein (United States), was organized to "construct a global active fault and seismic source database with a common set of strategies, standards and formats to be placed in the public domain." This book is sponsored by that initiative.

As a consulting geologist, I must frequently familiarize myself with the active-fault geology and paleoseismology of a faraway part of the world where my company has a new project. It is easier to obtain a synthesis of regional geology and of global plate tectonics than a summary review of the tectonic setting of active faults of a region leading to an assessment of seismic hazard, including slip rates and earthquakes that have struck those faults, both those based on paleoseismology and on the historical record. What has been lacking is a description of these faults in their tectonic environment, that is, an active tectonic geography of the world's active faults. This book seeks to meet that need.

Included in the book is a compilation of regional syntheses of earthquake geology, including plate-tectonic setting, crustal deformation rates based on geodesy, a description of large earthquakes based on the historical record and on paleoseismology, and a description of earthquake source faults, including plate-boundary faults and those in plate interiors. In many cases, especially on dry land, a plate boundary is not marked by a single fault but by a diffuse zone of deformation that is hundreds or even thousands of kilometers across. Examples include the Pacific–North America plate boundary that extends from offshore California to Utah, and the India–Eurasia plate boundary that extends from the Himalayan front to the Tien Shan and Lake Baikal in Siberia. The book has a much stronger focus on faults on land, recognizing that many plate boundaries are offshore, but these require special technology for working in the marine realm. Faults onshore are easier to study and to trench and are more likely to be close to major population centers. The large number of faults and regions studied does not permit the listing of all original contributions, but I have included summary papers that do include references to these original contributions.

An objective of this book is to encourage governmental organizations and international engineering firms to include in their analyses of major engineering projects in seismogenic regions a more thorough evaluation of earthquake geology, leading to a more refined estimate of probabilistic and deterministic earthquake hazard. Because new data are being brought forward, particularly in the developing world, this is a work in progress.

The growing understanding of active faults is happening at the same time that large populations are moving to megacities, with little attention paid to earthquake-resistant

construction standards, particularly in the developing world, and some of these overcrowded megacities are close to active faults. This fact was brought home to me when I wrote the chapter on the Caribbean Plate in 2009 and identified Port-au-Prince, Haiti, as a potential earthquake time bomb. Soon afterwards, the 12 January 2010 earthquake destroyed that city, and I decided that the book should focus on other earthquake time bombs as well. If attention can be focused in advance on the hazard to these cities, lives can be saved.

Many people have provided information and hard-to-find references that have guided this book and have reviewed sections where my familiarity is only through the literature. I am especially grateful for assistance and advice from Clarence Allen, Manuel Berberian, Kelvin Berryman, Roger Bilham, Dan Clark, Lloyd Cluff, Carlos Costa, Tony Crone, James Dolan, John Fletcher, Eldon Gath, Chris Goldfinger, Tania Gonzalez, Lisa Grant Ludwig, Peter Haeussler, Bill Hammond, Christian Hibsch, Michiharu Ikeda, Yasutaka Ikeda, James Jackson, Yann Klinger, Andrey Kozhurin, Corné Kreemer, Peter LaFemina, Robert Lagerbäck, Willie Lee, Paul Mann, José Martínez Díaz, Rob McCaffrey, Bill McCann, Mustapha Meghraoui, Walter Montero, Robert Muir-Wood, Eliza Nemser, Jay Noller, Yukinobu Okamura, Koji Okumura, John Oldow, Yoko Ota, Spyros Pavlides, George Plafker, Ren Junjie, Tom Rockwell, Rob Rogers, Brian Sherrod, Kerry Sieh, Chris Sorlien, Seth Stein, Iain Stewart, Yuichi Sugiyama, Max Suter, Uri ten Brink, Hiroyuki Tsutsumi, Soe Thura Tun, Brian Tucker, Pilar Villamor, Claudio Vita-Finzi, Carrie Whitehill, Ivan Wong, and Xu Xiwei, plus many others through emails and conversations over the past 3 years. Kristi Weber prepared the illustrations, Annemarie Christophersen coordinated our project with GEM, and Mark Meyers allowed me the use of the OSU Geosciences Terra Cognita lab. Laura Clark, Lucy Edwards, and Susan Francis of Cambridge University Press patiently led me through the production process, as did Bekki Levien and Angela Yeats.

I dedicate this book to my colleagues who passed away prior to the full recognition of the contribution each of them made to earthquake science: Aykut Barka of Turkey, Sarah Beanland of New Zealand, Zhang Buchun of China, Abul Farah of Pakistan, Paul Hancock of Great Britain, Kazuo Huzita and Sohei Kaizuka of Japan, Hervé Philip of France, Carlos Schubert of Venezuela, and Bob Wallace and Tom Fumal of the United States.