U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

NATURAL HAZARDS POTENTIAL MAP OF THE CIRCUM-PACIFIC REGION
Southwest Quadrant

R. W. Johnson, Chair, Southwest Quadrant Panel

By R.W. Johnson[1], R.J. Blong[2], and C.J. Ryan[3] (Compilers)

[1]Australian Geological Survey Organisation
[2]Macquarie University, Australia
[3]Australian Bureau of Meteorology

Prepared by
CIRCUM-PACIFIC COUNCIL FOR ENERGY AND MINERAL RESOURCES

CIRCUM-PACIFIC MAP SERIES
Published by the U.S. Geological Survey, 1995

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

TO ACCOMPANY MAP CP-43

EXPLANATORY NOTES FOR THE NATURAL HAZARDS POTENTIAL MAP OF THE CIRCUM-PACIFIC REGION SOUTHWEST QUADRANT

1:10,000,000

CIRCUM-PACIFIC COUNCIL FOR ENERGY AND MINERAL RESOURCES

1995

Natural Hazards:

their Potential in the Pacific Southwest

INTERNATIONAL DECADE FOR NATURAL DISASTER REDUCTION
AUSTRALIA

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

R.W. Johnson, R.J. Blong, and C.J. Ryan (Compilers)

Australian Geological Survey Organisation
Australian Coordination Committee for the International Decade for Natural Disaster Reduction

CIRCUM-PACIFIC COUNCIL FOR ENERGY AND MINERAL RESOURCES
Michel T. Halbouty, Chair

CIRCUM-PACIFIC MAP PROJECT
John A. Reinemund, Director
George Gryc, General Chair

EXPLANATORY NOTES FOR THE NATURAL HAZARDS POTENTIAL MAP OF THE CIRCUM-PACIFIC REGION, SOUTHWEST QUADRANT

Scale: 1:10,000,000

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY
Minister for Resources: The Hon. David Beddall, MP
Secretary: Greg Taylor

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION
(Formerly BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS)
Executive Director: Harvey Jacka

U.S. DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

Contributors and affiliations:

V.R. Ashby (cartography), Cartographic Services Unit, Australian Geological Survey Organisation, G.P.O. Box 378, Canberra, A.C.T. 2601.

G.S. Beard (droughts), National Climate Centre, Australian Bureau of Meteorology, G.P.O. Box 1289K, Melbourne, Victoria 3001.

R.J. Blong (landslides, tsunamis, and general text), Natural Hazards Research Centre, School of Earth Sciences, Macquarie University, New South Wales 2109.

N.P. Cheney (bushfires), CSIRO, Division of Forestry, Commonwealth Scientific and Industrial Research Organisation, P.O. Box 4008, Canberra, A.C.T. 2600.

J.W. Handmer (floods), Centre for Research and Environmental Studies, Australian National University, G.P.O. Box 4, Canberra, A.C.T. 2601.

J.E. Hobbs (floods), Department of Geography and Planning, University of New England, Armidale, New South Wales 2351.

R.W. Johnson (volcanoes and general text), Geophysical Observatories and Mapping Division, Australian Geological Survey Organisation, G.P.O. Box 378, Canberra, A.C.T. 2601.

T.D. Jones (earthquakes), Australian Seismological Centre, Australian Geological Survey Organisation, G.P.O. Box 378, Canberra, A.C.T. 2601.

M. Michael-Leiba (earthquakes), Australian Seismological Centre, Australian Geological Survey Organisation, G.P.O. Box 378, Canberra, A.C.T. 2601.

C.J. Ryan (tropical cyclones and severe thunderstorms), Severe Weather Warning Service, Australian Bureau of Meteorology, G.P.O. Box 1289K, Melbourne, Victoria 3001.

C.J. Simpson (volcanoes), School of Earth Sciences, University of Melbourne, Parkville, Victoria 3052.

G.A. Young (cartography), Cartographic Services Unit, Australian Geological Survey Organisation, G.P.O. Box 378, Canberra, A.C.T. 2601.

Other members of Natural Hazards Map Working Group:

J.P. Barr, Emergency Management Australia, P.O. Box 1020, Dickson, A.C.T. 2602.

T.L. Jeggle, Asia Disaster Preparedness Centre, Asian Institute of Technology, P.O. Box 2754, Bangkok, Thailand 10501.

H. Letz, Geophysical Observatory, P.O. Box 323, Port Moresby, Papua New Guinea.

P.D. May, Emergency Management Australia, P.O. Box 1020, Dickson, A.C.T. 2602.

W.D. Palfreyman, Marine, Petroleum and Sedimentary Resources Division, Australian Geological Survey Organisation, G.P.O. Box 378, Canberra, A.C.T. 2601.

Recommended bibliographic citation:

Johnson R.W., Blong, R.J., and Ryan C.J. (compilers),1995. Explanatory notes for the natural hazards potential map of the circum-Pacific region, southwest quadrant: U.S. Geological Circum-Pacific Map Series CP-43, 60 p., scale 1:10,000,000.

Contents

Introduction

The map that forms part of the cover of this booklet is an adapted, smaller version of a 1:10 million-scale map that has been produced separately to illustrate the pattern of natural-hazards potential. The region covered by the map is what we refer to in this booklet as the 'Pacific Southwest'. The map does indeed cover all the southwestern Pacific, including Australia and New Zealand, but it also includes parts of southeast Asia, the Indian Ocean, and Antarctica (Figure 1).

The Pacific Southwest region is one of great climatic and geological diversity, and hazard distribution is correspondingly diverse. The 1:10 million map has been designed to show the distribution, size, frequency, and potential of the major natural hazards in the region—events such as earthquakes, tropical cyclones, volcanoes, and landslides. The map and booklet have been produced in the hope of contributing to an increased awareness of natural hazards in the region, and of making a contribution to the United Nations sponsored International Decade for Natural Disaster Reduction (1990-99).

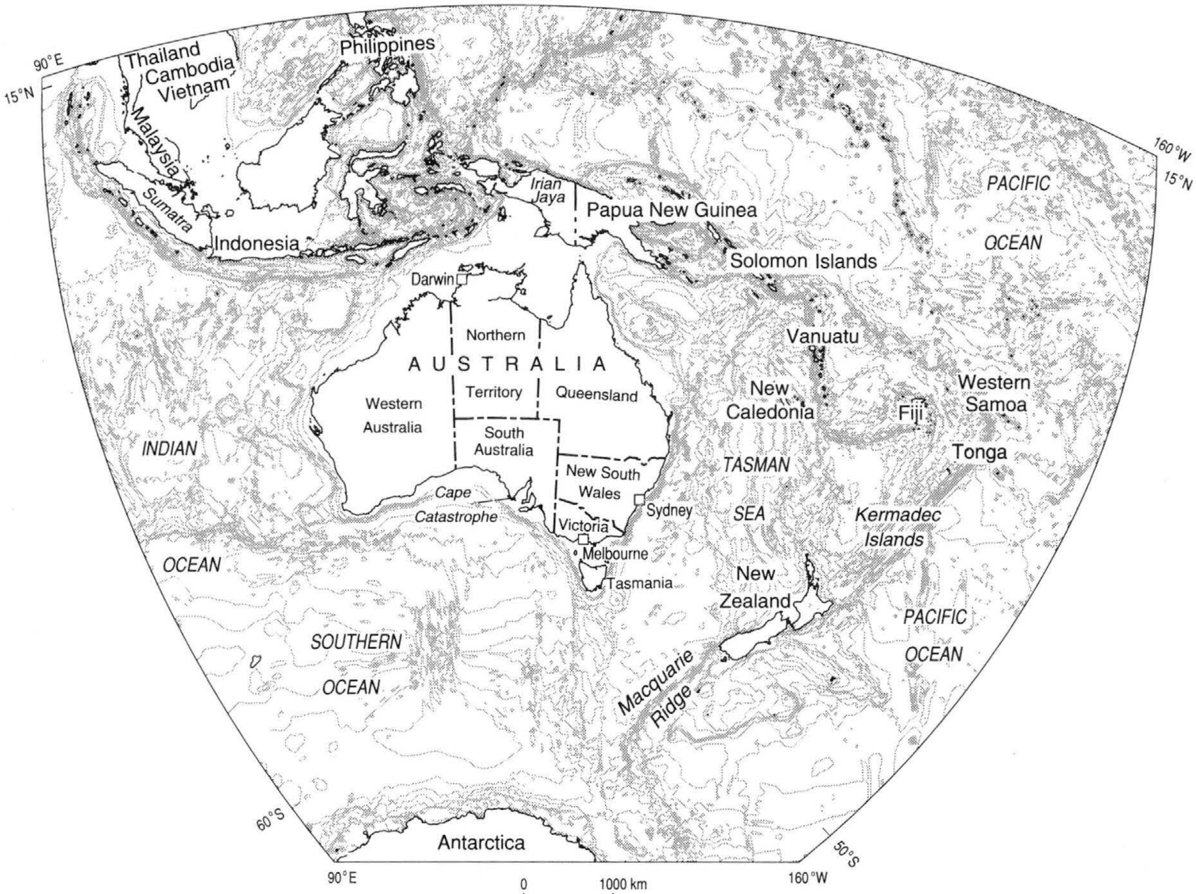

Figure 1. The Pacific Southwest map used in this booklet and for the 1:10 million-scale map of natural-hazards potential is a Lambert azimuthal equal-area projection centered on 35°S and 135°E, appropriately near Cape Catastrophe on the southern coast of Australia.

Hazards, Vulnerability, Risk, and Disaster

Natural hazards are produced by meteorological and geological events that commonly involve enormous forces or amounts of energy. The term *natural hazards* can be defined in different ways, but basically they are natural events that make a harmful impact on human beings and their environment. A physical event is not a hazard unless people are affected by its impact.

People, buildings, lifelines, crops, and farm animals are all threatened by natural hazards. Some people—particularly the elderly, the very young, and the disabled—are more vulnerable than are young, fit, healthy people. Similarly, modern buildings and structures that have been well engineered are less vulnerable than are those that have not been designed to resist extreme forces. Tree crops commonly are more damaged by violent winds than are root crops. Human societies and their economies therefore differ in their degree of *vulnerability* where exposed to a natural hazard of a given strength or magnitude. The magnitude and frequency of occurrence of human vulnerability and natural hazards are different from place to place, and so the *risk* —the expected degree of loss of lives, damage to property and disruption of economic activity —is also different. The simple equation *risk = hazard x vulnerability* illustrates the relationships between these three concepts that are vital to an understanding of how natural hazards affect our lives and activities.

A *natural disaster* is produced where a natural hazard of sufficient intensity strikes a population or society that is vulnerable. There are no precise definitions for disaster (or for *accident* and *catastrophe*), although a disaster might be considered to result in the loss of tens, hundreds, or thousands of human lives, or to produce monetary losses of millions or even billions of dollars. Large death tolls or enormous numbers of dollars (or both) may provide suitable measures of disaster size in western societies, but they can be of limited relevance in relatively small isolated communities where the daily routine revolves around subsistence agriculture. Natural disasters in most cases should be considered as the result of the breakdown in the day-to-day functioning of society as the result of an impact of a natural hazard.

The concern of this booklet is primarily with natural hazards—particularly with hazard magnitude and frequency—rather than with risk, vulnerability, and disaster. Most maps of natural hazards provide a picture of events that have taken place in the past —a kind of historical inventory. In contrast, the maps presented here are attempts to glimpse the future by presenting information on natural-hazard *potential* - that is, indications of the future distribution and intensity of hazards. The maps, inevitably, must be based in part on past events, but we recognize that registers of hazards are incomplete, that human records commonly are short, and that some events are sufficiently rare that they have not been noted in written history.

The chief purpose of this booklet is to provide a straightforward explanation of the nature of the hazards portrayed on the 1:10 million hazard-potential map. However, the booklet also includes (1) a rationale for the map's construction, (2) a description of the data sources used, and (3) brief descriptions of some of the consequences of natural hazards in the Pacific Southwest. The booklet can be used to greatest effect in conjunction with the separate, 1:10 million-scale map sheet.

Meteorological and Geological Framework

The climate of the Pacific Southwest is dominated by oceans that cover more than three-quarters of the region. Major ocean currents are strong influences on weather patterns, particularly the belt of warm water along the Equator from Indonesia to east of Papua New Guinea, that has been called the 'boiler box' of the world's climate (Figure 2). This water 'hot spot' is a major source of heat and moisture to the atmosphere, and its fluctuations are transmitted around the world as part of the complex El Niño-Southern Oscillation (ENSO) mechanism that causes extremes of weather in many remote parts of the world (Zillman and others, 1989). ENSO is like a 'seesaw' of air between the central Pacific and the eastern Indian oceans. Oscillations last two to seven years.

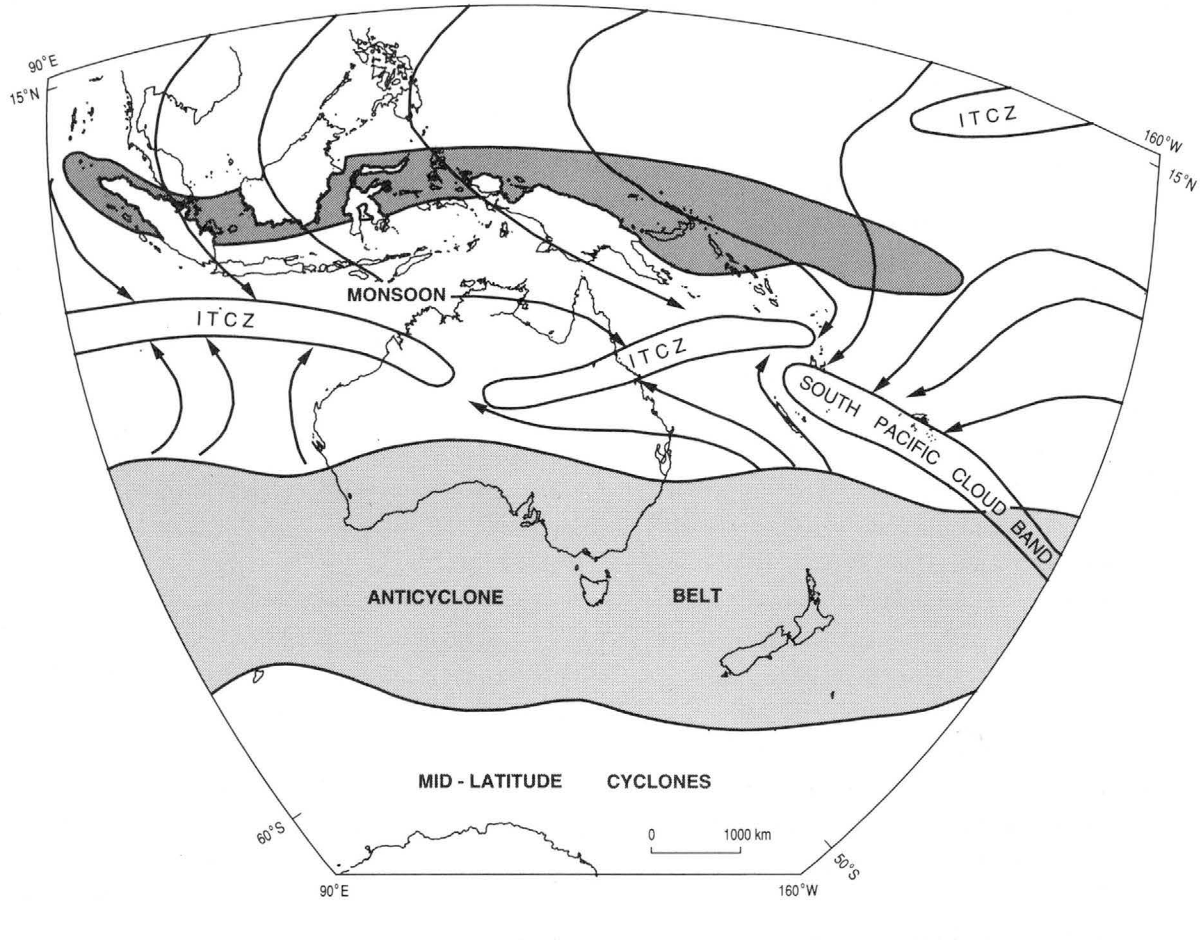

Figure 2. Simplified atmospheric and oceanic features of the Pacific Southwest typical of January. Heavier stippling represents the area where sea-surface temperatures do not fall below 28 °C (a sea-surface 'hotspot'). Arrowhead lines represent typical, broad-scale wind patterns. ITCZ: Inter-Tropical Convergence Zone.

Large-scale atmospheric circulations of the Pacific Southwest are dominated by anticyclones and the Inter-Tropical Convergence Zone (ITCZ; shown as three parts in Figure 2). There are five main categories of weather-producing systems within this very broad framework:

1. The *monsoon* is characterized by a marked transition between 'wet' and 'dry' seasons caused by the annual north-south oscillation of the ITCZ. The most common cycle begins with heavy monsoon rains over southeast Asia in May, extending north and west through June-July, then starting to retreat to the Equator in September, and moving erratically further south to northern Australia during October to December.

2. *Tropical cyclones* (or *typhoons*) south of the Equator are generated over an area of sea from Fiji to off the northwestern coast of Australia. Most of them move in a general westwards or southwestwards direction, either meeting the Australian continent or curving away to the southeast. Tropical cyclones develop regularly in northern summer in the extreme northern part of the Pacific Southwest map sheet area, east of the Philippines. This particular area spawns more tropical cyclones than does any other part of the world.

3. *Tropical cloud bands* include the South Pacific Cloud Band, which is a relatively stationary convergence zone between semipermanent anticyclones in the southeast Pacific and eastward-moving anticyclones over Australia and New Zealand (Figure 2). The Northwest Cloud Band extends southeastwards from near Sumatra to central Australia as a more irregular midyear feature (and therefore not shown in the January map in Figure 2).

4. An *anticyclone belt* (Figure 2) - called the 'sub-tropical ridge' - oscillates (like the ITCZ) northwards in winter, and southwards in summer, generally bringing dry settled weather.

5. A belt of *mid-latitude cyclones* to the south of the sub-tropical ridge follows the seasonal fluctuations of the ridge and ITCZ. The cyclones in winter pass over southeastern Australia and New Zealand, some causing severe weather, whereas in summer they generally pass further south.

An equally broad geological framework of the Pacific Southwest is dominated by four of the Earth's great tectonic plates (Figure 3):

1. The *Indo-Australian plate* that carries the Australian continent and which extends across the central and western parts of the map.

2. The *Pacific plate* whose southwestern boundary with the Indo-Australian plate forms two arms that meet in a right angle near Samoa and Tonga. This plate boundary consists mainly of *subduction zones* where one tectonic plate plunges beneath the other, and where the passage of the plate into the Earth's interior is marked by inclined zones of earthquakes that may reach as deep as 700 km.

3. The *Eurasian plate* covering most of Indonesia and some of the Indo-China Peninsula, in the northwestern corner of the map area. Its boundaries, too, are mainly subduction zones.

4. The *Antarctic plate* in the extreme southwest whose northern margin, as well as the southern margins of the Indo-Australian and Pacific plates, are being created by seafloor spreading at mid-ocean ridges where submarine volcanic activity forms new crust and the plates move apart from each other. Both the earthquake and volcanic activity along these plate margins cause little threat and so are excluded from the 1:10 million map.

Other tectonic plates are represented on the map, including the southern end of the large Philippine plate in the northern part of the map area. The region also includes several minor plates, particularly in the Papua New Guinea region. These additional plates (not all are shown in Figure 3) contribute to great tectonic complexity in the northern and northwestern part of the region, making up there perhaps the most complicated tectonically active region anywhere in the world. Earthquakes and volcanoes are concentrated along or near to the boundaries of all the plates.

An important point to note is that tectonic and volcanic activity is not restricted entirely to these plate boundaries. *Intraplate* earthquakes and volcanoes in the region—particularly in Australia —represent tectonic activity well away from plate boundaries. There are also lines of volcanoes in the Pacific Ocean and Tasman Sea. These are believed to form above so-called 'mantle hotspots' that may be giant plumes of material that have risen from deep within the Earth's mantle and have impinged on the base of the Earth's crust causing volcanoes to grow on the plate that moves over the 'hotspot'. The Samoa islands chain consists of hotspot volcanoes thought to have been built in this way. In addition, *passive-margin* volcanoes are found along the eastern seaboard of Australia—the youthful Newer Volcanics Province of southeastern Australia is a good example. These are related to the formation of the mountains caused by uplift of the eastern edge of the Australian continent when the floor of the Tasman Sea formed by seafloor spreading 80-60 million years ago.

Landslides and tsunamis are the two other geological hazards considered in this booklet. Both may be produced as result of earthquake and volcanic activity, but landslides may be caused by other factors too, such as heavy rainfall.

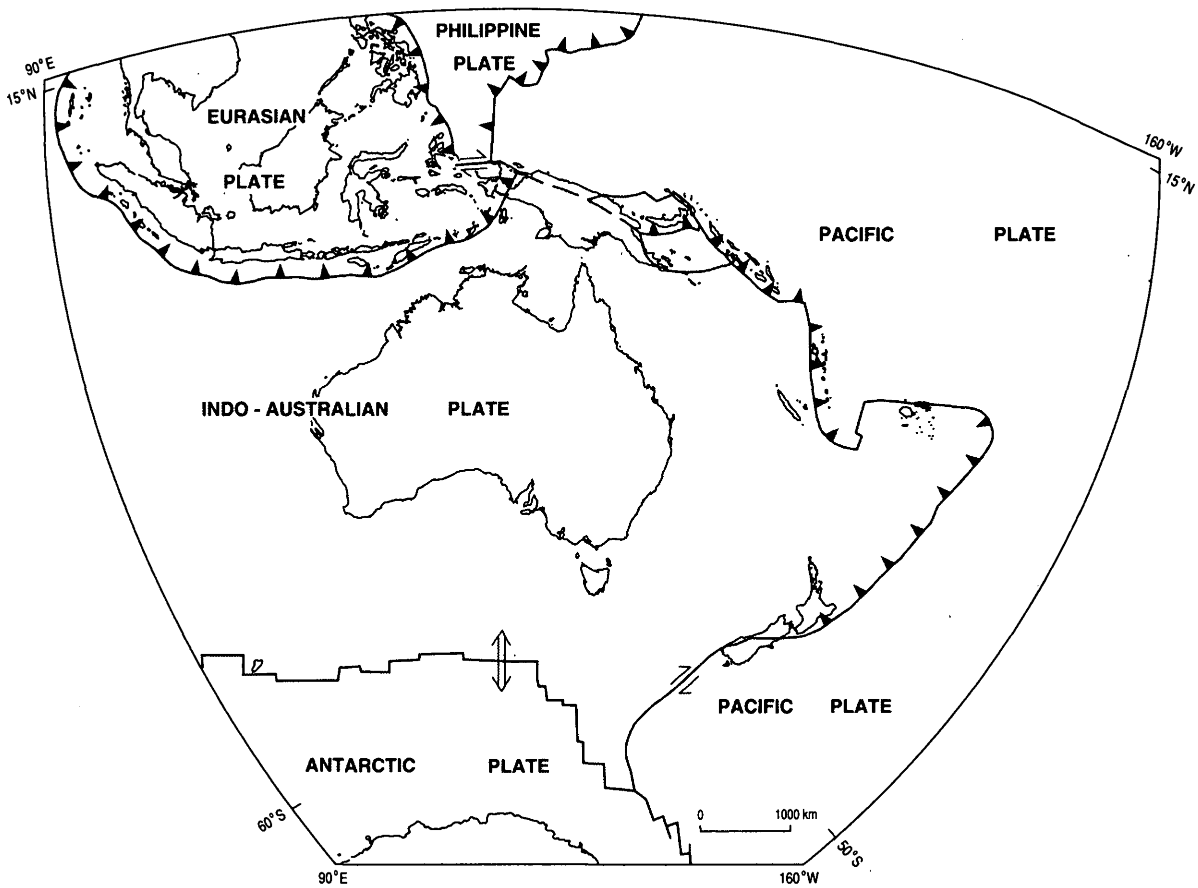

Figure 3. The boundaries of the four major plates that dominate the Pacific Southwest region have tectonically complex boundaries that are shown here in simplified form (modified from Doutch, 1981). The saw-tooth pattern refers to the main subduction zones of the region. Seafloor spreading between the Antarctic and Indo-Australian plates is shown by the open-stemmed, double-headed arrow. Half-headed arrows refer to horizontal sliding (transcurrent motion) between plates. Dashed line represents a collision zone (between the northern edge of the Australian continent and an ancient volcanic arc) where the plate boundary is poorly defined.

Natural Hazards Potential Map

A Natural Hazards Map Working Group was established in Australia in order to plan and produce the 1:10 million-scale map of natural hazards in the Pacific Southwest (the Southwest Quadrant of the Circum-Pacific Map Project). Members of the group first met in 1991 to discuss the aims of the map, the hazards that needed to be portrayed, and the methodologies that would be used. The consensus was that the aim would be to develop a map that portrayed an integrated view of natural-hazards *potential*—that is, a map of the spatial distribution and intensity of future hazards, rather than simply a record of past events. The group also decided to exclude from consideration potentially destructive phenomena such as soil salinity, greenhouse sea-level rise, and accelerated soil erosion, which involve human activities threatening the state of the environment (as opposed to natural hazards threatening the lives and property of people). Biological hazards (human, animal, and plant diseases) also were excluded.

Records of the historical past for many hazards reflect adequately the intensity and distribution of future hazards. This is particularly true for some meteorological hazards, but is less so for geological ones such as earthquakes and volcanic eruptions. This is because the intervals between successive geological events at one location may be sufficiently long that historical records are too brief to provide an indication of hazard potential. This applies particularly to those areas, such as many of the Pacific islands, where written history spans a century or less and insufficient attempts have been made to interpret oral traditions. The hazards-potential map attempts to overcome the inadequacies of the record and to interpret the potential for the occurrence and magnitude of future hazards.

Neither the 1:10 million map nor the additional maps in this booklet span the entire range of meteorological and geological hazards in the Pacific Southwest. There was so little information available for some hazards that there was little choice but to omit them. For example, expansive soils are an economically important hazard but had to be excluded for lack of suitable data. Furthermore, the problem of incomplete data was compounded for other hazards, such as storm surges and coastal erosion, by the difficulty of portraying at the map scale the potential of a hazard that affects only a very narrow coastal margin. Twelve hazards divided into three groups (see below) finally were selected after consideration of such problems (Table 1).

Selection of the twelve natural hazards led to recognition of other challenges. The most important of these was scarcity of information for some of the hazards in some areas, but a plethora of data for some hazards elsewhere, particularly for Australia. Computer databases on earthquakes and tropical cyclones are available for the whole region, whereas

Table 1. Twelve hazards shown on the natural-hazards potential map

Group 1	Group 2	Group 3
Tropical cyclones	Severe thunderstorms	Wave heights
Earthquakes	Floods	Sea-ice limits
Volcanoes	Droughts	Superstructure ice
Landslides	Bushfires	
Tsunamis		

there are none for landslides, floods, and bushfires, for example. We recognized also that a good deal of information about hazards is probably available in different parts of the region, but that it is either difficult to access or requires substantial further work in order to make it suitable for mapping and database purposes.

A second challenge was coping with the problems of potential overcrowding on a map portraying twelve natural hazards. This problem was alleviated to some extent by the absence or non-availability of information for certain areas and certain hazards (adequate data simply could not be collected for use on the map within the available time constraints), but in other instances more drastic action had to be taken. Thus, bushfire and drought potential for Australia were transferred to a separate, smaller-scale map on the main 1:10 million-scale sheet because of problems of crowding and the paucity of information on these hazards in most other areas. Similarly, landslide hazard potential was left off the Australian portion of the map so as to avoid overcrowding (landslides are less important in Australia than they are in many of the other nations of the region).

The twelve hazards represented on the map, then, fall into three groups (Table 1): (1) those that can be represented across the whole map sheet on the basis of existing information; (2) those where the information is readily available for Australia alone; (3) those at the high latitudes of the map sheet area where the other hazards are of limited importance and where there is therefore free space available for mapping. Earthquakes and tropical cyclones are judged to be the most significant hazards in the region (see below) whereas the group-3 hazards are the least important.

Global and Regional View of Natural Hazards

Which natural hazards are the most important on a global or regional scale? The answer to this question depends first on answering 'important for whom or what'? Does the question mean the most frequent hazards, or the most powerful? Are the hazards those that produce the most human deaths, the greatest suffering, the greatest damage to buildings, or the greatest financial losses? One might think that these questions are relatively easy ones. There are indeed some global databases on disasters, but in fact good statistics are not generally available. Not all of the databases identify a wide range, or provide an adequate breakdown, of natural-hazard types, or provide statistics on a country-by-country basis. Estimating financial losses is especially difficult. Answers to the above questions therefore remain rather imprecise.

Some answers to the questions come from data collected for the period 1947-1981 from the New York Times Index and the Encyclopedia Britannica Yearbook, by the Natural Hazards Research Applications and Information Center at the University of Colorado, USA (Thompson, 1982). The database includes only those events in which more than 100 people were killed or injured, or in which more than US$2.8 million (in 1981 dollars) damage was caused, but nevertheless represents one of the more complete databases. Tropical cyclones, floods, and earthquakes are shown in Table 2 to be the most frequent disasters (in terms of the criteria used in the survey), and earthquakes and tropical cyclones are the most deadly in that they result in the highest death tolls per hazard event. In addition, meteorological hazards are shown to be much more frequent on a global basis than geological hazards. Loss-of-life data are available from this survey for Asia (including the whole continent from Turkey to Malaysia and the islands to the east and south—Japan, the Philippines, and Indonesia), and for Australasia (including Australia, New Zealand, Papua New Guinea, and the other islands of the Pacific). The Asian death toll for the period of the survey represents nearly 86 percent of the global total of 1,208,000 deaths. In contrast, the Australasian region contributed only 0.4 percent of the recorded global deaths.

These statistics are useful indicators, but of course need to be treated cautiously as the data on which the evidence is based are incomplete. The data already are more than a decade out of date (no update is available). Furthermore, the statistics ignore droughts and their associated famines which account for more deaths and suffering than do any other type of natural disaster (see, for example, National Land Agency, 1994). The statistics also do not include the myriad small disasters that kill fewer than 100 people. In addition, just a few large catastrophes dominate the picture. For example, just two events — the 1970 Bangladesh tropical cyclone and the 1976 Tangshan (China) earthquake—produced more than 40 percent of the deaths included in the total. A single giant tsunami on a densely populated coast could produce a death toll in the hundreds of thousands and switch the relative balance of the importance of geological and meteorological disasters based on deaths.

Table 2. Global frequency of natural disasters and deaths per event for 1947-81 (based on data in Thompson, 1982)

	Number of disasters	Percentage frequency	Average deaths per event
Geological hazards			
Earthquakes	161	16.6	2652
Tsunamis	10	1.0	856
Volcanoes	18	1.9	525
Landslides	29	3.0	190
Sub-total:	218	22.7	
Meteorological hazards			
Tropical cyclones	211	22.0	2373
Floods	343	35.8	571
Thunderstorms	36	3.8	587
Heatwaves[1]	22	2.3	315
Tornadoes[2]	127	13.3	65
Sub-total	739	77.2	

[1] Heatwaves are excluded from the natural hazards considered in the main part of this booklet and shown on the 1:10 million map, largely because of the absence of information through the Pacific Southwest and the inherent difficulties of mapping heatwave potential.

[2] Tornadoes are included in the severe-thunderstorms category used in this booklet.

Informative global statistics on natural disasters tabulated in relation to the wealth of countries (low, middle, and high income), reflect the particular vulnerability to natural hazards of low-income developing countries (National Land Agency, 1994). For example:

- low-income countries have 58 percent of the world population yet account for 88 percent of the victims of natural disasters and 92 percent of the sufferers in the world from 1965 to 1992;
- the numbers of sufferers per total population in low-income countries is 45 times that for high-income countries;
- the number of deaths per total population in low-income countries is 25 times that for high-income countries.

Most countries in the Pacific Southwest region classify as low-income.

A data set prepared by the Centre for Research on the Epidemiology of Disasters (CRED) covering the period 1966-1990 ranks the Philippines, Indonesia, Australia, and New Zealand in the top ten countries in the world for the number of disasters, and the Philippines in the top ten for the number of deaths (CRED, 1993; see also Table 3). CRED also prepared a 'spatial risk index' that takes the area of the country into account, and which has the Philippines, New Zealand, Vietnam, and Indonesia in the top ten countries in the world. The numbers of disasters for the 1900-94 period for those Pacific Southwest countries identified in the CRED database are listed in Table 3 where the Philippines, Indonesia, and Australia are shown to have the most recorded disasters in the Pacific Southwest region. Note, however, that all of these results, like the ones referred to in the previous paragraphs, tell as much about the databases as they do about the hazards and disasters in the region.

The above picture concerning human deaths in natural disasters is unclear, but it is far clearer than any view can be of the *costs* of disasters. Some data are available on total costs of a few disasters from the international reinsurance company Munich

Table 3. Natural disasters in countries of the Pacific Southwest from 1900 to 1994[1]

Country[2]	Number of disasters[3]	Number of dead
Philippines	289	58576
Indonesia	183	55509
Australia	175	1181
New Zealand	103	443
Vietnam	65	16937
Tonga	54	14
Fiji	46	603
Papua New Guinea	39	7486
Vanuatu	33	213
Solomon Islands	25	407
Thailand	24	2837
New Caledonia	16	18
Malaysia	12	269
Cook Islands	8	6
Western Samoa	7	281
Samoa	6	115
Tokelau	5	0
Tuvalu	5	6
Guam	5	20
Wallis and Futuna	4	6
Niue	4	0
Cambodia	3	100
Kiribati	1	3

[1]Data from the EMDAT database on disasters provided courtesy of the Centre for Research on the Epidemiology of Disasters (CRED), University Catholique de Louvain, Brussels, Belgium. The data shown above are for natural disasters only and exclude events such as technological accidents, wars and other civil conflicts, and epidemics. No claim is made that the data are definitive

[2]Some countries and territories of the Pacific Southwest are not identified in the CRED database

[3]Disasters in the CRED database are those that required relief assistance at the national or international level, or caused at least 10 deaths, or affected at least 100 people

Reinsurance (see, for example, Berz, 1988), but sample sizes are adequate only for tropical cyclones (17 events) and earthquakes (8 events). Average losses in cyclones were US$1 billion, while those in earthquakes were just over $2 billion, based on a summary of 1960-83 insurance data (Blong, 1992). Small island nations with relatively small populations appear to bear the largest per capita costs, on the basis of rather limited data. Developing countries globally have been affected economically by natural disasters more seriously than have developed countries (National Land Agency, 1994). Absolute and per capita amounts of direct economic losses are highest in high-income countries, as expected, but the ratio of direct economic losses to Gross National Product is highest in low-income countries (over seven times that of high-income countries).

Some general conclusions can be drawn from the disparate statistics available:

- floods, tropical cyclones and earthquakes are the natural hazards that produce disasters most frequently;
- droughts, earthquakes, tropical cyclones, and floods produce the most deaths;
- the majority of the global deaths in natural disasters are in Asia;
- meteorological hazards and disasters are more common and produce more deaths than geological hazards and disasters;
- large economic losses are associated most commonly with earthquakes and tropical cyclones, although the available data are very incomplete;
- natural disasters in small countries tend to produce higher costs per capita than those in countries having large populations.

Interactions between Hazards and Effects

We have seen that coming to grips with simple questions such as 'which is the most costly or deadly hazard?' is not easy and that the poor quality of the available statistics is the major reason for this. In addition, there is a need to recognize that (1) each hazard can produce a range of effects, (2) that different hazards may operate together or be related to each other, and (3) that 'technological' hazards may result from natural hazards, although these are not separable from one another easily.

Tropical cyclones (typhoons) produce damage in several different ways. Most of the hundreds of thousands of people killed in the Bangladesh cyclones of 1970 and 1991 undoubtedly drowned in the storm surges that inundated large areas of low-lying coastal land along the Bay of Bengal. In contrast, the dramatic destruction of Darwin, Australia, on Christmas Eve in 1974 was produced almost entirely by strong winds. Similarly, associated flooding can be important agents of damage (or death) in some tropical cyclones. Even the damage to crop land by windblown salt may be an important consequence of tropical cyclones. Earthquakes cause ground shaking that leads to collapse of buildings, but there are other earthquake effects too. Ground failure, including landslides, lateral spreading, and liquefaction of surface materials, commonly takes place in relatively severe earthquakes. Surface faulting may cause direct damage to buildings and roads.

The twelve hazards are mapped separately on the 1:10 million sheet and are treated separately in the sections that follow, but several of these are the cause of other hazards. Landslides and tsunamis may result from earthquakes. Tsunamis may result from collapse of volcanoes near the sea during periods of volcanic activity. Storm surges and coastal erosion are produced by the passage of cyclones. Major bushfires follow periods of drought that produce dry forest and grass fuels. In addition, some hazards may affect an area together at the same time without being related.

For example, the northern Philippines were affected in mid-June 1991 not only by the explosive eruptions at Pinatubo volcano but, coincidently, also by the high winds and rain of Typhoon Diding. Apportioning costs and deaths to individual natural hazards (such as in Table 2) in these circumstances can be rather arbitrary.

Natural hazards can lead to technological ones, and the boundary between the two is vague. Fires can break out in the aftermath of larger earthquakes as a result of electrical short circuits or chemical spills, and oil spills and toxic gas releases are not uncommon. These associated or subsidiary hazards produce collateral or secondary damage or deaths. On the other hand, technological activity such as road building may cause undercutting of land slopes and initiate landslides. Interactions between natural hazards and technological hazards are likely to be of increasing concern in technologically advanced societies.

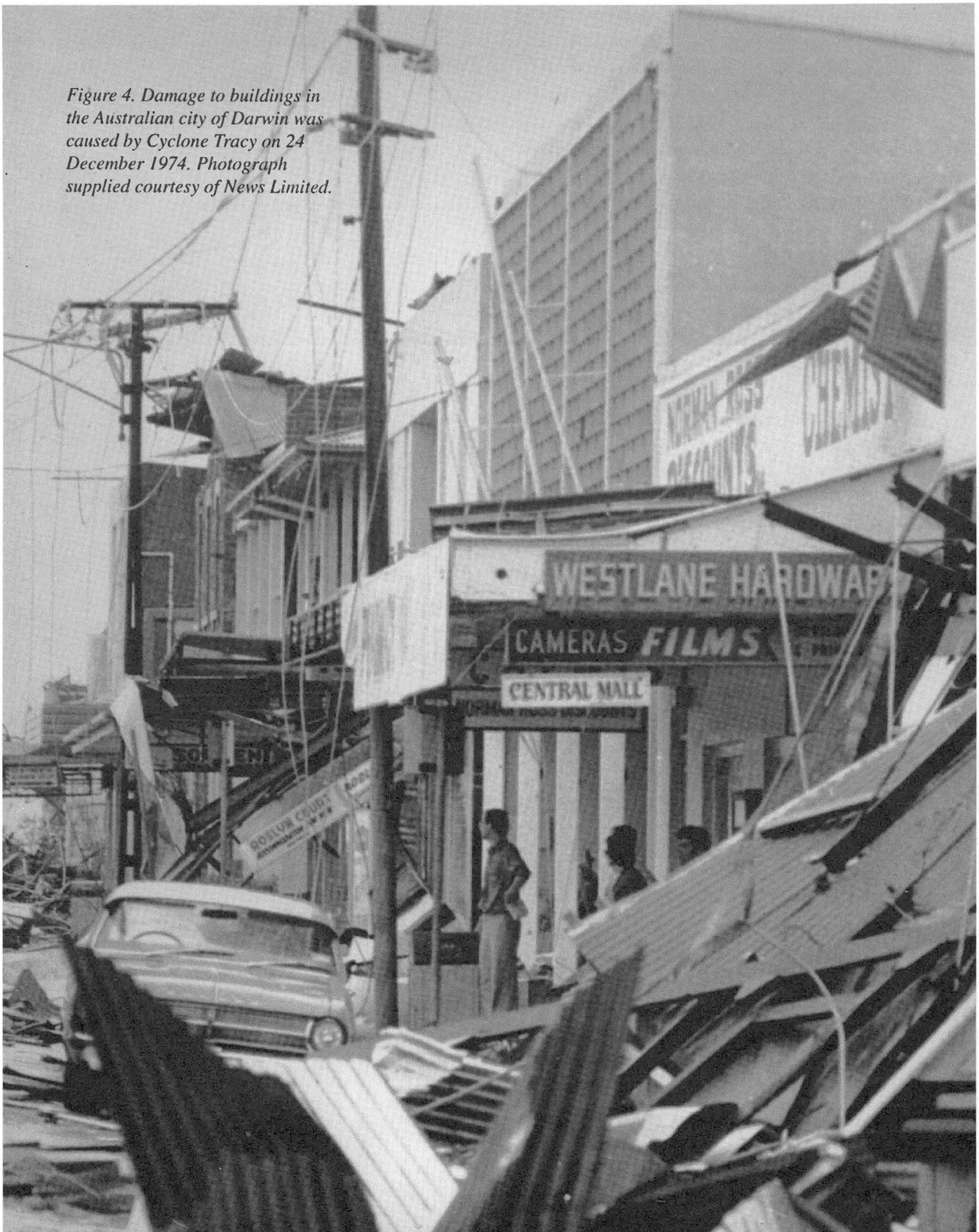

Figure 4. Damage to buildings in the Australian city of Darwin was caused by Cyclone Tracy on 24 December 1974. Photograph supplied courtesy of News Limited.

Tropical Cyclones

Tropical cyclones are called *typhoons* in eastern Asia and are known as *hurricanes* in other parts of the world. Definitions differ a little around the globe, but the three names generally are used interchangeably to refer to a closed, surface, atmospheric circulation having high sustained wind speeds (Figure 5). A minimum wind speed of 118 km/hr (64 knots) is used in many parts of the world, including eastern Asia, but a value of 63 km/hr (34 knots) is used throughout the south Pacific region, including Australia and New Zealand. Tropical cyclones require for their formation convergence of air masses at a low level in the atmosphere, divergence at high levels, angular momentum derived from the earth's rotation, and warm sea surface temperatures. These constraints, in general, mean that tropical cyclones cannot form within 5-6 ° latitude of the Equator, but require sea-surface temperatures above 27 °C for their initiation. Cyclones tend to form in summer months and have a peak occurrence in the later half of the summer.

Most tropical cyclones move towards the poles from their area of initiation and last from a few days to a few weeks. Damaging winds at any one site rarely last more than a day or so, but stalled cyclones can produce immense amounts of rain. Tropical cyclones tend to decay rapidly on passing over cooler water or over land, commonly becoming tropical rain

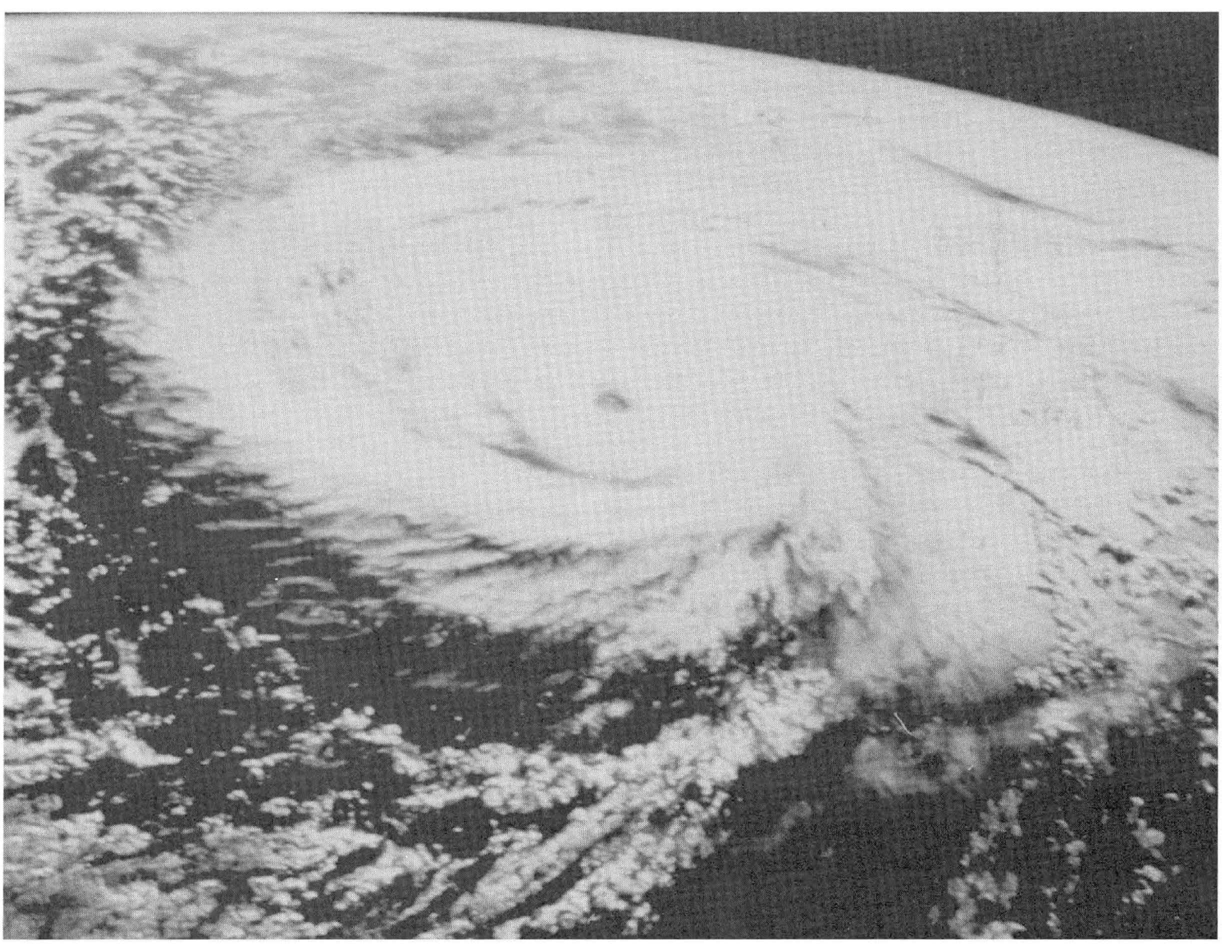

Figure 5. Typhoon Odessa over the Philippines is seen in this satellite view in October 1988. The spinning direction is counterclockwise because the typhoon is in the Northern Hemisphere. Note the well-defined central 'eye' of the cyclone. Photograph supplied by the Australian Bureau of Meteorology.

depressions. Hurricanes and typhoons in the Northern Hemisphere revolve in a counterclockwise direction (Figure 5), but rotate clockwise in the Southern Hemisphere.

A mature tropical-cyclone air mass may have a diameter of as much as 2000 km. The diameter of the 'eye' is typically 10-50 km, and wind speeds are most intense just outside the eye where gust speeds may be as much as 300 km/hr. The forward motion of the cyclone is typically 10-20 km/hr, and therefore the maximum wind speeds in the Southern Hemisphere are in the left leading quadrant (the front left quadrant facing in the direction of travel, as the eye of the cyclone approaches the coast). Maximum winds in the Northern Hemisphere are experienced in the leading quadrant to the right of the eye. This simple pattern may be modified by the terrain as the cyclone eye crosses the coast.

The low atmospheric pressure associated with the eye of the cyclone produces an inverted barometer effect so that the ocean surface is elevated about 10 mm for each 1 hPa (or 1 mb) pressure drop. The maximum water surface elevation from this effect may be about 1 m. However, powerful wind stresses on the water-surface also pile water up so that storm surges of several meters height are possible, posing significant hazards especially if the eye of the cyclone crosses the coast at high tide. The storm-surge 'dome' may have a diameter of 60-80 km, but as the major component of the surge is wind-driven, the maximum surge height will be in the same quadrant as the maximum wind. The near-shore topography and bathymetry, and the distribution of bays and

Table 4. Tropical cyclone intensity scale

Category	Maximum wind gust (km per hour)	Central pressure (hPa)	Effects
1	Less than 125	983-994	Negligible house damage. Some crop and tree damage. Craft may drag moorings.
2	125-170	965-982	Minor house damage. Significant damage to signs and trees. Heavy damage to some crops. Risk of power failure. Small craft may break moorings.
3	170-225	941-964	Some roof and structural damage. Power failures likely.
4	225-280	899-940	Significant roofing loss and structural damage. Dangerous airborne debris. Widespread power failures.
5	Greater than 280	Less than 899	Extremely dangerous. Widespread destruction.

estuaries, can modify the simple pattern of surges producing heights up to 50 percent higher in inlets compared to the open coast.

Intense rainfalls are common during tropical cyclones and may peak as the cyclone decays. Rainfalls of as much as 800 mm/day are not uncommon near the eye of a cyclone (remembering that the cyclone normally moves forward so that not all of the rain falls at the one spot). The rate of rainfall decreases away from the center, but the total area experiencing rainfall is enormous, and flooding (see below) can be a major problem. The total volume of rainfall produced by a mature tropical cyclone is about 17 cubic kilometers per day, according to one analysis.

A major hazard produced by tropical cyclones is strong wind (Figures 4 and 6). However, storm surges produced by tropical cyclones have killed hundreds of thousands people in some parts of the world. Other associated hazards can be highly destructive, too, including coastal erosion produced by large waves acting at higher than normal elevations, flooding produced by intense rains, saline intrusion from wind-driven salt spray, and bushfires fanned in the dry continental interior by strong winds hundreds of kilometers from the eye. Swell waves produced by cyclone winds are also a major problem for low-lying islands.

Figure 6. Cyclone Val swept across Savai'i island in Western Samoa on 7-10 December 1991, causing considerable damage. Almost all houses in this photograph have been totally destroyed, and trees stripped of foliage in what normally is a lush, tropical setting. Photograph courtesy of the Disaster Awareness Program, Emergency Management Australia.

Tropical cyclones in Australian waters are categorized on a 5-point scale according to wind speed. Physical characteristics and the typical effects of strong winds can be assigned for each category (Table 4).

The dataset used to plot the cyclone-frequency contours (numbers of cyclones of *all* categories per decade) on the 1:10 million map and in Figure 7 contains cyclone positions and intensities for the period 1959-1988—that is, from the beginning of the period when satellite imagery became available for tropical-cyclone tracking. The plotted contours of tropical-cyclone frequency were calculated for each point on a latitude and longitude grid having one-degree squares (each grid cell is about 110 x 110 km). The cyclone frequency was derived by counting the number of times within the dataset that each grid cell lay on the tracks of tropical cyclones. Counting was repeated for each of the five cyclone-intensity categories shown in Table 4. The track data are held in the database as three-hourly positions and intensities, but a stationary or slow-moving cyclone would not be counted more than once at one grid cell even if it maintained its position for more than three hours.

The cyclone contours used in the 1:10 million map were compiled from the tropical cyclone databases of the Australian Bureau of Meteorology (Holland, 1981), the Fiji Meteorological Service, the New Zealand Meteorological Service Ltd., and the Guam Joint Typhoon Warning Center, combined with data provided by Charles J. Neumann of Science Applications International Corporation, Miami, Florida, U.S.A.

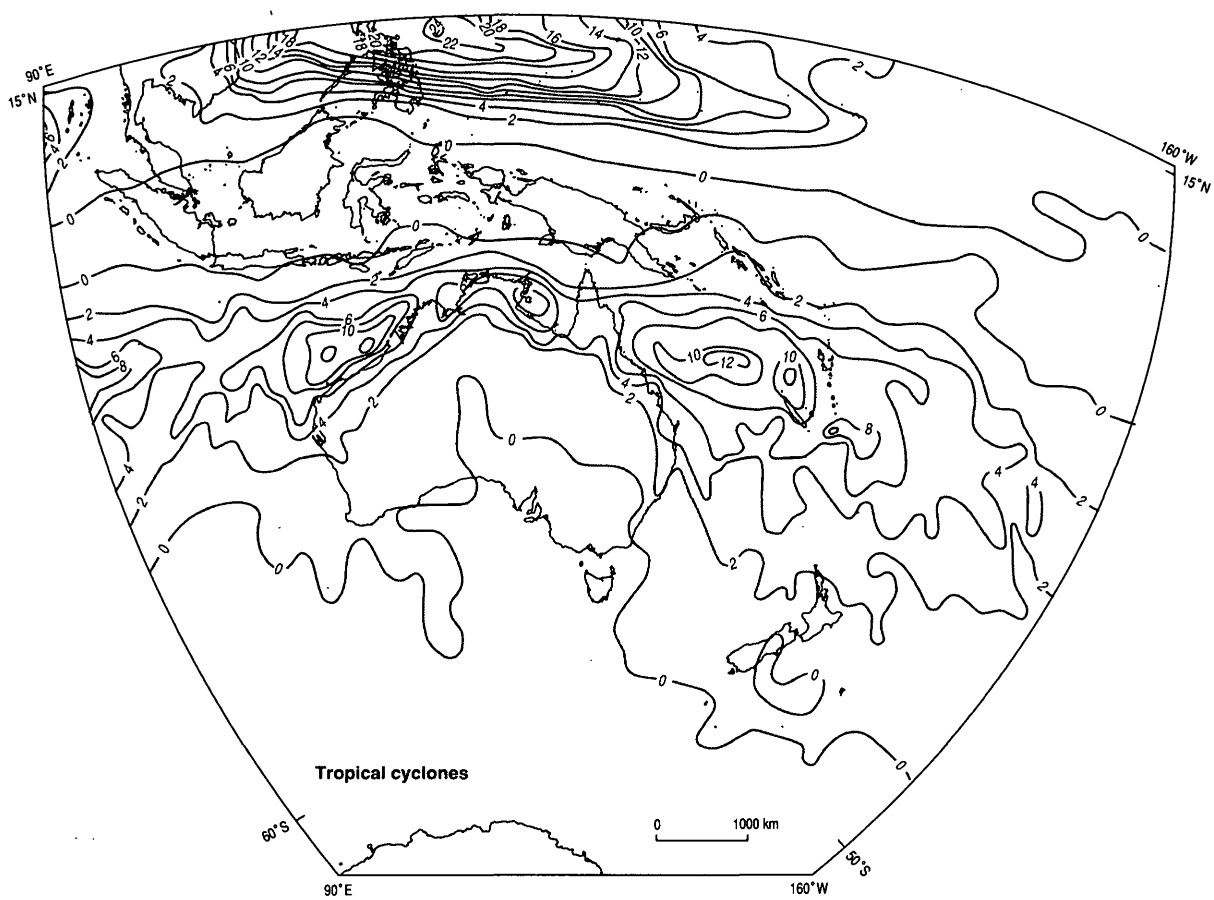

Figure 7. Cyclone-frequency contours (number of cyclones per decade) for cyclones of all intensities (see Table 4) for 1959-1988 (see text for method of plotting).

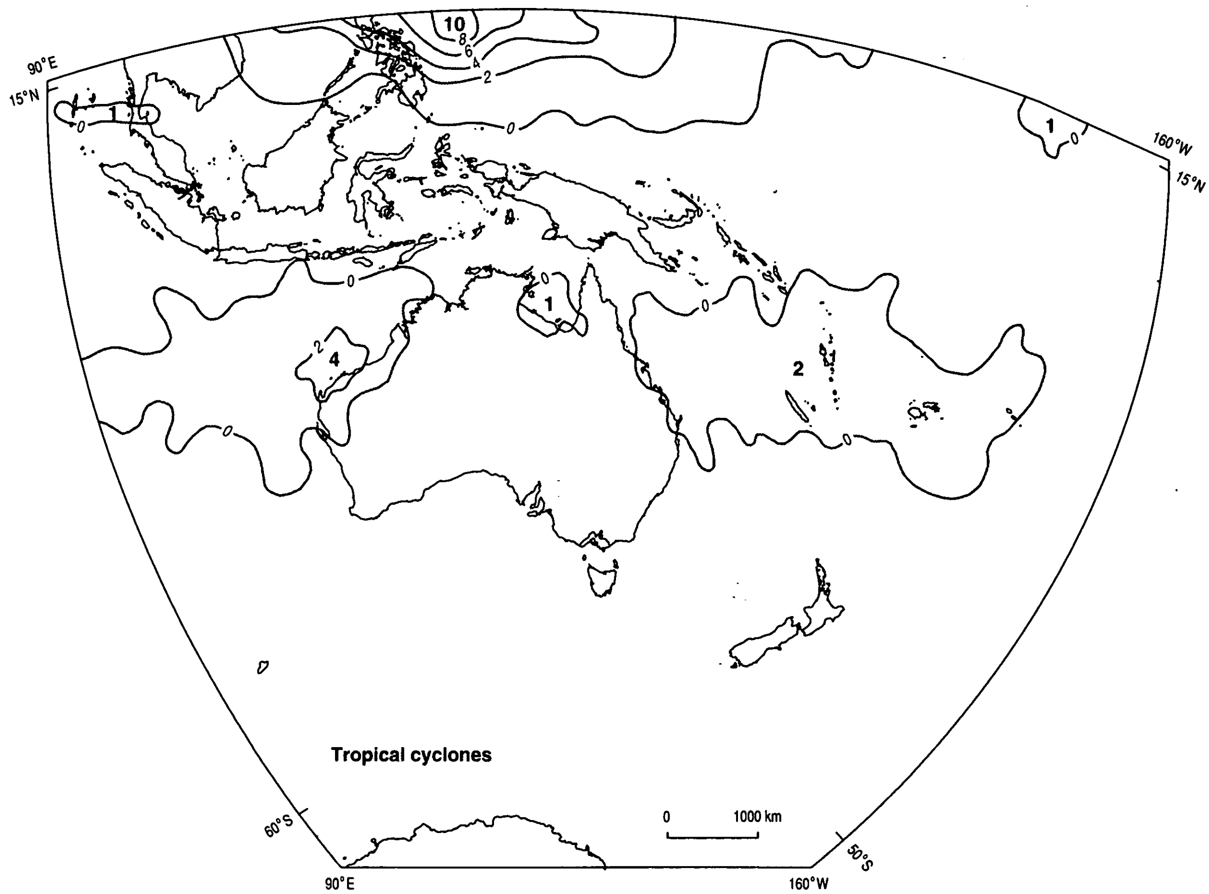

Figure 8. The contours shown here are for tropical cyclones of the greatest intensity (3-5 in Table 4) per decade during the 1959-88 period. Note the difference in pattern compared to the contours for all cyclones per decade for this period shown in Figure 7. The numbers set within contour-defined areas refer to the maximum number of cyclones in that area.

Few cyclones begin close to the Equator so that countries such as Malaysia and Singapore are essentially cyclone-free, but parts of Papua New Guinea and Indonesia can be affected. Cyclones are more frequent on the northwestern coast of Australia than on the northeastern coast, and they penetrate further inland in the northwest, perhaps because the coastal topography is less elevated than on the northeastern coast. In addition, more cyclones penetrate further south on the western coast of the continent.

Frequencies of cyclones of all intensities for the 30-year period (1959-88) in the area east of the Philippines are shown to be more than twice that of the maximum frequencies off the Australian coast on the 1:10 million map and in Figure 7. The importance of this difference is even more evident in a plot of frequency of only Category 3 -5 cyclones (Figure 8). More intense cyclones are shown to be more common on the western coast of Australia than on the eastern, but the most striking feature is that the area of the eastern Philippines is seen to be affected much more frequently by stronger cyclones. This east-Philippines area generates more tropical cyclones than any other place in the world, as mentioned previously.

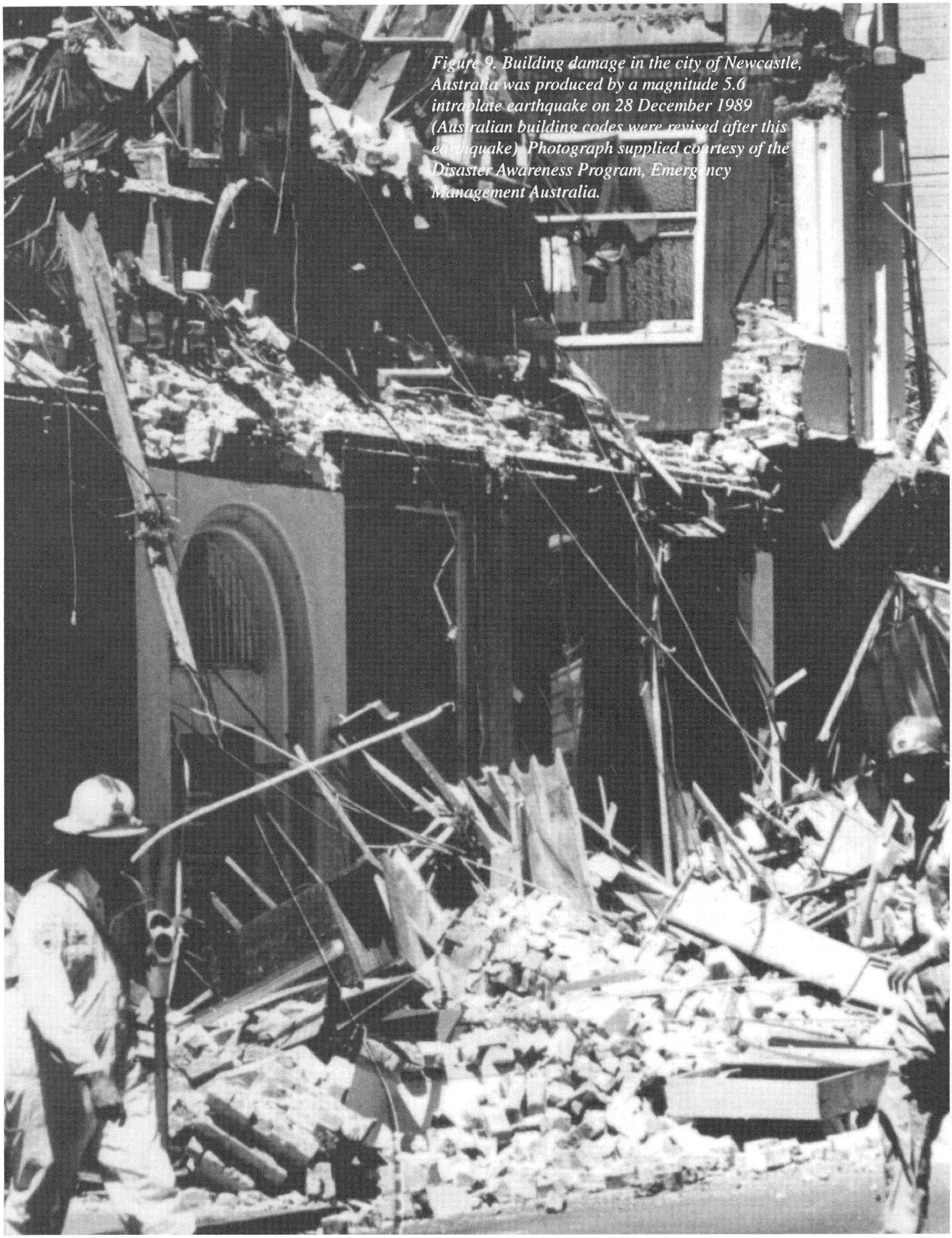

Figure 9. Building damage in the city of Newcastle, Australia was produced by a magnitude 5.6 intraplate earthquake on 28 December 1989 (Australian building codes were revised after this earthquake). Photograph supplied courtesy of the Disaster Awareness Program, Emergency Management Australia.

Earthquakes

Earthquake activity in the Pacific Southwest is controlled largely by the interaction of the Indo-Australian plate with the plates around it (Figure 3). The zones of highest earthquake hazard are those at the northern and eastern margins of the plate where it converges on the Eurasian and Pacific plates - that is, in most of Indonesia, Papua New Guinea, the Solomon Islands, Vanuatu, Tonga, the Kermadec Islands, and New Zealand. Earthquake activity at the boundaries between the Eurasian, Philippine, and Pacific plates (Figure 3) affects the Philippines, Marianas, and northeastern Indonesia.

Australia is the only large landmass in the Pacific Southwest not lying on a plate boundary. Earthquakes on plate boundaries can be explained by the interactions between the adjacent plates, but earthquakes taking place in Australia are more difficult to understand. Most earthquakes in Australia have been shown to be caused by horizontal compression of the rocks in the upper crust of the continent. The level of earthquake activity in Australia is less than in plate-boundary countries, but the majority of Australian earthquakes are very shallow - within the top 10 km of the Earth's crust - so that even small events in populated areas may be felt quite strongly. This is why the earthquake hazard

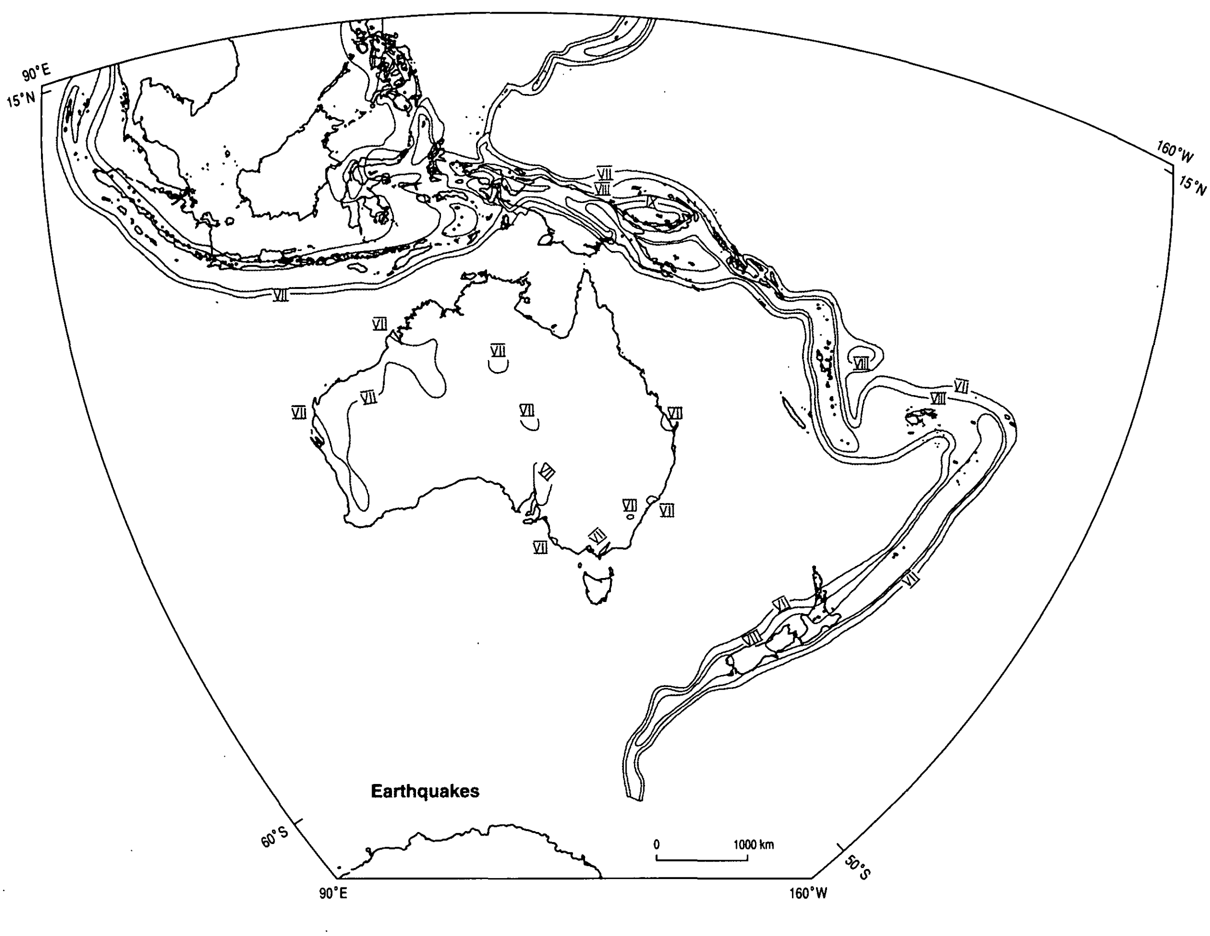

Figure 10. Zonation for earthquakes of Modified-Mercalli intensity VII to greater than IX (see Table 5). Each zone represents a 10-percent chance of earthquake shaking of the given intensity being equalled or exceeded in a 50-year period. Contours over water are shown in the 1:10 million map as dashed lines in order to represent uncertainty (because there are no seafloor observations of intensity) but here are shown as solid lines for clarity.

in some parts of Australia is high enough to be shown on the 1:10 million map. In contrast, earthquakes extend down from near the surface to more than 300 km in parts of most countries on plate boundaries in the region.

Areas on the 1:10 million map, and in Figure 10, assessed as having the highest earthquake hazard include eastern Indonesia, northern mainland Papua New Guinea, southern New Britain and southern New Ireland, parts of the Solomon Islands, Vanuatu, Tonga, and in New Zealand (the southeastern half of the North Island, and the northern part and the southwestern tip of the South Island). These regions are assessed as having a 10-percent probability of earthquake shaking equalling or exceeding Modified Mercalli (MM) intensity IX in a 50-year period.

The Modified Mercalli scale of earthquake intensity is a 12-point scale rating earthquake effects (for example, Eiby, 1966) that can be observed by people without the aid of scientific instruments (Table 5). MM I is the lowest perceptible intensity and MM XII is the highest. MM VII is the smallest value contoured on the 1:10 million map and marks the onset of other than isolated cases of structural damage to buildings that have low standards of workmanship. However, superficial and slight structural damage may result at lesser intensities.

The MM intensity experienced during an earthquake depends upon its Richter magnitude (the 'size' of the earthquake), the distance of the place from the epicenter of the earthquake (the point on the surface above the earthquake), the depth of the earthquake, the type of faulting that caused the earthquake, and the foundation conditions at the site of the observer. The Richter magnitude of an earthquake is related to its energy. A magnitude-7 earthquake has about 32 times the energy release of a magnitude-6 one, and about 1000 times that of a magnitude-5 earthquake.

The larger the magnitude, the higher the Modified Mercalli intensity observed at a particular site, all other factors being equal.

Table 5. Abbreviated version of the Modified Mercalli earthquake intensity scale

(adapted from Eiby 1966)

I	Not felt except for a very few people.
II	Felt only by a few people at rest indoors.
III	Felt quite noticeably indoors. Standing motor cars may rock slightly.
IV	Felt by most people indoors. Very light sleepers may be awakened. Dishes, windows, and doors rattle.
V	Felt by nearly everyone. Most awakened. Some dishes, windows, etc. broken.
VI	Felt by all. A few instances of fallen plaster or damaged chimneys. People alarmed. Objects fall from shelves.
VII	No damage to buildings of good design and construction. Slight to moderate damage in well-built ordinary structures. Damage considerable in poorly built or badly designed structures.
VIII	No damage to specially designed structures, but damage can be considerable in ordinary substantial buildings, including partial collapse. Great damage in poorly built structures. Fall of walls, columns, monuments, and factory stacks.
IX	Damage great, including partial collapse, of substantial buildings. Well-designed frame structures distorted. Unsecured buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. Serious damage to reservoirs.
X	Some well-built wooden structures seriously damaged. Most masonry structures and foundations destroyed. Dams seriously damaged. Paved roads badly cracked or thrown into waves. Railway lines slightly bent. Large landslides on steep slopes.
XI	Wooden frame structures destroyed. Great damage to underground pipes and railway lines.
XII	Damage virtually total. Objects thrown upward into the air. Large rock masses displaced.

Strong ground shaking from an earthquake dies away markedly with distance from the epicenter so, naturally, the MM intensity tends to be highest near the epicenter. However, the rate of decay of ground shaking can differ significantly between different geological settings. In addition, an earthquake tens or hundreds of kilometers deep will tend to be felt less strongly than if it were only, say, 10 km deep. The depth of earthquakes in an area therefore will influence the hazard potential, and shallow earthquakes will be the main contributors. Energy from an earthquake tends not to be radiated uniformly in all directions. Rather, it depends upon the nature of the fault, so the orientation of the observation site relative to the fault can affect the MM intensity. Finally, the type of foundation material affects the ground shaking, which will be less on sites underlain by hard rock compared to those on alluvium.

The main factors determining earthquake hazard shown on the relatively small-scale, 1:10 million map are the relative frequencies of earthquakes of different magnitudes, their depths, and how rapidly strong ground shaking declines with distance from the earthquake. Earthquake hazard on the map is contoured as MM intensities (VII and greater) having a 10-percent probability of being equalled or exceeded in a 50-year period. The contours are for 'average' sites—that is, those on firm ground, but not hard rock—and they do not take into account the dramatic

Figure 11. Ground shaking caused by earthquakes in Pacific countries leads to building damage and to the collapse and toppling of some designs of water tanks, as shown here in two photographs taken (by R.W. Johnson) in the Rabaul area of Papua New Guinea. This damage was caused by a magnitude-7.9 earthquake in the Solomon Sea on 14 July 1971.

Figure 12. Earthquakes can be caused by movements along faults that break the Earth's surface. The split in the ground shown in this photograph (taken by L. Homer, Institute of Geological and Nuclear Sciences, New Zealand) was produced by an earthquake of magnitude 6.5 on 2 March 1987 at Edgecumbe, New Zealand. Note the relative downward displacement of the ground to the right.

magnification of earthquake ground motion by alluvium, fill, or other soft ground. There are no instruments in the region that measure strong earthquake shaking on the sea floor, so contours over the oceans are shown as dashed lines in order to emphasize the greater uncertainty in their positions.

Contour positions on the Australian part of the map are based on the hazard map in the Australian Standard 1170.4 (1993). The method of derivation of this map (from that of Gaull and others, 1990) is described by McCue (1993). Earthquake contours for the rest of the Pacific Southwest map sheet were derived from a wide range of sources, and hazard estimates based on the distribution and density of shallow earthquakes and on tectonics were used to fill gaps. Hazard contours in Indonesia and islands to the northwest are modified from the work of Hattori (1979) taking seismicity and tectonics into account. Su (1988) published hazard maps for the Philippines which were adapted for use here. Contours for Papua New Guinea are based on those on the zoning map by McCue (1984), and these have been extended westwards into Irian Jaya on the 1:10 million map. Earthquake-hazard assessment for the Solomon Islands made use of the seismicity maps and the two-tier zoning classification of Tuni (1981). Earthquake-hazard zonation for Vanuatu, Fiji, Tonga, the Kermadec Islands, and the Macquarie Ridge, is based on unpublished results by T.D. Jones (presented here for the first time). Hazard contours for New Zealand were taken directly from Smith and Berryman (1986).

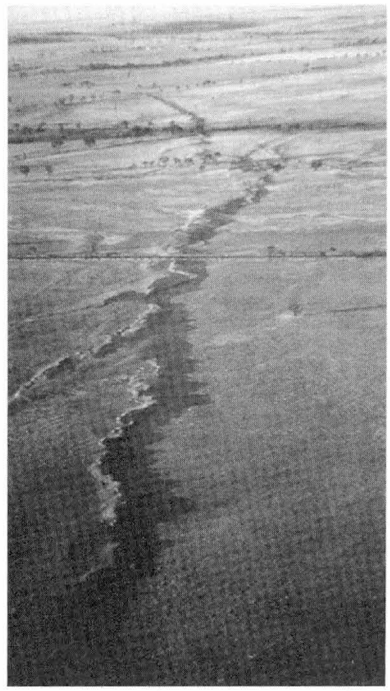

Figure 13. A 37-km-long surface fault scarp was formed at Meckering, Western Australia, on 14 October 1968 following a magnitude-6.8 intraplate earthquake. Photograph taken by I.B. Everingham.

The zones depicted on the 1:10 million map and the discussion here relate particularly to the potential for ground-shaking hazards (Figures 9 and 11). However, ground-failure hazards—surface faulting (Figures 12 and 13), landslides, liquefaction, and lateral spreading—are of major importance in many areas, particularly where there are steep slopes on weak rocks or soft alluvial and estuarine deposits. The effects of tsunamis (see below) are not considered in the earthquake-hazard zonings, even though they can be catastrophic in low-lying coastal areas of island nations.

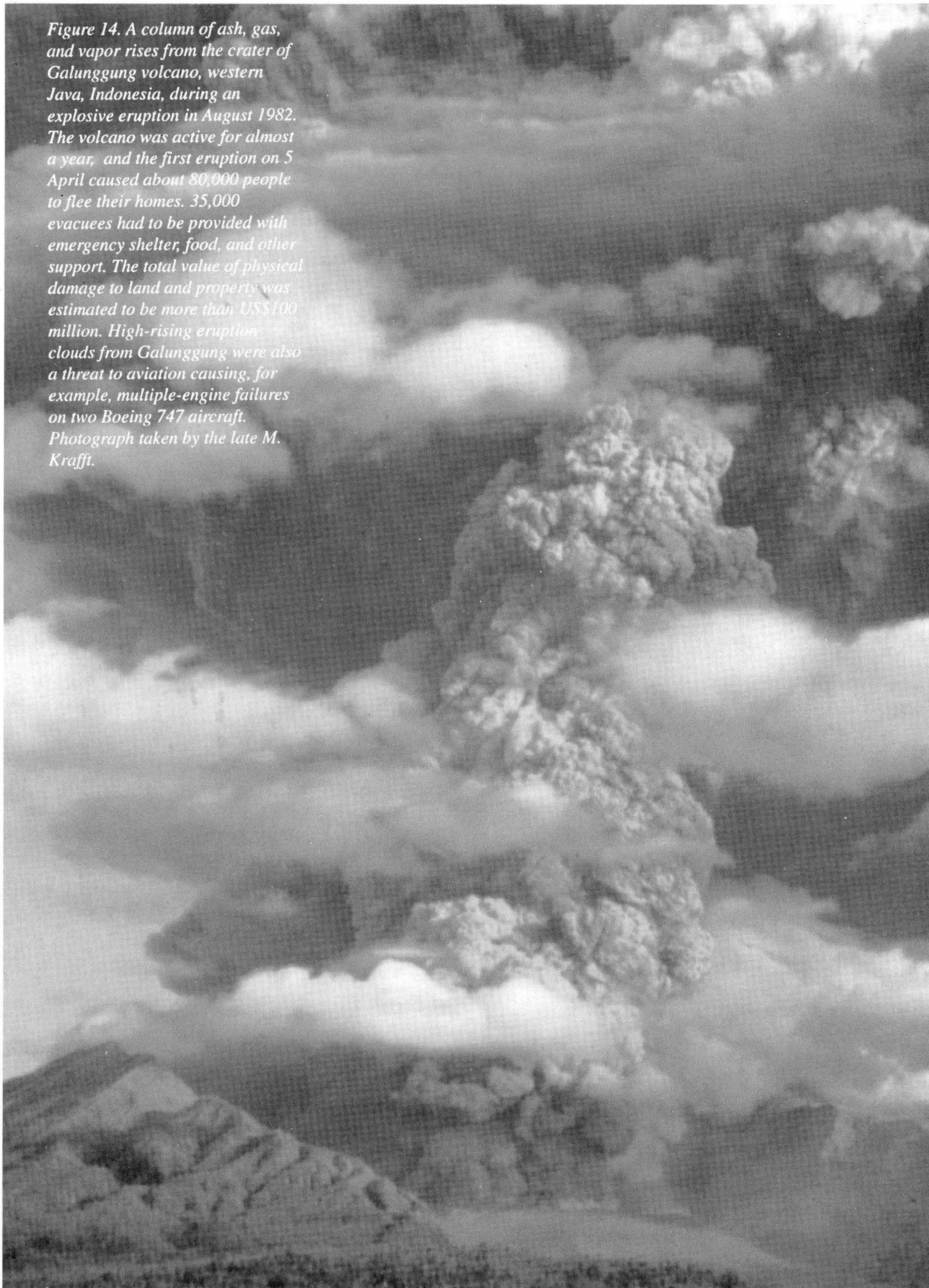

Figure 14. A column of ash, gas, and vapor rises from the crater of Galunggung volcano, western Java, Indonesia, during an explosive eruption in August 1982. The volcano was active for almost a year, and the first eruption on 5 April caused about 80,000 people to flee their homes. 35,000 evacuees had to be provided with emergency shelter, food, and other support. The total value of physical damage to land and property was estimated to be more than US$100 million. High-rising eruption clouds from Galunggung were also a threat to aviation causing, for example, multiple-engine failures on two Boeing 747 aircraft. Photograph taken by the late M. Krafft.

Volcanoes

Volcanic eruptions are a natural activity of a dynamic planet such as Earth, but they can be harmful to people and to the buildings and agricultural lands that sustain them. Many different kinds of hazards threaten people who live on or near volcanoes. Thick ash deposits may fall on towns and villages from drifting eruption clouds. Streams of hot lava that flow down volcanoes may bulldoze buildings and cover agricultural lands, but generally are slow enough for people to be able to escape them.

Explosive eruptions (Figure 14) and catastrophic collapses of volcanoes are probably the most hazardous volcanic events. Some explosive eruption clouds above a volcano may collapse, producing hot pyroclastic flows that race down the sides of the volcanoes. Less dense, hot blasts ('surges') of ash and gas may sweep across populated areas during explosive volcanic activity (Figure 15). Steam explosions caused by the heating of groundwater take place at some active volcanoes. Major rock avalanches caused by the catastrophic collapses of volcanoes are also potentially disastrous events, as are mud flows and floods caused by excessive runoff of surface waters and debris from the flanks of volcanoes, or by the breaching of crater lakes. Dense volcanic gases emitted from volcanoes may move down valleys, hugging the ground and asphyxiating people who happen to be there.

Figure 15. A laterally directed cloud of hot gas and ash from Lamington volcano, Papua New Guinea, blasted the government settlement at Higaturu on 21 January 1951. Almost 3000 people were killed in the zone of devastation. The effects of the blast are seen in this photograph (from the files of the Australian Geological Survey Organisation, Canberra) showing tree trunks stripped and broken, a jeep hurled up onto the stumps of trees, and, on the extreme left, the end of a bent radio mast.

Mapping of volcanic hazards is undertaken most commonly on individual volcanoes at scales of, say, 1:25,000-100,000. This permits a level of detail that is useful for long-range planning of land uses on and around the volcano, and for determining those areas that should be evacuated and avoided during eruptions (Crandell and others, 1984). The former may include estimates of the frequency with which hazardous events have taken place in the past (as a guide to future events). The latter may be a map showing different kinds of hazards, so that people could be evacuated in different stages from different areas depending on the type of expected volcanic eruption.

The 1:10-million scale of the Pacific Southwest map is far too small to be valuable for the mapping of volcanic hazards on individual volcanoes. However, it is useful for showing the general distribution of volcanoes in the region by using point symbols for each volcano and by adopting a classification that draws attention to those volcanoes whose eruptions might have a *regional* effect—that is, well beyond the foot of any single erupting volcano (Figure 16).

Regional volcanic hazards are of three main types:

(1) Large explosive eruptions will produce extensive ash clouds that are carried by winds well away from the volcano and may deposit ash hundreds or even thousands of kilometers away. Drifting ash clouds are also a hazard to aircraft operating on routes distant from the active volcano (see Figure 14).

(2) Sulfur-dioxide gas is produced in copious amounts during large eruptions and is injected into the stratosphere

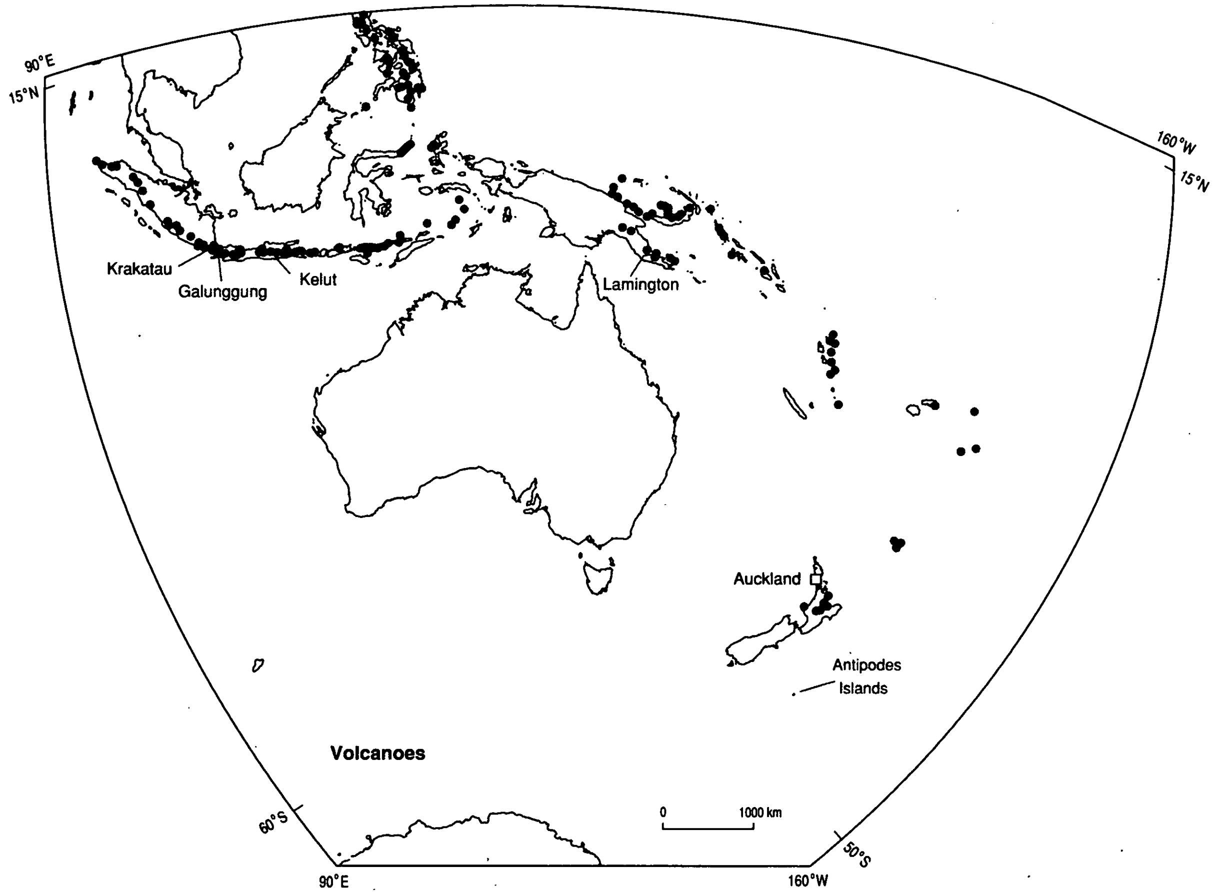

Figure 16. Distribution of volcanoes (represented by filled circles) having the potential for large explosive eruptions that may have a regional rather than simply a local effect. These volcanoes classify in three separate groups (2-4) in Table 6, but are here shown together using the same symbol.

Table 6. Classification of volcanoes in the Pacific Southwest

1. Frequently active	Volcanoes that have produced at least two eruptions since 1850 A.D. The potential for *major* explosive eruptions is considered to be low because of insufficient time for the buildup of significant eruptive potential.
2. Infrequently active	Volcanoes known to have been active during the Holocene (the last 10,000 years) from oral or written history, or from radiometric dating. Includes volcanoes producing only one post-1850 A.D. eruption, but many volcanoes in this group have not erupted since 1850.
3. Active calderas[1]	Calderas exceeding 5 km in diameter for which there is a known date or other reasonable evidence for formation during the Holocene. Calderas of *unknown* age are included here only if there are known post-caldera magmatic eruptions. Calderas of unknown age that do *not* have known post-caldera Holocene eruptions (but which may have thermal activity) are excluded. Volcanoes within or on the rim of known pre-Holocene calderas are classified in one of the other categories.
4. Uncertain activity	No dated magmatic eruptions during the Holocene. Based on volcanoes having youthful morphological features, thermal activity, or a general lack of erosion. Also includes prominent thermal areas that are associated with minor volcanoes or volcanic rocks of Holocene age.
5. Fields of minor volcanoes	Areas of many (perhaps hundreds) of small volcanoes, most of which are probably extinct, although the area itself may produce volcanic activity at some new vent in the future.

[1]Active calderas are giant collapse depressions (large craters) that are evidence for the presence of large, shallow magma reservoirs beneath a volcanic center. Their formation in subduction-zone settings commonly is accompanied by large explosive eruptions. There may be evidence at the volcanic centre for several calderas having been formed successively.

where it is gradually converted to sulfuric-acid aerosols which may be distributed globally. Aerosol layers in the atmosphere cut down some of the solar radiation that otherwise would reach the Earth's surface, leading to cooling over wide regions and possibly producing climate changes.

(3) Volcanoes that collapse gravitationally can produce huge rock avalanches (Figure 17) which, if they reach the sea, will generate tsunamis—sea waves that travel hundreds of kilometers, washing up and damaging shores a long way from the volcano that produced them (see *Tsunamis* section). Underwater explosions and volcanic earthquakes, as well as pyroclastic flows crashing down on the sea, may produce similar effects.

Volcanoes plotted on the 1:10 million map were divided into five groups (Table 6) starting with the listing of the *Volcanoes of the World Data File* (Smithsonian Institution, 1992). The volcanoes in this listing were classified initially into nine groups on the basis of known past eruptive activity and geology, using a wide range of published sources. The information supporting the classification is by no means detailed. Many volcanoes in the region are still poorly studied, and the radiometric dating of past eruptions at very many of them is sparse. However, the classification does provide a general indication of the distribution and abundance of the high-potential explosive volcanoes of the region.

Four of the nine groups (1-4 in Table 6) capture volcanoes known or presumed to have been in eruption explosively sometime during the last 10,000 years (that is, during the Holocene). Three of the four (2-4 in Table 6) are believed to have volcanoes carrying the potential for producing explosive eruptions that may have a *regional* effect (Figure 16). The selection criteria for these three volcano groups are sufficiently imprecise that not *all* the volcanoes in each of the groups can be regarded as having such potential. Indeed, some of the volcanoes in the three groups may have become extinct already, others no longer may have the capacity to produce major activity, and indeed still others, in the absence of definitive information to the contrary, may never have had such capacity. In other words, the three groups together represent an attempt at casting a wide net to include all the high-potential, Holocene volcanoes of the region, but acknowledging that the attempt has netted some lesser volcanoes too.

The fifth group (5 in Table 6) is included mainly to show the large clusters of small volcanoes such as that in the populated Auckland area of New Zealand where there is a significant volcanic risk. Some group-5 volcanic clusters (the Newer Volcanics area of southeastern Australia is another example) have had minor explosive eruptions in the past, and they are unlikely to produce large explosive eruptions of regional effect in the future.

The four of the nine volcano types that are *not* included in the Pacific Southwest map are:

1. Hot-spring and other thermal areas that do not appear to be associated with Holocene volcanoes.

2. Volcanoes that are unlikely to have erupted magmatically in the last 10,000 years. All Pleistocene volcanoes cannot be regarded as extinct, but there is no easy method of identifying those having the potential for future magmatic activity.

3. Deep-water submarine volcanoes active in the Holocene. Those that have produced ephemeral islands during the Holocene are included in one of the other categories of Table 6.

4. Intraplate volcanoes that have been active in the Holocene and which do not classify in group 5 of Table 6. This group includes hotspot volcanoes, the New Zealand Antipodes Islands, and the continental volcanoes of the Indo-China Peninsula. None of these volcanoes is identified as having the capacity to produce large explosive eruptions. However, those of them that have grown in or near the sea may have the potential for collapse and the generation of volcanic tsunamis.

The pattern of volcano distribution on the 1:10 million map is distinctive as there is a close correspondence between the volcano symbols and the zones of greatest earthquake hazard (compare Figures 10 and 16). This is a reflection of the network of subduction zones of the region that extends from New Zealand, northeastwards to Tonga, then across to Indonesia where the earthquake zone splits into three, each extending off the sheet area into other parts of east Asia and the western Pacific (Figure 3). Indonesia has by far the greatest number of 'high-potential' volcanoes, followed by the Philippines, Papua New Guinea, and New Zealand.

Figure 17. Volcanoes can collapse, producing avalanches and related mudflows and floods that may flow rapidly many tens of kilometers from the volcano. This has taken place in the past at Taranaki (or Egmont) volcano, New Zealand, where evidence of past avalanches is seen in a 'ring plain' of deposits almost completely surrounding the present-day volcano. These deposits are seen in this photograph (taken by L. Homer, Institute of Geological and Nuclear Sciences, New Zealand) by the light-colored area between the volcano and the Tasman Sea in the background. Tarankai was last in eruption in about 1755 and has the potential to produce explosive eruptions as well as major collapses. Features at risk include several settlements in the area (including New Plymouth), water supplies, highways, and several major industrial projects.

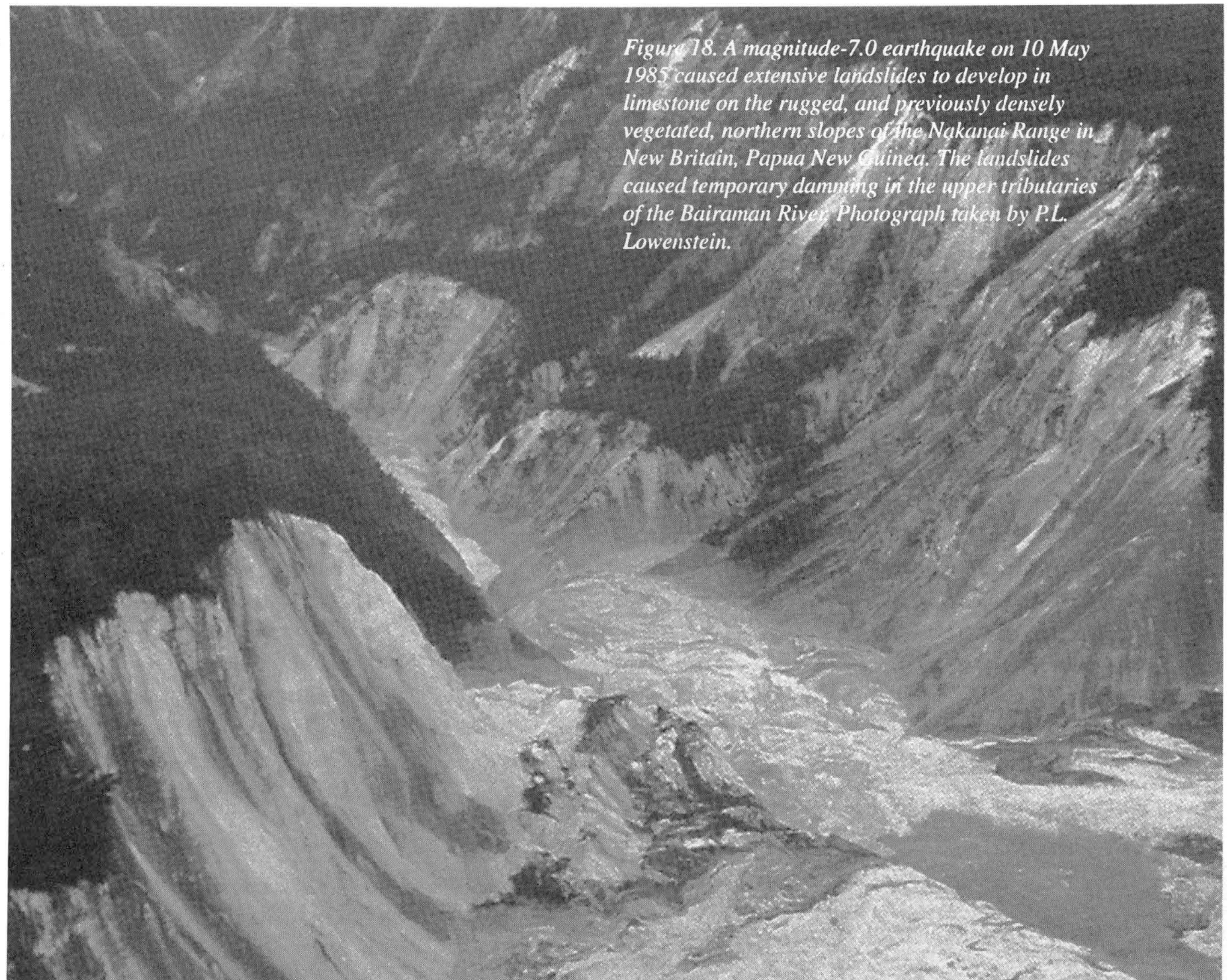

Figure 18. A magnitude-7.0 earthquake on 10 May 1985 caused extensive landslides to develop in limestone on the rugged, and previously densely vegetated, northern slopes of the Nakanai Range in New Britain, Papua New Guinea. The landslides caused temporary damming in the upper tributaries of the Bairaman River. Photograph taken by P.L. Lowenstein.

Landslides

Landslides are an important natural hazard in the Pacific Southwest region, although comprehensive information about their scale and potential is generally lacking as relatively little mapping of landslide distribution and type has been undertaken. In addition, such mapping is best undertaken at scales many times larger than the 1:10 million scale of the natural-hazard potential map (see also Figure 19). Indeed, representing landslide hazard potential was perhaps one of the more difficult problems in producing the 1:10 million map.

Individual landslides can involve one or more of four basic types of movement—fall, slide, rotation, or flow. Different types of landslides produce different hazards. Some landslides (rotational slumps, for example) move only a few meters downslope whereas mudflows can travel tens of kilometers along river channels. Most landslides are shallow, involve the stripping of soils, and are less than a few tens of cubic meters in volume. At the other extreme are large rock and debris avalanches that can dam (or even obliterate) river channels (Figure 20) and which contain cubic kilometers of rock debris including individual blocks many times the size of a house. Landslides have a considerable diversity of types and potential consequences.

Numerous factors contribute to an appreciation of landslide potential. The most important (possibly in order of significance) include the presence of past landslides, weak mudstones, steep slopes, excessive rainfalls caused frequently by cyclones, earthquakes, susceptible volcanic terrains, tectonically-disturbed terrains, vegetation removal, and other human interference.

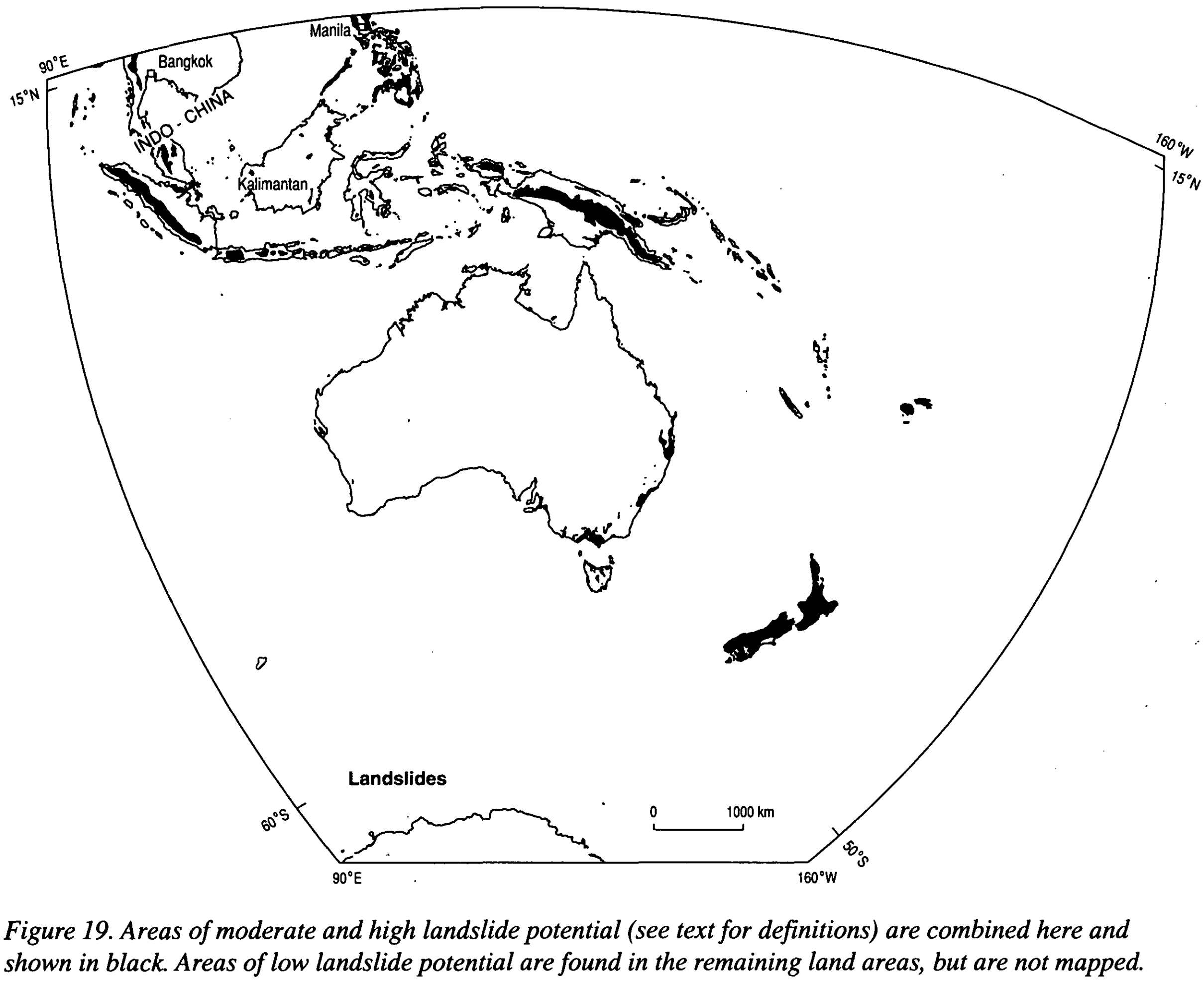

Figure 19. Areas of moderate and high landslide potential (see text for definitions) are combined here and shown in black. Areas of low landslide potential are found in the remaining land areas, but are not mapped.

No attempt has been made on the 1:10 million map (see also Figure 19) to differentiate types of landslides, as little systematic information is available, except for New Zealand (Eyles, 1983). The 1:10 million map has two categories of landslide potential—high and moderate (a category for low potential was used during the preparation of landslide information, but was excluded from the map in order to avoid overcrowding with other hazard types). Both the high and moderate landslide-potential categories are found mainly in the earthquake-prone, mountainous parts of the northern and eastern margins of the Indo-Australian plate (Figure 3). These are tectonically active areas where young, soft rocks form steep-sided mountain ranges that induce orographic rainfall, and are susceptible to landslides.

Also excluded from the map is the landslide potential for islands less than a few thousand square kilometers in extent where scale limitations on the maps prevent the portrayal of landslide potential. Numerous islands in this category are present from Indonesia to Tonga and many have significant landslide potential. Volcanic islands, in particular, have the potential to cause large landslides that may produce tsunamis of widespread effects (see *Volcanoes* section above).

High landslide potential areas include those where past landslide disasters have taken place. These are commonly areas where outcrops of weak mudstone, or thick deposits from volcanic eruptions, or nearby earthquakes, and high rainfall, are likely to

Figure 20. The landslide shown in this photograph (taken by N.A. Trustrum, Manaaki Whenua Landcare Research, New Zealand) was produced in the Waerengaokuri district, 30 km west of Gisborne, on the east coast of the North Island, New Zealand, as a result of Cyclone Bola on 9-12 March 1988. The slide in Tertiary sedimentary rocks has dammed a stream valley, causing a lake to form. Note the many other small landslides in other parts of the photograph.

produce future landslides. They commonly have high potential because landslides have taken place repeatedly - for example, in the case of volcanic mudflows on volcanoes such as Kelut in eastern Java. Similarly, areas in Papua New Guinea where thousands of landslides have taken place as a result of large earthquakes, and which have the potential for the recurrence of similar events, have been included in this category. A number of areas across the mapped region that undoubtedly should be included in this category have been omitted because of lack of information.

Areas of *moderate* landslide potential include those areas where landslides are known to be common, together with adjacent areas of similar terrain, lithology, and exposure to seismicity or intense rains (or both). There is probably some inconsistency in the expression of the moderate category from one country to another, particularly where countries in which a great deal is known about landslide distribution and potential (in particular, New Zealand) are compared with countries or regions where very little is known (for example, Kalimantan, Indonesia).

The *low* landslide potential category covers most of the Pacific Southwest land area and has three components:

(1) Areas of rather gently sloping land that, nevertheless, do have a low potential for landsliding.

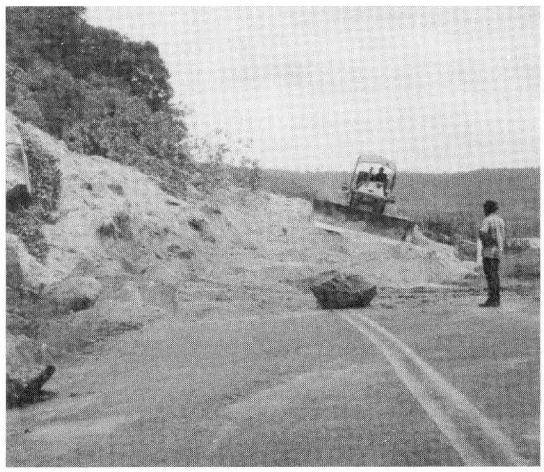

Figure 21. The 14 July 1971 earthquake that caused the damage shown in Figure 11 also produced many small landslides in the Rabaul area of Papua New Guinea. The landslide shown in the left-hand side of the photograph (taken by R.W. Johnson) caused the temporary blocking of the road.

(2) Flat-lying land, including floodplains and other plains such as those around Manila and Bangkok and the eastern margin of Sumatra, where landslides are not really possible, other than along river banks.

(3) Areas such as Kalimantan and all of Indo-China where there is very little information about landslide potential other than the implication (perhaps incorrect), that absence of information means absence of landsliding. Absence of information more likely implies an absence of economic development, as much of the available data on landslides from many countries comes from geotechnical investigations associated with the development of transport and other infrastructure.

Data on which the map of landslide potential was based were drawn from numerous sources, using the broad principles outlined above. The most important of these were for Australia (Fell, 1992), New Zealand and Papua New Guinea (Blong and Eyles, 1989), Indonesia (Wirasuganda, 1983; Elifas, 1987; Pandjaitan and others, 1981), and the Pacific Islands (files of the Natural Hazards Research Centre, Macquarie University; G. Shorten, Queensland University of Technology, personal communication; Crozier, 1989). The publications of Brand (1984, 1989) were invaluable general sources for much of southeastern Asia.

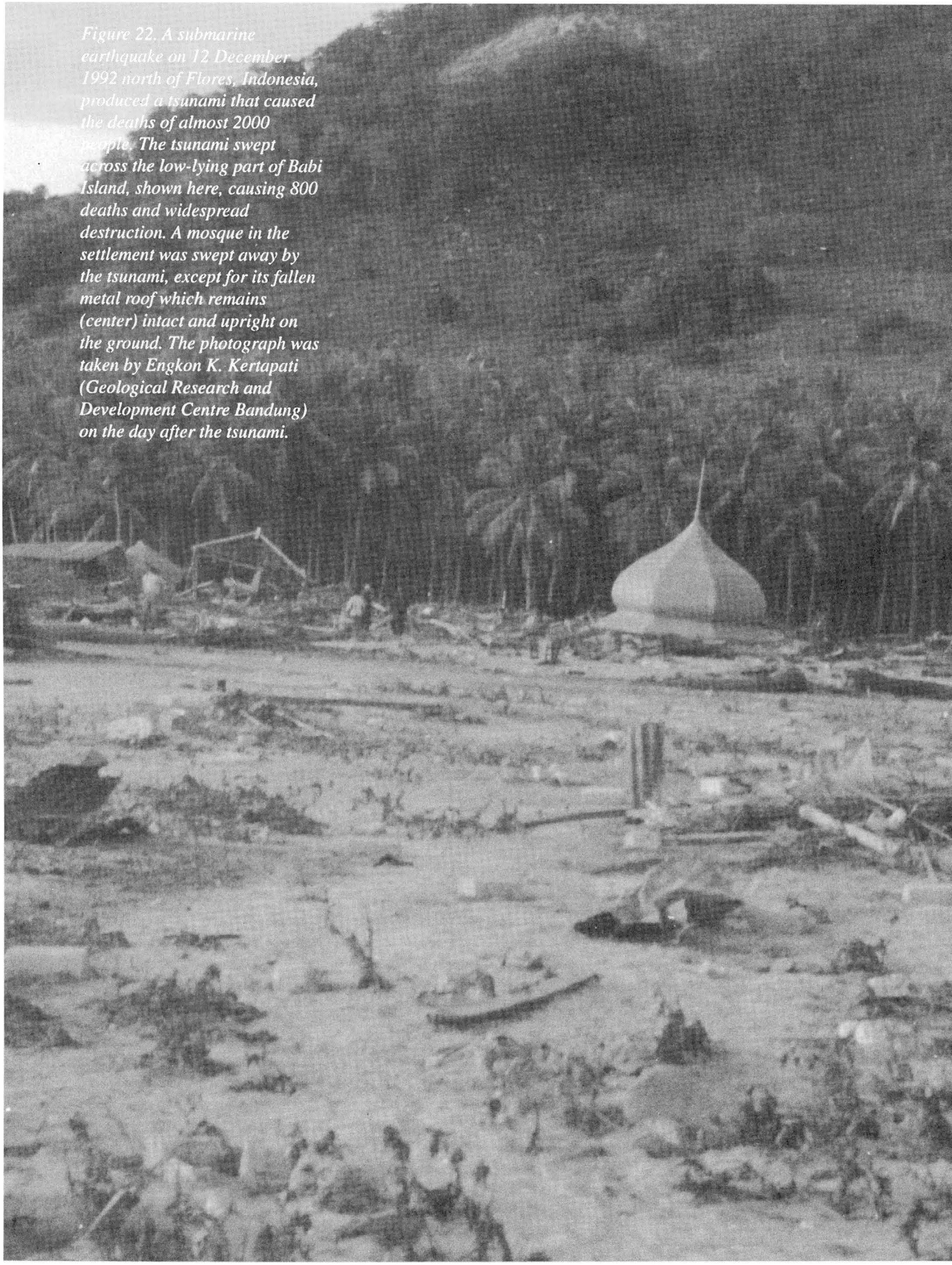

Figure 22. A submarine earthquake on 12 December 1992 north of Flores, Indonesia, produced a tsunami that caused the deaths of almost 2000 people. The tsunami swept across the low-lying part of Babi Island, shown here, causing 800 deaths and widespread destruction. A mosque in the settlement was swept away by the tsunami, except for its fallen metal roof which remains (center) intact and upright on the ground. The photograph was taken by Engkon K. Kertapati (Geological Research and Development Centre Bandung) on the day after the tsunami.

Tsunamis

The term 'tsunami' comes from a Japanese word meaning 'harbor wave'. Tsunamis commonly are called 'tidal waves' but are not caused by tides. They are long-period waves less than 1 or 2 meters in height that travel across the deep, open ocean at speeds of more than 800 km/hr. Their speed drops and the height of the wave increases as the waves approach coastlines and the water shallows. Tsunamis more than 30-40 m high are known to have taken place, but most waves reaching shorelines are much smaller. The waves are reflected and refracted, depending upon the shape of the coastline and the offshore bathymetry. Areas most at risk include those where funnel-shaped bays and harbors boost wave height. Tsunamis are enormously damaging, producing high death tolls and almost complete destruction in areas where there is wave run-up (Figure 22).

Tsunamis can be generated in several ways, although all involve the movement of a part of the ocean floor, or adjacent land mass, that generates a displacement of water. Most tsunamis are caused by shallow submarine earthquakes generally having Richter magnitudes greater than 6.5. Tsunamis also can be produced during large volcanic eruptions, when massive volumes of pyroclastic flows are dumped in the water, or as the result of the collapse of a volcanic edifice. Some of the largest tsunamis (more than 30 m high) reported in the Pacific Southwest region were on the western coast of Java during the 1883 volcanic eruption at Krakatau. They contributed significantly to the total death toll of more than 36,000. Tsunamis also form where large landslides take place on the submarine parts of river deltas, or where terrestrial slopes slide into the ocean. Tsunamis in Antarctic waters are generated by calving icebergs that overturn suddenly when melting disturbs their equilibrium.

Table 7. Tsunami magnitude scale (adapted from Iida, 1963)

Tsunami magnitude	Run-up height (meters)
0	1-1.5
1	2-3
2	4-7
3	8-15
4	16-31
5	32 and greater

These causes of tsunamis—earthquakes, volcanic eruptions, and large landslides—mean that areas of tsunami generation are concentrated along the earthquake belts where, in addition, volcanoes, steep slopes, and weak rocks are to be found. However, tsunamis can travel enormous distances across the open ocean so that sources outside the Pacific Southwest map region also must be considered. For example, damage was caused in several areas in the Pacific Southwest as a result of tsunamis generated by the 1960 Chilean and 1964 Alaskan earthquakes. There is also some evidence that tsunamis may have reached the map region from large landslides produced from the flanks of volcanoes on Reunion Island (Indian Ocean) and in Hawaii.

Tsunami magnitude commonly is measured as 'run-up' height —that is, the maximum height reached by the tsunami above sea level (Table 7).

Tsunami hazard potential on the 1:10 million map (excluding Antarctica) was developed by plotting the locations of all known tsunami magnitudes in the map region, together with limited information about arrival direction and source. These data then were generalized to cover strips of coast 400-500 km long. Generalized zones of high, moderate, and low tsunami potential are shown on the 1:10 million map, and in Figure 23, as capital letters.

High tsunami potential refers generally to the reporting of tsunamis having magnitude 2, or greater, on a section of the coast during historical times. In addition, it refers to the likelihood that a tsunami can be expected, based on the location of the coast adjacent to a major earthquake belt of relatively frequent, shallow-focus, Richter-magnitude earthquakes of 6.5 or greater. Areas where more than one tsunami of unknown magnitude, but with reported damage, has taken place are included in this category.

Moderate tsunami potential corresponds to magnitude 0-1 tsunamis being reported along sections of coast, or where there is reasonable certainty from reports in adjacent areas that tsunamis are likely to have taken place there.

Low tsunami potential is identified for sections of coast where no tsunamis have been reported, or those reported have magnitudes of less than 1 or no damage has been reported (or both), or else there is no information about tsunamis along the coastal section. Most areas included in this category have the risk posed by collapse of large volcanic edifices such as Reunion Island and Hawaii. However, these events have frequencies of less than once in 10, 000 years.

The basic data set for tsunamis is from the relevant parts of *World-Wide Tsunamis, 2000 B.C. - 1990* file of the National Geophysical Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. Additional data for the Papua New Guinea to Fiji area and for Australia is from the files of the Natural Hazards Research Centre, Macquarie University. Information on tsunami magnitude and frequency for Indonesia and the Philippines was developed from the analyses by Nakamura (1978, 1979) using additional information from Berninghausen (1969).

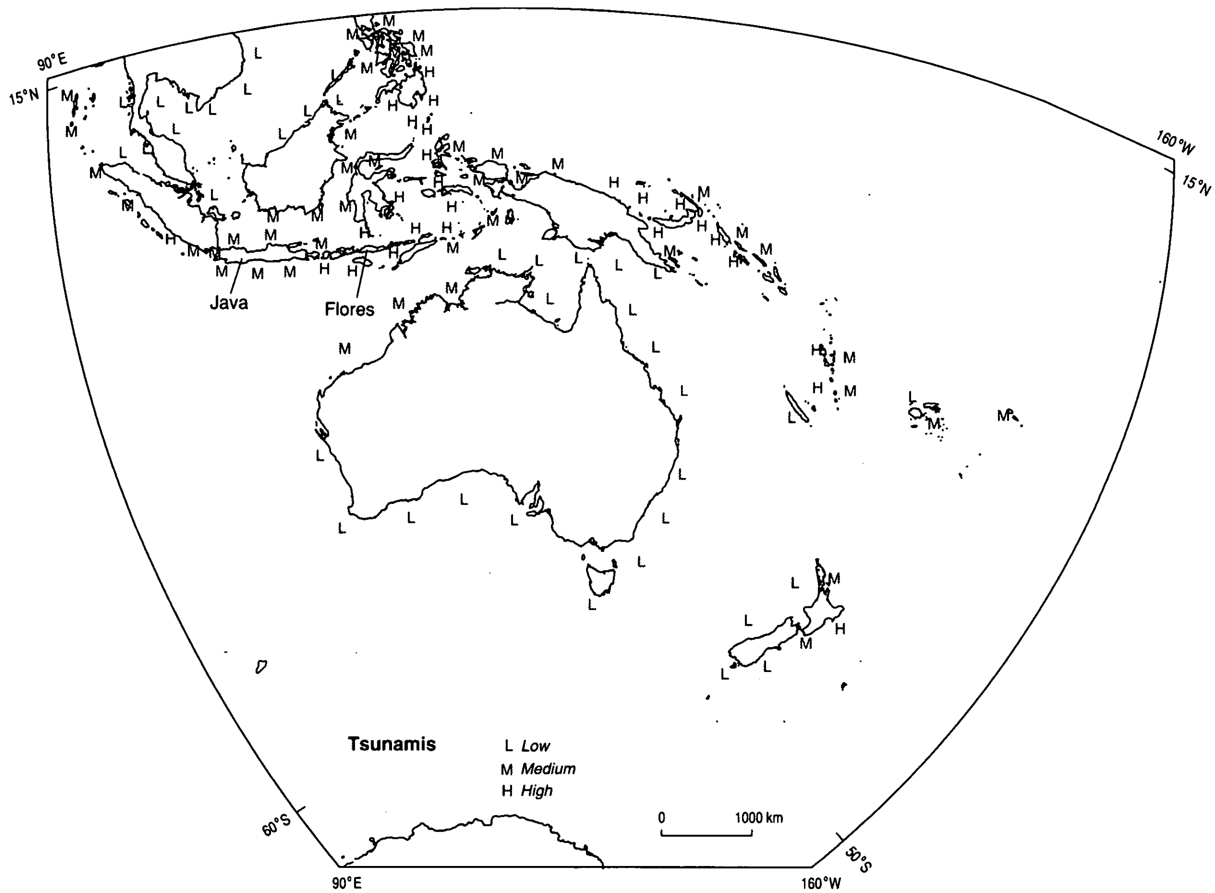

Figure 23. Tsunami potential, excluding Antarctica. L signifies low potential—reported run-up heights of less than 2 m, no damage reported, or no tsunami reported. M signifies moderate potential —reported run-up heights of 2-4 m and adjacent areas where such tsunamis are judged likely. H signifies high potential—reported run-up heights of greater than 4 m, damage reported, or coasts adjacent to tsunami source areas.

Figure 24. Tsunami-hazard potential along the southeastern coast of Australia is shown on the 1:10 million map as low. However, the huge boulders shown in these photographs taken (by E.A. Bryant) on the south coast of New South Wales, are piled on top of one another many meters above present-day sea-level. They are thought unlikely to have been deposited there by storms or gales, and geologists have suggested that the boulders may have been piled up by a large, prehistoric tsunami. Such a tsunami would impact catastrophically along this now populated coastline, were it to happen today.

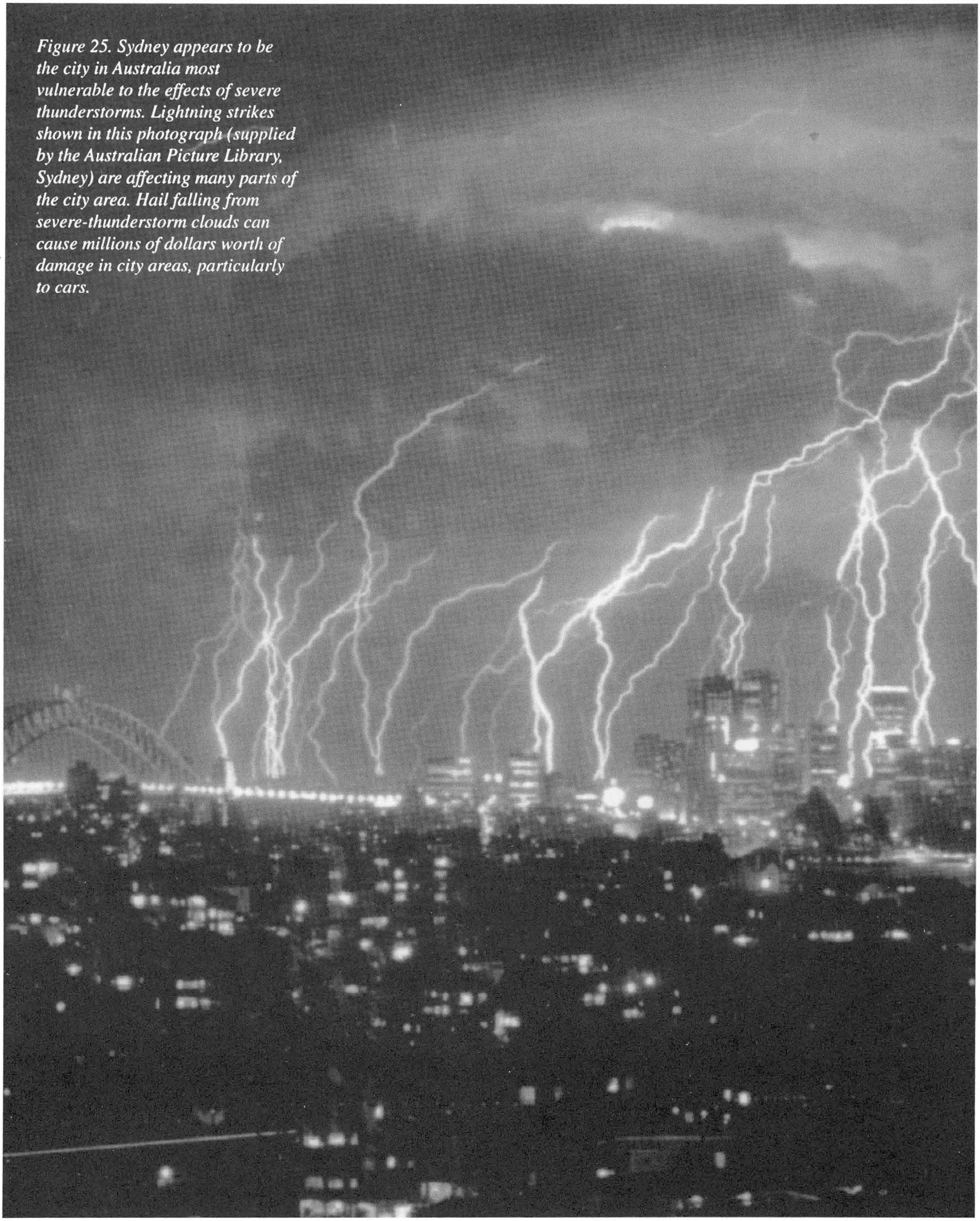

Figure 25. Sydney appears to be the city in Australia most vulnerable to the effects of severe thunderstorms. Lightning strikes shown in this photograph (supplied by the Australian Picture Library, Sydney) are affecting many parts of the city area. Hail falling from severe-thunderstorm clouds can cause millions of dollars worth of damage in city areas, particularly to cars.

Severe Thunderstorms

Severe thunderstorms are defined commonly as those storms producing wind gusts of 90 km/hr or greater, or hail storms that produce stones 2 cm in diameter or greater. Thunderstorms also can produce flash flooding and lightning (Figure 25). They also may produce *tornadoes* which are violently twisting columns of air, several tens of meters in diameter, that reach from the ground to the thunderstorm cloud (Figures 26 and 28). Definitions of severe thunderstorms differ, especially from country to country, and so a consistent analysis has not been possible over the entire area of the 1:10 million map. In addition, most countries do not maintain a compiled database of severe thunderstorm events. Most attention therefore has been focused on Australia in the analysis of severe-thunderstorm potential undertaken for the 1:10 million map.

Exclusion of severe-thunderstorm potential from the remainder of the mapped region has the cartographic advantage of avoiding overcrowding of different hazard types, as mentioned above. Nevertheless, severe thunderstorms — as well as flooding, drought, and bushfire potential (see below)—are significant natural hazards outside of Australia. Damaging storms take place during the 'wet season' of many tropical countries of the region, although tornadoes and large hail are rare. Severe wind gusts in New Zealand are associated most commonly with depressions of tropical origin or intense troughs arriving from the west. Tornadoes and extreme wind gusts from thunderstorms are rare. Neale (1984) calculated that an average of nine severe hailstorms takes place each year in New Zealand, but there are large differences from year to year.

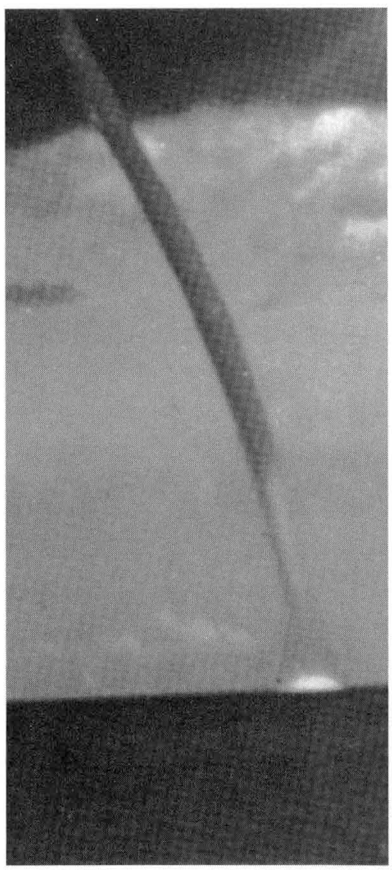

Figure 26. Tornadoes form during severe thunderstorms and can threaten island communities and shipping in the open ocean. Photograph supplied courtesy of the Disaster Awareness Program, Emergency Management Australia.

The relative severe-thunderstorm frequency plotted for Australia on the 1:10 million map, and shown in Figure 27, was derived from the Australian Severe Thunderstorm Archive maintained by the Australian Bureau of Meteorology. This archive has been compiled from newspaper accounts, Bureau of Meteorology observing-station records, and reports from volunteer storm-spotters. The archive includes the data on tornado climatology described by Allen (1980). General information on thunderstorm frequency and intensity elsewhere in the region was provided by the Malaysian Meteorological Service, the Meteorological Department of Thailand, the Department of Civil Aviation in the Ministry of Communications in Brunei, the Meteorological Service of Singapore, the National Institute of Water and Atmospheric Research Ltd. of New Zealand, the Philippine Atmospheric Geophysical and Astronomical Services Administration, and the National Oceanic and Atmospheric Administration of the United States. Information on Pacific island storms is available also in the 1986-7 reports of climate and weather by the New Zealand Meteorological Service, Wellington. However, general conclusions about severe-thunderstorm potential on a consistent regional basis are not possible from the data available.

Severe wind-producing storms for Australia were identified from data collected at 39 Bureau of Meteorology observing stations scattered across the country. Records were based on anemographs of wind gusts and weather registers of thunderstorms. Tornadic and severe hail-producing storm frequencies at the same 39 locations were extracted from the severe-thunderstorm archive, using records from the period 1972-1991. These frequencies then were normalized to represent an area of 100 square kilometers, using the known built-up area of each town or city. The smallest 'towns' were assigned the minimum area of 100 km^2. The normalized frequency of tornadic and hail storms then was added to the frequency of wind storms, providing the total decadal frequency of severe thunderstorms. Cyclone gusts were not combined with the thunderstorm data.

Contour intervals of the number of storms per decade per 100 square kilometers were chosen to represent low, moderate, and high relative frequencies (Table 8) on the map. The pattern obtained should be regarded as providing a broad view rather than being accurate at high resolution, because of the small number of data points used as the basis for contouring across Australia. Other choices of threshold values (Table 8) would produce different contour patterns.

Australia overall is dominated by areas of moderate

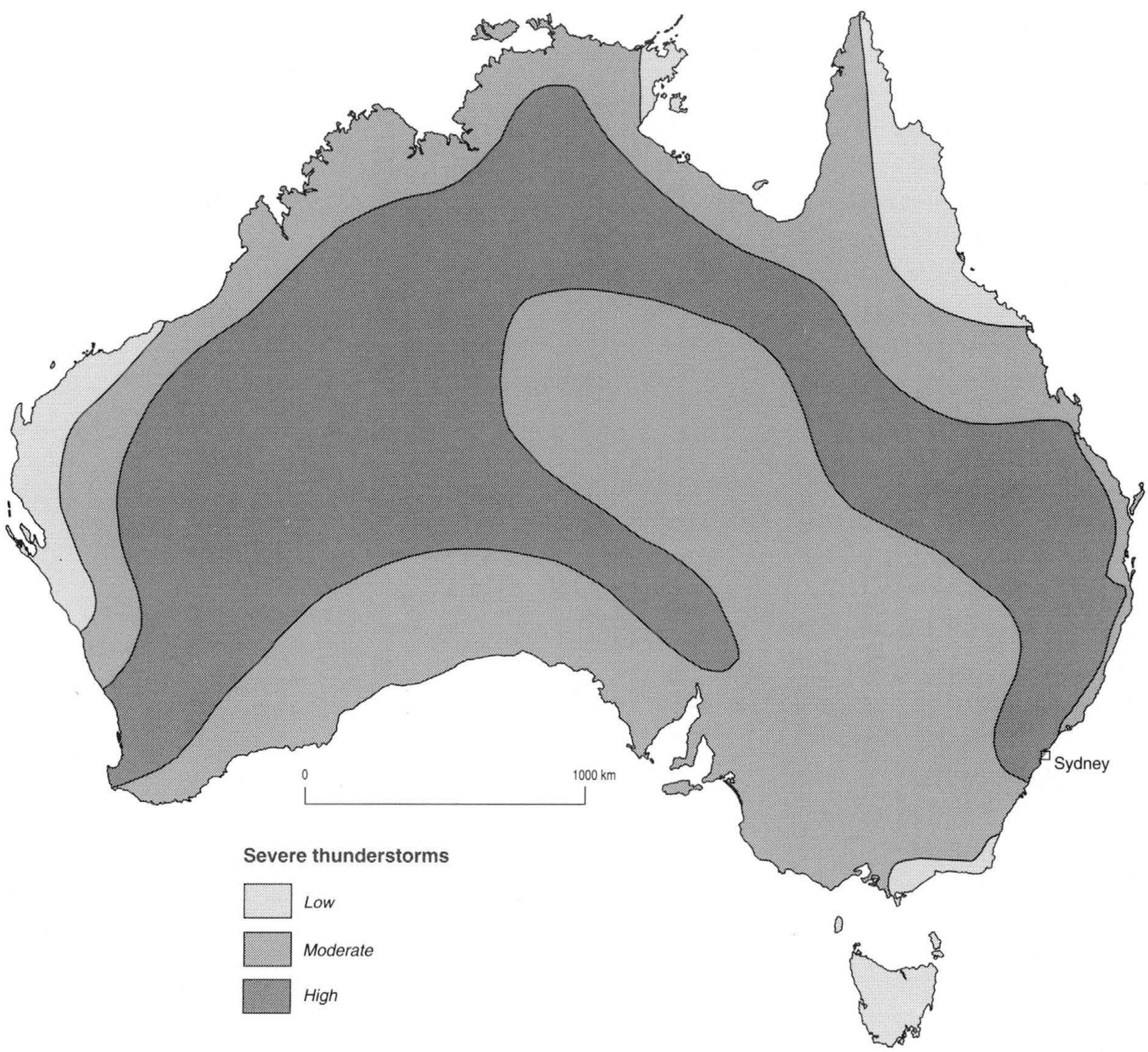

Figure 27. Severe-thunderstorm potential in Australia. The calculation of frequency (see text and Table 7 for details) is designed to give values that are comparable over a large area, despite significant differences in quality of record from location to location (the normalization process results in values that are more meaningful as relative rather than absolute frequencies).

and high thunderstorm frequency. This is indicative that almost all of the country has more than four severe thunderstorms per decade per 100 square kilometers. The areas of highest severe-thunderstorm frequency are inland of the Australian coast, except for parts of the coast of Western Australia and New South Wales. The highest severe-thunderstorm frequency calculated by the above method was 12.9 storms per decade per 100 square kilometers at Sydney. Areas having the lowest frequencies are scattered along coastal areas of all states except South Australia.

Table 8. Severe thunderstorm potential categories

Category	Frequency/ decade /100 sq.km.
Low	Less than 4
Moderate	4 to 7.9
High	Greater than or equal to 8

The most damaging elements of severe thunderstorms are difficult to determine. At least 650 people have died in Australia as a result of lightning strikes since European settlement (Coates and others, 1993). This total is almost equal to the deaths recorded in bushfires. Very few deaths have been recorded in tornadoes (41 deaths from tornadoes are known for Australia) and few (if any) in hailstorms, but hail falls are one of the most expensive natural hazards in Australia. Crop hail losses differ greatly depending on the type of crop and the stage of maturity. Building damage also can be severe, and motor vehicles are particularly prone to hail damage, even in some cases by hail less than 2 cm in diameter. A hailstorm in Sydney in March 1990 produced stones up to 8 cm in diameter and cost the insurance industry more than A$320 million.

Figure 28. Tornadoes form during severe thunderstorms in inland areas, as shown in this photograph (supplied courtesy of the Australian Bureau of Meteorology) taken near Northam, Western Australia.

Figure 29. Widespread flooding in the Hawkesbury Valley, near Windsor, New South Wales, in May 1988. Even the highway has become a waterway. Photograph supplied by the Australian Picture Library, Sydney.

Floods

Floods are a frequent occurrence in many parts of the 1:10 million map area. Monsoon rains bring seasonal flooding to many northern parts of the Pacific Southwest (Figure 2), and flooding also is related in some parts to tropical-cyclone activity, storm surges, and severe thunderstorms. However, comprehensive data on flood frequency are lacking for most parts of the region. Major cities such as Bangkok are flood prone because of the interaction of urban development, runoff, and subsidence as a result of ground-water withdrawal. Towns in New Zealand, Papua New Guinea, and Fiji also suffer inundation by flood waters. Early European settlers in Australia have been criticized for placing residences within flood reach, and the continuing flood problems of many towns and villages are a legacy of the original settlement patterns (Figure 29). Other heavily populated areas such as the Mekong delta also suffer from periodic flooding. Many other urban and rural areas across the region have flood problems, but accessible data are lacking and only Australia therefore is mapped for flooding on the 1:10 million sheet.

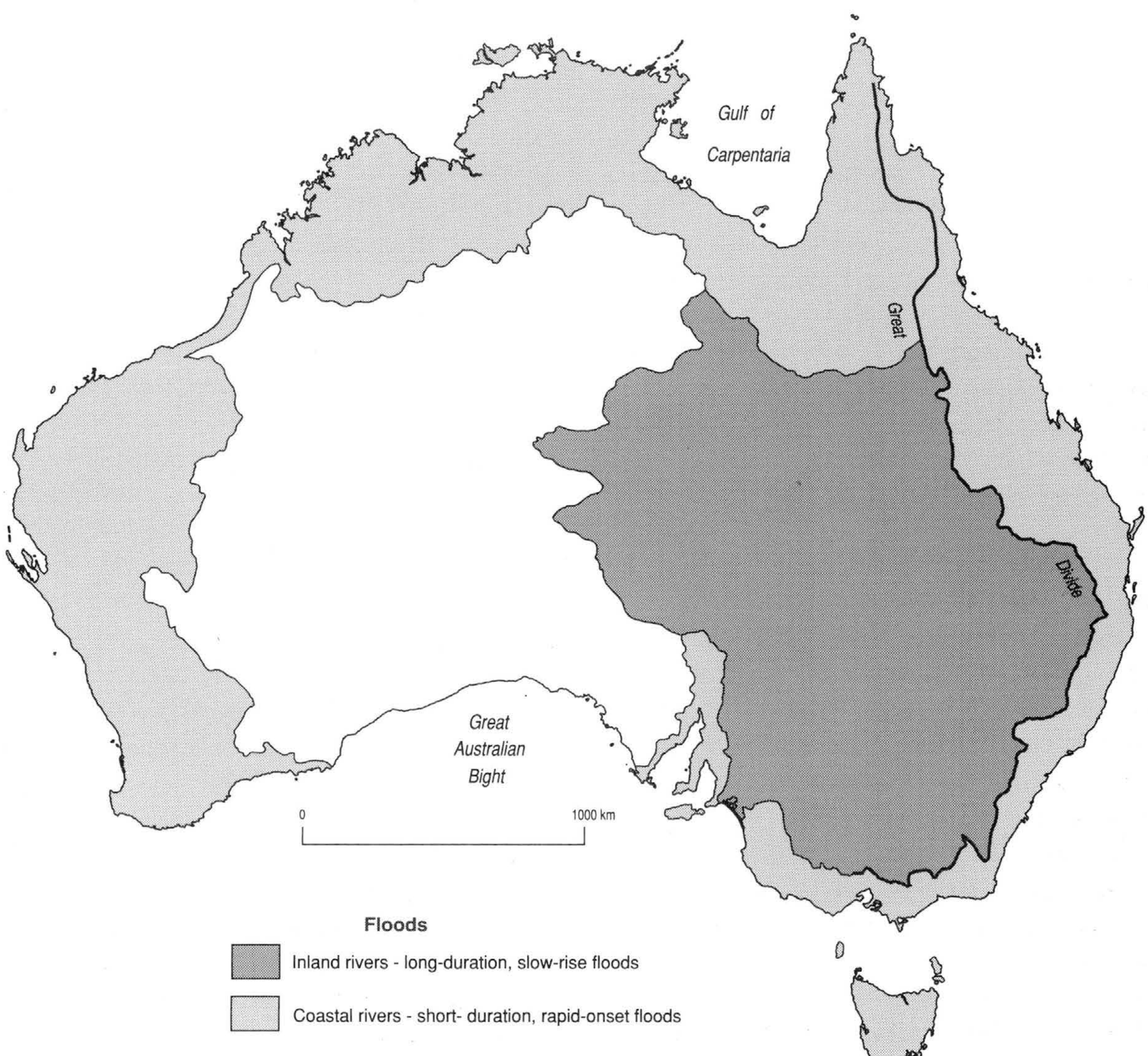

Figure 30. Flood potential in Australia. All of Australia is susceptible to flash flooding. The Great Divide represented by the thick line is the major watershed in eastern Australia that separates westward-flowing rivers from those flowing eastward.

Almost every Australian river is affected by floods having different frequencies and magnitudes, according to the type of rain-producing event and the character of the drainage basin. Almost all of Australia is susceptible to flash floods—that is, situations where streams and creeks rise rapidly (and subside almost as quickly) in response to short-duration, high-intensity rainfall commonly produced by severe thunderstorms. Flash flooding is exacerbated by the high proportion of impervious roofs, driveways, and roads in urban areas, and by overgrazed and otherwise devegetated rural areas which promote runoff and reduce the time that rainfall takes to reach channels.

Two contrasting types of flood potential are shown on the Australian part of the 1:10 million map and in Figure 30. First are the *long-duration, slow-rising floods* of inland Australia. The area shown as affected by this type of flooding includes all of the eastern half of the continent except for its narrow coastal fringe. Communities in northern Australia, such as those around the Gulf of Carpentaria, expect to be cut off for long periods when tropical cyclones bring prolonged heavy rain in the summer. Slow downstream passage of a flood area in the interior of Australia will inundate thousands of square kilometers of sparsely populated inland.

The second type of flood in Australia is described on the map as *short-duration, rapid-onset floods* which characterize coastal rivers. All of the area adjacent to the coast around Tasmania and mainland Australia, except for the coast along the Great Australian Bight, is included in this category. Residents along the eastern coast of Australia are accustomed to the sudden flooding of relatively short, coastal rivers following heavy rains (Figure 29). Tropical cyclone-affected coasts that have relatively high relief experience relatively frequent heavy rainfall and many short-duration, moderate-depth, high-velocity floods. The coastal rivers of southern Queensland and of New South Wales flood frequently and commonly are associated with tropical cyclones or rain depressions off the eastern coast. Catchments are relatively small, streams rise rapidly, warning times are short, and flood velocities are high, but flood duration is usually short (up to a few days). Similar flood characteristics typify most rivers around the periphery of the continent. Most major urban centers, including the State capitals, are affected by this type of flooding.

Northern Australia has a seasonal contrast between wet summers and dry winters, but areas like northern New South Wales are the victims of the interplay between tropical systems and mid-latitude systems approaching from the west and southwest. The spatial and temporal distribution of floods then is closely related to the chances of heavy rain-producing systems developing at any time of the year.

A frequent pattern is heavy rainfall about the Great Divide, and a rapid rise of both coastal streams and the headwaters on the western slopes of the Divide. A gradual downstream progression of a flood wave then is seen in the inland rivers, sometimes over a period of several months. The floods spread to cover vast areas as the water moves downstream in the inland basins, leading to extensive but temporary inland lakes. Every inland river has to be regarded as a flood-risk area, where headwaters have shorter-lived, higher-velocity floods like coastal streams, but the major parts of basins have long-period, slow-velocity floods that can be predicted many weeks in advance of their arrival. Long-term isolation and disruption of services and social structures commonly accompany such floods.

Flash flooding can take place almost anywhere in the continent, but it is a particular problem for many urban areas where drainage systems are unable to cope with intense downpours (Figure 31). Over 100,000 properties in New South Wales alone are thought to be susceptible to urban runoff flooding. Such flooding is unpredictable and short-lived, but nevertheless can cause fatalities and considerable damage. Flash flooding is also characteristic of arid and semiarid Australia (much of the continent), where soil erosion then becomes a major problem.

No part of Australia having river-channel systems, whether permanent or ephemeral, can be said to be free from flood hazards. However, detailed information on frequency, depth of inundation, velocity, rate of rise, or duration is generally lacking for much of the country, which is the reason for the broad categorization of flood type adopted for the 1:10 million map. These categories provide a general indication of the different magnitude of the risk, of the opportunities for warning and mitigation, and of the accompanying risks likely to life and property.

The coastal floodplains of eastern Australia must be regarded as the most flood prone in any hierarchy of risk of flood-prone areas. These zones have the greatest investment in flood-mitigation works, have more towns protected by levees, and have more organizations working to alleviate the flood damage and the flood risks. Indeed, some authorities regard flood hazard, after that of drought, as the most expensive natural hazard in Australia.

Figure 31. Flash flooding in built-up areas can be severe, as seen in this photograph (supplied courtesy of The Age newspaper) of Elizabeth Street, Melbourne, in 1971.

Droughts

There is a general dearth of systematic information concerning drought in the countries of the Pacific Southwest, just as there is for severe thunderstorms and floods (see above) and for bushfires (see below). Most of the readily available information comes from Australia, which is dealt with in this section. Yet there are countries in the Pacific Southwest region where the natural fluctuations of rainfall, temperature, and humidity cause periods of dryness which stress communities that are particularly dependent on agriculture. For example, the coral-atoll island communities of the Pacific are vulnerable to droughts. Drought is an inevitable part of the normal variability of climate. It is experienced, to some extent, in all climatic regions that ordinarily have sufficient rainfall for agriculture and water supply. Australia in particular has been known as *the dry continent* since European settlement, and the hardships and losses associated with drought have been suffered by generations of Australians (Figure 32).

Figure 32. Droughts in Australia cause the drying out of soils and water holes for long periods, the killing off of pasture, crops, and stock, and great hardship and loss to rural communities. Photograph taken at Mittagong, New South Wales, in April 1991, and supplied courtesy of the Sydney Morning Herald.

There are numerous definitions of drought, none of which are entirely satisfactory. The simple description 'dryness due to lack of rain', for example, could be applied to many inland areas of Australia where such conditions would be regarded as normal rather than as a drought situation. The most satisfactory definition depends on the acceptance of drought as a supply-and-demand phenomenon. Thus, drought is where there is 'lack of water to meet normal requirements'. However, what is considered drought by one section of the community (for example, a market gardener) may not be regarded as drought by another (say, a sheep farmer). The Australian Bureau of Meteorology maintains a Drought Watch service and identifies areas with *serious rainfall deficiency* when the rainfall of a period of three months or more falls within the lowest 10 percent of all previous totals for the same period of the year. Allowances are made for the seasonal nature of the rainfall in many parts of the country. For example, a drought watch is not maintained in parts of northern Australia during the dry season (May to October), nor is dryness monitored in parts of South

Australia and Western Australia during the summer.

Severe drought has been a recurring theme in Australian history since European settlement, and different areas are affected during individual droughts. Severe droughts affected large areas of the country in 1895-1903, 1911-16, 1938-45, 1951-52, 1954-55, 1965, 1967-69, 1972-73, 1979-83, and 1991-1994. Perhaps the most severe drought since European settlement was in 1979-83 (Figure 34). This drought resulted in no known deaths from starvation or disease, but the impact on the economy was more than A$7 billion (in 1983 dollars) according to some estimates.

Many of the droughts listed above apparently were related to the El Niño-Southern Oscillation, or ENSO, events that affect rainfall and temperature patterns across large areas of the globe for periods of up to several years. Papua New Guinea, most of Indonesia, the southern Philippines, and Australia (particularly northeastern Australia) are drought affected during ENSO events. However, the same areas in Australia are not affected in all ENSO droughts, so areas affected across the countries north of Australia are likely to differ also.

Areas of very high, high, moderate, and low drought

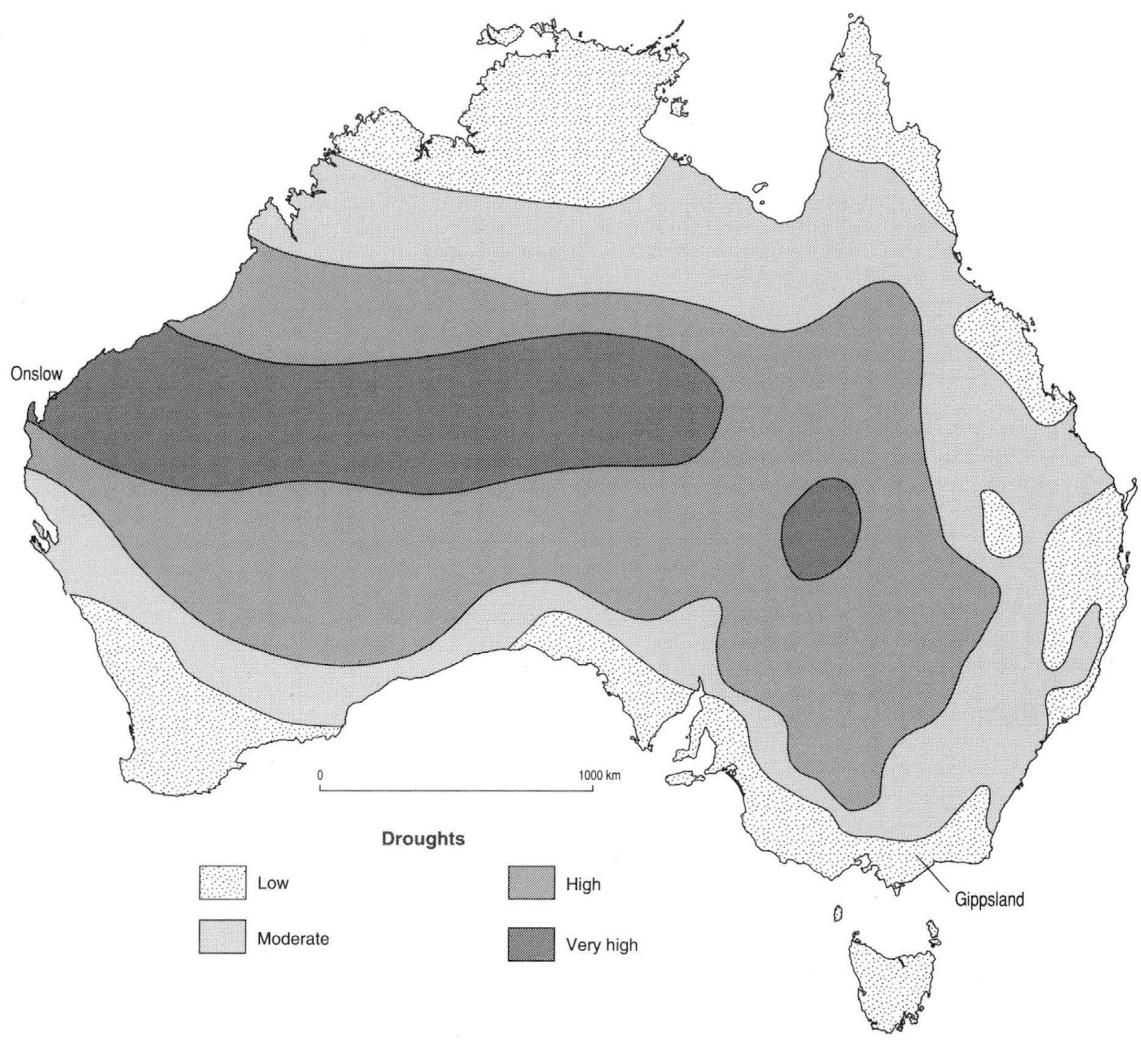

Figure 33. Drought potential in Australia using categories shown in Table 9, which represent the degree to which rainfall in dry years is different from normal years, measured by the ratio of the rainfall in the driest 10 percent of years to the normal (median rainfall).

potential are plotted on an inset to the 1:10 million map, and in Figure 33. These four categories were derived by examining the pattern of annual rainfall totals (from Australian Bureau of Meteorology data files), thereby eliminating the effect of seasonal variations, and assigning percentage values (Table 9). A higher drought potential is represented by a lower percentage. All districts throughout Australia can be compared for relative annual drought potential using these drought-potential percentages.

The four categories of drought potential (Table 9) were derived by examining the pattern of annual rainfall totals. A serious rainfall deficiency exists when the rainfall for the period in question is within the first decile—the rainfall amount which is not exceeded in 10 percent of years or, conversely, is exceeded in 90 percent of years. So, 90 percent of years for annual totals will have a rainfall amount above the first decile for the 12-month period January-December, 80 percent of years will have a rainfall above the second decile, and so on. The median or fifth decile is exceeded in 50 percent of years and is a good representation of 'normal' rainfall. Drought severity can be gauged by the degree to which dry years are different from normal years. There are considerable differences in rainfall amounts across Australia. Furthermore, rainfall variability is markedly different from region to region, even if the normal rainfall is similar. For example, the annual rainfall totals in West Gippsland (eastern Victoria) and the east central coast of northeastern Queensland are very similar, but the rainfall in northeast Queensland is spread over a much larger range. Thus, dry years are *relatively* drier in northeast Queensland than dry years in West Gippsland. This can be represented by the ratio of decile 1 to decile 5 which equals 0.80 or 80 percent for West Gippsland and 0.57 or 57 percent for northeast Queensland. Decile 1 was chosen for the ratio because it relates to the drought-watch criterion of the Australian Bureau of Meteorology. All districts throughout Australia can be compared for relative annual drought potential using the ratio of decile 1 to decile 5 expressed as a percentage.

The line on the 1:10 million map (and in Figure 33) dividing high and very high drought-potential areas represents 50 percent, and the area of very high drought potential is a swathe that extends from the central coast of Western Australia westwards to the center of the continent. There is also a relatively small area of very high potential near the border of Queensland, New South Wales, and South Australia. The highest drought potential (38 percent) in the whole country is at Onslow on the Western Australia coast.

Areas having the lowest drought potential are in northern Australia (including much of the area with a marked wet season), part of the coast of southern Queensland and northern New South Wales, and across southern Victoria, Tasmania, southern South Australia, and the southwestern corner of South Australia. These areas of low drought potential include all the larger cities in Australia, except Sydney. The lowest drought potential area is in southwestern Victoria (84 percent).

Table 9. Drought potential categories

Drought potential class	%
Very High	Up to 50
High	51-60
Moderate	61-70
Low	Above 70

Figure 34. Severe drought developed in many parts of Australia during the 1982-83 ENSO. Dust in farming areas to the west of Melbourne was caught up by strong winds, and a dramatic dust front advanced on the city of Melbourne on 8 February 1983. Soil loss was caused by the drought, but also by certain farm-management practices that over many years made the soil cover vulnerable to drought and wind erosion. Photograph supplied courtesy of the Australian Bureau of Meteorology.

Figure 35. An intense bushfire rages through a forest of jarrah in an isolated part of southwestern Western Australia. Photograph courtesy of the CSIRO Division of Forestry, Canberra.

Bushfires

Bushfires, also known as *forest fires* or *grass fires*, take place in several countries in the Pacific Southwest map region (Figure 35). For example, more than 5 million hectares of tropical forest in Indonesia and Malaysia were burned and severely affected during the 1982-3 ENSO. Bushfires also have taken place on smaller Pacific islands, such as recently in Western Samoa. However, the available information region-wide is insufficient to enable bushfire potential to be mapped in these areas, and so only Australian bushfire potential is shown on the 1:10 million map (Figure 36). Nevertheless, many of the comments given in the following on bushfire physics have a much wider applicability.

The distinction is made commonly in Australia between *grass fires* and *forest fires* (Cheney, 1989). Grass fires burn through pastoral areas, open grasslands and cereal crops, savanna grasslands, and open woodlands with a grass understory. Grass fuels build up after good winter and spring rains and become most flammable when they are fully cured, generally after 6 to 8 weeks without rain and after the grasses have flowered and the seed set. Forest fires burn through forest litter including leaf, twig and bark

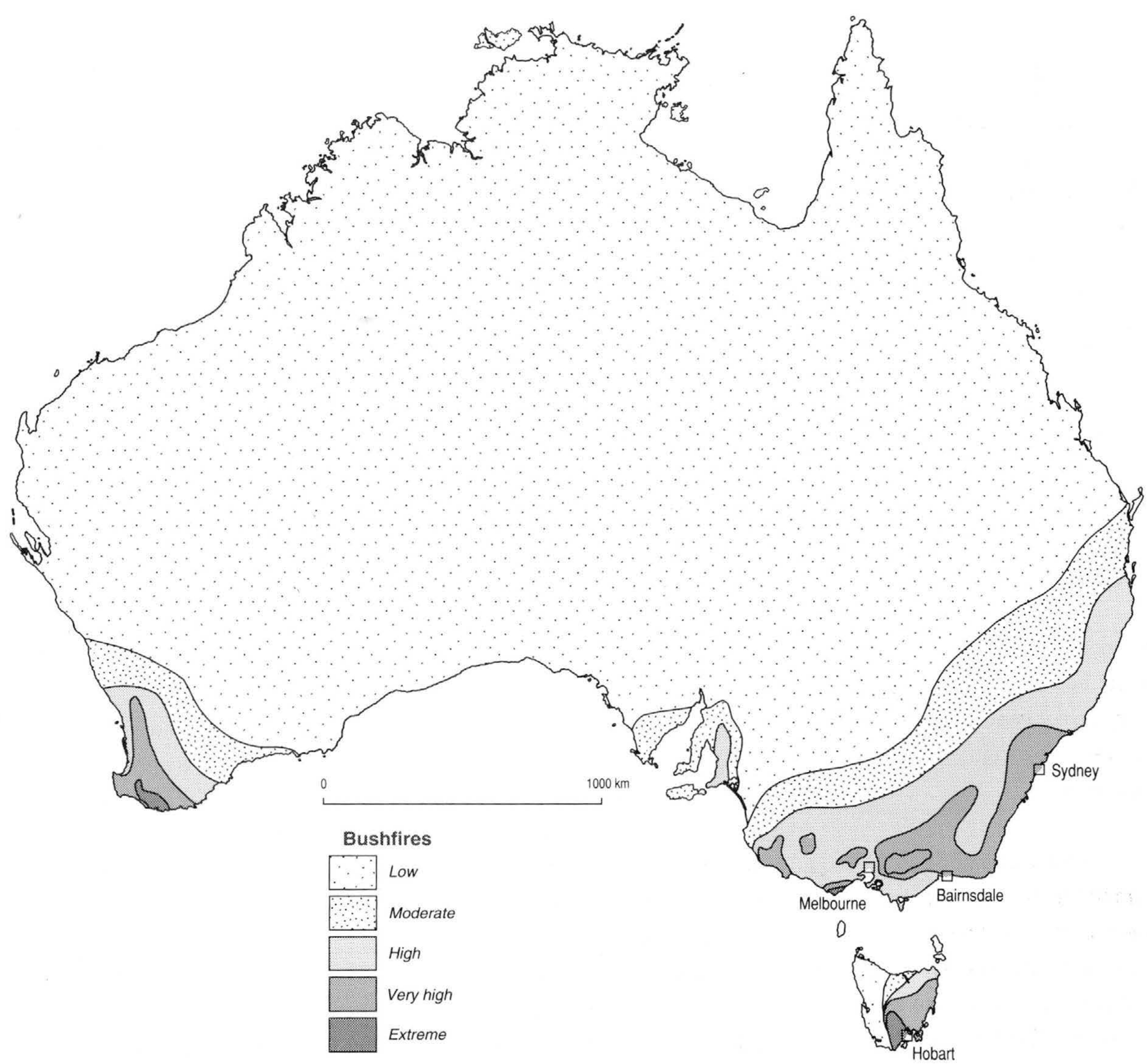

Figure 36. Bushfire potential in Australia using categories given in Table 10.

Table 10. Bushfire potential categories

Low	Combination of heavy continuous grass and extreme fire weather is rare
Moderate	Predominantly in light-grass fuel loads or where extreme fire weather is relatively uncommon
High	Predominantly in grassland fuels or forests and woodlands with grass understories, extreme fire weather somewhat variable within zone
Very high	Moderate forest fuels, moderate frequency of extreme fire weather
Extreme	Heavy forest fuels, relatively low frequency of extreme fire weather

material, and shrubs on the forest floor, but fires can extend to the crowns of trees, tens of meters above the floor (Figure 35).

Fire intensity and speed are governed by several factors including both fuel characteristics and weather. Fuel provides the energy that drives a bushfire, and fuel is the most important factor affecting fire behavior. The moisture content of the dead fuel is particularly important, as combustion takes place only where the moisture content of the fire fuel is between 3 and 25 percent. The lower moisture content is reached only during conditions of prolonged drought and low humidity.

Weather patterns are also important, and the term *fire weather* is used commonly in Australia. The wind speed near the flame zone is dependent not only on the weather but also on interactions between terrain, vegetation, and the fire itself. This relationship can be very complex, especially where the terrain is hilly. Strong inflow winds may result in large fires, and convective winds can help fires to propagate up steep slopes, although a strong prevailing wind normally is required to drive the fire forward.

Another important factor influencing human and building vulnerability to bushfires is the *residence time*—that is, the time that flaming combustion persists at a site. This is a function of the diameter of individual particles and the depth of the fuel bed. Residence time for a grass fire is 5-10 seconds, and smouldering combustion will persist for about a minute after the fire front has passed. However, longer residence time (2-5 minutes) and smouldering logs in a forest fire may make the forest floor intolerably hot for a further 60 minutes. Not only is 'spotting' ahead of a fire front a potent ignition source for many fuel types, but also ember production after the passage of the fire front can ignite buildings that survived the passage of the fire itself.

Major or 'conflagration' fires require the presence of several elements: (1) a drought of sufficient intensity and duration is needed to reduce the moisture content of the whole profile of litter to a uniformly low level, to induce significant moisture stress in the living understory, and to ensure the complete curing of annual plants; (2) the simultaneous occurrence of strong winds, high temperatures, and low humidity; and (3) heavy fuel loads that are found commonly in those frequently moist forest environments where fires are infrequent.

Major bushfires in Australia have produced significant losses. At least 678 people have died in bushfires since European settlement began, although many more deaths probably have gone unrecorded. About five people per year have died on average in recent years, but 30 percent of the deaths resulted from just three days of widespread fires: Black Friday, Victoria, in 1939; the southern Tasmania (including Hobart) fires of 1967; and the Ash Wednesday fires of 1983 in Victoria and South Australia (Figure 37). Most of the devastating bushfires in Australia have taken place where high-intensity fires burnt into the suburban fringes of major cities. 1929 homes were destroyed and 3714 other buildings were burnt in the Ash Wednesday fires. Few lives were lost in the Sydney fires of January 1994, but about 200 houses were destroyed.

Five categories of bushfire potential are shown on the 1:10 million map (Table 10). Areas of moderate to extreme bushfire potential are concentrated on the southern and southeastern margins of Australia (Figure 36). All the areas of high to extreme bushfire potential are in areas recognized as having a low or moderate drought potential. Only three areas of extreme bushfire potential have been identified—on the southern tip of Western Australia, northeast of Melbourne, and around Hobart. Areas of very high potential surround each of these areas, and a major area extends along the New South Wales coast and includes Sydney. Almost all of Victoria has a high to extreme bushfire potential. Thousands of fires take place across Australia in most years, but large fires are most frequent along the coastal strip of southeastern Australia from north of Sydney to Bairnsdale, east of Melbourne. A large fire breaks out somewhere in this region every three years or so, and a disastrous fire perhaps every 10 to 20 years.

Figure 37. The aftermath of a bushfire is shown in this photograph (supplied courtesy of The Advertiser, Adelaide) taken at Greenhill, South Australia, after the severe 1983 'Ash Wednesday' (16 February) fires. Two people were killed during this bushfire at Greenhill.

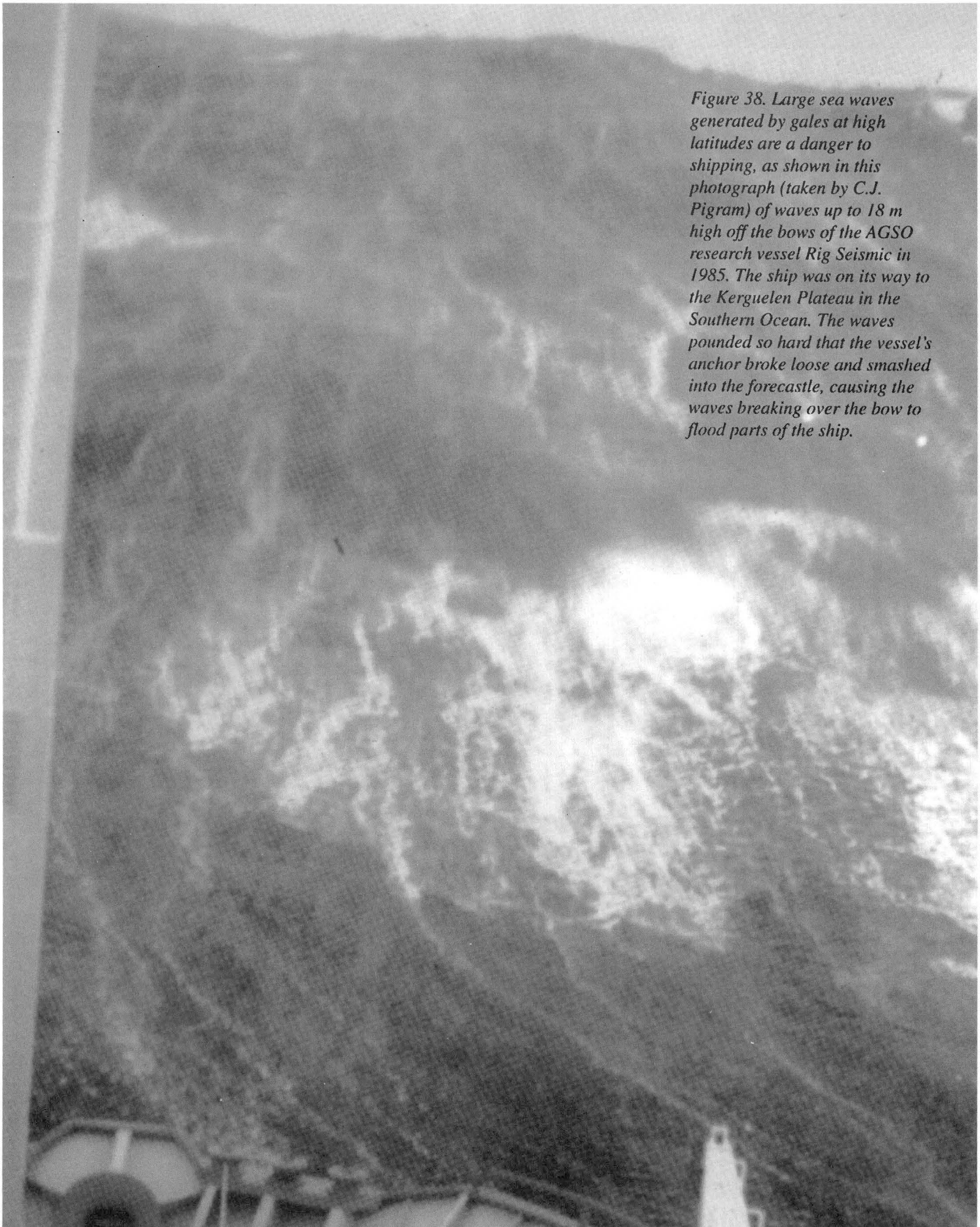

Figure 38. Large sea waves generated by gales at high latitudes are a danger to shipping, as shown in this photograph (taken by C.J. Pigram) of waves up to 18 m high off the bows of the AGSO research vessel Rig Seismic in 1985. The ship was on its way to the Kerguelen Plateau in the Southern Ocean. The waves pounded so hard that the vessel's anchor broke loose and smashed into the forecastle, causing the waves breaking over the bow to flood parts of the ship.

Wave Heights and Ice

Three hazards shown on the 1:10 million map refer to waves and ice in the oceans off the coast of Antarctica. Information for these three hazards has been transferred directly from the Circum-Pacific Map Project 1:17 million natural hazards map (Lockwood and others, 1990). The three hazards are of virtually no threat to centers of population, but they are a significant danger to shipping operating at high latitudes (Figures 38 and 40).

Wave heights are shown on the map (see also Figure 39) as a series of contours of percentage of wintertime wave heights equal to or greater than 6 m. These are based on ship observations collected by the maritime nations of the world and archived at the National Climatic Data Center, North Carolina, USA (Elms, 1990). Wave heights have been recorded in a relatively consistent quantitative code since the late 1940s, and provisions were made in 1963 to report both sea waves and swell (sea waves are produced by local winds, whereas swell waves have moved out of the generating area). Reported wave heights in

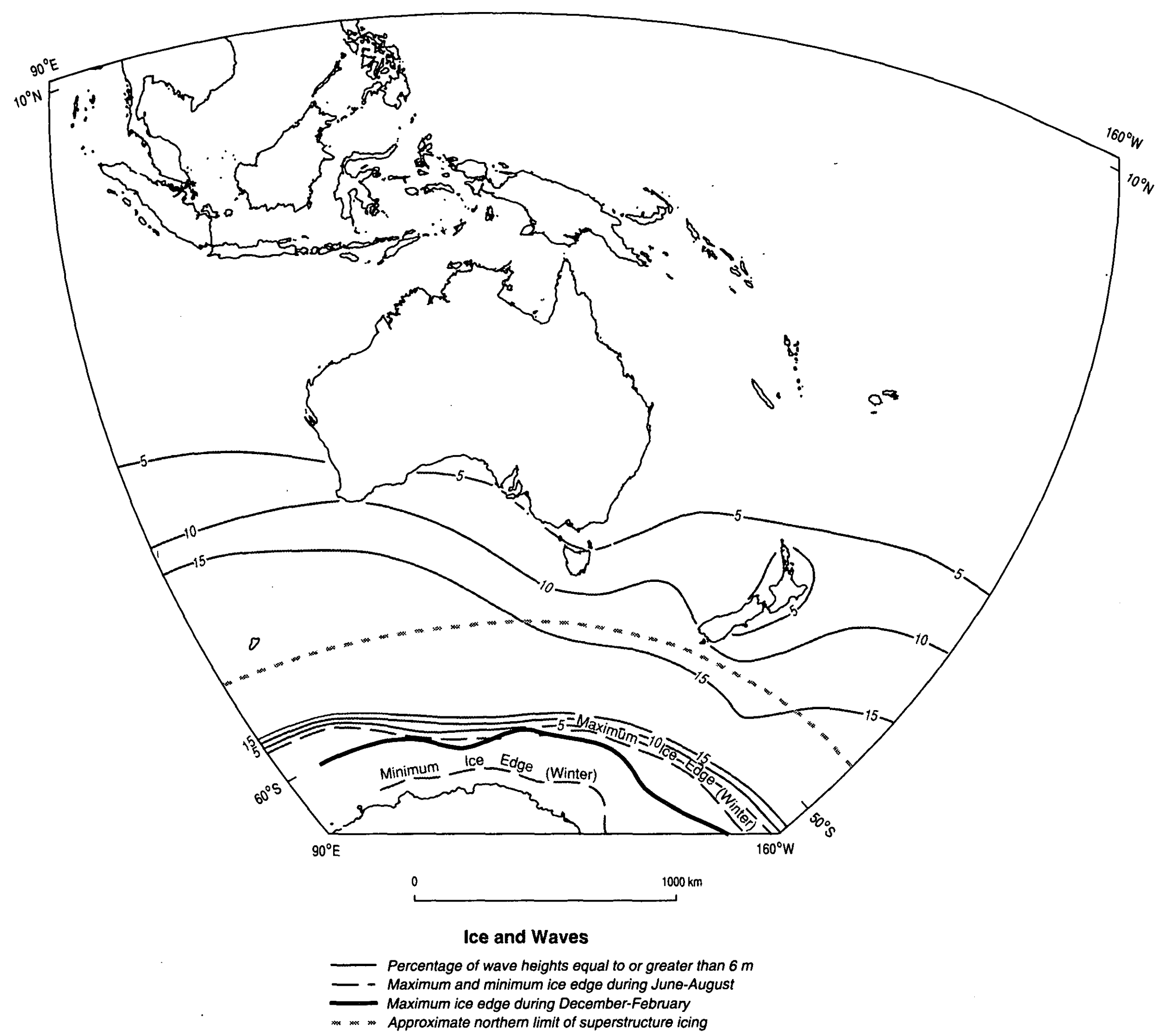

Figure 39. Wave-height and ice distribution in the southern part of the Pacific Southwest.

observations from ships are defined as the average of the highest one-third of waves in view, although the observing procedure is subjective in practice and may be difficult for an observer in confused seas.

Maximum *sea-ice limits* are shown on the 1:10 million map (see also Figure 39) for the Southern Hemisphere summer (December-February), and for both minimum and maximum sea-ice limits for June-August (winter). These limits skirt the coast of Antarctica and are based on a weekly analysis produced at the Joint Ice Center for the period 1973-82 (see Elms, 1990). The data are derived from shore-station reports, ship reports, aerial reconnaissance, and satellite data, and are digitized by the National Climatic Data Center.

Superstructure icing results from the accumulation of ice on exposed structures such as ships, oil rigs, and buoys and takes place where the structure encounters weather conditions such as snow, freezing rain, freezing drizzle, or freezing sea spray (Elms, 1990). It can be a serious problem, especially for smaller vessels, because they are vulnerable to the danger of a shift in the center of gravity of the vessel caused by the ice loading. The greatest potential for superstructure icing is when a ship heads into the wind at an angle of 15-45° to the wind. There is somewhat less potential when heading directly into the wind and much less when heading downwind. A ship's captain therefore can take steps to lessen the threat to the ship where operating in an area of potential superstructure icing. The limit of superstructure icing is shown on the 1:10 million map as a generalized boundary that follows latitude 50°S closely, passing south of New Zealand and north of Macquarie Island.

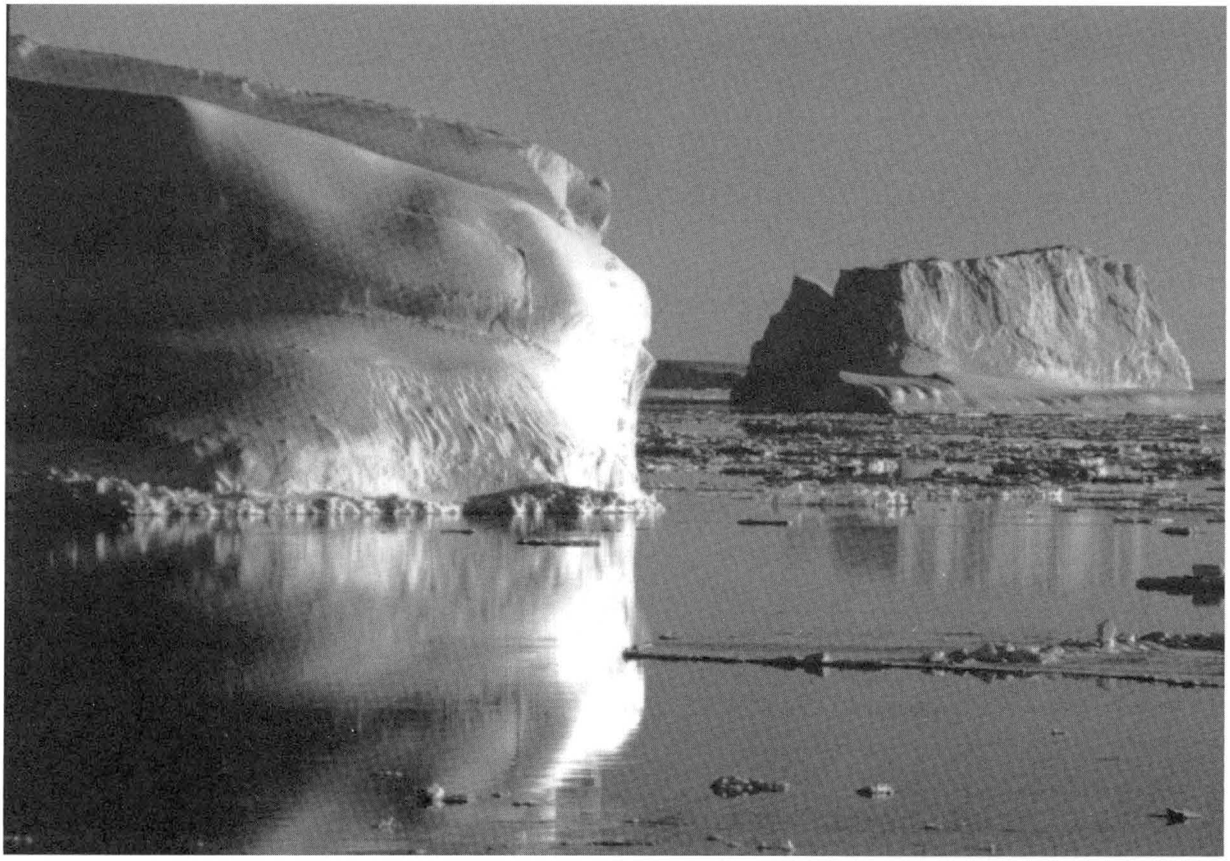

Figure 40. Icebergs and pack ice are a threat to shipping operating close to Antarctica. Photograph taken by J.W. Sheraton.

Concluding Remarks

Preparation of the 1:10 million natural-hazard potential map has been an education for the members of the Natural Hazards Map Working Group. First, the group discovered that the availability of data on natural hazards in the Pacific Southwest region is very uneven. There are good regional datasets for cyclones and earthquakes at one extreme, but very poor ones for hazards such as severe thunderstorms and bushfires at the other. In addition, data may exist in some places, but is either difficult to access or requires a considerable amount of work to transform it into information suitable for mapping purposes.

There are strong interplays between the twelve hazards selected to be mapped separately on the 1:10 million map (and between these and hazards *not* mapped), as stressed at the beginning of this booklet. There is an understandable tendency for individual hazards to be analyzed separately, but the necessity of working towards *multi-hazard* analysis should be recognized and, consequently, the technical need to employ relatively new computing techniques in the compilation and analysis of digitized hazards data. Geographic Information Systems (GIS) provide an excellent starting point for the spatial analysis of natural-hazards datasets.

The mapping exercise, therefore, has drawn attention to the need for *digital* sources of hazards data and for a regional network of databases that can be linked for analysis purposes in a GIS computing environment. Such an approach may be essential in the future as the increasing populations of the Pacific Southwest region become more and more vulnerable to the wide range of intensive geophysical phenomena that impact on this developing region.

Acknowledgments

We gratefully acknowledge Emergency Management Australia (Australian Department of Defence) for providing excellent support and facilities at its Australian Emergency Management Institute, Mount Macedon, Victoria, for three meetings of the Natural Hazards Map Working Group. Production of the 1:10 million-scale natural-hazards potential map, and this booklet, received support also through two grants awarded by the Australian Coordination Committee for the International Decade for Natural Disaster Reduction, to whom we express our sincere appreciation. Our thanks are extended also to the staff of the AGSO Cartographic Services Unit for their unfailing support, service, and advice throughout the period of production of the map and booklet, and particularly to Leanne McMahon and Saimonne Bissett for booklet design and Greg Michalowski for the line diagrams.

Each of us who had responsibility for collating information on each of the hazards shown on the map and described here contacted a wide range of people for advice and data. The cooperation and assistance we received from them were substantial. We extend our individual thanks to them all, and regret that space limitations do not permit them, and their organizations, being named individually.

Our thanks are extended also to Fran Mills and George Gryc of the United States Geological Survey and the Circum-Pacific Map Project, Menlo Park, California. They offered timely and valuable advice at all stages of map and booklet production.

Drafts of the text of this booklet were reviewed by David Palfreyman and Jan Knutson, both of the Australian Geological Survey Organisation, and by Colin Pierrehumbert and Frank Woodcock of the Australian Bureau of Meteorology. AGSO contributors publish with the permission of the Executive Director of the Australian Geological Survey Organisation, and Australian Bureau of Meteorology contributors with that of the Director of Meteorology.

References

Allen, S. C., 1980, A preliminary Australian tornado climatology: Bureau of Meteorology Technical Report, v. 39, 14 p.

Berz, G., 1988, List of major natural disasters, 1960-1987: Natural Hazards, v. 1, p. 97-99.

Berninghausen, W. M., 1969, Tsunamis and seismic seiches of Southeast Asia: Bulletin of the Seismological Society of America, v. 59(1), p. 289-297.

Blong, R.J., 1992, Some perspectives on geological hazards, *in* McCall, G.J.H., Laming, D.J.C., and Scott, S.C., eds., Geohazards: natural and man-made: London, Chapman and Hall, p. 209-216.

Blong, R. J., and Eyles, G.O., 1989, Landslides: extent and economic significance in Australia, New Zealand and Papua New Guinea, *in* Brabb, E. E., and Harrod, B. L., eds., Landslides: extent and economic significance: International Geological Congress, 28th, Washington, D.C., 1989, Proceedings, Rotterdam, A.A. Balkema, p. 343-355.

Brand, E. W., 1984, Landslides in Southeast Asia: a state-of-the-art report: International Symposium on Landslides, 4th, Toronto, 1984, Proceedings, v. 1, p. 17-59.

Brand, E. W., 1989, Occurrence and significance of landslides in Southeast Asia, *in* Brabb, E. E., and Harrod, B.L., eds., Landslides: extent and economic significance: International Geological Congress, 28th, Washington, D.C., 1989, Proceedings, Rotterdam, A.A. Balkema, p. 303-324.

Centre for Research on the Epidemiology of Disasters (CRED), 1993, Disaster ranking over 25 years from CRED Disaster Events Database: Catholic University of Louvain, Brussels, CRED Bulletin, v. 2.

Cheney, N.P., 1989. Bushfires: their threat to life and property, *in* Oliver, J., and Britton, N. R., eds., Natural hazards and reinsurance: Proceedings of a seminar sponsored by Sterling Offices (Australia) Ltd., Cumberland College of Health Sciences, Sydney, p. 60-70.

Coates, L., Blong, R. J. and Siciliano, F., 1993, Lightning fatalities in Australia, 1824-1991: Natural Hazards, v. 8(3), p. 217-233.

Crandell, D.R., Booth, B., Kazumadinata, K., Shimozuru, D., Walker, G.P.L., and Westercamp, D., 1984, Source-book for volcanic hazards zonation: Paris, UNESCO Natural Hazards Series, v. 4., 97 p.

Crozier, M. J., 1989, Landslide hazard in the Pacific Islands, *in* Brabb, E. E., and Harrod, B. L., eds., Landslides: extent and economic significance: International Geological Congress, 28th, Washington, D.C., 1989, Proceedings, Rotterdam, A.A. Balkema, p. 357-366.

Doutch, H.F., 1981, Plate-tectonic Map of the circum-Pacific region, southwest quadrant: American Association of Petroleum Geologists, scale 1:10 million.

Eiby, G.A., 1966, The Modified Mercalli Scale of earthquake intensity and its use in New Zealand: New Zealand Journal of Geology and Geophysics, v. 9, p. 1-2.

Elifas, J. D., 1987, Landslides in Indonesia, its occurrences and the effort made to overcome the problems: US-Asia Conference on Engineering for Mitigating Natural Hazards Damage, Bangkok 1987, C5-1 -C5-15, 96 p.

Elms, J.D., 1990, Weather hazards, *in* Lockwood, M., and others, Explanatory notes for the natural-hazards map of the circum-Pacific region, Pacific basin sheet: U.S. Geological Survey Circum-Pacific Map Series CP-40, scale 1:17,000,000, p. 4-13.

Eyles, G.O., 1983, The distribution and severity of present erosion in New Zealand: New Zealand Geographer, v. 39, p. 12-28.

Fell, R., 1992, Landslides in Australia: International Symposium on Landslides, 6th, 1992, Christchurch, New Zealand, Proceedings, theme address, Rotterdam, A.A. Balkema, 3 v.

Gaull, B.A., Michael-Leiba, M.O., and Rynn, J.M.W., 1990, Probabilistic earthquake risk maps of Australia: Australian Journal of Earth Sciences, v. 37, p. 169-187.

Hattori, S., 1979, Seismic risk maps in the world (maximum acceleration and maximum particle velocity) (II) - Balkan, Middle East, Southeast Asia, Central America, South America and others: Bulletin of the International Institute of Seismology and Earthquake Engineering, v. 17, p. 33-96.

Holland, G. J., 1981, On the quality of the Australian tropical cyclone database: Australian Meteorological Magazine, v. 29, p. 169-181.

Iida, K., 1963, Magnitude, energy and generation mechanisms of tsunamis and a catalogue of earthquakes associated with tsunamis: IUGG Monograph, v. 24, p. 7.

Lockwood, M., Elms, J.D.,Lockridge, P.A., Moore, G.W., Nishenko, S.P., Simkin, T., and Newhall, C.,1990, Explanatory notes for the natural hazards map of the circum-Pacific region, Pacific basin sheet: U.S. Geological Survey Circum-Pacific Map Series CP-40, scale 1:17,000,000, 31 p.

McCue, K., 1984, Discussion of the paper: 'The development of seismic zones and the evaluation of lateral loadings for earthquake resistant design of buildings in Papua New Guinea', by R.D. Jury, Hollings, J.P., and Fraser, I.A.N.: Bulletin of the New Zealand National Society for Earthquake Engineering, v. 17, p. 292.

McCue, K., 1993, The revised Australian seismic hazard map (1991), *in* Earthquake resistant design and insurance in Australia: Proceedings of a conference held by the Australian Earthquake Engineering Society and the Specialist Group on Solid-Earth Geophysics, Sydney, 1992, Australian Earthquake Engineering Society, p. 21-25.

Nakamura, S., 1978, On statistical tsunami risk of the Philippines: South East Asian Studies, v. 15, p. 581-590.

Nakamura, S, 1979, On statistics of tsunamis in Indonesia: South East Asian Studies, v. 16, p. 664-674.

National Land Agency, 1994, Natural disasters in the world—statistical trend on natural disasters: Japan, International Decade for Natural Disaster Reduction Promotion Office, National Land Agency.

Neale, A. A., 1984, Severe hailstorms *in* Speden, I., and Crozier, M.J., eds., Scientific, economic, and social reviews of natural hazards in New Zealand: New Zealand National Commission for UNESCO, Wellington, p. 49-55.

Pandjaitan, B.T.D., Udihartono, Amnon, M., Sunardi, and Suprapto, P., 1981, Erosion potential and its damage in Timor. Proceedings of the South-East Asian Regional Symposium on Problems of Soil Erosion and Sedimentation, Bangkok, Thailand, p.129-141.

Smith, W.D., and Berryman, K.R., 1986, Earthquake hazard in New Zealand: inferences from seismology and geology: Royal Society of New Zealand Bulletin, v. 24, p. 223-243.

Smithsonian Institution, 1992, Volcanoes of the World Data File: Global Volcanism Program, Smithsonian Institution, Washington, D.C.

Su, S.S., 1988, Seismic hazard analysis for the Philippines: Natural Hazards, v. 1, p. 27-44.

Thompson, S., 1982, Trends and developments in global natural disasters, 1947-1981: University of

Colorado Natural Hazards Research Applications and Information Center Working Paper, v. 45, Boulder, Colorado.

Tuni, D., 1981, The regional distribution of earthquakes greater than magnitude 5.5 in the Solomon Islands from 1960 to 1980: Ministry of Lands, Energy and Natural Resources, Solomon Islands Government, Geological Survey Division Report, 81/14.

Wirasuganda, S., 1983, Landslide hazard: investigation and mitigation in Indonesia: Bulletin of the Directorate of Environmental Geology, v. 1, p. 13-24.

Zillman, J.W., Downey, W.K., and Manton, M.J., 1989, Climate change and its possible impacts in the Southwest Pacific region: Session, World Meteorological Organization Regional Association V, 10th, 1989, Melbourne, Australia, Proceedings, Bureau of Meteorology.