Intergovernmental Oceanographic Commission

Workshop Report No. 40 - Supplement

First International Tsunami Workshop on Tsunami Analyses, Prediction and Communications

Sidney, B.C., Canada, 29 July - 1 August 1985

Submitted Papers

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IOC Workshop Reports

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2	CICAR Ichthyoplankton Workshop Mexico City, 16-27 July 1974 (Unesco Technical Paper in Marine Sciences No. 20)	Division of Marine Sciences Unesco Place de Fontenoy 75700 Paris France	English (out of stock) Spanish (out of stock)
3	Report of the IOC/GFCM/ICSEM International Workshop on Marine Pollution in the Mediterranean, Monte Carlo, 9-14 September 1974	IOC, Unesco Place de Fontenoy 75700 Paris France	English French Spanish (out of stock)
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7	Report of the Scientific Workshop to Initiate Planning for a Co-operative Investigation in the North and Central Western Indian Ocean, organized within the IDOE under the sponsorship of IOC/FAO (IOFC)/Unesco/EAC, Nairobi Kenya 25 March-2 April 1976	IOC, Unesco Place de Fontenoy 75700 Paris, France	English French Spanish Russian
8	Joint IOC/FAO (IPFC)/UNEP International Workshop on Marine Pollution in East Asian Waters Penang 7-13 April 1976	IOC, Unesco Place de Fontenoy 75700 Paris France	English (out of stock)
9	IOC/CMG/SCOR Second International Workshop on Marine Geoscience Mauritius 9-13 August 1976	IOC, Unesco Place de Fontenoy 75700 Paris France	English French Spanish Russian
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11	Report of the IOC/FAO/UNEP International Workshop on Marine Pollution in the Caribbean and Adjacent Regions, Port of Spain Trinidad 13-17 December 1976	IOC, Unesco Place de Fontenoy 75700 Paris France	English Spanish (out of stock)
11 Suppl	Collected contributions of invited lectures and authors to the IOC/FAO/UNEP International Workshop on Marine Pollution in the Caribbean and Adjacent Regions, Port of Spain, Trinidad 13-17 December 1976	IOC, Unesco Place de Fontenoy 75700 Paris France	English Spanish
12	Report of the IOCARIBE Interdisciplinary Workshop on Scientific Programmes in Support of Fisheries Projects, Fort-de-France, Martinique 28 November-2 December 1977	IOC, Unesco Place de Fontenoy 75700 Paris France	English French Spanish
13	Report of the IOCARIBE Workshop on Environmental Geology of the Caribbean Coastal Area, Port of Spain, Trinidad 16-18 January 1978	IOC Unesco Place de Fontenoy 75700 Paris France	English Spanish
14	IOC/FAO/WHO/UNEP International Workshop on Marine Pollution in the Gulf of Guinea and Adjacent Areas, Abidjan, Ivory Coast, 2-9 May 1978	IOC Unesco Place de Fontenoy 75700 Paris France	English French
15	CPPS/FAO/IOC/UNEP International Workshop on Marine Pollution in the South East Pacific, Santiago de Chile 6-10 November 1978	IOC Unesco Place de Fontenoy 75700 Paris France	English (out of stock)
16	Workshop on the Western Pacific, Tokyo, 19-20 February 1979	IOC, Unesco Place de Fontenoy 75700 Paris, France	English French Russian
17	Joint IOC/WMO Workshop on Oceanographic Products and the IGOSS Data Processing and Services System (IDPSS), Moscow, 9-11 April 1979	IOC, Unesco Place de Fontenoy 75700 Paris, France	English
17 Suppl	Papers submitted to the Joint IOC/WMO Seminar on Oceanographic Products and the IGOSS Data Processing and Services System, Moscow, 2-6 April 1979	IOC, Unesco Place de Fontenoy 75700 Paris France	English
18	IOC/Unesco Workshop on Syllabus for Training Marine Technicians, Miami, 22-26 May 1978 (Unesco reports in marine sciences, No. 4)	Division of Marine Sciences Unesco Place de Fontenoy 75700 Paris, France	English (out of stock) French Spanish (out of stock) Russian
19	IOC Workshop on Marine Science Syllabus for Secondary Schools Llantwit Major, Wales, U.K., 5-9 June 1978 (Unesco reports in marine sciences No. 5)	Division of Marine Sciences, Unesco Place de Fontenoy 75700 Paris France	English French Spanish Russian Arabic
20	Second CCOP-IOC Workshop on IDOE Studies of East Asia Tectonics and Resources, Bandung Indonesia, 17-21 October 1978	IOC, Unesco Place de Fontenoy 75700 Paris France	English
21	Second IDOE Symposium on Turbulence in the Ocean, Liège, Belgium, 7-18 May 1979	IOC, Unesco Place de Fontenoy 75700 Paris, France	English French Spanish Russian
22	Third IOC/WMO Workshop on Marine Pollution Monitoring, New Delhi 11-15 February 1980	IOC Unesco Place de Fontenoy 75700 Paris, France	English French Spanish Russian
23	WESTPAC Workshop on the Marine Geology and Geophysics of the North West Pacific, Tokyo 27-31 March 1980	IOC, Unesco Place de Fontenoy 75700 Paris France	English Russian
24	WESTPAC Workshop on Coastal Transport of Pollutants, Tokyo 27-31 March 1980	IOC, Unesco Place de Fontenoy 75700 Paris, France	English (out of stock)
25	Workshop on the Intercalibration of Sampling Procedures of the IOC/WMO UNEP Pilot Project on Monitoring Background Levels of Selected Pollutants in Open-Ocean Waters, Bermuda, 11-26 January 1980	IOC, Unesco Place de Fontenoy 75700 Paris, France	English (superseded by IOC Technical Series No. 22)
26	IOC Workshop on Coastal Area Management in the Caribbean Region, Mexico City, 24 September-5 October 1979	IOC, Unesco Place de Fontenoy 75700 Paris France	English Spanish
27	CCOP SOPAC-IOC Second International Workshop on Geology, Mineral Resources and Geophysics of the South Pacific, Nouméa, New Caledonia, 9-15 October 1980	IOC, Unesco Place de Fontenoy 75700 Paris France	English
28	FAO/IOC Workshop on the effects of environmental variation on the survival of larval pelagic fishes Lima, 20 April-5 May 1980	IOC, Unesco Place de Fontenoy 75700 Paris France	English
29	WESTPAC Workshop on Marine biological methodology Tokyo 9-14 February 1981	IOC, Unesco Place de Fontenoy 75700 Paris France	English
30	International Workshop on Marine Pollution in the South-West Atlantic Montevideo 10-14 November 1980	IOC, Unesco Place de Fontenoy 75700 Paris France	English (out of stock) Spanish
31	Third International Workshop on Marine Geoscience Heidelberg 19-24 July 1982	IOC Unesco Place de Fontenoy 75700 Paris France	English French Spanish
32	UNU/IOC/Unesco Workshop on International Co-operation in the Development of Marine Science and the Transfer of Technology in the context of the New Ocean Regime Paris, 27 September - 1 October 1982	IOC, Unesco Place de Fontenoy 75700 Paris France	English French Spanish

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Intergovernmental Oceanographic Commission

Workshop Report No. 40 - Supplement

First International Tsunami Workshop on Tsunami Analyses, Prediction and Communications

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PREFACE

The First International Tsunami Workshop on the Technical Aspects of Tsunami Analyses, Prediction and Communications, sponsored and convened by the Intergovernmental Oceanographic Commission (IOC), was held during 29 July - 1 August 1985 at the Institute of Ocean Sciences in Sidney, British Colombia. The Workshop was organized by the Canadian Organizing Committee, headed by Mr. S. Wigen and assisted by the International Tsunami Information Center (ITIC). The Workshop preceded the Tenth Session of the International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU) which was held in Sidney, and the International Symposium of the Tsunami Commission of the International Union of Geodesy and Geophysics, held in nearby Victoria. Because of the near collocation of these meetings, attendance at the Tsunami Workshop was excellent and approximately 60 persons from seventeen countries participated to make the First International Tsunami Workshop a great success.

The Program was arranged in eight major areas of interest covering the following: Opening and Introduction; Tsunami Data Collection Activities and Responsibilities of Existing Tsunami Warning Systems; Need for and Structure of Future Regional Tsunami Warning Centers; Operational Procedures; Tsunami Preparedness; Tsunami Research; and Instrumentation.

Twenty-three specific presentations were made, by qualified experts, each followed by round table discussion. A number of specific problems were resolved during the general group discussions, or by ad-hoc committees. These committees met separately during lunch breaks or after hours, and reported their findings to the General Assembly for further discussion, deliberation, or adoptation. As a result, the Workshop not only served as a valuable training exercise to participants, but also facilitated the resolution of a number of problems of operational nature, since most of the principals in the Pacific Tsunami Warning System were present.

The Workshop program was succeeded by showings of tsunami films, a tour of the technical facilities of the Institute of Ocean Sciences, and a final General Group Discussion and Workshop Evaluation. During the latter, the summary of the Workshop proceedings were presented by the Chairman and were approved and adopted by the Assembly.

Following the Workshop, I was charged with the responsibility of collecting the full texts of all presentations made, editing the material received, and preparing a camera-ready final edition of the complete Proceedings, as shown in the present volume.

I wish to express my appreciation to all lecturers of providing their full presentations in a well-organized format, thus making my editing task a great deal easier. Finally, on behalf of all participants of the first International Tsunami Workshop I wish to express our sincere thanks and appreciation to the Canadian Organizing Committee and in particular to Mr. S. Wigen and his staff, to the Canadian Government for making available their fine facilities at Patricia Bay, and to the Intergovernmental Oceanographic Commission (IOC) for sponsoring and supporting financially this successful Tsunami Workshop.

George Pararas-Carayannis
Editor of the Proceedings
Workshop Chairman

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WELCOME ADDRESS

W.J. Rapatz
Regional Tidal Superintendent

Ladies and gentlemen, on behalf of the Department of Fisheries and Oceans and the Canadian Institute of Ocean Sciences, I welcome you to the Workshop on the technical aspects of tsunami analyses, prediction and communications. This is the first time such a Workshop has been organized and there is a great deal of information to cover in a comparatively short space of time. I would therefore, ask you to bear in mind that one of the main objects of the Workshop is to focus on the practical solutions to tsunami hazards, by attempting to identify lines of investigation and the actions required to improve tsunami mitigation. Some member nations have greater resources than others in the field of investigation and I am sure that all of us will benefit from their findings. But, whether our resources are large or small, I am convinced that the exchange of views and knowledge of tsunamis discussed in this room and outside will assist us all in the future.

I - OPENING AND INTRODUCTION

IOC-ITSU ROLES AND SIGNIFICANCE IN THE TSUNAMI WARNING SYSTEM

G. Pararas-Carayannis (Director ITIC),
I. Oliounine (IOC)
N. Ridgway (ICG/ITSU Chairman)

Abstract

The Intergovernmental Oceanographic Commission (IOC) has played a very important role in the formation of the International Pacific Tsunami Warning System. Prior to 1960, countries such as U.S.A., Japan and U.S.S.R. operated national tsunami warning systems for the protection of their own national interests. These systems had limited data collection and communication capabilities. The great destruction caused by the May 1960 Chilean tsunami and by that of the March 1964 Alaskan Tsunami, focused attention to the need for an International Tsunami Warning System. In 1965, the IOC accepted the offer of the United States to undertake the expansion of its existing Tsunami Warning Center in Honolulu to become the headquarters of the International Tsunami Warning System. IOC also accepted the offer of other Member States to integrate their existing facilities and communications into this International Warning System. At a meeting in Honolulu in 1965 an agreement was reached and IOC established the International Tsunami Information Center (ITIC) and the International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU).

ITIC was given the general mandate of mitigating the effects of tsunamis throughout the Pacific by: a) supporting Member States in ICG/ITSU in developing and improving preparedness for tsunamis; b) monitoring and seeking to improve the Tsunami Warning System for the Pacific; c) gathering and disseminating knowledge on tsunamis, and fostering tsunami research; and d) bringing to non-member states a knowledge of the Tsunami Warning System and information on how to become participants through ICG/ITSU.

The International Coordination Group (ICG/ITSU) was established as a subsidiary body of IOC meeting every two years at a Member State to coordinate and review the activities of the International Tsunami Warning System (ITWS). Since 1965, and with IOC support, the Tsunami Warning System integrated with other regional tsunami warning systems, has become the nucleus of a truly international network. Twenty-three nations are now members of ICG/ITSU. Several non-member states and territories maintain stations. The System makes use of approximately 31 seismic stations, 53 tidal stations and 101 dissemination points scattered across the Pacific under the varying control of the Member States of ITSU.

The International Tsunami Warning System in the Pacific is one of the most successful international scientific programs with the direct humanitarian responsibility of mitigating the effects of tsunamis by saving lives and protecting property. The System has been made possible by IOC's involvement and by the active coordination of ITIC and of ICG/ITSU, and by the interest and generosity of the Member Nations.

Introduction

Tsunamis are among the most destructive and complex natural disasters which have been responsible for great loss of life and extensive destruction to property. Historical records show that enormous destruction of coastal communities throughout the world has taken place. In the Pacific Ocean where the majority of these destructive waves have been generated, the historical record shows that these disasters have had an unparalled adverse impact on the socioeconomic resources of Pacific Nations. The significance of this hazard has been particularly emphasized in the last twenty years by the rapid growth and development of the coastal areas in most of the developing or developed Pacific nations. This is the result of a population explosion and of technological and economic developments in the coastal zones.

The Tsunami Hazard: The hazard which is called tsunami is a series of ocean waves of very great length and period generated by impulsive disturbances of the earth's crust. These disturbances are caused primarily by large earthquakes or volcanic eruptions. However, submarine landslides are also responsible for tsunami generation but their effects are usually localized. Large earthquakes with epicenters under or near the ocean are the most common cause of catastrophic tsunamis. In the last century, alone, tsunamis have claimed the lives of thousands of people and the damages to property have been incalculable.

Intergovernmental Oceanographic Commission: As early as 1965, a relatively young organization of the United Nations, the Intergovernmental Oceanographic Commission (IOC) decided to play a role in mitigating the effects of this natural hazard in the Pacific, where the frequency of recurrence was highest. In order to understand this important role that IOC has had in the Pacific Tsunami Warning System, a review of the history of the system and its evolution should be presented.

Prior to 1960, countries such as U.S.A., Japan, and USSR had established rudimentary national warning systems, with the responsibility of warning primarily their own civil defense authorities and protecting their own national interests. These systems had limited data collection capabilities, limited communications within their own national jurisdictions, and limited warning dissemination capability.

The great destruction caused by the May 1960 Chilean tsunami prompted a large number of countries and territories to express to IOC their interest in joining the rudimentary Pacific Tsunami Warning System, at least by contributing some data and information and receiving warnings in exchange. The great Alaskan earthquake of 1964 generated a devastating tsunami that affected a good part of the Pacific. This tsunami focused additional attention to the need for a well coordinated International Tsunami Warning System.

During the Third Session of the Intergovernmental Oceanographic Commission (IOC) in June of 1964, the Commission passed a resolution (IOC III.8) requesting the Secretariat to arrange for the convening of a meeting, preferably in Honolulu, to discuss the international aspects of the Tsunami Warning System with a view towards securing the best possible international co-operation in all phases of the Tsunami Warning System, viz: tidal and seismic monitoring stations, internal and international communications, and the issuance and dissemination of warnings. Invitations were extended to all IOC Member States with interests in the Pacific with specific invitations to the United States Coast and Geodetic Survey, the Japan Meteorological Agency, the Hydrometeorological Service of the USSR, the United Nations Educational, Scientific and Cultural Organization (UNESCO), the World Meteorological Organization (WMO), the Tsunami Committee of the International Union of Geodesy and Geophysics (IUGG), the International Telecommunications Union, and other national or international interested bodies.

A working group on the international aspects of the Tsunami Warning System in the Pacific met in accordance to the Intergovernmental Oceanographic Commission's request during the month of April 1965, in Honolulu. The Group discussed the resolution (IOC III.8) and its implication for the benefit of Member States, and the actions required, to provide on an international basis timely warnings, whenever a seismic event within the Pacific generated a tsunami.

The working group recommended that an International Tsunami Information Center (ITIC) be established on a permanent basis to collect and interpret seismic and sea-level data on a real-time basis to act as a source from which national centers may obtain data on which to base their warnings, and further that the United States Government be asked to strengthen its existing tsunami warning service based at the Honolulu Observatory to enable it to act, in addition, as the International Tsunami Information Center. It was also anticipated that other nations would be prepared to assist in operating this Center, for instance by providing personnel. In addition, the working committee recommended the formation of an International Coordination Group.

International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU): During that meeting the United States offered to undertake the expansion of its existing Tsunami Warning Center in Honolulu to become the headquarters of an International Pacific Tsunami Warning System and IOC accepted this offer, as well as the offer of other of its member countries to integrate their existing facilities and communications into this International Tsunami Warning System. The International Coordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU) was also formed as a subsidiary body of IOC to coordinate and review the activities of the International Tsunami Warning System (ITWS). An elected chairman for the group was appointed and the initial 11 Member States appointed National Contacts to serve as liaison with IOC and the proposed International Tsunami Information Center

(ITIC). The recommendation on the formation of the ICG/ITSU Group was also acted upon and ICG/ITSU was formed and held i's first session in March, 1968 in Honolulu.

The role of ICG/ITSU was to reduce the risk to lives and property in Member States whose coastal areas are threatened by tsunamis, and to carry out this role by recommending improvements to the TWS; by promoting regional co-operation between Member States; by contributing to the scientific and technical training of tsunami experts, and the education of the general public in tsunami awareness; by encouraging the development of improved instrumentation and communication systems; by ensuring the exchange of information between participating countries and between such organizations as the WMO and IUGG, and by offering assistance to the national and regional needs of Member States.

The Group was to hold its sessions every two years, and during the intersessional periods, the Group's recommendations were to be pursued and acted upon jointly by the Group Chairman and the IOC Secretariat, assisted by the Director, ITIC and the National ITSU Contacts of Member States.

Since 1968 the membership of the Group has grown from 11 Member States to 23 Member States at the present time. The TWS was integrated with the Systems of Japan, USSR, Chile, and of other regional centers, and became the nucleus of a truly international system. The following twenty-three nations are now members of ITSU in the Pacific: Australia, Canada, China, Chile, Colombia, Cook Islands, Ecuador, Fiji, France, Guatemala, Hong Kong, Indonesia, Mexico, Japan, Korea, New Zealand, Peru, Philippines, Singapore, Thailand, USSR, USA and Western Samoa. Several non-member states and territories maintain stations for the IWTS.

Eleven Sessions of the ICG/ITSU have taken place since the formation of the Group, with IOC sponsorship. A number of intersessional meetings with smaller groups have been held. Appendix 1 shows the different Member States of IOC which have become members of ICG/ITSU and have attended its sessions.

The International Tsunami Information Center (ITIC): The recommendation to establish on a permanent basis an International Tsunami Information Center was also acted upon by the United States without delay, and in 1966 the Center was officially established. The Pacific Field Director of the USGS was named as the first ITIC Director. Captain D. Whipp of the USGS was designated as the first ITIC Director, but was succeeded in early 1967 by Commander R. Munson.

ITIC was given the general mandate of mitigating the effects of tsunamis throughout the Pacific. More specifically the ITIC mandate was to insure dissemination of Tsunami Warnings; to collect tsunami information on a real time basis; to encourage tsunami research; and to promote the exchange of scientific and technical personnel and data among the participating nations.

The establishment of the U.S. National Oceanic and Atmospheric Administration (NOAA) prompted organizational changes and changes in the Directorship of ITIC and its functional responsibilities.

Dr. Gaylord Miller, the Director of the Joint Tsunami Research Effort, University of Hawaii and Mr. Robert Eppley, National Weather Service, Pacific Region Headquarters, respectively, occupied the post of the Director of ITIC until 1974.

At its Third Session in 1972 in Tokyo the ITSU Group was made aware of these organizational changes. The Group, recognizing the importance of the existance of the International Tsunami Information Center (ITIC) and its work in the development of the Tsunami Warning System in the Pacific, then recommended that its activities should not be diminished in any way by such internal organizational changes and that the attention of the ITIC should be devoted primarily to the collection and dissemination of information on research and technical developments on tsunamis, as well as promoting the exchange of scientific and technical personnel among participating countries. It further recommended that the Member Countries should provide all possible support to the ITIC, and that the Director should prepare a description of the functions and main activities of the ITIC and include in an issue of its Newsletter.

During the Fourth Session in 1974 at Wellington, New Zealand, ITSU considered that ITIC provided effective means in the coordination of warning and research activities and noted also a proposal made by Canada that it would be advantageous to the international community and to ITIC to select among the other participating Member States as Associate Director who would work in close co-operation with the Director in the operation of the Tsunami Warning System and the ITIC. The Group endorsed the view of the Tsunami Committee of IUGG that visits of scientists, particularly from countries whose tsunami observing and warning systems were still developing, to institutions of other countries were an effective way of improving experience and facilitating intercommunication of ideas for the better understanding of all aspects of tsunami research, and recommended the adoption of a new and expanded mandate and functions for ITIC.

During the later part of 1974 Dr. George Pararas-Carayannis was appointed Director of ITIC. In reference to the IOC resolution and recommendation, Mr. Sidney Wigen from Canada was elected as the first Associate Director and joined during 1975 the Center at Honolulu, located then within the campus of the University of Hawaii.

ITSU's members discussed at the Fifth Session in Lima, Peru, in 1976, the existing mandate again, and asked for changes. It was recommended at that meeting that the Secretary of IOC, in cooperation with the Director of ITIC, the Chairman of ITSU, and the appropriate U.S. authorities, develop a mandate which reflected the functions of the Center more closely in light of the U.S. Weather Service having taken over the responsibilities for ITIC and the Pacific Tsunami Warning Center, as well as in reference to World Data Center-A and its tsunami data storage involvements. A new mandate and functions was submitted to the IOC and approved at the Tenth Session of the Assembly in 1977.

The new mandate was more comprehensive, and included the conduct of extensive surveys following a significant tsunami. Most of the functions remained unchanged but the scope of the ITIC work was expanded. The one significant change was the operational responsibility of ITIC. ITIC was identified as a separate entity from the Pacific Tsunami Warning Center, thus minimizing real-time operational responsibility in favor of long term overview and improvement of the operational efficiency of the TWS through international coordination. The most recent Mandate and Statement of Functions, reflecting the most recent changes, is given as Appendix 2 of this report.

The International Tsunami Warning System (ITWS): Present protective measures involve primarily the use of the existing Tsunami Warning System employing advanced technological instrumentation for data collection and for warning communications. Countries like Japan, the Soviet Union, Canada, and the United States have developed sophisticated warning systems and have accepted the responsibility to share warning information with other countries of the Pacific. Their resources have been integrated into the ITWS.

The present system makes use of 31 seismic stations, 53 tide stations and 101 dissemination points scattered throughout the Pacific Basin under the varying control of the Member States of ITSU. The Pacific Tsunami Warning Center (PTWC) in Honolulu, operated by the United States National Weather Service, is the operational center for the system. The objectives of the ITWS are to detect and locate major earthquakes in the Pacific region, determine whether they have generated tsunami, and provide timely and effective information and warnings to the population of the Pacific region in order to minimize the effect of the hazards on life and property.

Functioning of the system begins with the detection by any participating seismic observatory of an earthquake of sufficient size to trigger the alarm attached to the seismograph at that station. Earthquakes of 6.5 or greater on the Richter scale are investigated. PTWC collects the data and, when sufficient data has been received, locates the earthquake and computes its magnitude. When reports from tide stations show that a tsunami poses a threat to the population in part or all of the Pacific, a warning is transmitted to the dissemination agencies for relaying to the public. The agencies then implement predetermined plans to evacuate people from endangered areas. If the tide station reports indicate that a negligible or no tsunami has been generated, PTWC issues a cancellation. In addition to the International Tsunami Warning System, a number of Regional Warning Systems have been established to warn the population in areas where tsunami frequency is high and where immediate response is necessary. Such regional tsunami warning systems have been established in the Soviet Union, Japan, Alaska and Hawaii. These facilities which are under the control of ITSU member nations have greatly assisted in improving the operation of the ITWS.

IOC-Sponsored Training and Education: In addition to improvements in instrumentation, communications, and procedures, and through the efforts of IOC and its subsidiary bodies (ICG/ITSU and ITIC), training programs have been established. Tsunami educational opportunities for tsunami experts, particularly from developing countries, have been successfully provided including a training visitation program at ITIC and a workshop. IOC has provided generous support of such training. Furthermore, IOC has sponsored and funded post-tsunami surveys and missions to a number of countries to assist Member States in developing their national tsunami warning systems, and in achieving better tsunami preparedness. Also IOC spearheaded the effort for a Master Plan, which identifies the future needs and priorities to be pursued to improve the ITWS. Finally, not the least significant benefit which IOC provides, is the opportunity for delegates from Pacific member countries to meet and exchange views and opinions in improving the tsunami warning service.

Summary and Conclusions: In conclusion, it can be stated that the role of IOC and its subsidiary bodies (ICG/ITSU, ITIC) has been very significant in dealing effectively with the tsunami hazard in the Pacific Ocean.

The International Tsunami Warning System is the result of IOC's involvement and active coordination. It is one of the most successful international scientific programs with the direct responsibility of mitigating the effects of tsunamis, the saving of lives and the preservation of property. It is an operational program with a direct humanitarian objective. Its value in the protection of human lives in the International Community of Pacific Nations, cannot be overemphasized.

APPENDIX 1

SESSIONS OF ICG/ITSU AND MEMBER PARTICIPATION

Nation	Year of ITSU Session									
Australia										1985*
Canada	1965	1968*	1970	1972	1974	1976	1978	1980	1982	1984	1985
Chile	1965	1968*	-	1972	-	1976	1978	1980	-	1984	1985
China	1965	- *	-	-	-	-	-	-	-	1984	1985
Colombia	-	-	-	-	-	-	-	-	-	-	1985
Cook Islands	-	-	-	-	-	-	-	- *	-	-	-
Ecuador	-	-	-	-	-	1976	1978*	1980	-	-	1985
Fiji	-	-	-	-	-	-	1978*	1980	1982	-	1985
France	1965	1968*	1970	1972	1974	1976	1978	1980	-	-	1985
Guatemala	-	-	-	1972	-	-	-	-	-	-	1985
Indonesia	-	-	-	-	-	-	1978	1980*	-	-	-
Japan	1965	1968*	1970	1972	1974	-	1978	-	1982	1984	1985
Korea, Republic of	-	- *	-	-	-	-	-	-	-	-	1985
Mexico	1965	-	-	-	-	1976	-	- *	-	-	-
New Zealand	1965	- *	-	-	1974	-	-	-	1982	1984	1985
Peru	1965	-	-	1972*	-	1976	-	1980	1982	-	1985
Philippines	1965	- *	1970	1972	1974	1976	1978	-	1982	-	-
Singapore	-	-	-	-	-	-	-	-	-	-	-
Thailand	-	-	-	1972*	-	-	1978	-	-	-	-
Hong Kong (U.K.)	-	-	-	-	-	-	- *	-	-	1984	-
U.S.A.	1965	1968*	1970	1972	1974	1976	1978	1980	1982	1984	1985
U.S.S.R.	1965	1968*	1970	1972	1974	1976	1978	-	-	1984	1985
Western Samoa	1965	-	-	-	-	-	-	-	-	-	-
Tonga (Observer)	-	-	-	-	-	-	-	-	1982	-	1985

* Joined during the intersessional periods.
1965 - Attended the session

APPENDIX 2

NEW MANDATE AND FUNCTIONS OF ITIC

The mission of the International Tsunami Information Center (ITIC) is to mitigate the effect of tsunamis throughout the Pacific:

A. MANDATE

1. by monitoring the international tsunami warning activities in the Pacific and recommending improvements with regard to communications, data networks, data acquisition, and information dissemination;

2. by bringing to Member and non-Member States knowledge on tsunami warning systems, on the affairs of ITIC and on how to become active participants in the activities of the International Co-ordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU);

3. by assisting Member States of ITSU in the establishment of national warning systems and improving preparedness for tsunamis for all nations throughout the Pacific Ocean;

4. by gathering and promulgating knowledge on tsunamis and fostering tsunami research and its application so as to prevent loss of life and damage to property;

5. by co-operating with the World Data Centers in making available and providing through appropriate channels all records pertaining to tsunamis;

6. by assisting national authorities in making investigations of all aspects of major tsunamis and developing standard survey procedures for such investigations.

B. FUNCTIONS

1. a. Monitor the performance and effectiveness of the International Tsunami Warning System and seek the co-operation of all participating agencies in improving response times and accuracy to provide better analyses and forecasting procedures.

   b. Develop and maintain communication with gauging authorities and agencies throughout the Pacific, and maintain an information file on tidal installations to facilitate the assessment of data received or required in developing appropriate models for both applied and pure research in the field of tsunamis.

2. a. Arrange for the availability of technical information on the equipment required for an effective tsunami warning system. Co-operate with experts and seek the advice of specialists to ensure that knowledge of new technology applicable to the warning system is made available to all participants.

   b. Publish a newsletter on a regular basis.

3. a. Arrange for, on request, the provision of advisory and consultative services to Member States wishing to develop or improve their warning system capability. Provide liaison between Member States in the planning and development of regional warning systems.

   b. Provide advice and support in soliciting international funds for the development of warning system capability.

   c. Arrange for or conduct, on request, assessment of existing facilities and the promotion of improvements, in such areas as instrument standardization, automation, and real-time communications.

4. a. Encourage and arrange for facilities for a visiting scientist programme within the IOC tsunami program, and promote the exchange of scientists among countries.

   b. Initiate, coordinate, or conduct technical training programmes, workshops, and seminars, dealing with all aspects of tsunami preparedness.

   c. Initiate and foster the preparation, publication, and dissemination of educational materials relative to tsunamis.

   d. Co-operate with national and international scientific and professional organizations in the encouragement and application of tsunami research, and in the standardization of tsunami data collection.

   e. Disseminate annual reports of tsunami research in progress by Member States and others.

   f. Support and participate in the publication of tsunami information, such publications to include regional tsunami catalogues and summaries of tsunamis.

   g. Co-operate with the IUGG in identifying research that is needed for the Tsunami Warning System.

5. a. For each tsunami, assist the World Data Centers (Tsunami) in soliciting and collecting as complete a set as possible of seismic and water level records showing the event, together with suplementary data and descriptive information of the event.

   b. Ensure that the requirements of ITSU for archiving and retrieving data are made known to the World Data Centers (Tsunami). Maintain a data file and library on tsunamis sufficient to meet ITIC requirements and responsibilities, utilizing the World Data Centers (Tsunami) as a primary source of these data.

   c. Prepare and disseminate a summary report for each tsunami.

6. a. Encourage, facilitate, and when invited, participate in the field investigation of tsunamis of large magnitude.

II - TSUNAMI DATA COLLECTION

HISTORICAL TSUNAMI DATA COLLECTION

George Pararas-Carayannis
International Tsunami Information Center

Abstract

A systematic compilation of all data pertaining to tsunamis observed and recorded in the Pacific Ocean since the beginning of recorded history was undertaken as early as 1960, and a Preliminary Catalog of Tsunamis in the Pacific was published in 1965 under the combined authorship of Iida, Cox and Pararas-Carayannis. Twenty years of additional research of historical tsunamis have added significantly to the completion and accuracy of this catalog. The work of Professor Soloviev has been integrated into this original catalog and a revised and corrected historical database exists now as a computer listing under the authorship of Iida, Cox, Soloviev and Pararas-Carayannis. This listing is now ready for publication.

The International Tsunami Information Center (ITIC), in close collaboration with the World Data Center-A, has published catalogs of historical tsunamis in Hawaii and in Alaska. Listings have also been compiled by ITIC of historical tsunamis in Samoa, Indonesia, the Atlantic Ocean and elsewhere. Recent events have been documented by ITIC in a file and routinely published in the Tsunami Report series or the Tsunami Newsletter. Historical tsunami data collection is important for the basic understanding of the tsunami phenomenon, its generation, its propagation, and its terminal characteristics. The historical database is widely used for coastal zone management, engineering design criteria and disaster preparedness. The data also serves as the basis for operational analysis of tsunami and is becoming an indispensable tool in the real-time evaluation of such events by the Pacific Tsunami Warning Center (PTWC) and other organizations. Thus, the historical tsunami data has been used for the preparation of decision, maps, the establishment of thresholds for operational procedures for hazard risk analysis, and for statistical probability studies.

HISTORICAL TSUNAMI DATA COLLECTION

One of the principal directives in the International Tsunami Information Center (ITIC) Mandate is to gather and promulgate knowledge on tsunamis and to foster tsunami research and its application to prevent loss of life and damage to property. Furthermore, ITIC has been charged with the responsibility of supporting and participating in the publications of tsunami information, such publications to include regional tsunami catalogues and summaries of tsunamis.

The Mandate and Functions of ITIC as revised by the 10th Session of the IOC General Assembly held in Paris from 10 October - 10 November 1977, instructed ITIC to prepare and publish tsunami data and descriptive information on all recently occurring tsunamis, and to conduct surveys of major tsunamis, whenever possible. Such historical tsunami data is needed for the Tsunami Warning System for insurance purposes, for coastal zone management, for designing important engineering structures such as nuclear power plants, for disaster preparedness, and for a variety of other reasons.

In meeting these directives of the ITIC Mandate, a basic prerequisite is the development of a complete and thorough tsunami historical database that can be easily filed and retrieved to serve the above stated needs, but primarily the operational needs of the Tsunami Warning System in the Pacific, and those of IOC member states seeking to improve their tsunami preparedness and coastal zone management.

Since its establishment in 1965, ITIC has been working diligently in documenting fully all tsunami events of the last 20 years. In addition, ITIC has engaged in historical research locating original references and records, and documenting past events. A systematic compilation of all data pertaining to tsunamis observed and recorded in the Pacific Ocean since the beginning of recorded history was undertaken as early as 1960 and a Preliminary Catalog of Tsunami in the Pacific was published in 1965 as a Hawaii Institute of Geophysics Report under the combined authorship of Iida, Cox and Pararas-Carayannis. Twenty-two years of additional research of historical tsunamis have added significantly to the completion and accuracy of this catalog and the work of Professor Soloviev has been integrated into this original historical Catalog of Tsunamis.

Revisions of individual events continue to the present day involving research of original accounts and references, evaluating accuracy of original documentations, correcting dates of different calendars and collecting new data. This is necessary because the literature contains a great deal of errors and contradictions that need to be reconciled once and for all. Thus, the task of editing and correcting has taken a long and careful review of the original references and literature, rather than reliance on existing listings.

This Catalog now resides in three different computer files, partially processed by a Data General minicomputer at the World Data Center A-Tsunami. ITIC has assisted in the past with the editing, but it has been difficult because the three files have not been formatted in a way that would meet all requirements. The editing work has been complicated by the lack of standardization in formatting for easy cross-referencing, for programming it for statistical treatment, and for decision-making in operational procedures.

ITIC has also compiled regional historical catalogs of tsunamis in Hawaii, Alaska, Samoa, Indonesia, Mexico and the Atlantic Ocean. However, not all of these catalogs have been published. Also, in 1977, ITIC began a publication entitled, "Tsunami Reports" in which all current tsunami events and investigations by the Pacific Tsunami Warning Center were documented. These publications were designed to provide information about those seismic events which are thought likely to produce a tsunami. Accordingly, whenever such a seismic event occurred, ITIC requested tidal records from appropriate authorities and, after examining the records, a tsunami report was issued. The report showed what records were examined, whether or not a tsunami had been generated and, if so, information about the tsunami was given.

Each event was assigned a sequential number for each calendar year. If an undesignated event was later found to have produced a tsunami, it was given an appropriate intermediate decimal number, eg 1985-2.5. The International Numbering System for Tides (INST) was used as the reference numbering system for tidal stations. Each tsunami report included all the pertinent seismic data and if the event had been tsunamigenic, a complete description of the tsunami including marigraphic recordings.

This turned out to be an arduous task for ITIC's small staff. Subsequently, the tsunami reports were discontinued, but the tsunami event designation was continued and all available relevant tsunami data was collected and published, whenever possible, in the Tsunami Newsletter.

The need to computerize these listings is evident. ITIC has developed the guuidelines for developing a standardized computer format which will permit cross-referencing and retrieval of pertinent data in a variety of fields ranging from date, earthquake epicenter, earthquake magnitude, geographical region of tsunami impact, tsunami magnitude, and bibliographical reference. Once the appropriate software is prepared, ITIC will proceed with the development of its large tsunami database.

HISTORICAL STUDY OF TSUNAMIS

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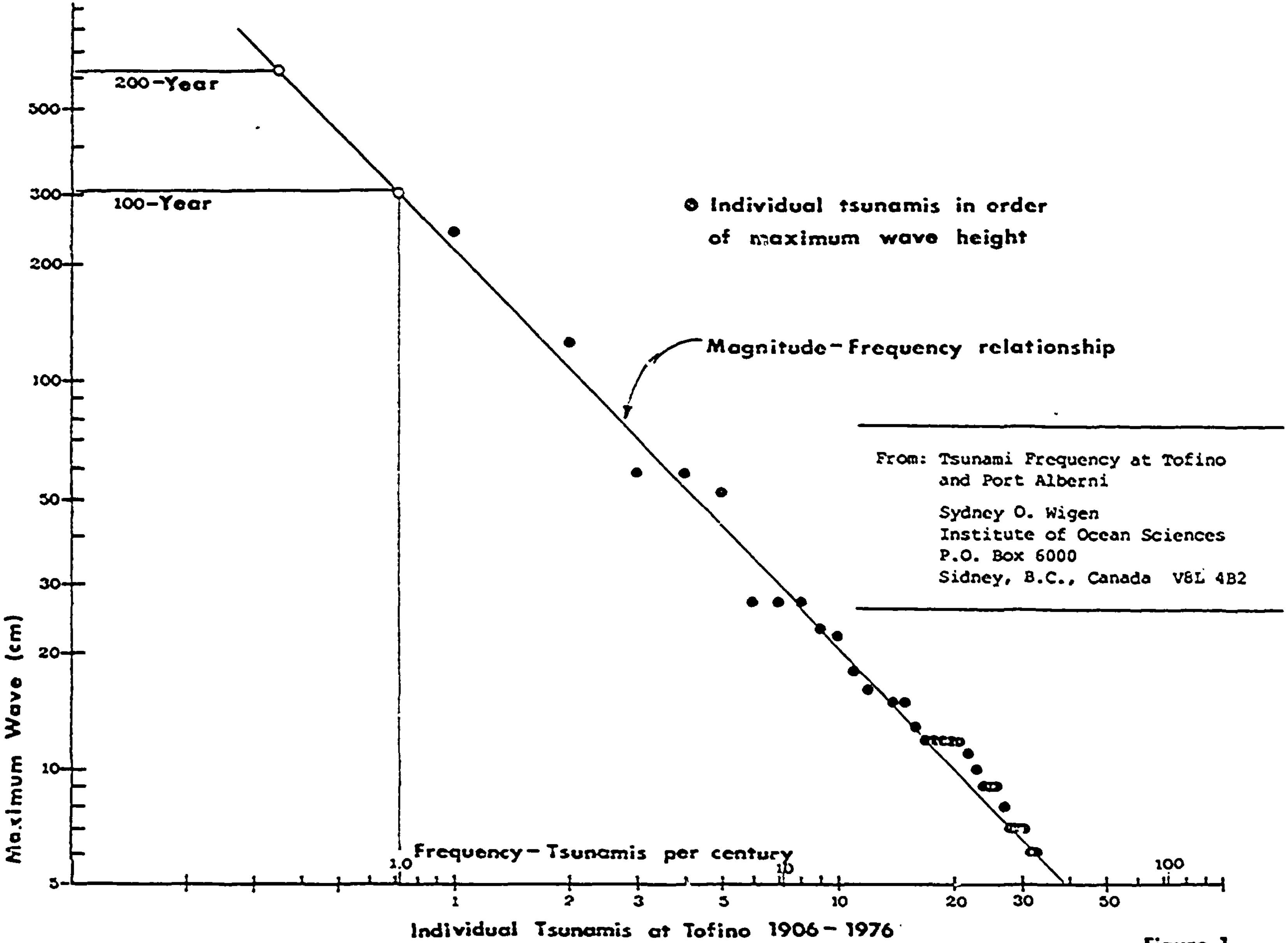
Much work remains to be done in the systematic compiling of tsunami data from analogue tide records. For many tidal stations only the large tsunamis have been extracted. Yet the systematic compilation of all data from a tide station, for tsunamis both large and small, provides a data set from which the frequency of tsunamis of any given intensity can be predicted. When the study also identifies which tsunamigenic events did not register at the tide station, these data help to define the regions to which a tsunami did not propagate, as well as the regions to which it did.

The publication, Historical Study of Tsunamis - an Outline (Wigen, 1978), sets out the standardized system of data extraction developed at ITIC for historical studies. The Historical Study of Tsunamis, Chronological and Area Lists (Wigen, 1977), and updated lists known and possible tsunamigenic events to be searched for, starting with the year 1883. Included in the Outline is a method for removal of tidal component to the tsunami record, allowing for a more accurate intercomparison of data.

Two examples of Historical Studies are included in the publication, Tsunamis: Their Science and Engineering, edited by K. Iida and T. Iwasaki. These studies are for the ports of Miyako, Japan, by M. Okada, and of Tofino, Canada, by Wigen. In each study a graphical plot of tsunami heights is used to develop the frequency-intensity relationship for the given port.

A Historical Study of Tsunamis is best carried out for a permanent tide station for which many years of analogue records are available. However, studies can be initiated for any station, and updated as additional records accumulate. Study results have direct application in hazard evaluation, engineering, and planning of port and coastal facilities. Travel times, extracted in each study, can be used in compiling or calibrating travel time charts for tsunamis.



From: Tsunami Frequency at Tofino
and Port Alberni

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Figure 1

TSUNAMI DATA BASE

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The World Data Center-A has been compiling data bases to support research and hazard preparedness activities related to tsunamis for over a decade. The principal data bases are shown in Table 1. Bathymetry data are useful in developing models and travel time prediction; mareograms, both digital and analog, are useful as a recording of the time history of the tsunami; seismic data are useful in determining tsunami source characteristics; photographs are a visual record of effects useful for public education and engineering analysis; and publications are a convenient media to distribute histories and maps. Recent publications include "Tsunami of the Pacific Basin" map and SE Report-39, "Tsunamis in Peru-Chile," both prepared in support of the US-AID THRUST project. A digital tsunami history file was created, partly to facilitate the production of the Tsunami of the Pacific Basin map. This file has information on all historical tsunamis in the Pacific, along with information on the effects such as wave heights, damage and fatalities.

Table 2 shows the data presently available for some of the larger tsunamis.

The digital history is a convenient form to ask many questions about the occurrence of tsunamis. The rest of the paper will show the results from asking some obvious questions of the digital file.

Table 3 shows the file contents for tsunamis of the Pacific Basin. It is noteworthy that more than half of the total number of reported tsunamis occurred in the 20th century due to increased observing and reporting systems. Most of the destructive tsunamis are in the earlier history due to the longer period of record.

Tsunami reports are classified on a scale of 0 to 4 as to certainty of the accuracy of the date and cause. Reports known to be in error (often due to an incorrect date from some calendar conversion) are left in the file with validity 0 so that some later revisions will not rediscover the erroneous report and reenter it. It may be difficult to distinguish wave activity due to distant storms from tsunamis if the descriptions are inadequate. These are given intermediate validities of 1, 2 or 3, depending on the uncertainty. Figure 1 shows the file contents for each validity level for each century. Thus the file has information on 433 definite tsunamis or 602 definite and probable tsunamis by mid-1985. The file is still growing as new sources are being added.

Figure 2 shows a system for defining regions around the Pacific Basin from 0 to 9 based on the Preliminary Catalog of Tsunamis Occurring in the Pacific Ocean (Iida and Cox 1967). This has proved useful in comparing histories from various regions.

Table 4 shows the number of events by region in the file. Japan is seen to have the most reported tsunamis by a substantial amount. If we limit our count to only those with a reported wave height of 1.5 meters or more to partially compensate for the better reporting of tsunamis from Japan, we see that they are nearly equal with four other regions - New Guinea/Solomon Islands, Indonesia, Kuril/Kamchatka and South America.

Table 5 lists 10 tsunamis with the highest loss of life. These 10 events caused about 150,000 deaths. Six were in the Japan region as were about 85,000 of the fatalities. The largest one was the tsunami associated with the 1883 eruption of Krakatoa. Damage and fatality reports vary widely and may include destruction due to the earthquake or volcano as well as the resulting tsunami.

Table 6 lists the destructive tsunamis of the last 100 years with number of fatalities and a damage code for each region.

Table 7 lists all of the tsunamis that caused damage beyond their source region in the last 100 years. All but one had a magnitude of 8.2 or greater. There were only nine such tsunamis in 100 years or about one per decade. South America and the Aleutians/Alaska accounted for three each and Kuril/Kamchatka and Japan for the remaining three. In almost every case the maximum effect beyond the source region was in Hawaii and Hawaii had the most fatalities from tsunamis outside of the source region.

Figure 3 shows the number of tsunamis reported and number of destructive tsunamis reported this century by decade. There have been 82 destructive tsunamis in 85 years, about one per year. There does not appear to be a marked increase in the number of tsunamis reported over the whole period or since the beginning of the tsunami warning service as one might expect. Dips in total number of tsunamis in 1910-1919 and 1946-1949 may be related to the World Wars. Also noteworthy is the dearth of tsunamis in the current decade. Unless there is a lot of activity in the next four years, this will be the quietest decade of the century in terms of total number of tsunamis and destructive tsunamis.

Table 8 lists the locally destructive tsunamis with source earthquake magnitudes below 7.5. It is clear that these lower magnitude events can cause damage in the tens of millions of dollars and fatalities in the hundreds. Some destructive tsunamis were associated with earthquakes with magnitudes below 6. More than twice as many people were killed by these lower earthquake magnitude tsunamis (over 1300) than by great tsunamis remote from the source region (500). This underlines the importance of local warning systems, including education of the population of the tsunami risk if reduced loss of life is to be achieved.

Figure 4 shows the location of the source earthquakes for the destructive tsunamis of the last 100 years. They are concentrated in the Western Pacific.

Figure 5 shows the epicenters of the tsunamis causing damage beyond their source region. These originate most commonly in the Eastern Pacific. A much higher percentage of Aleutian/Alaskan and South American tsunamis cause damage beyond their source region than elsewhere.

Figure 6 shows the correlation of maximum wave height and earthquake magnitude. It is poorly correlated.

Figure 7 compares the tsunami source region and affected regions. The diagonal counts locally destructive tsunamis. Region 4, the Philippines, for example, was the source of seven tsunamis causing local damage. They also suffered damage from one other tsunami originating from region 9, South America. It is clear that South American tsunamis have affected the most areas outside of their source region. The Aleutian/Alaska and Kuril/Kamchatka tsunamis account for almost all of the remaining remotely damaging tsunamis.

Figure 8 shows similar data with respect to fatalities. Clearly, the major loss of life is within the source region (about 99 percent).

Figure 9 shows the areas reported observing the tsunami of March 27, 1964. If we limit our consideration only to reports of waves of 1.5 meters or more, Figure 10 shows that the waves were highly directional to the South and Southeast. Figures 11 and 12 show similar directionality for different regions when only the larger waves are considered.

Figure 13 shows the sources of tsunamis reported by Hawaii. Clearly, it is the universal receptor for tsunamis and probably the wave heights at Hawaii could be used to predict wave heights elsewhere.

Table 9 summarizes some of the conclusions reached by examining the digital data base. Many of these conclusions have been reached by earlier researchers and are shown here as a demonstration of the use of the file.

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Solov'ev, S.L. and Ch.N. Go, A Catalogue of Tsunamis on the Western Shore of the Pacific Ocean, Academy of Sciences of the USSR, "Nauka" Publishing House, Moscow, 1974, 308 p.

Solov'ev, S.L. and Ch.N. Go, A Catalogue of Tsunamis of the Eastern Shore of the Pacific Ocean, Academy of Sciences of the USSR, "Nauka" Publishing House, Moscow, 1975, 202 p.

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Table 1

TSUNAMI-RELATED DATA

Bathymetry	Surveys; 30 million points, covering U.S. coastal waters Gridded; 5' x 5' worldwide oceans depth values, DBDB5
Mareograms	3,000 analog records for 350 tsunamis 45 digital records for 9 tsunamis
Seismic	Epicenters and magnitudes for 20th century earthquakes
Photographs	About 750
Publications	Catalogs published for Hawaii, Alaska, and Peru-Chile "Tsunamis of the Pacific Basin" map published
Digital History	About 890 tsunamis and 3,702 records of effects, including wave height, damage, and fatalities

Table 2

MAREOGRAPHIC AND PHOTOGRAPHIC DATA AVAILABLE FOR REPRESENTATIVE TSUNAMI EVENTS

EVENT DATE	EPICENTER	MAREOGRAMS ANALOG	MAREOGRAMS DIGITAL	PHOTOGRAPHS
1856 03 02	Celebes, N. Moluccas	3		
1868 08 13	Peru-N. Chile	13		1
1923 09 01	Tokaido, Japan	10		
1933 03 03	Sanriku, Japan	19		
1946 04 01	Aleutian Is.	43	4	322
1952 03 04	Hokkaido, Japan	68		
1952 11 05	Kamchatka, USSR	69	7	16
1957 03 09	Aleutian Is.	61	7	26
1960 05 22	Chile	62	12	60
1961 10 18	Chile		1	
1963 09 26	Peru		2	
1964 03 27	Alaska	104	7	194
1964 06 16	Niigata, Japan	32		1
1966 10 17	Peru	37	2	
1968 15 16	Honshu, Japan	44		3
1974 10 03	Lima, Peru	3		1
1971 07 09	Chile		3	
1975 07 26	Solomon Is.			3
1975 11 29	Hawaii	61		93
1976 08 16	Mindanao, Philippines			2
1983 05 26	Japan Sea	57		17
1984 08 07 (JST)	Japan	4		
1984 09 19 (JST)	Japan	7		
1985 03 03	Chile	20*	(7) **	13
1985 09 19	Mexico	3		

A total of 3,000 tide gage records are available in analog form for 350 tsunamis.

* Additional records expected from Alaska, Ecuador, and Tahiti.

** Expected

TABLE 3

TSUNAMI DATA FILE CONTENTS - PACIFIC BASIN

	NR. OF EVENTS (validities 2-4)	NR. OF EVENTS REPORTING WAVE OBSERVATORIES	NR. OF WAVE OBSERVATIONS REPORTED	NR. OF EVENTS REPORTING DEATHS OR DESTRUCTION	NR. OF LOCATIONS REPORTING DEATHS OR DESTRUCTION
CURRENT FILE	887	405	3702	287	680
CHILE ONLY	250	82	295	34	126
20TH CENTURY ONLY	482	295	3140	93	255

Table 4

DISTRIBUTION OF TSUNAMIS 1900 TO PRESENT
BY SOURCE REGION

REGION	TOTAL NUMBER	NUMBER WITH RUNUP GREATER THAN 1.5 M
Japan	100	20
New Guinea/Solomon Islands	64	20
Indonesia	46	16
Philippines	48	7
Kuril Islands/Kamchatka	42	18
W. Coast of South America	91	18
New Zealand/South Pacific	35	9
W. Coast North and Central America	27	12
Alaska and Aleutian Islands	22	9
Hawaii	7	4
Total	482	133

Table 5

TEN TSUNAMIS WITH HIGH DEATH TOLLS*

EVENT DATE	REGION	DEATHS
1605 02 03	Nankaido, Japan	5,000
1611 12 02	Sanriku, Japan	5,000
1707 10 28	Tokaido-Nankaido, Japan	30,000
1746 10 29	Callao, Peru	4,000
1792 05 21	SW. Kyushu, Japan	15,030
1854 12 24	Nankaido, Japan	3,000
1868 08 13	Peru-N. Chile	25,000
1883 08 26	Java-S. Java	36,000
1896 06 15	Sanriku, Japan	26,360
1976 08 16	Morro Gulf, Philippine Islands	5,000
		about 150,000

* Some deaths may have resulted from earthquake or volcano

TABLE 6

DESTRUCTIVE TSUNAMIS OF LAST 100 YEARS SORTED BY REGION WITH DAMAGE CODE AND NUMBER OF DEATHS 1885-1984

DATE	LAT.	LONG.		E.MAG	RUNUP	SOURCE	VALID.	CAUSE	DAMAGE	DEATHS
REGION 0	3 TOTAL; 1 CONSIDERABLE DAMAGE; 35 DEATHS									
1903 11 29					10.0	HAWAII	4		C	
1951 08 21	19.5	-156.0	12	6.90	3.6	HAWAII	4	T	C	33
1975 11 29	19.4	-155.1	05	7.20	8.0	HAWAII	4	T	B	2
REGION 1	3 TOTAL; 1 CONSIDERABLE DAMAGE; 10 DEATHS									
1917 06 25	-15.6	-173.0	SH	8.30	12.0	SAMOA ISLANDS	4	T	B	
1947 03 26	-38.8	17[illegible].6	SH	7.00	4.6	N. NEW ZEALAND	3	T	C	
1953 09 14	-18.6	178.6	60	6.80	2.0	FIJI ISLANDS	4	T&L	C	C
REGION 2	15 TOTAL; 6 CONSIDERABLE DAMAGE; 3 EXTENSIVE DAMAGE; 407 DEATHS									
1895 03 06	-8.5	150.0		7.5		W. SOLOMON SEA	4	T	A	26
1906 09 15	-7.0	149.0	SH	8.00	1.5	W. SOLOMON SEA	4	T	B	
1919 05 07	-6.0	153.0		7.75	2.5	BISMARCK SEA, NEW GUINEA	4	T	B	C
1926 09 17	-11.6	160.0	50	7.00	2.0	SOLOMON ISLANDS	4	T	B	
1930 12 24	- 1.3	144.3		5.75	2.5	MELANESIA	4	T	A	5
1931 10 04	-10.6	161.8	SH	7.90	9.0	SOLOMON ISLANDS	4	T	A	50
1938 05 13	- 6.0	147.7	SH	7.50		BISMARCK SEA, NEW GUINEA	3	T	C	
1939 04 30	-10.6	158.6	50	8.00	10.5	SOLOMON ISLANDS	3	T	C	12
1951 02 22	- 3.6	142.6			3.5	BISMARCK SEA, NEW GUINEA	2	T	C	
1970 11 01	-4.9	145.5	20	7.00	3.0	BISMARCK SEA, NEW GUINEA	4	T	C	3
1971 07 14	- 5.5	153.9	47	8.00	3.0	BISMARCK SEA, NEW GUINEA	4	T	C	1
1971 07 26	- 4.9	153.2	48	8.00	3.5	BISMARCK SEA, NEW GUINEA	4	T	B	
1974 02 01+	- 7.4	155.6	40	7.00	4.0	SOLOMON ISLANDS	4	T	C	
1975 07 21	- 6.6	154.9	50	6.70	2.0	SOLOMON ISLANDS	4	T	B	200
1979 09 12	- 1.7	135.9	05	8.10	2.0	W. IRIAN, INDONESIA	2	T	B	100
REGION 3	18 TOTAL; 6 CONSIDERABLE DAMAGE; 6 EXTENSIVE DAMAGE; 5,378 DEATHS									
1885 04 30	-2.5	127.5		7.2		CERAM	3	T&V	C	C
1889 09 06	3.1	125.6		8.0		N. MOLUCCA IS., INDONESIA	4	T&V	B	C

TABLE 6

DATE	LAT.	LONG.		E.MAG	RUNUP	SOURCE	VALID.	CAUSE	DAMAGE	DEATHS
1899 09 30	-3.5	128.5		7.8		BANDA SEA, INDONESIA	4	T&V	A	3,620
1907 01 04	1.5	97.0		7.50	2.8	SW. SUMATRA	4	T	A	400
1907 03 30	3.0	122.0		7.25	4.0	CELEBES SEA, INDONESIA	2	T	A	
1918 08 15	5.6	123.0	SH	8.30	7.0	CELEBES SEA, INDONESIA	4	T	B	8
1921 05 14	0.0	118.1		6.25		MAKASSAR STRAIT, INDONESIA	2	T	B	
1927 12 01	- 0.5	119.5		6.00	15.0	CELEBES SEA, INDONESIA	2	T	C	14
1928 08 04	-8.3	121.5		----	10.0	FLORES SEA, INDONESIA	4	V	B	128
1938 05 20	- 0.7	120.3		7.50	2.8	N. MOLUCCA ISLANDS, INDONESIA	4	T	C	17
1939 12 22	0.0	123.0	150	8.60		N. MOLUCCA ISLANDS, INDONESIA	3	T	C	
1965 01 24	- 2.4	126.0	6	7.60	4.0	CERAM ISLAND, INDONESIA	4	T	B	71
1967 04 11	- 3.3	119.4	33	5.50	3.0	MAKASSAR STRAIT, INDONESIA	3	T	C	13
1967 04 12	5.5	97.3	58	7.50	2.0	MALAY PENINSULA	3	T	C	
1968 08 14	0.2	119.8	23	6.10	10.0	BANDA SEA	4	T	A	200
1969 02 23	-3.1	118.8	33	6.88		MAKASSAR STRAIT, INDONESIA	4	T	A	600
*1977 08 19	-11.0	118.4	SH	8.00	30.0	SUNDA ISLANDS	4	T	B	100
1979 07 18	- 8.5	123.5			10.0	LOMBLEN ISLAND, INDONESIA	2	T&L	A	187

REGION 4   7 TOTAL; 5 CONSIDERABLE DAMAGE; 5,059 DEATHS

1897 09 21	6.8	122.5		8.5		SULU SEA, PHILIPPINES	4	T	B	13
1933 12 25	12.8	124.0		----	1.4	E. SAMAR ISLAND, PHILIPPINES	2	V	B	9
1934 02 14	17.6	119.0	SH	7.60	1.0	W. LUZON ISLAND, PHILIPPINES	4	T	B	
1948 01 25	10.6	122.0	SH	8.20	2.0	SULU SEA, PHILIPPINES	4	T		20
1949 12 29	18.0	121.0	SH	7.20	2.0	E. LUZON ISLAND, PHILIPPINES	3	T	C	16
1975 10 31	13.0	126.2	33	7.40		PHILIPPINE TRENCH	4	T	B	1
1976 08 16	6.3	124.0	SH	8.00	4.9	MORO GULF, PHILIPPINES	2	T	B	5,000

REGION 5   13 TOTAL; 3 CONSIDERABLE DAMAGE; 7 EXTENSIVE DAMAGE; 36,500 DEATHS

*1896 06 15	39.6	144.2		7.6		SANRIKU, JAPAN	4	T	A	26,360
1911 06 15	29.0	129.0		8.90	2.0	RYUKYU TRENCH	4	T	B	6
1914 01 12	31.0	130.4		6.20	3.0	SEIKAIDO, JAPAN	4	T	C	35
1923 09 01	35.3	139.5	SH	8.20	12.1	TOKAIDO, JAPAN	4	T	A	2,144
1927 03 07	35.6	135.0	10	7.60	11.3	SW. HONSHU ISLAND, JAPAN	4	T	A	1,100
*1933 03 03	39.2	143.0	10	8.30	28.0	SANRIKU, JAPAN	4	T	A	3,000
*1944 12 07	33.8	136.0		8.30	8.4	TOKAIDO, JAPAN	4	T	A	1,000
1946 12 21	33.0	135.6	30	8.00	6.0	NANKAIDO, JAPAN	4	T	A	1,997
1952 03 04	42.2	143.8	45	8.00	6.5	SE. HOKKAIDO ISLAND, JAPAN	4	T	A	33

DATE	LAT.	LONG.		E.MAG	RUNUP	SOURCE	VALID.	CAUSE	DAMAGE	DEATHS
1964 06 16	38.3	139.2	40	7.60	6.4	NW. HONSHU ISLAND, JAPAN	4	T	C	26
1968 04 01	32.3	132.5	32	7.75	2.3	SEIKAIDO, JAPAN	4	T	B	
1968 05 16	41.4	142.9	33	7.05	5.0	JAPAN TRENCH	4	T	B	
1973 06 17	43.2	145.8	33	6.50	3.0	KURIL, USSR-HOKKAIDO, JAPAN	4	T	C	
*1983 05 26	40.2	140.0	24	7.80	14.1	NOSHIRO, JAPAN	4	T	B	107

REGION 6 7 TOTAL; 4 CONSIDERABLE DAMAGE; 2 EXTENSIVE DAMAGE; 258 DEATHS

DATE	LAT.	LONG.		E.MAG	RUNUP	SOURCE	VALID.	CAUSE	DAMAGE	DEATHS
1918 09 08	45.6	151.6	SH	8.30	12.1	S. KURIL ISLANDS, USSR	4	T	C	23
1923 02 04	54.0	161.0	SH	8.30	8.0	KAMCHATKA PENINSULA, USSR	4	T	B	3
1923 04 14	56.6	162.6	SH	7.20	20.0	KAMCHATKA PENINSULA, USSR	4	T	B	18
1940 08 02	44.0	139.6	10	7.00	3.5	W. HOKKAIDO ISLAND, JAPAN	4	T	A	7
*1952 11 05	52.8	159.6	45	8.30	18.0	KAMCHATKA PENINSULA, USSR	4	T	A	A
1958 11 07	44.6	148.9	100	8.30	4.0	S. KURIL ISLANDS, USSR	4	T	B	

REGION 7 7 TOTAL; 3 EXTENSIVE DAMAGE; 371 DEATHS

DATE	LAT.	LONG.		E.MAG	RUNUP	SOURCE	VALID.	CAUSE	DAMAGE	DEATHS
1899 09 10	60.0	140.0		8.2		GULF OF ALASKA	4	T&L	C	
1936 10 27	58.6	-137.1		----	150.0	S. ALASKA	4	L	C	
*1946 04 01	52.8	-163.5	50	7.40	32.0	E. ALEUTIAN ISLANDS	4	T	A	247
*1957 03 09	51.3	-175.8		8.30	16.0	CENTRAL ALEUTIAN ISLANDS	4	T	A	
1958 07 09+	58.0	-138.8	SH	7.50	525.0	S. ALASKA	4	T&L	C	2
*1964 03 27+	61.0	-147.7	33	8.40	32.0	GULF OF ALASKA-ALASKA PENINSULA	4	T	A	122
1965 02 03	51.2	178.6	40	8.70	10.0	W. ALEUTIAN ISLANDS	4	T	C	

REGION 8 7 TOTAL; 3 CONSIDERABLE DAMAGE; 676 DEATHS

DATE	LAT.	LONG.		E.MAG	RUNUP	SOURCE	VALID.	CAUSE	DAMAGE	DEATHS
1887 05 03	-31.0	109.0		8.0		N. MEXICO	2	T	C	44
1902 02 26	13.5	- 89.5			5.0	GUATEMALA-NICARAGUA	4	T	B	185
1907 04 14	17.0	-100.0		8.00	1.8	S. MEXICO	4	T	C	8
1928 06 16	16.3	- 98.0	SH	7.90	2.0	S. MEXICO	4	T	C	4
1932 06 03	19.8	-104.2	SH	8.00	2.8	CENTRAL MEXICO	4	T	B	425+
1932 06 22	18.7	-104.7	SH	6.90	6.0	CENTRAL MEXICO	4	T	B	C
1934 07 17	8.0	-82.5		7.75	2.0	COSTA RICA-PANAMA	4	T	C	

TABLE 6

REGION 9 14 TOTAL; 5 CONSIDERABLE DAMAGE; 3 EXTENSIVE DAMAGE; 2,878 DEATHS

DATE	LAT.	LONG.	E.MAG	RUNUP	SOURCE	VALID.	CAUSE	DAMAGE	DEATHS
*1906 01 31	1.0	- 81.5	SH 8.60	5.0	COLOMBIA-ECUADOR	4		C	500+
*1906 08 16	-33.0	- 72.0	SH 8.40	3.6	S. CENTRAL CHILE	4	T	C	
1914 01 12	-12.0	- 76.6		3.0	PERU	4		B	
1918 12 04	-26.0	- 71.0	SH 7.80	5.0	N. CENTRAL CHILE	4	T	C	
*1922 11 10	-29.0	- 71.0	8.25	9.0	N. CHILE	4	T	A	A
1927 11 21	-44.6	- 73.0	SH 7.00	2.8	S. CHILE	4	T	B	
1943 04 06	-30.8	- 72.0	55 7.90		N. CENTRAL CHILE	4	T	B	C
1955 04 19	-30.0	- 72.0	30 7.00	1.0	N. CENTRAL CHILE	4	T	A	1
1958 01 19	1.5	- 79.5	40 7.50	4.0	COLOMBIA-ECUADOR	4	T	C	5
*1960 05 22+	-39.5	- 74.5	8.30	22.6	S. CHILE	4	T	A	1,590
1960 11 20	- 6.9	- 80.8	55 6.75	9.0	PERU	4	T	B	13
1966 10 17	-10.7	- 78.8	24 8.00	3.0	PERU	4	T	B	
1971 07 09	-32.5	- 71.2	58 6.80	1.2	CHILE	2	T	C	
1979 12 12	1.5	- 79.3	24 7.70	4.9	COLOMBIA-ECUADOR	4	T	A	259

DAMAGE CODE:
C = MINOR DAMAGE I.E. FEW HOUSES, BOATS, ONE LOCATION
B = CONSIDERABLE DAMAGE, I.E. 100 HOUSES, ONE LOCATION
A = EXTENSIVE DAMAGE, I.E. 1000 HOUSES, ONE LOCATION OR MANY HOUSES AT SEVERAL LOCATIONS

DEATH CODE:
C = FEW
B = MANY

CAUSE:
T = TECTONIC (EARTHQUAKE)
L = LANDSLIDE
V = VOLCANIC

VALIDITY:
4 = DEFINITE
3 = PROBABLE
2 = QUESTIONABLE

*INDICATES TSUNAMIS THAT CAUSED DESTRUCTION OR FATALITIES BEYOND SOURCE REGION

DEATHS AND DAMAGE FIGURES INCLUDE EFFECTS CAUSED OUTSIDE REGION OF ORIGIN

TABLE 7

TSUNAMIS DESTRUCTIVE BEYOND SOURCE REGION

THIS IS A LISTING OF TSUNAMIS OF THE LAST 100 YEARS INCLUDING INFORMATION ABOUT THE LOCATION AND SIZE OF THE EARTHQUAKES THAT GENERATED THEM; THE LOCATION AND HEIGHT OF THE GREATEST RUNUP PRODUCED BY EACH TSUNAMI; AND THE LOCATIONS OF DAMAGE PRODUCED OUTSIDE THE REGION OF THE EARTHQUAKE EPICENTER.

EVENT DATE	SOURCE REGION NAME	EQ.MAG.	REGION OF GREATEST RUNUP MEASURED IN METERS		DAMAGED AREAS	DEATHS
1906 08 16	S. CENTRAL CHILE	8.4	MAALAEA, MAUI, HI	3.6	HAWAII	
1922 11 10	N. CHILE	8.2	HILO, HI	2.1	JAPAN,PHIL.,TAIWAN,SAMOA,HAWAII	
1923 02 04	KAMCHATKA PENINSULA, USSR	8.3	HILO, HI	6.1	HAWAII(1)	1
1933 03 03	SANRIKU, JAPAN	8.3	MIDWAY IS., HI	6.5	HAWAII	
1946 04 01	E. ALEUTIAN ISLANDS	7.4	NE COAST HAWAII, HI	17.0	HAWAII(241),CHILE,CALIF.	241
1952 11 05	KAMCHATKA PENINSULA, USSR	8.3	HAENA POINT, HI	10.5	MIDWAY,HAWAII,SAMOA,PERU,CHILE,ECUADOR	
1957 03 09	CENTRAL ALEUTIAN ISLANDS	8.3	HAENA POINT, HI	16.0	CALIF.,EL SALVADOR,JAPAN,HAWAII	
1960 05 22	S. CHILE	8.3	HILO, HI	10.5	CALIF.,SAMOA,HAWAII(61),JAPAN (199)	260
1964 03 27	GULF OF ALASKA-ALASKA PENINSULA	8.4	CRESCENT CITY, CA	6.3	CANADA,W.COAST U.S.A.(15),HAWAII	15

	NUMBER OF TIMES EACH REGION APPEARS IN ABOVE TABLE AS A SOURCE FOR A MAJOR TSUNAMI		NUMBER OF TIMES EACH REGION RECORDED THE MAXIMUM RUNUP HEIGHT FROM A MAJOR TSUNAMI OUTSIDE THAT REGION		NUMBER OF TIMES EACH REGION RECEIVED DAMAGE FROM A MAJOR TSUNAMI OUTSIDE THAT REGION		DEATHS IN EACH REGION
0	HAWAII	= 0	HAWAII	= 8	HAWAII	= 9	303
1	NEW ZEALAND,SOUTH PACIFIC ISLANDS	= 0	NEW ZEALAND	= 0	NEW ZEALAND,SAMOA	= 3	
2	NEW GUINEA AND SOLOMON ISLANDS	= 0	NEW GUINEA (& AUSTRALIA)	= 0	NEW GUINEA	= 0	
3	INDONESIA	= 0	INDONESIA	= 0	INDONESIA	= 0	
4	PHILIPPINES	= 0	PHILIPPINES	= 0	PHILIPPINES (TAIWAN)	= 1	
5	JAPAN	= 1	JAPAN	= 0	JAPAN	= 3	201
6	KURILE ISLANDS, KAMCHATKA	= 2	KURIL IS., KAMCHATKA	= 0	KURIL IS.,KAMCHATKA	= 0	
7	ALEUTIAN ISLANDS, ALASKA	= 3	ALASKA	= 0	ALASKA	= 0	
8	WEST COAST NORTH AND CENTRAL AMERICA	= 0	NORTH & CENTRAL AMERICA	= 1	N. & C. AMERICA	= 4	15
9	WEST COAST SOUTH AMERICA	= 3	SOUTH AMERICA	= 0	SOUTH AMERICA	= 2	

TABLE 8 - DAMAGING TSUNAMIS WITH MAGNITUDE LESS THAN 7.5 IN 20TH CENTURY - BY MAGNITUDE

EVENT DATE	EQ.MAG.	MAX. RUNUP	LOCATION OF EARTHQUAKE	LOCATION OF DAMAGE	TYPE OF DAMAGE	DEATHS
1967 04 11	5.50	3.0	MAKASSAR STRAIT, INDONESIA	MOUTH OF TINAMBUNG RIVER	BOATS DESTROYED	13
1930 12 24	5.75	2.5	MELANESIA	N. COAST NEW GUINEA	VILLAGES DAMAGED	5
1927 12 01	6.00	15.0	CELEBES SEA, INDONESIA	PALU BAY, SULAWESI IS.	HUTS, PIER DESTROYED	14
1968 08 14	6.10	10.0	BANDA SEA	DONGOLA DISTRICT, INDON.	800 HOUSES DESTROYED	200
1914 01 12	6.20	3.0	SEIKAIDO, JAPAN	KAGOSHIMA, JAPAN	BOATS DAMAGED	15
				ALL OF JAPAN		35
1921 05 14	6.25		MAKASSAR STRAIT, INDONESIA	SEKURAH, INDONESIA	SEVERE DAMAGE	
1973 06 17	6.50	3.0	KURIL, USSR-HOKKAIDO, JAPAN	HOKKAIDO, JAPAN	FISHING BOATS SUNK	
1975 07 21	6.70	2.0	SOLOMON ISLANDS	TOROKINA, SOLOMON IS.	VILLAGE DESTROYED	200
1960 11 20	6.75	9.0	PERU	PERU		11
1953 09 14	6.80	2.0	FIJI ISLANDS	BEGA, SUVA IS.	BOATS DAMAGED	SEVERAL
1971 07 09	6.80	1.2	CHILE	VALPARAISO, CHILE	SOME DAMAGE	
1969 02 23	6.88		MAKASSAR STRAIT, INDONESIA	W. COAST CELEBES IS.	4 VILLAGES DESTROYED	600
1932 06 22	6.90	6.0	CENTRAL MEXICO	CAYUTLAN, MEXICO	SEVERE DAMAGE	
1951 08 21	6.90	3.6	HAWAII	KONA COAST, HAWAII, HI	MINOR DAMAGE	
1926 09 17	7.00	2.0	SOLOMON ISLANDS	GUADALCANAL, SOLOMON IS.	PORT INUNDATED	
1927 11 21	7.00	2.8	S. CHILE	AISEN PROVINCE, CHILE	INUNDATION ALONG COAST	
1940 08 02	7.00	3.5	W. HOKKAIDO ISLAND, JAPAN	RISHIRI IS., JAPAN	1000 BOATS LOST	7
				VLADIVOSTOK, PRIMORSKIY, USSR	EXTENSIVE DAMAGE	
				SW. COAST SAKHALIN, USSR	CELLARS FLOODED, BOATS WASHED AWAY	
				E. COAST KOREA	MERCHANT VESSEL CAPSIZED	
1955 04 19	7.00	1.0	N. CENTRAL CHILE	LA SERENA, COQUIMBO	DAMAGE	1
1970 11 01	7.00	3.0	BISMARCK SEA, NEW GUINEA	N. COAST NEW GUINEA	WAVES UPSET CANOE	3
1974 02 01	7.00	4.0	SOLOMON ISLANDS	KOROVU, SHORTLAND IS.	POLICE STATION FLOODED	
1923 04 14	7.20	20.0	KAMCHATKA PENINSULA, USSR	UST' KAMCHATSK	CANNERIES, BOATS, HOUSES DESTROYED	
				E. COAST KOREA	FISHING STATION DESTROYED	
1949 12 29	7.20	2.0	E. LUZON ISLAND, PHILIPPINES	CAGAYAN RIVER, LUZON	BOATS SUNK	16
1975 11 29	7.20	8.0	HAWAII	HAWAII	$1.5 MILLION DAMAGE	2
				CATALINA IS., CA	$2,000 DAMAGE	
1907 03 30	7.25	4.0	CELEBES SEA, INDONESIA	KARAKELONG IS.	CULTIVATED AREAS DEVASTATED	
1946 04 01	7.40	32.0	E. ALEUTIAN ISLANDS	UNIMAK IS., ALEUTIAN IS.	LIGHTHOUSE DESTROYED	5
				SANTA CRUZ, CA		1
				HILO, HAWAII	$26 MILLION DAMAGE	68
				NE. COAST HAWAII	$10 MILLION DAMAGE	173
				IQUIQUE, CHILE	BOATS DAMAGED	
				ISLA JUAN FERNANDEZ,CHILE	DAMAGE	
1975 10 31	7.40		PHILIPPINE TRENCH	SAMAR IS., PHIL	30 HOUSES DESTROYED	1

Table 9

1. There is an average of 1 damaging tsunami per year.
2. 90% of damaging tsunamis have only regional effects.
3. 99% of tsunami fatalities are local to source region.
4. Indonesia, Philippines, Peru-Chile, and Japan have histories of greatest loss.
5. Only a few areas have produced damaging Pacific-wide tsunamis.
6. The effect of Pacific-wide tsunamis beyond the source area is greatest in Hawaii.
7. Only Hawaii has a greater threat from distant tsunamis than from local tsunamis.
8. Tsunamis maximum effects are highly directional.
9. Local damage from tsunamis with magnitude less than 7.5 is more than the damage from Pacific-wide tsunamis beyond their source regions.
10. The correlation between earthquake magnitude and maximum run-up height is poor.

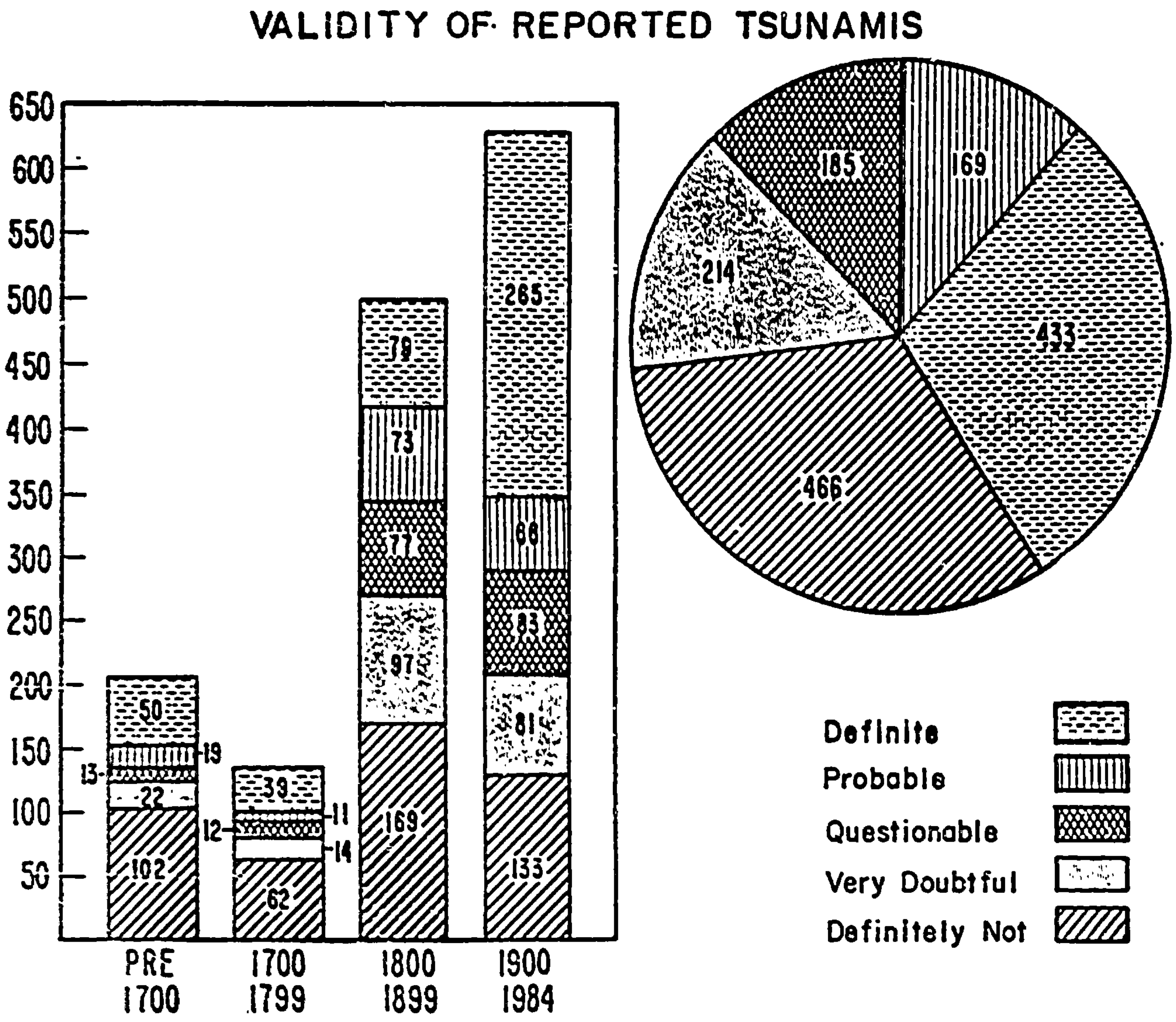
VALIDITY OF REPORTED TSUNAMIS
650
600
550
500
450
400
350
300
250
200
150
100
50
PRE 1700
1700 1799
1800 1899
1900 1984
50
19
13
22
102
39
11
12
14
62
79
73
77
97
169
265
66
83
81
133
169
433
466
214
185
Definite
Probable
Questionable
Very Doubtful
Definitely Not

Figure 1

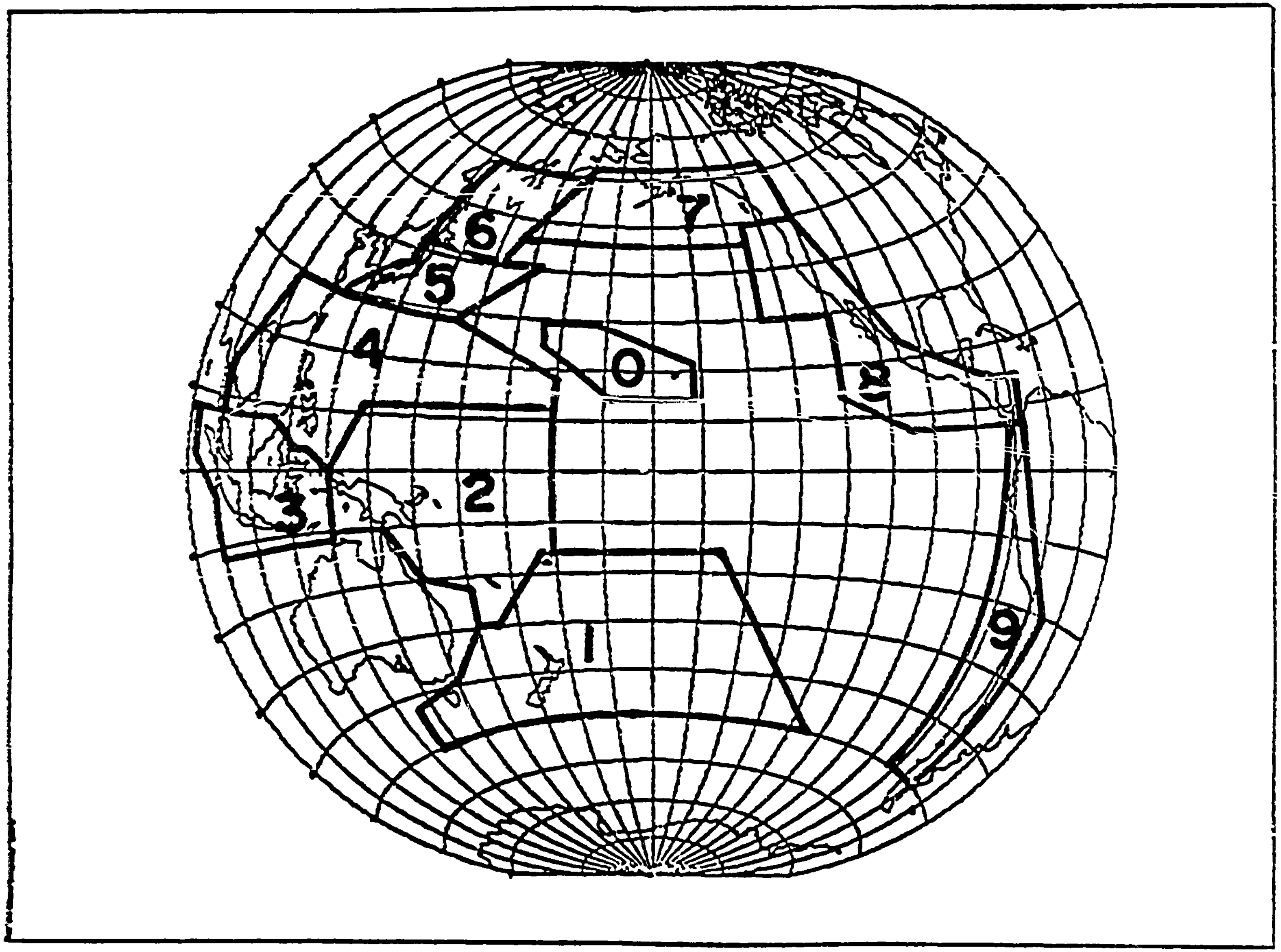

Figure 2 - Tsunami region boundaries

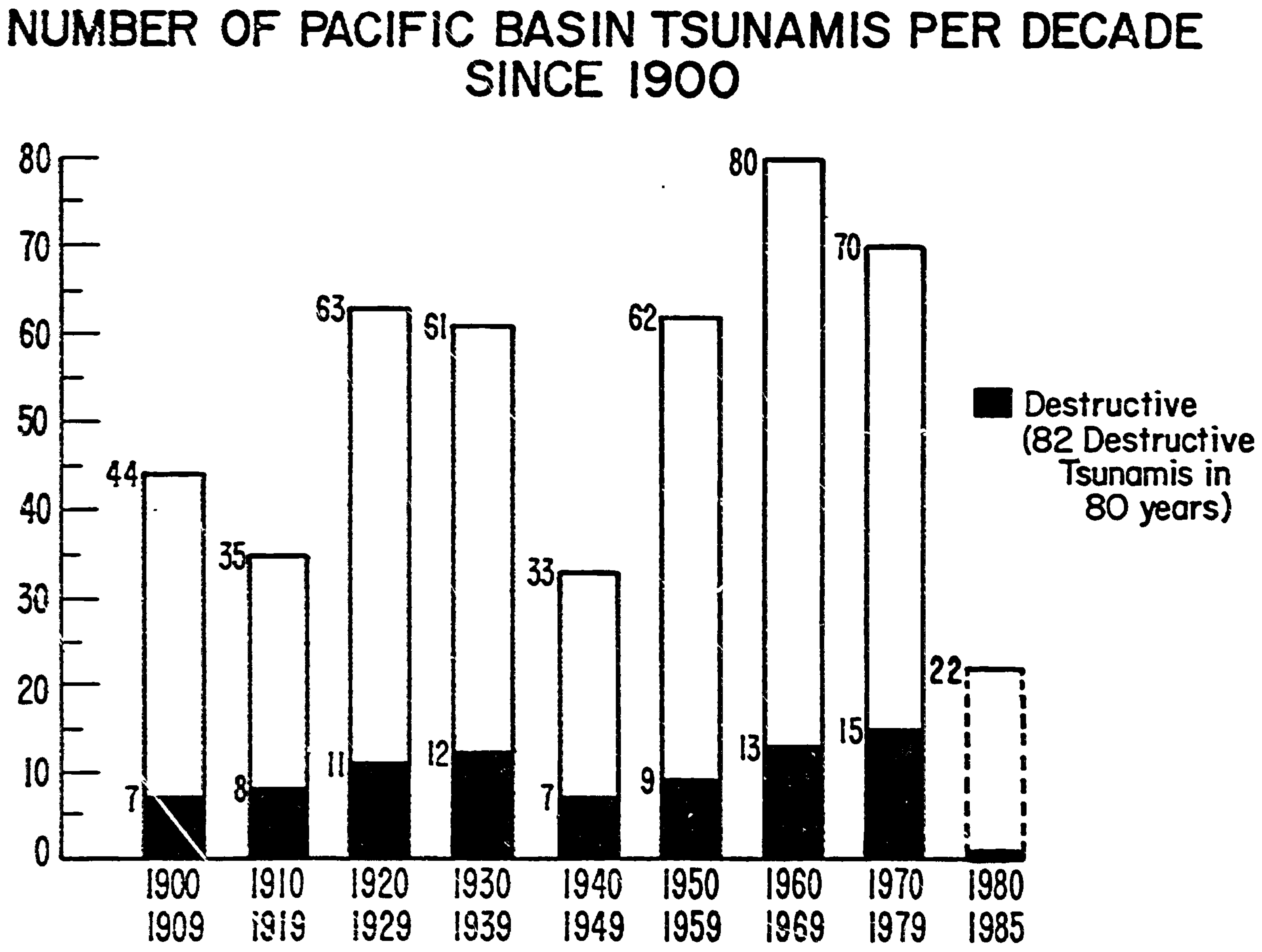
NUMBER OF PACIFIC BASIN TSUNAMIS PER DECADE SINCE 1900

Figure 3

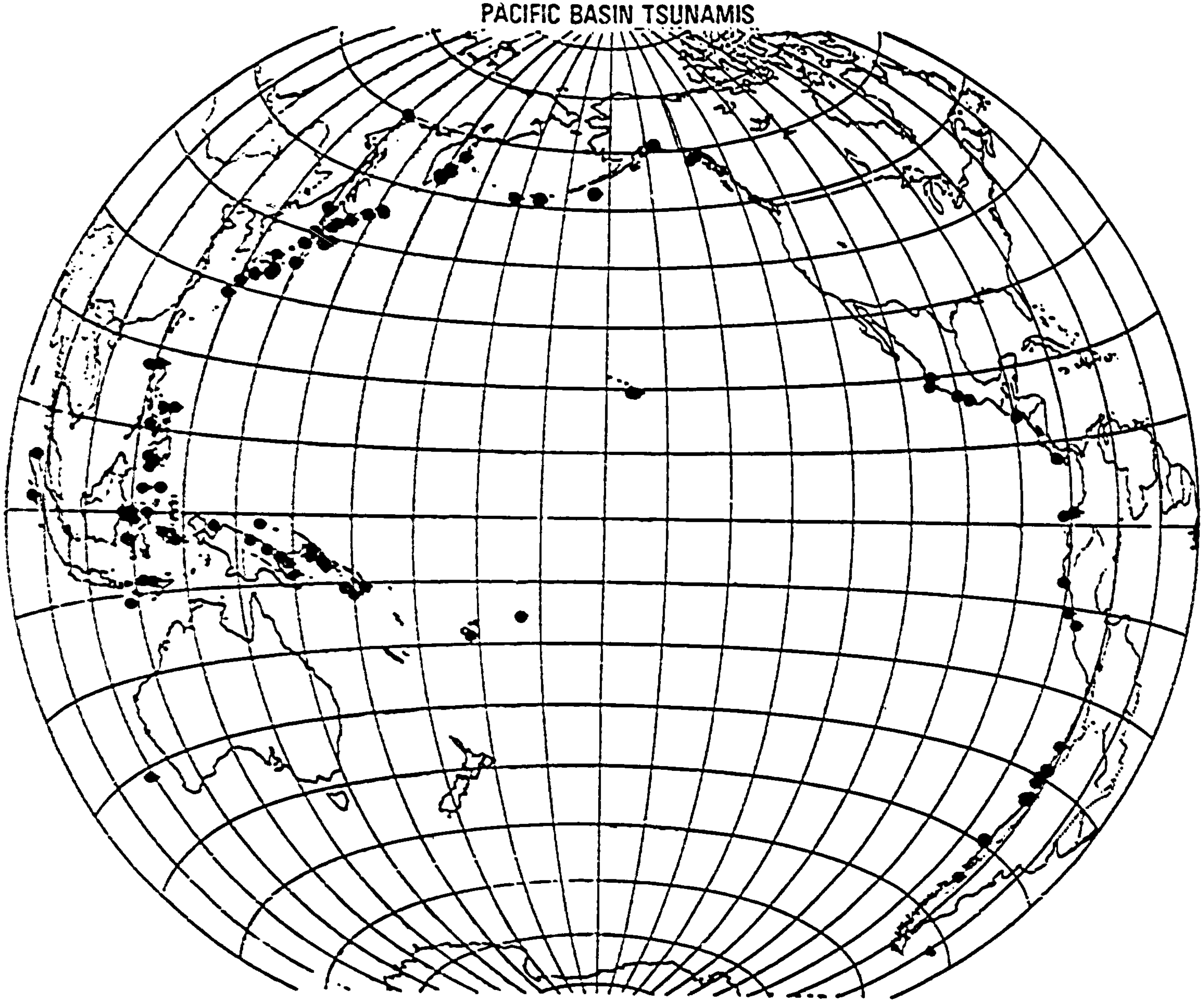

Figure 4 - Sources of destructive tsunamis - 100 years

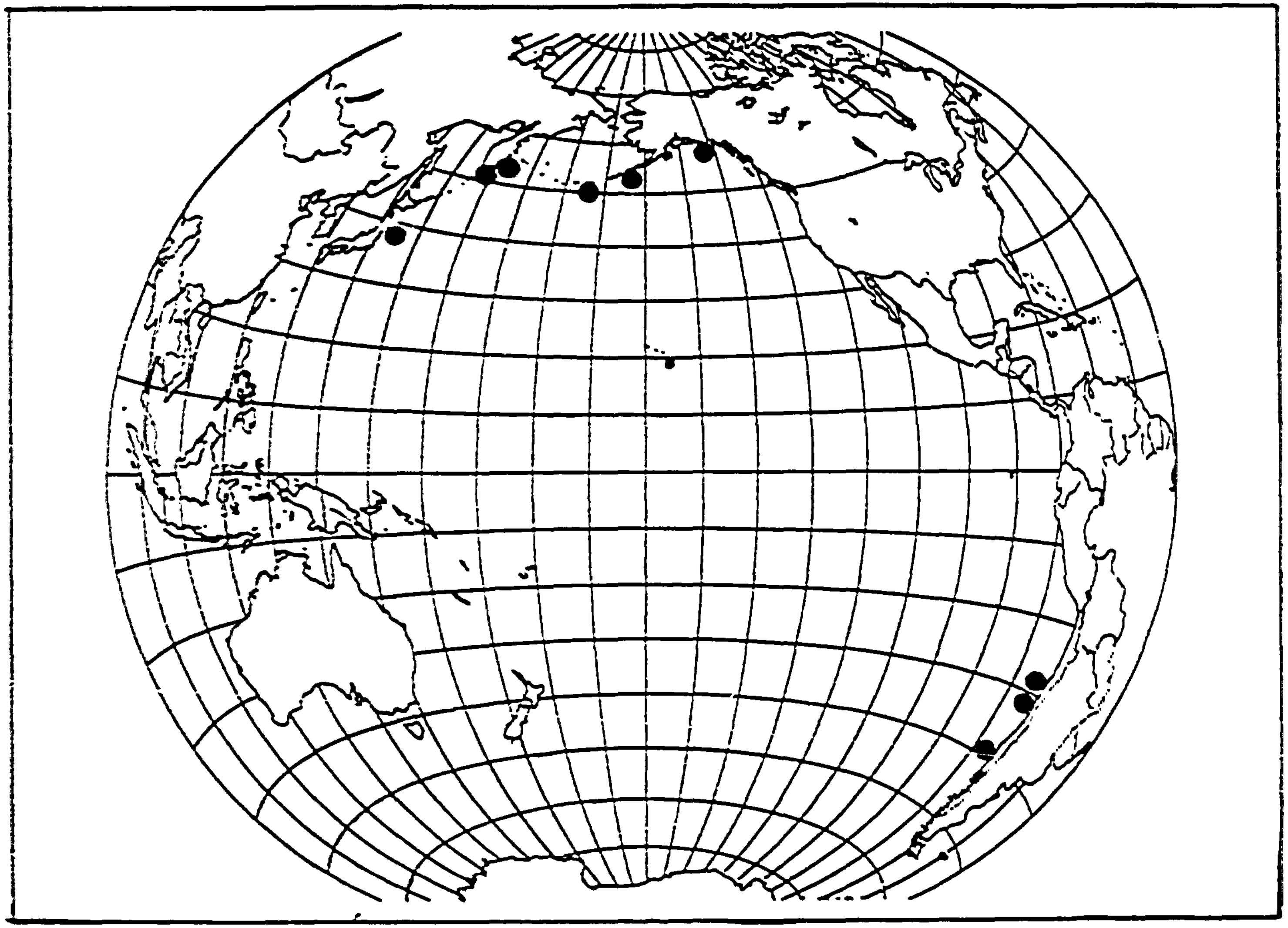

Figure 5 - Source of tsunamis causing damage beyond their source region - 100 years

MAXIMUM TSUNAMI RUN-UP HEIGHTS VS EARTHQUAKE MAGNITUDE

1900 - 1983

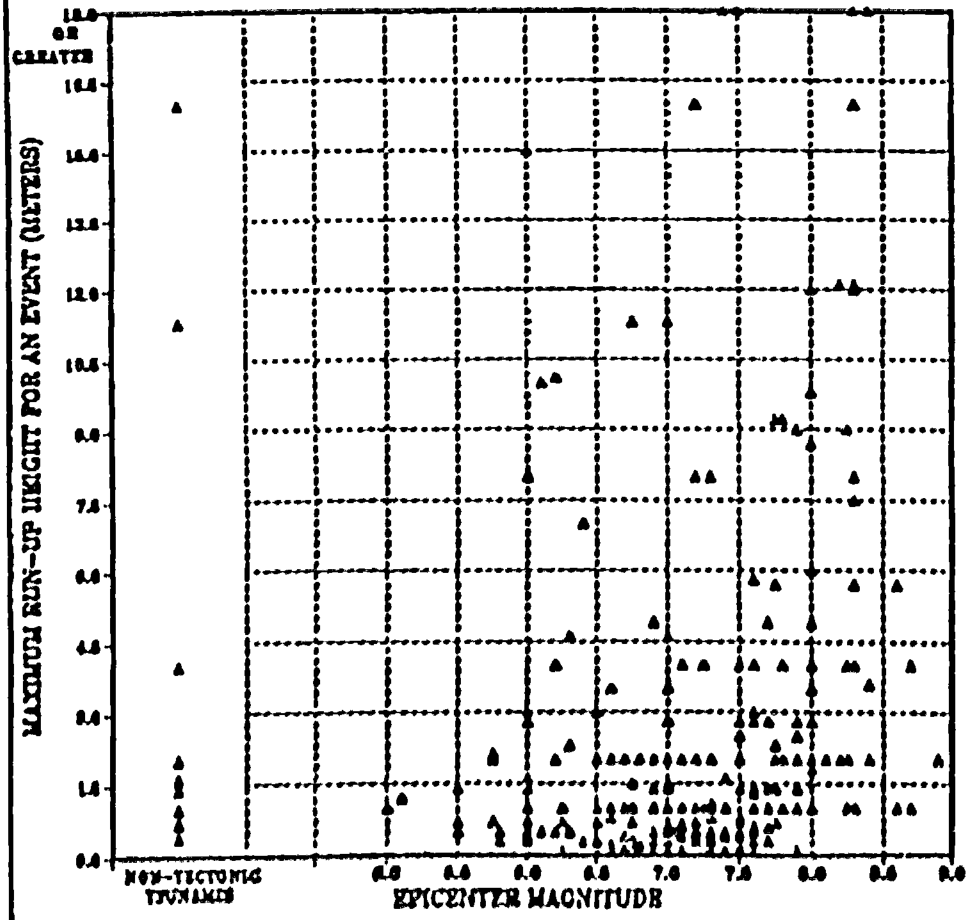

Figure 6

NUMBER OF TIMES TSUNAMIS HAVE CAUSED DAMAGE

BY REGION - 100 YEARS

SOURCE REGION

AFFECTED REGION	0	1	2	3	4	5	6	7	8	9
0	3					1	2	3		3
1		3					1			2
2			15							
3				18						
4					7					1
5						13	2*	1		2
6							7*			
7								7		
8								3	7	1
9							1	1		14

* Includes Hokkaido and Noshiro tsunamis

Key:
0 - Hawaii
1 - South Pacific
2 - New Guinea/Solomon Islands
3 - Indonesia
4 - Philippines
5 - Japan
6 - Kuril-Kamchatka
7 - Alaska & Aleutian Islands
8 - West Coast, North & Central America
9 - South America

Figure 7

DEATHS FROM TSUNAMIS
BY REGION - 100 YEARS

SOURCE REGION

AFFECTED REGION

	0	1	2	3	4	5	6	7	8	9
0	35						1	241		61
1		10								
2			407							
3				5,400						
4					5,000					
5						36,500				199
6							257			
7								115		
8								15	676	
9										2,618

Key:
0 - Hawaii
1 - South Pacific
2 - New Guinea/Solomon Islands
3 - Indonesia
4 - Philippines
5 - Japan
6 - Kuril-Kamchatka
7 - Alaska & Aleutian Islands
8 - West Coast, North & Central America
9 - South America

Figure 8

PACIFIC BASIN TSUNAMIS
RESULTING FROM EARTHQUAKE OF MARCH 27, 1964
(ALL RECORDED RUN-UP HEIGHTS)

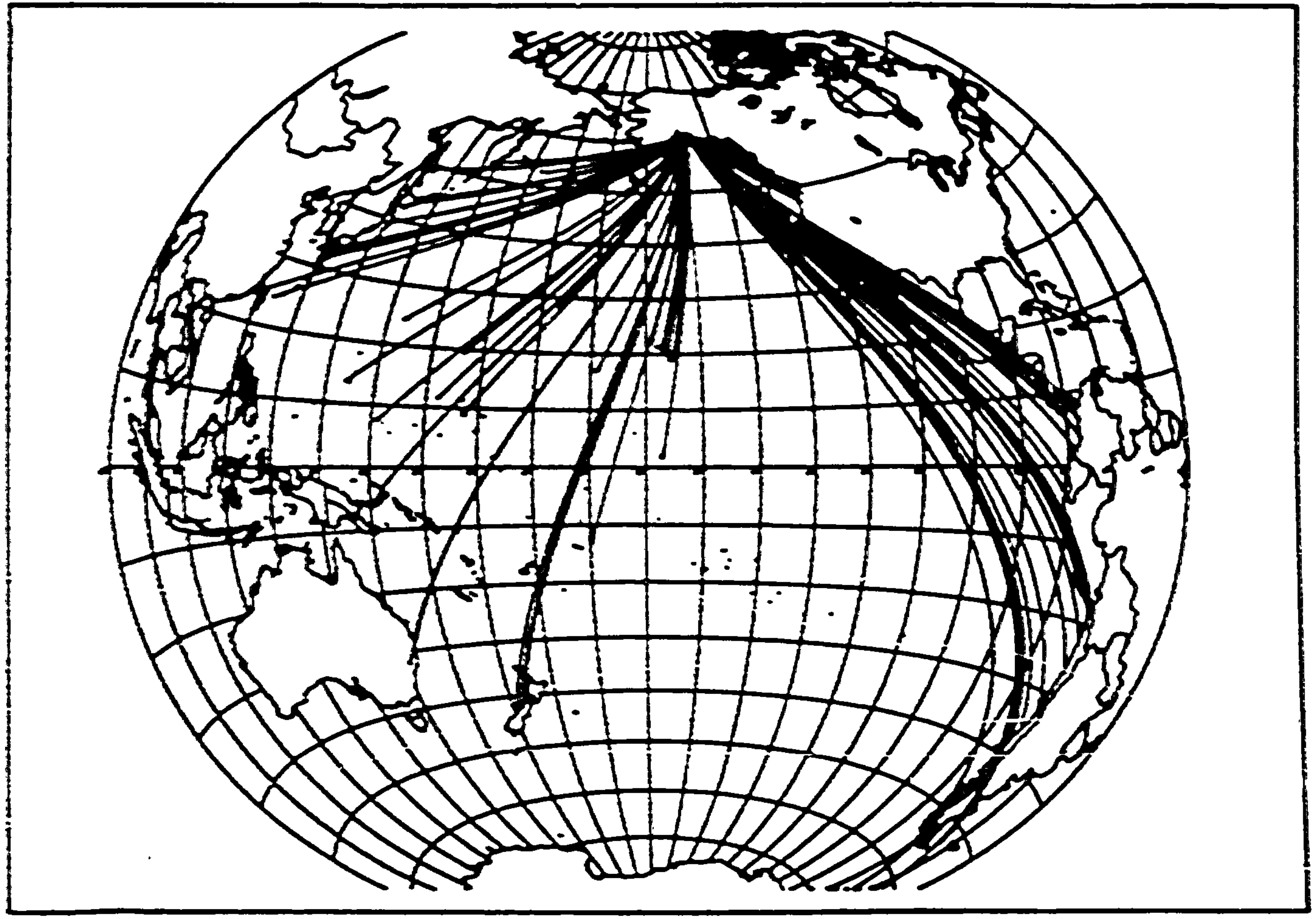

Figure 9

PACIFIC BASIN TSUNAMIS
RESULTING FROM EARTHQUAKE OF MARCH 27, 1964
(RUN-UP HEIGHTS ≥ 1.5 METERS)

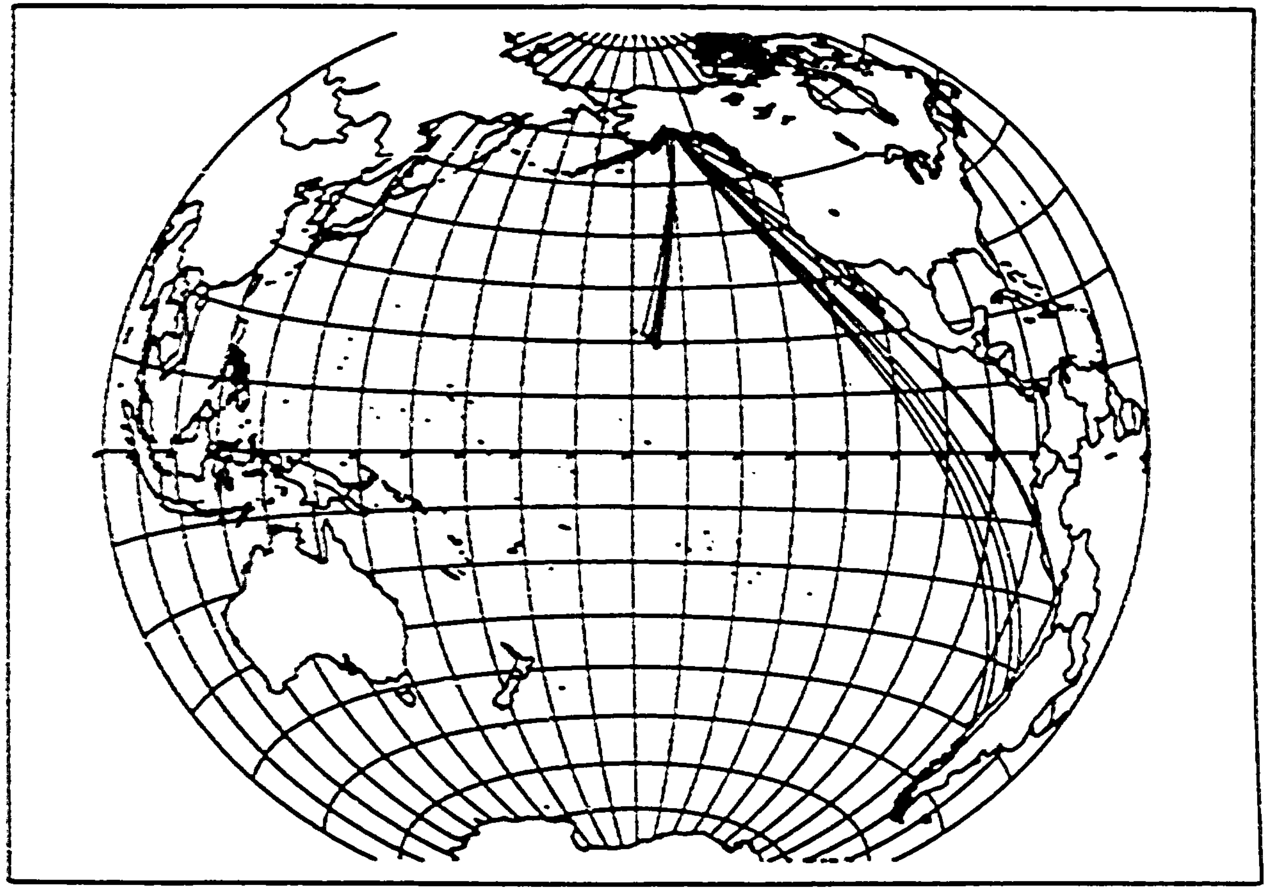

Figure 10

PACIFIC BASIN TSUNAMIS
RESULTING FROM EARTHQUAKE OF NOVEMBER 5, 1952
(RUN-UP HEIGHTS ≥ 1.5 METERS)

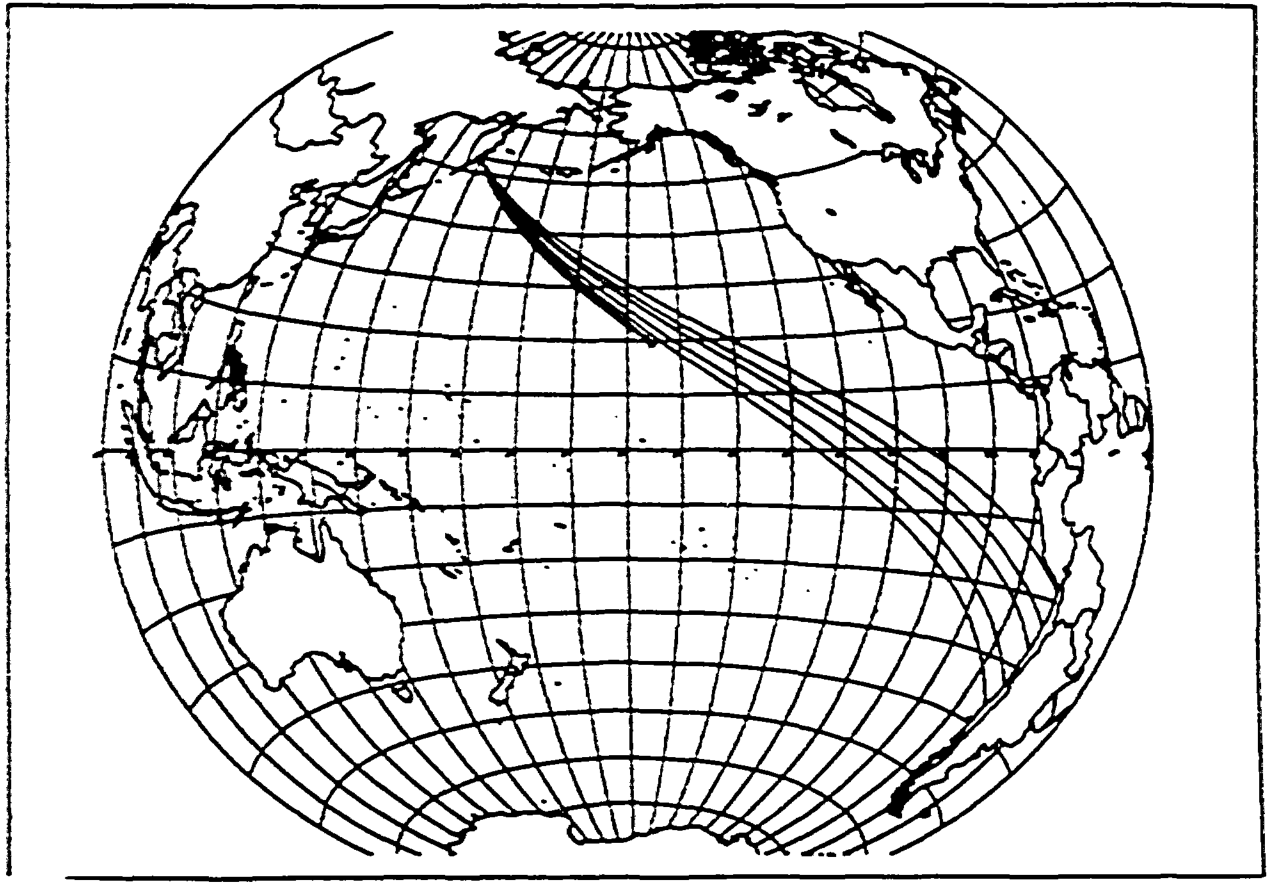

Figure 11

PACIFIC BASIN TSUNAMIS
RESULTING FROM EARTHQUAKE OF MAY 22, 1960
(RUN-UP HEIGHTS ≥ 1.5 METERS)

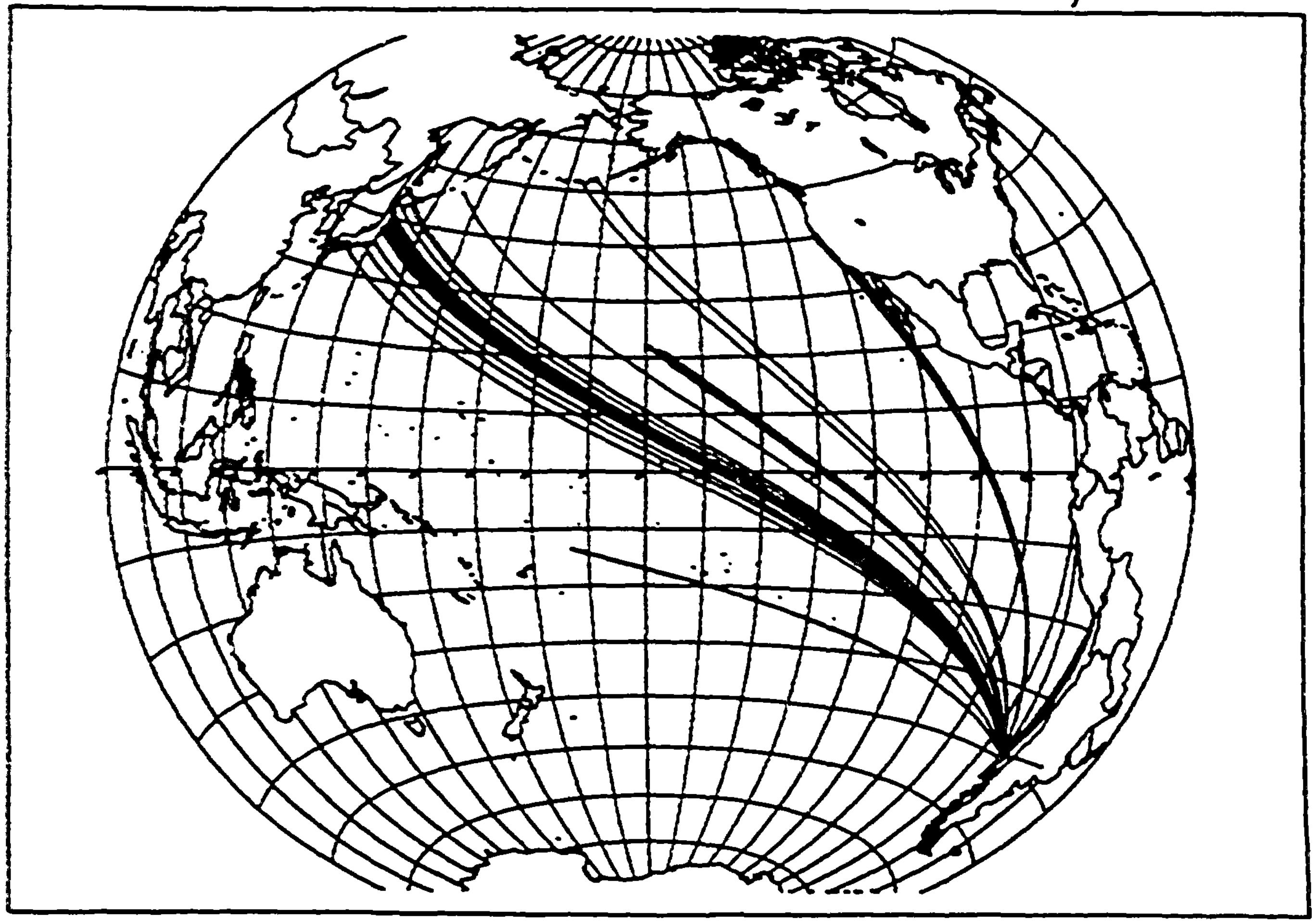

Figure 12

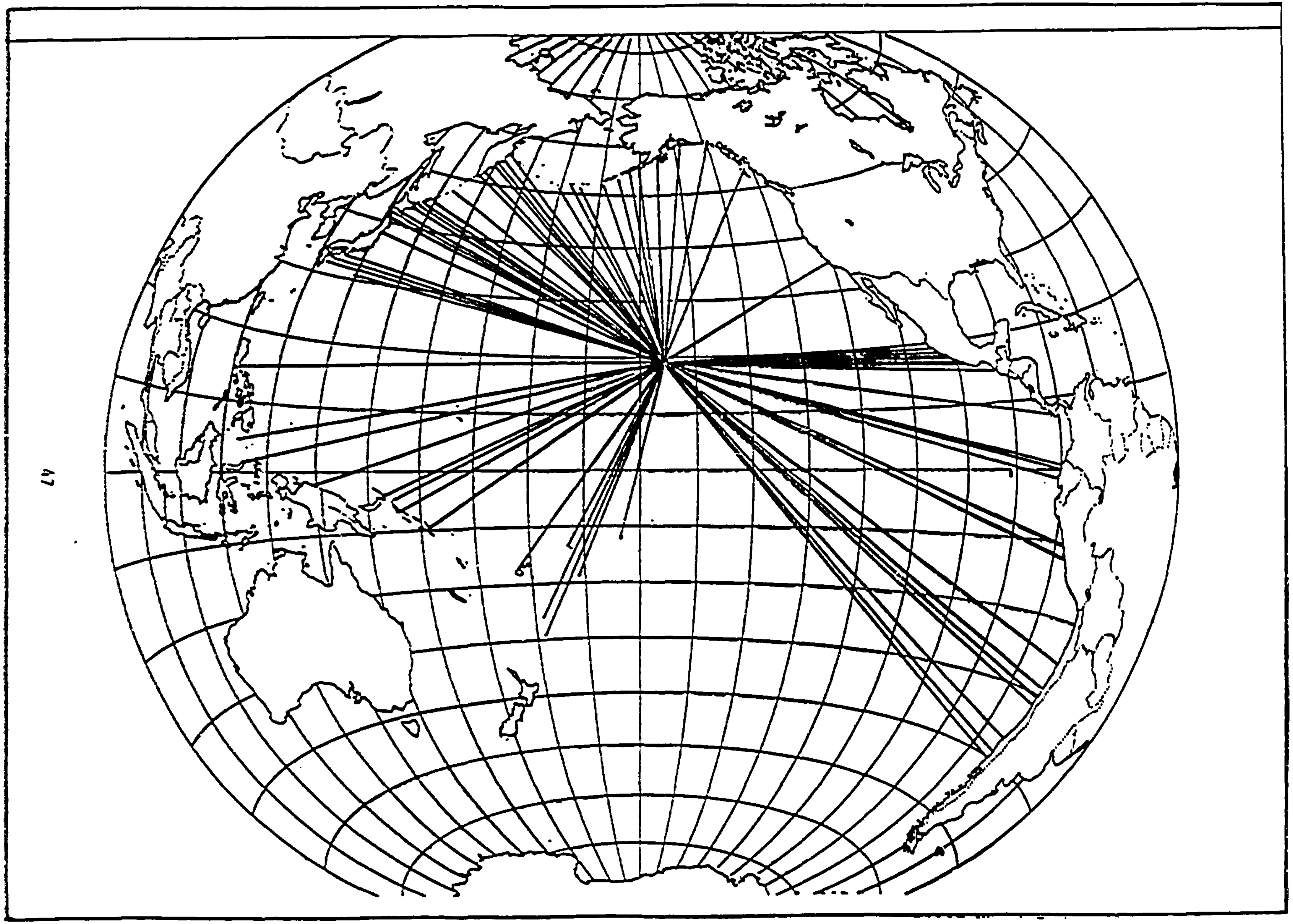

Figure 13 - Source regions for tsunamis observed in Hawaii

III - ACTIVITIES AND RESPONSABILITIES OF EXISTING TSUNAMI WARNING SYSTEMS

ACTIVITIES AND RESPONSIBILITIES OF THE PACIFIC TSUNAMI WARNING CENTER (PTWC)

Gordon D. Burton, Pacific Tsunami Warning Center

The Pacific Tsunami Warning Center (PTWC) is located on a 175 acre site at Ewa Beach on the island of Oahu, Hawaii. Formerly designated as Honolulu Observatory, PTWC is one of the oldest geophysical observatories in the United States, having been in operation since 1902 as a geomagnetic observatory to monitor time variations of the earth's geomagnetic field. Seismic observations began in 1903, with PTWC now functioning as the Hawaii station for the World Wide Standardized Seismograph Network (WWSSN). Though seismic and geomagnetic data are still continuously recorded, PTWC also now functions as the Regional Tsunami Warning Center for Hawaii, as the National Tsunami Warning Center for the United States, and as the operational control center for the Tsunami Warning System of the Pacific.

Thirteen buildings are located at PTWC, including housing for five personnel (four geophysicists and a secretary) who serve on a rotating basis as the duty watchstanders. Two people are on standby watch at any one time to respond 24 hours-a-day to any alarm events which occur. In addition, three electronics technicians work at the observatory to maintain all the instrumentation.

PTWC is operated and administered by the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA). On an international basis, participating nations are organized under the Intergovernmental Oceanographic Commission (IOC) as the International Coordination Group of the Tsunami Warning System of the Pacific (ICG/ITSU).

PTWC's stated mission as established by the NWS is to detect tsunamis in the Pacific, to predict their arrival and, when possible, run-up on the coasts, and to provide timely and effective tsunami information and warnings to the population of the Pacific to minimize the hazards of tsunamis. With only minor changes in wording to reflect the area of responsibility, this mission statement seems applicable to any Tsunami Warning Center, either on a regional or national basis. In keeping with the intent of this IOC Tsunami Workshop to discuss practical aspects of Tsunami Warning Systems, this paper will first address the general operational requirements for any Tsunami Warning Center and then specifically address how PTWC meets these general criteria, together with recent operational improvements which have been made.

A detailed analysis of the above stated mission identifies three separate operational phases, i.e., tsunami detection, tsunami evaluation, and information dissemination. Each of these three phases will be discussed in detail.

Tsunami Detection

The initial operational phase to be considered for any Tsunami Warning Center is logically that of detection, the simple recognition that a tsunami has been generated. Though simply stated, this may be an extremely complex requirement to satisfy. A satisfactory solution requires a complete understanding of the various source mechanisms which might result in tsunami generation within the Center's area of responsibility and a data acquisition network sufficient both in type and extent to determine that a tsunami has been generated.'

Tsunami source mechanisms vary from submarine to subaerial landslides, volcanic eruptions, structural displacement of the underlying seabed caused by seismic activity, nuclear explosions, sudden atmospheric pressure pulses, or indeed any mechanism which results in a significant vertical displacement of the ocean from a state of equilibrium. More than one mechanism may be involved for the same event. For instance, the 1964 earthquake in Alaska resulted in landslides generating local tsunamis within Prince William Sound as well as a major tsunami caused by structural displacement over several thousand square miles of the northwestern Gulf of Alaska. The extent of destruction of tsunami activity may vary from insignificant to localized or regionalized destruction to destruction over large portions of the Pacific.

Therefore, to be effective, a Tsunami Warning Center must first identify the problem, i.e., what is the operational capability to respond to the tsunami threat within its area of responsibility. It must be recognized that in many instances, a Warning Center simply can not be capable of tsunami detection prior to near-source coastal inundation. This is particularly true when initial waves are impacting a coastal area within 2-3 minutes of generation. In these instances a Tsunami Warning Center may serve to warn of the potential threat of additional waves or to warn those further removed from the region nearest the source, or it may effectively only serve the role of identifying the occurrence of a tsunami so that disaster relief may more rapidly be provided. A careful analysis of the potential tsunami threat to be addressed combined with the operational requirements to detect that threat can determine the technological requirements for a Tsunami Warning Center, or indeed the real need for any Center at all.

The operational effectiveness of a Tsunami Warning Center is directly related to the extent and timeliness of its data acquisition network. The rapid acquisition of data is necessary, with critical data required on a real-time basis. Sea level data is required to confirm the existence of a tsunami and to determine the impact on coastal areas. However by the time sea level data are available, near-source coastal areas have already been inundated.

Because the generation of most tsunamis is either directly or indirectly associated with seismic activity, the monitoring of earthquakes provides the basis for the initial detection phase and an evaluation of the probability of tsunamigenesis. Indeed, for many areas of responsibility, the operation of a Tsunami Warning Center can be based entirely on the acquisition and evaluation of seismic data with a high probability of operational effectiveness. Even seismic data from a single station can provide the basis for a Tsunami Warning Center, with the Hawaii Regional Tsunami Warning Center being only one example of this capability. This will be discussed in the following presentation on the "Activities and Responsibilities of the Hawaii Regional Tsunami Warning Center". The basic requirement for seismic data acquisition is the need to detect the occurrence and approximate location of a significant earthquake, and to measure the size of the earthquake in some manner to establish the relationship between earthquake energy release and probability of tsunamigenesis. Based on a correlation with historic data for the area of responsibility, seismic thresholds can be established for the issuance of Tsunami Warnings.

The acquisition of sea level data provides the second phase of tsunami detection, that of actual confirmation or negation that a tsunami has been generated. Real-time sea level data acquisition is always preferable, but near real-time data may be adequate for many responsibilities. Sea level data may consist of instrumental measurements, with tide gauges providing the most common example, or of visual observations received from a reliable observer. Though subjective in nature, visual reports from reliable sources may in many cases be more meaningful to a Tsunami Warning Center than instrumental data received from tide gauges.

Tsunami Evaluation

The second part of the mission statement set forth previously was that of predicting tsunami arrival and "when possible, run-up on the coasts". This is a formidable task fraught with possible judgmental error.

As with tsunami detection, the initial phase of tsunami evaluation is based upon an analysis and interpretation of seismic data to determine the probability not only that a tsunami has been generated, but also the location of the source region to determine tsunami arrival at coastal areas and, based on the size of the earthquake, some measure of probability of the destructive threat posed by a potential tsunami. A detailed study of the historical earthquake and tsunami data for a region can provide the basis for developing operational procedures relating earthquake size and location to the probability of the destructive potential of a possible tsunami.

The second phase of tsunami evaluation is based on analyses of sea level data, whether measured or observed. Because of the dynamic characteristics of tsunami impact along a coastline, it may often be impossible to accurately predict the extent of potential tsunami impact based on isolated measurements. Sea level activity recorded at a tide gauge may not be indicative of the actual tsunami impact occurring elsewhere. As with seismic data, the correlation of reported sea level data with the historical data for that region may provide an improved evaluation capability of probable tsunami coastal impact.

The provision of estimated times of arrival (ETA's) along a coastline must necessarily be based on an interpolation of pre-computed values or the use of previously constructed tsunami travel-time charts. During an actual event there is not sufficient time to complete the lengthy computations that would otherwise be required. ETA's may vary from a few minutes after earthquake origin to several hours depending on the distance to the source region.

Ultimately the most comprehensive tsunami evaluation is based on an integration of the evaluation of the seismic data, the evaluation of the sea level data, and a correlation of the current event with the historical data for that region. It must be recognized that the tsunami evaluation completed at a Tsunami Warning Center on an operational basis is subjective in nature based on the data available and the experience of the watchstander.

Information Dissemination

The third phase of the mission of a Tsunami Warning Center is the dissemination of information to responsible authorities and to the public, the ultimate users of tsunami warnings. The NWS mission statement stresses that tsunami information be "timely and effective" to minimize the hazards of tsunamis to the population.

Timeliness of information is obviously critical, with the goal of the Tsunami Warning Center being that of providing a warning to authorities in time to evacuate potentially impacted areas prior to tsunami inundation. This not only requires a rapid response by the Center in the detection and evaluation of a tsunami, but also a rapid means of communicating Tsunami Warnings. Communication methods and facilities may vary from voice communication to teletype messages to radio or television or activation of sirens. The nature and method of communication facilities used should be adequate to provide the most rapid possible dissemination of information by the Center.

The second criteria of effectiveness of information is a measure of the accuracy of the information released by the Tsunami Warning Center and the manner in which that information is provided to responsible authorities. With regard to accuracy, it is possible that false warnings or erroneous information may occasionally be issued, but such instances should be minimized. Of equal importance is the manner in which information is provided to minimize confusion and misunderstanding by local authorities and by the public. The terminology used must clearly state the circumstances and provide authorities with necessary information to assist in the determination as to the appropriate mitigation measures to implement.

Evaluation Criteria for a Tsunami Warning Center

The above discussion relating to the detection and evaluation of a tsunami and the dissemination of information applys in general to any Tsunami Warning Center. How well these parameters are defined and applied determines the operational effectiveness of the Center. Three additional critera may be used in providing an evaluation of a Tsunami Warning Center. These are timeliness, dependability, and accuracy.

By timeliness I mean the operational response of a Center from the time of tsunami generation to the time of receipt of information by responsible authorities and by the public. For a detailed analysis, one must examine the time delay from the occurrence of an earthquake to the activation of an alarm system, the time required for a watchstander to respond to the alarm and determine the probability of tsunamigenesis, and the time to disseminate information.

By dependability I mean the actual probability that the Center will be there to function when it's needed. This covers various factors including the operating reliability of all critical instrumentation, emergency power sources, redundancy of methods of communication, and various "people factors" relating to the availability, training, and experience of watchstanders.

By accuracy I mean the accuracy of information disseminated by a Tsunami Warning Center as to earthquake location and size and tsunami detection and evaluation. Ultimately a Tsunami Warning Center is only as good as its credibility, and the issuance of repeated false warnings or erroneous information can significantly affect the response of the public and responsible authorities.

When considered in detail, the above criteria will vary when applied to different regional, national, or Pacific-wide responsibilities. The remainder of this presentation will discuss recent improvements at the Pacific Tsunami Warning Center in the context of the above operational parameters and criteria for evaluation.

Status of Seismic Data Acquisition at PTWC

Since early 1983, the National Weather Service has maintained a dedicated satellite circuit for data exchange between PTWC and the USGS/National Earthquake Information Center (NEIC) in Golden, Colorado. By means of this circuit seismic data from Hawaiian stations are transmitted to NEIC and a network of 14 seismic stations recorded at NEIC are transmitted to PTWC on a continuous basis in real-time. Of these 14 stations, 9 are short-period seismic stations with data transmitted at a rate of 20 samples per second and 5 are long-period seismic stations with data transmitted at a rate of 1 sample per second.

The geographical distribution of the 9 short-period stations reaches from the Eastern United States to the Western Aleutians and provides PTWC with sufficient real-time seismic data to obtain a preliminary location for earthquakes located throughout the Pacific. The accuracy of these preliminary epicenter locations varies from within an average of 30 nautical miles for events in the northern Pacific to an average of approximately 100 nautical miles for events in southern Chile or the far southwestern Pacific. For these areas additional seismic data is required from ITSU participants to determine more precise epicenter locations. Significant operational and communication improvements have occurred with several ITSU seismic observatories for rapidly providing seismic data to PTWC. This remains a continued operational priority.

Staff personnel at PTWC have designed and implemented a new seismic alarm system based on earthquake detection at two mainland seismic stations, French Village (FVM) and Albuquerque (ALQ). This 2-station alarm provides an earlier response by PTWC watchstanders, particularly for earthquakes in Central and South America. For earthquakes in Central America, the alarms now activate within 6 minutes, giving the PTWC watchstander an opportunity to begin locating the epicenter before the first seismic phases have even reached Hawaii stations. For earthquakes in southern Chile, the seismic alarms will now activate within 12 minutes as compared to the previous average of 25-30 minutes. This effort has resulted in a considerable improvement in PTWC's response time for detection of possible tsunamigenic events.

PTWC's seismic alarm system has also been improved by the installation of a radio pager alarm system in addition to the earlier house alarm system. Both watchstanders now carry radio page units with them when on duty to provide more flexibility and an improved reliability in responding to seismic alarms.

Status of Tsunami Data Acquisition at PTWC

One of the most significant recent improvements for PTWC has been the field installation of a number of satellite Data Collection Platforms (DCP's) which are transmitting sea level data via GOES from remote sites. Data from many tide gauges in South America and in the South and Southwestern Pacific are now available to PTWC in near real-time (3-5 minutes). These DCP's are being installed as part of a cooperative program with member countries, Dr. Klaus Wyrtki of the University of Hawaii, and Dr. David Enfield of Oregon State

University. These units provide tsunami data to PTWC and also transmit continuous measurements for mean sea level studies being conducted by Dr. Wyrtki and Dr. Enfield, who are funding all field installation costs and providing many of the DCP's. Efforts are also being made to provide the sea level data to the participating countries in which the DCP's are located.

Status of Tsunami Evaluation at PTWC

Efforts are continuing at PTWC to develop improvements in tsunami evaluation through concentrated studies of designated seismic gap areas and through a detailed area-by-area analysis of historical earthquake/tsunami events.

For seismic gap studies, a dozen locations around the Pacific have been chosen as areas of high potential for the future occurrence of large earthquakes and a high probability of tsunamigenesis. Each of these areas is then studied in great detail to evaluate the operational capability of PTWC to perform if and when such an event should occur. Given a presumed earthquake at a seismic gap location, the travel times of various seismic phases can be contoured graphically to determine probable times of alarm activation, epicenter location, magnitude determination, and the distribution of seismic stations available to provide data to PTWC. Likewise, given a presumed tsunami, the tsunami travel times can be contoured to graphically determine the time in which tide gauge data may be available to PTWC and the distribution of tide gauges from which data may be used for tsunami evaluation. An operational model can then be developed based on the times in which seismic and tsunami data will be available and the times in which appropriate messages will be disseminated. By correlation with the historical earthquake data for that area and historical tide gauge data available for tsunamis generated from that area, operational thresholds can be determined to aid PTWC in the issuance of Tsunami Watches and Warnings.

In conjunction with the seismic gap studies, an operational analysis of available historic earthquake/tsunami data is being conducted on an area-by-area basis around the Pacific. By designating areas which are tectonically homogeneous, the earthquake and tsunami history can be studied to more realistically evaluate the potential tsunami threat from that area. All earthquakes which are associated with tsunamis and all other earthquakes of sufficient magnitude to activate PTWC's alarm system are included for study. These studies then provide the basis for improved application of PTWC's operational procedures for issuance of Tsunami Watches and Warnings as well as the basis for development of improved procedures for a predictive tsunami evaluation capability.

Status of Information Dissemination Capability at PTWC

Several recent improvements in communications have occurred at PTWC, with the Tenth Edition of the Communication Plan for the Tsunami Warning System being published in February 1984. A commercial TELEX circuit has been installed which serves as the primary communication link with the Instituto Hidrografico de la Armada in Valparaiso, Chile. The National Weather Service has also installed a new satellite circuit which provides improved communications to the Trust Territories of the Southwest Pacific.

Computer Automation at PTWC

Recent improvements have been made at PTWC in both computer hardware and software. A second Data General S/230 Eclipse minicomputer has been installed at PTWC to serve as a backup should the primary computer system fail and to provide operational flexibility by using two computers simultaneously. In addition a state-of-the-art microcomputer (IBM-XT compatible) has been received at PTWC to test and evaluate the capability of modern microcomputers to accomplish many of the tasks presently performed by the older generation minicomputer.

A further enhancement at PTWC has been the upgrading of the emergency power generator and Uninterruptible Power Supply (UPS) at PTWC to provide a stable and reliable electrical power source independent of any fluctuation or loss of regular commercial power. The functioning of a computer is directly dependent on the availability of air conditioning to maintain a cool operating temperature and the maintenance of a non-variable power source. In both areas PTWC maintains a nearly 100% operational reliability to ensure full computer operations during any event.

A significant software enhancement for the S/230 minicomputer has been conversion of all operational software to a new operating system, the Advanced Operating System (AOS). This provides a multiuser, multitasking capability so that watchstanders at different computer terminals can be simultaneously performing separate tasks such as sending messages, working up an earthquake, or working up two earthquakes at the same time. Other software improvements have been and are continuing to be made in the PTWC operational computer programs to reflect improved procedures and provide added reliablity of operations. Among these has been the development of online processing of seismic data in real-time. Seismic data from 20 remote stations located in the Hawaiian Islands and across North America are automatically computer processed to determine first-arrival times for epicenter locations.

Summary

With regard to the three evaluation factors mentioned earlier of timeliness, dependability, and accuracy, PTWC has made operational improvements in all areas. The real-time satellite transmission of seismic data from the mainland and the development of the two-station alarm system have greatly improved PTWC's response capability and accuracy of earthquake evaluation. The near real-time acquisition of tide gauge data from remote stations via GOES has significantly improved PTWC's timeliness and accuracy of tsunami detection and evaluation. The installation of a radio alarm system, the installation of a second computer system, and the upgrading of the electrical power capability have enhanced PTWC's dependability of operations. Further improvements are obviously needed, both in PTWC's internal operational capability and in the exchange of information with participants of the Tsunami Warning System of the Pacific.

ACTIVITIES AND RESPONSIBILITIES OF THE HAWAII REGIONAL TSUNAMI WARNING CENTER

Gordon D. Burton, Pacific Tsunami Warning Center

The Hawaii Regional Tsunami Warning Network (HRTWN) is operated by the Pacific Tsunami Warning Center (PTWC) at Ewa Beach, Hawaii. The present HRTWN is an outgrowth of an experimental Hawaii Tsunami Warning Network originally proposed by the Hawaii Institute of Geophysics of the University of Hawaii. The initial instrumentation became operational in early 1970 and now consists of a network of 10 seismic stations and 6 tide stations located throughout the Hawaiian Islands from which real-time seismic and tidal data are continuously transmitted to PTWC.

Hawaii is a volcanic chain of islands formed by the northwestward movement of the Pacific Plate over an underlying Hotspot. The most probable source for earthquake activity is related to the present Hotspot location beneath the Island of Hawaii (the Big Island), or to structural faulting associated with the intersection of the Molokai Fracture Zone and the Hawaiian Ridge. An analysis of the historical tsunami data for Hawaii indicates an infrequent occurrence of destructive tsunamis. The most probable source region for tsunami generation is along the southeast coast of the Big Island, with coastal inundation generally within 2-3 minutes.

As a Regional Tsunami Warning Center, PTWC's operational procedures are aimed at providing the most rapid response possible to notify Hawaii Civil Defense of the occurrence of a major earthquake and the probable generation of a tsunami. Because of this time constraint, the decision to issue a Tsunami Warning is based entirely on seismic data, with a local earthquake magnitude threshold of 6.8 (Ml) established for Hawaii. This threshold was determined as a conservative value based on the historical tsunami data for Hawaii and to provide a margin of accuracy for possible errors involved in rapidly computing the magnitude for a local earthquake.

A rapid response is the single most critical responsibility of a Regional Warning Center, and the risk of issuing a false Warning may be high. Still, the basic decision must be quickly made as to whether coastal evacuation is required or not required. There is no other option to consider with regard to the population in the area of immediate potential impact. The risk of issuing a false Warning is offset in part by the limited population receiving that Warning, but it still remains a major operational problem for a Regional Warning Center. To be most effective, a Regional Warning Center not only needs the seismic data to rapidly issue a Warning, but also the sea level data to rapidly cancel a false Warning, preferably before excessive dislocation of the population has occurred.

PTWC has a commitment to Hawaii Civil Defense to provide tsunami warning services within less than 10 minutes, and has consistently achieved this response time. The most rapid response for an actual event has been 6 minutes, with 4-6 minutes being recognized as the absolute minimal response time that can be achieved. In these circumstances, the role of PTWC as a Regional Warning Center is for all practical purposes one of advising Civil Defense not to evacuate unnecessarily for the more common occurrence of non-tsunamigenic earthquakes and to issue Warnings as rapidly as possible for the infrequent tsunami that does occur.

The operational procedures of the Hawaii Regional Tsunami Warning Center can be developed to address the distinctive tectonics of the Hawaii chain. At the same time, a rapid and dependable response must be provided to Civil Defense. Therefore, optional procedures have been developed at PTWC to serve this purpose. Even though computer automation is available and a network of seismic data from remote stations is recorded in real-time, PTWC can function on a completely manual basis using data from only one station, the 3-component short period seismic data recorded at PTWC. Indeed this was the case for the actual event for which the minimal 6 minute response was achieved. This manual method will be discussed first as it illustrates how a Regional Warning Center can function effectively using a minimal application of high technology instrumentation. Application of computer technology and remote data acquisition will then be discussed.

For the Hawaiian Islands, in all probability, the most distant earthquake will be within 500 km of PTWC. Given this distance, the initial seismic P-phase will arrive at PTWC within approximately 1 minute, with the S-phase arriving less than a minute afterward. Activation of the PTWC seismic alarm, therefore, will occur in less than 2 minutes, with a watchstander responding and being in the office within another 2 minutes. By this time, 4 minutes after origin, all the seismic data needed for determining an initial location and magnitude will be available for analysis. A rapid measurement of the S - P interval will determine the distance of the epicenter from PTWC, with an approximation of direction available from first-motion data. For Hawaii, this is made much easier due to the natural elongation of the Island chain, with the most probable epicenter direction being southeastward of PTWC. The S - P interval, therefore, can be used to determine an approximate initial epicenter location based only on distance and direction from PTWC. An initial magnitude (Ml) determination can be made from the horizontal seismograph components, and a basic decision immediately available as to whether the location and magnitude exceed the threshold established for issuance of a Warning. As stated earlier, this procedure has been used operationally at PTWC to provide tsunami information to Civil Defense within 6 minutes of earthquake origin. The obvious limitation of this technique is that it is effective only over distances of a few hundred kilometers. The above example is used primarily to illustrate that a Regional Tsunami Warning Center capability can be developed on a limited basis using seismic data from only one station, without application of computer technology.

The use of a computer and the availability of a network of real-time seismic data from remote stations obviously improves the operational capability of a Regional Warning Center. For the HRTWN, seismic data from 9 remote sites is telemetered to PTWC using various combinations of VHF or microwave transmission or hardwire telemetry via telephone lines. In addition to the seismic alarm for the PTWC seismometers, a seismic alarm system has been established for two stations on the Big Island to provide the earliest possible detection of an earthquake.

The PTWC minicomputer has been programmed for several applications. Seismic data from all HRTWN stations are automatically processed using a P-Picker algorithm to determine first seismic arrivals at all stations. The sequence of first arrivals at only a few stations may be sufficient to quickly determine epicenter location by geographic sector, rather than using a more complex, and often unreliable, computer algorithm for determining the geographic coordinates of the epicenter. The computer is also programmed for other epicenter location techniques, including various combinations of S - P values, first arrival sequences, arrival time differences between particular sets of stations, and use of epicenter algorithms.

The basic approach in the development of epicenter location techniques for the Hawaii Regional Tsunami Warning Network has been the recognition that only a finite geographic area is involved, and then determining the standard of accuracy required for epicenter location. For Hawaii, it has been determined that any epicenter location within 6 km of the actual epicenter is the maximum accuracy required, with the larger the magnitude of the earthquake, the more acceptable a larger error in location. The geographical area of responsibility can then be subdivided into sectors and optimal techniques developed for presumed earthquakes which might occur in each sector. The computer can then be programmed to automatically select the optimal location technique based on an analysis of station data input.

The determination of earthquake magnitude is a critical parameter upon which is based the ultimate issuance of a Warning. PTWC presently determines surface wave magnitude (Ml) from the 3-station short period seismometer located at PTWC's seismic vault, with horizontal component data recorded at X1000, X100, and X10 magnifications to ensure onscale measurements of deflections. Instrumentation calibrations are conducted weekly. Even with the utmost precaution applied, there still exists an inherent error in accurately determining the magnitude of a local earthquake, particularly when the magnitude is near the threshold value established for the issuance of Warnings. By using this method, unnecessary or false Warnings are occasionally inevitable and constitute an ongoing problem for a Regional Tsunami Warning Center.

The final operational phase is that of information dissemination. For local earthquakes within the Hawaiian Islands, PTWC functions entirely using voice communications over the Hawaii Warning System (HAWAS), a dedicated telephone circuit connecting PTWC simultaneously with all Civil Defense Warning Points and Operating Centers throughout the Islands. Predetermined voice messages can be immediately transmitted to either notify of the occurrence of a local earthquake or to issue an Urgent Tsunami Warning. Civil Defense then has the responsibility to activate the public siren system and to issue public broadcasts over the Emergency Broadcasting System.

A Regional Tsunami Warning Center functions on the concept of threshold determination of an earthquake. If an earthquake exceeds a certain magnitude threshold, a Warning will be issued and standard operating procedures will be set into motion by civil authorities which will be the same regardless of how much the actual earthquake magnitude exceeds the predetermined threshold value. An earthquake of lesser magnitude will be regarded as non-tsunamigenic, even though the earthquake itself may be locally destructive. The decision to be made by the Regional Tsunami Warning Center is a simple "Yes" or "No", but it is an extremely difficult decision to rapidly make on a consistently accurate basis. Ultimately, the effectiveness of a Warning Center is only as good as its credibility.

THE ALASKA TSUNAMI WARNING CENTER'S RESPONSIBILITIES AND ACTIVITIES

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ABSTRACT

The Alaska Tsunami Warning Center was established in 1967 to provide timely tsunami watches and warnings to Alaska for Alaskan tsunamigenic events. Since the initial inception to the present time, many changes have occurred in areas, such as: responsibility, data networks, technique developments, operational procedures, and community preparedness. The watch and warning responsibilities have increased to include the west coasts of Canada and the United States. Seismic and tide data networks have been enlarged to enhance the accuracy of earthquake locations and sizing, and for confirming the existence of a tsunami. New procedures are continually being implemented at the ATWC, using advanced techniques and mini and micro computer systems, for processing data and disseminating information. In addition to advancing the ATWC's operational capabilities, community preparedness efforts continue to aid those individuals who may be caught in the immediate vicinity of a violent earthquake and its subsequent tsunami.

Introduction

The Alaska Regional Tsunami Warning System (ARTWS) was established as the result of the great earthquake occurring in the Prince William Sound area of Alaska on March 27, 1964. This event alerted State and Federal officials to the need for a facility to provide timely and effective earthquake and tsunami information for Alaska and the northern Pacific. The city of Palmer, located 40 miles north of Anchorage, was selected as the site for a primary observatory. Two other observatories, located at Sitka and Adak, were incorporated into the system. An extensive telecommunication and data telemetry network was established in 1967 and the ARTWS became operational. Initially, the tsunami watch and warning responsibility for Alaska was shared by the three observatories. The responsibilities of Adak and Sitka were to issue a tsunami warning if an event were to occur within 300 miles of each location. In later years, the responsibility to provide tsunami warning services for Alaska was transferred from the Adak and Sitka Observatories to the Palmer Observatory. In 1973, the Palmer Observatory was transferred to the National Weather Service's Alaska Region, and subsequently, renamed the Alaska Tsunami Warning Center (ATWC). In 1982, the responsibility for issuing tsunami watches and warnings to the U.S. west coast and Canada, for earthquakes occurring in those areas, was transferred to the ATWC. From the inception of this system to the present time, many operational changes have taken place and are discussed in this paper.

Missions

The primary mission of the ATWC is detecting and locating major earthquakes (events), and if they are potentially tsunamigenic, providing tsunami watches and warnings for Alaska, California, Oregon, Washington, and British Columbia in Canada, for events that occur in those regions. For non-tsunamigenic events, or ones outside of those regions, the event's parameters and other associated information are immediately disseminated to the Pacific Tsunami Warning Center (PTWC), National Earthquake Information Center (NEIC), and other appropriate agencies. This service is provided on a 24 hour basis, for each day of the year, by two duty personnel. During those times that the Center is not manned, the duty personnel are in a paid standby status. To ensure a rapid response to events occurring at night and on weekends, all personnel are required to live and remain within 5 minutes travel time to the Center. They are notified of the occurrence of an event, or irregularities in the Center's operations, by a radio-alarm system that can be activated by eight separate devices.

In addition to performing the primary mission, the ATWC personnel process, archive, and disseminate collected data; participate in fulfilling cooperative agreements; and, conduct advanced technique and equipment developments to improve the present system. The improvements involve both the reactive and predictive areas of the ATWC operational system. The reactive part concerns the reduction of response time between the occurrence of a tsunamigenic event and the issuance of a tsunami warning to people in the affected areas. In particular, this part seeks improvements in procedure modifications, present scientific methods used and development of advanced methods; advanced equipment and instruments; present and new software development and/or modifications; and, personnel performance. The predictive part involves both in-house and cooperative work efforts with other experts and/or agencies concerning areas, such as, tsunamigenic earthquakes and zones, and tsunami formation, propagation, run-up, and interaction with coastal shores.

The ATWC has both formal and informal cooperative agreements with many agencies and institutions. The agreements concern telemetry of seismic and tide data; seismic and tide site installations; cooperative technique and equipment developments; communications; equipment maintenance; and the exchange, reduction, and analysis of data. Some of these agreements involve daily collecting, processing, archiving, and disseminating data and records, to appropriate agencies. Additionally, develocorder data from the ATWC network are archived at the ATWC, and made available to visiting scientists to assist them in their work projects.

Seismic and Tide Networks

The ATWC is a large geophysical data acquisition Center which consists of 5 subnetworks owned and maintained by the ATWC, U.S. Geological Survey at Menlo Park (USGS-MENLO), NEIC, University of Alaska, and PTWC in Hawaii. These networks utilize more than 10,000 terrestrial miles of dedicated circuits to record and monitor approximately 120 analog seismic data traces in one common location at Palmer.

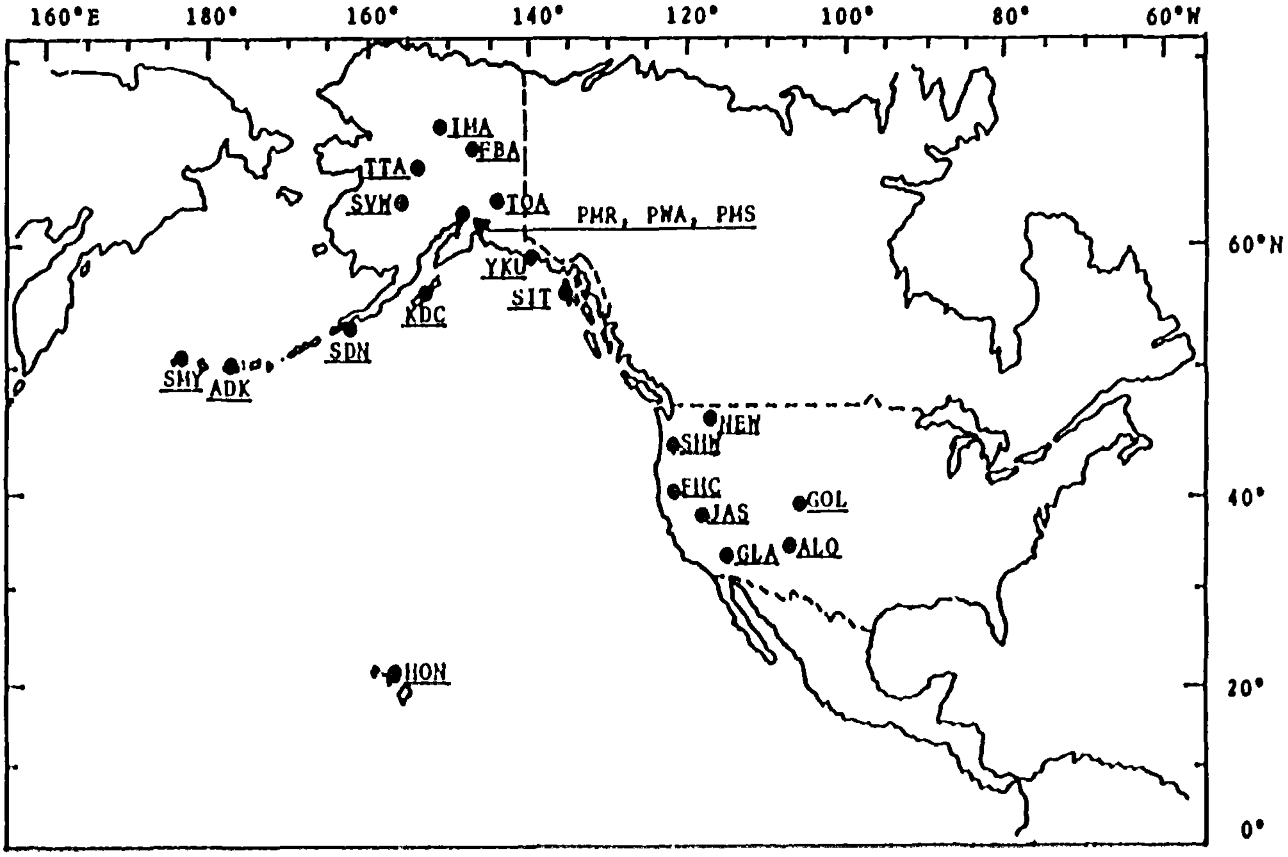

Fig. 1. A map showing seismic site locations in the U.S. that are telemetered to the ATWC in real-time.

The ATWC's seismic network, which extends throughout Alaska, is telemetered by satellite and microwave with very little interruption of data flow from the remote sites. Figure 1 shows the geographical location of the present ATWC network, and some site locations from the NEIC's network in the conterminous U.S. and PTWC's network in Hawaii. Not shown are approximately 80 seismic sites that telemeter data to the Center and belong to the University of Alaska and the USGS-MENLO. The ATWC's sites are visited each year for preventive maintenance, and as soon as possible, after equipment failure.

Tide data are available to the ATWC from subnetworks that are owned and maintained by NOAA's National Ocean Survey (NOS) and Canada. Figure 2 shows tide site locations near the coastal areas of Alaska and the west coasts of Canada and the U.S. Through a cooperative agreement with the NOS, the ATWC has equipment at each of the NOS sites in Alaska for telemetering data to the Center in real-time. Visitations to these sites, by personnel from the NOS and ATWC, are coordinated to minimize cost and maximize aid to each other. Data, from the tide sites near the west coasts of the U.S. and Canada, are not telemetered to the ATWC in real-time, and are obtained via teletypewriter, telephone, and the National Warning System.

All of the seismic and tide data, telemetered to and recorded at the ATWC, are monitored daily to ensure a continuous flow of data for conducting an earthquake/tsunami investigation.

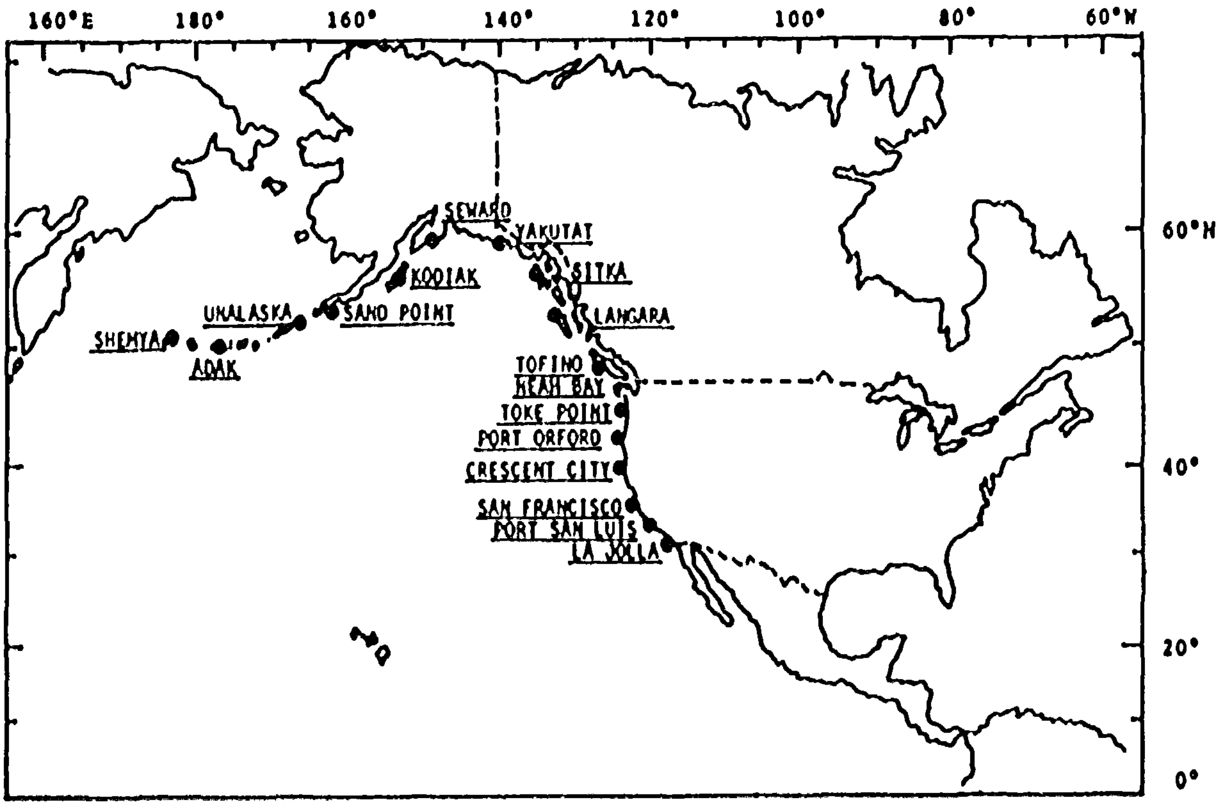

Fig. 2. A map showing the telemetered tide site locations near the coastal areas of Alaska and the west coasts of Canada and the United States.

Radio-Alarm System

The Center's personnel are alerted to large events, or equipment failure, by a radio-alarm system (RAS) which is connected to detectors that monitor incoming seismic data, a telephone system, and an uninterruptible power system (UPS). For events, six detectors continuously monitor both short and long period data from Palmer, Adak, Sand Point, and Sitka in Alaska, and Jamestown in California. The long period detector has its minimum threshold set for an event of magnitude 6.5 at a distance of 80 degrees (8889 km). The short period threshold, for local events, are set for a magnitude 6.0 at a distance of 8 degrees (889 km). Smaller magnitude earthquakes can activate the RAS if an event occurs near a site whose data are being monitored by a detector. Furthermore, the distribution of sites, that are monitored by detectors, permit multiple activations of the RAS for large events, thus ensuring notification that an event has occurred.

The Center's RAS can also be activated by dialing a special telephone number and by the failure of the UPS. Normally, for a commercial power failure, the UPS system and generator are automatically activated which results in no power loss or surges to the equipment. The RAS would be activated if the UPS or generator failed, or the equipment became overheated.

During those times that the station is unmanned, the RAS will activate alarms in the duty personnel's residences, as well as each person's VHF pocket-voice receiver. To ensure this station coverage, the following equipment is used to activate the Center's radio-alarm system: leased telephone lines from the office to each employee's residence; commercial automatic phone answering and recording devices; VHF transmitter with high gain omni-directional antennae; and, VHF pocket-voice receivers. For an event or equipment failure, the RAS will cause the telephone to ring continuously via the office switchboard/leased telephone lines , and simultaneously a continuous high pitched signal is emitted by the VHF pocket-voice receivers. When the unlisted number is dialed, the RAS will ring the telephone bell and a device answers and records the message(s). The caller's message is transmitted by the RAS to the VHF pocket-voice receivers, thus permitting the duty personnel to listen to the caller. This provides them with immediate knowledge of the caller and the urgency of the situation.

This system, which has been evolutionary over the years, provides total coverage even when the duty personnel are between the Center and their residences. The VHF system functions as both a primary alarm system and as an excellent backup to the leased line telephone system.

Earthquake/Tsunami Investigations

Events that activate the ATWC's RAS necessarily initiate an earthquake/tsunami investigation (ET) which includes locating and sizing the event, and culminates in processing the event routinely or in the issuance of a watch/warning (WW). During the past 17 years, the ATWC's personnel have conducted an average of 12.3 ET's per month. Figure 3 shows a block diagram of an ET when the office is not manned, e.g. at night.

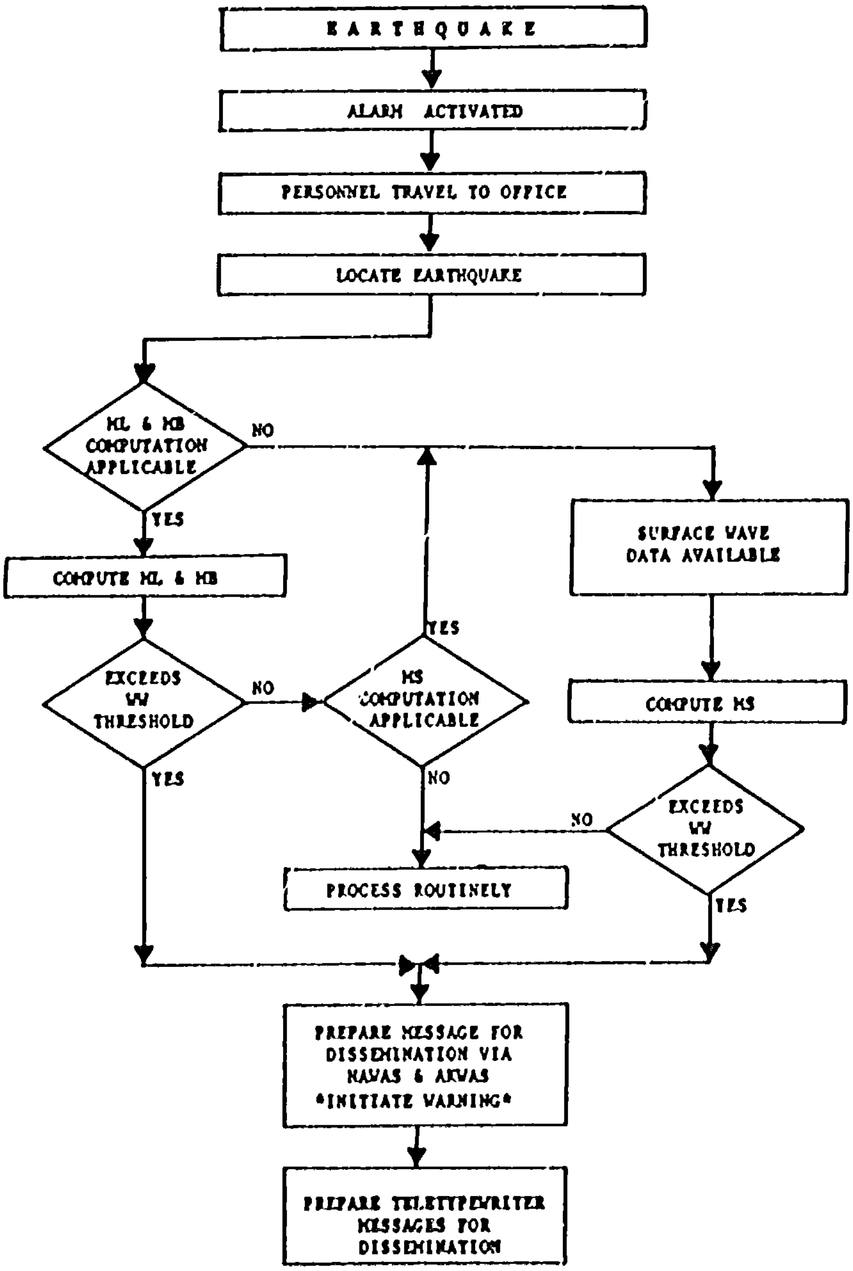

Fig. 3. A block diagram showing the procedural steps in conducting an earthquake/tsunami investigation.

An event's location and size are always the first actions to be taken for any ET which dictates whether the event will be processed in a routine manner or as a WW. Unfortunately, there is no single device, site, or method that would accurately, consistently, and rapidly size any local, regional, or teleseismic event. Therefore, as shown in the ET diagram, several accepted and appropriate magnitude determining methods are used to complete an ET. Event size determinations have been, and are being developed to enhance procedural responses in this area (Sindorf, 1972, 1974).

Appropriate tsunami and/or earthquake information which results from an ET are immediately provided to: Alaska Division of Emergency Services; Alaska Air Command; NEIC; PTWC; USGS-MENLO; Japan Meteorological Agency, Tokyo; USGS Observatory, Guam; Royal Observatory, Hong Kong; news media; and to many other recipients including both State and Federal disaster preparedness agencies and military bases, and appropriate agencies in Canada.

A WW is issued by the ATWC when the magnitude of an event has exceeded a predetermined magnitude threshold, and the event's location is near a coastal area, from Kamchatka through southern California. The threshold magnitude for issuing a WW to Alaska, for events in Alaska, is 6.75. The threshold for events near Kamchatka or near the west coasts of the U.S. and British Columbia is 7.5. When an event's magnitude has exceeded an area's threshold, a limited geographical area is placed in a warning status. Other geographical areas, outside the warned area, are placed in a watch status. A warned area includes those places that are within about 3 hours of water wave travel time from the epicenter.

After the initiation of a WW, tide site's data that are nearest the epicenter are monitored for the existence of a tsunami. Upon confirmation that a tsunami has been generated, the previously designated watch areas are upgraded to a warning, and the information is communicated to the recipients. Event's that are smaller than threshold, and important to Alaska, are processed on a routine basis and the information disseminated to appropriate officials.

The main methods for disseminating emergency and routine information (U.S. Department of Commerce, 1984) are by the National Warning System (NAWAS), Alaska Warning System (AKWAS), commercial telephones, Alaska Division of Emergency Services, VHF radio system, Federal and Military teletypewriter systems, VHF Weather Radio, HF Marine Weather Radio, Emergency Broadcast System (EBS) through the National Weather Service, and EBS and HF via the Coast Guard. The NAWAS, a voice disseminating system, is the primary one used to alert disaster officials in the U.S. and Canada of large events. The AKWAS, which is the State side of NAWAS, permits immediate voice communication with Alaska disaster officials. A teletypewriter system is a secondary means of disseminating the information which immediately follows the voice communicated messages.

Community Preparedness

The ability of any warning system to successfully save lives and reduce property damage depends upon getting the information to the public and getting them to respond to the emergency. The ATWC cooperates with the Alaska Department of Emergency Services and many other hazard officials on the west coasts of the U.S. and Canada and the far western Aleutian Is. to maximize the effectiveness of the community preparedness efforts. The main purpose of this program is to educate the public to help themselves if they are caught in the middle of a violent earthquake and/or tsunami. Additionally, the program involves the gathering of information concerning each community's preparedness procedures and their potential tsunami hazard (Carte, 1984). To each community, the program presents a detailed briefing of the TWS, seismicity of their area, past historical earthquake/tsunami damage, and estimates of what might happen if an earthquake/tsunami were to occur. The presentations use slides, movies, brochures, and other materials concerning the effects of earthquakes and tsunamis.

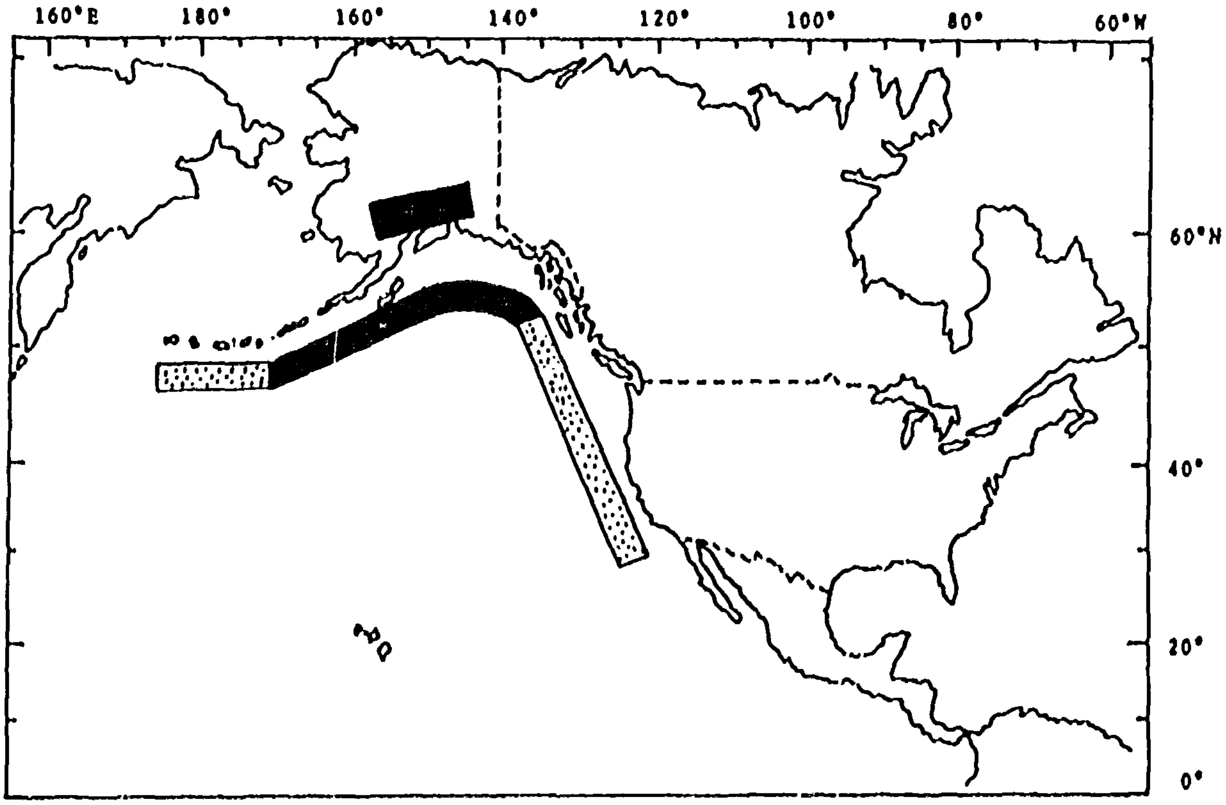

Fig. 4. A map showing areas involved in the ATWC's community preparedness efforts. Darkened areas are visited by the ATWC personnel. Stippled areas are ones where the ATWC personnel cooperate with hazard officials in those coastal areas.

All professional staff members are involved in the preparedness program which includes visits to distant out-lying coastal communities from Ketchikan to Dutch Harbor and to coastal and other local group facilities and schools that are within commuting distance of the ATWC. Also, presentations are given to hazard officials who are responsible for the far western Aleutian Is. and the west coasts of the U.S. and Canada. These areas are shown in Figure 4. In addition to the outside presentations, the ATWC facilities are opened to the public each Friday from 1 to 3 in the afternoon for local and other visitors.

The darkened areas in Figure 4 are ones that are visited by the ATWC personnel, either yearly or biennially, depending upon available resources. Frequent visitations are made to those areas that are within reasonable driving distance from the Center. Visitations to out-lying communities are made in alternating years. Groups, such as schools, are encouraged to video tape the ATWC presentations for later use. The stippled areas are ones where the ATWC cooperates with and/or assists hazard officials who are responsible for community preparedness in those areas.

ATWC Micro Computer Developments

The ATWC is continually improving its operations as a result of advancements in equipment and technique developments. In the last two years, the ATWC has integrated an automatic earthquake processing system (Sokolowski et al., 1983) into the operational procedures. An advancement of this system initiative has been introduced by the ATWC, and involves the use of several micro computer systems.

During the past year, the ATWC has conducted a feasibility study to determine the potential for integrating micro computers into the operations of the ATWC. This study has shown that the interactive processes of locating earthquakes, generating messages, and processing routine day-to-day tasks can be done by a micro computer. The test micro can interactively accept data from 32 seismic sites to rapidly compute an event's parameters. It can also produce computer generated messages for dissemination via the NAWAS and teletypewriter systems.

As a result of this feasibility study, the ATWC has introduced a micro computer system concept to integrate a distributed network of micro computers into the ATWC operations. Figure 5 shows a block diagram of the micro system. This concept envisions three micro systems (Sokolowski, 1985) that are physically distributed in the Center to maximize aid for the personnel, thus minimizing the response time between the occurrence of an event and the dissemination of critical information to the TWS recipients. The concept is evolutionary in that future tasks and additional micro systems can be integrated into the ATWC operations to enhance both the reactive and predictive parts of the operation. The micro systems are intended to communicate with each other, or function independently, to perform the operational tasks. This concept includes concurrent real-time and interactive processing in addition to obtaining and processing tide data in near real-time.

The first micro (Micro1) will be dedicated to detecting events and storing their associated data, and automatically computing the event's parameters. The seismic data will be selected from the network of sites that are available to the ATWC. The incoming data will be digitized, analyzed and processed in a similar manner to the existing mini computer system (Sokolowski et al., 1983). Appropriate data, stored by the Micro1 processes, would be made available to Micro2 and Micro3 for concurrent interactive processing.

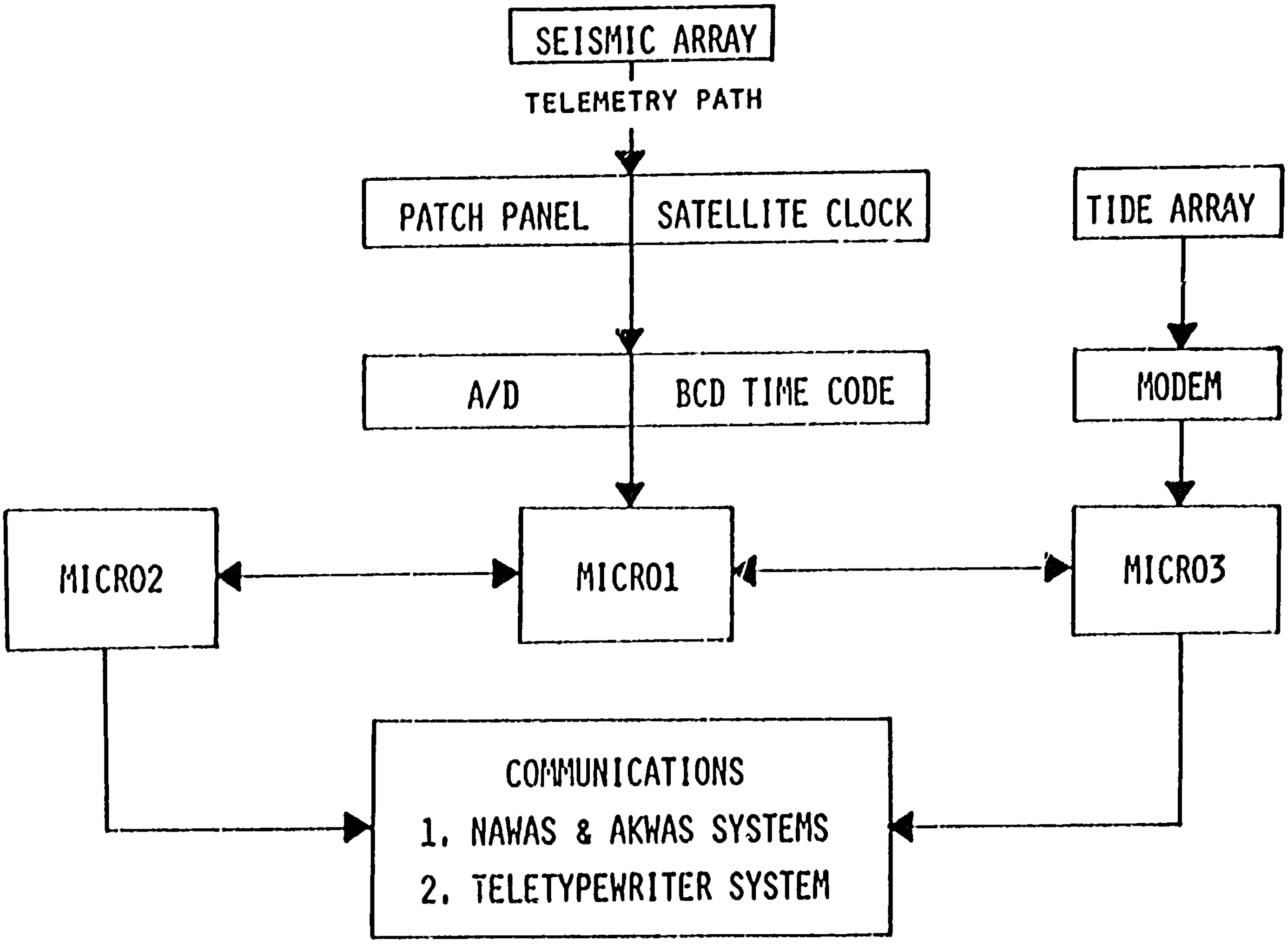

Fig. 5. A block diagram showing a distributed system of micro computer systems.

Micro2 would be used to interactively compute an event's parameters using data that are passed to it from Micro1, or manually read from the ATWC's helicorders and/or develocorders. The amount of interactive data, collected for processing, are dependent upon the event's size and location which normally dictate procedural expediency. This micro will also be used to interactively generate the messages for disseminating earthquake/tsunami information.

Micro3 will be used for processing tide data from sites that do not telemeter data to the ATWC in real-time. The first efforts will be to obtain data, in near real-time, from the west coast tide sites for analysis and processing at the ATWC. This will considerably enhance the ATWC's present procedures for obtaining tsunami confirmation from tide sites along the west coast. This micro will also be used for concurrent earthquake processing and message dissemination. Depending upon the ability of Micro1 to perform real-time processes, Micro3 could also serve as an aid to the Micro1 system in this area.

Conclusion

The ATWC continues to improve both the reactive and predictive areas of its operations to enhance the timeliness, quality, and quantity of data and information that are disseminated to the TWS recipients. The reactive area continues to examine and enhance the response time between the occurrence of an earthquake and the initial dissemination of critical warning information with regard to: procedure modifications; present scientific methods used, plus development of new methods and procedures; additional equipment requirements; present and new software development and/or modifications; and, personnel performance. In-house and cooperative work efforts with other agencies and individuals, continue to address the predictive areas. This concerns problems related to tsunamigenic earthquakes and zones, and tsunami formation, propagation, run-up, and interaction with coastal shores. The integration of micro computer systems into the operations provides considerable future potential for enhancing both the reactive and predictive areas, and thus the services to the TWS recipients. Getting the public to respond to disseminated earthquake/tsunami information is a vital part of the ATWC efforts and necessitates an educational community preparedness program. This program covers selected areas in large geographical areas, and in cooperation with other agencies and hazard officials.

Acknowledgments

The author expresses his appreciation to Mr. Stuart G. Bigler, Alaska Regional Director, and his staff for their valued comments and constructive criticism of this paper.

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JAPAN TSUNAMI WARNING CENTER

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Tsunami Warning Service in Japan

The Japan Meteorological Agency (JMA) is responsible for Tsunami Warning Service in Japan. In order to promote seismology/volcanology-related services including tsunami, the Seismological and Volcanological Department was established in JMA on July 1, 1984. The department is composed of three divisions: the Seismological and Volcanological Management Division; the Earthquake and Tsunami Observations Division; the Earthquake Prediction Information Division.

Tsunami warnings and advisories are handled by the Earthquake and Tsunami Observations (ETO) Division in the department. Because of localized nature of earthquakes and tsunamis, the Japanese Islands are divided into six regions to be covered by local centers located in six key cities - Sapporo, Sendai, Tokyo, Osaka, Fukuoka, and Naha. These local centers are deployed in the District Meteorological Observatories under JMA.

Individual local centers issue warnings and advisories for tsunamis generated by earthquakes in the responsible sea areas, within 600 km from the designated stretch of coastline. For the areas outside of the 600-km zone, the ETO Division, serving both as the local center for the Tokyo region and as the national center, assumes responsibility, relaying much on the information from PTWC at Honolulu.

Present Status of Tsunami Warning Operation

JMA has, at its Tokyo Headquarters, a computerized meteorological telecommunications computer system called ADESS (Automated Data Editing and Switching System). A smaller version of ADESS, called local ADESS, or L-ADESS, has been installed at each of the above-mentioned local centers except Naha over the past five years. Other than meteorological data, L-ADESSes collect and process seismological data. Digitized seismometer signals from ten to twenty selected stations are continuously fed to each L-ADESS and the signals exceeding a threshold value activates a disk drive, pen recorders and a buzzer.

From the pen recorders' traces the alerted duty officer enters P, S times and amplitudes of seismic wave into the computer by using an X-Y digitizer. The computer determines, through dialogue with the duty officer, the location and magnitude of the earthquake, the possibility of tsunami occurrence, the level of tsunami warning, and then produces wording of warning and/or advisory. At a touch of a button the warning messages are automatically transmitted to concerned field offices under JMA, relevant governmental bodies concerned with disaster mitigation, and the media including TV stations.

Manual processing of data for tsunami warning issuance used to take about 20 minutes based on teletype messages sent in from field offices. Introduction of L-ADESSes shortened the time for processing by a few minutes. In the case of the Japan Sea Earthquake (magnitude 7.7) of May 1983, it took 13 to 14 minutes to issue the warning from the registering of the shocks. Though it was the shortest the present system could do, the first waves of tsunami reached the coast nearest the source region in less than ten minutes and claimed many lives. This tragedy emphasized the need for cutting more minutes from the operating time.

Development of a New Computer System

JMA is responsible for monitoring of earthquakes with magnitude 3 or above occurring in and near the Japanese Islands.

To meet the requirement efficiently, JMA is going to set up a new computer system, through which seismological signals telemetered from selected stations will continuously be sampled, seismic wave phases will automatically be identified by use of the AR (Auto-Regressive) Models, and the epicenter location, focal depth and magnitude will also be determined automatically. Planned to be completed by March 1987, this system will shorten significantly the time for issuing tsunami warnings. It is hoped to accommodate in the tsunami prediction model such parameters as the fault and source mechanisms, topography of sea floor, configuration of coastline for better results.

Permanent Ocean Bottom Seismograph (POBS) System Off the Southeastern Coast of the Boso Peninsula

One POBS system has successfully been operating since 1978 off the south coast of the Tokai District, with 4 seismographs on a string of cable 110-km long from the coast to its southern end. This system includes a tsunami sensor - a quartz crystal pressure gage - - at the end of the cable, at depth of 2,200 m. The result of analyses of the pelagic tide indicates that this tsunami sensor has been functioning satisfactorily. Now JMA is going to lay another POBS system (see Figure 1) extending to about 100 km southeastwards from the coast of the Boso Peninsula. The submarine equipment will comprise one terminal apparatus (4,000-m depth) and three intermediate apparatus, each with seismographs and a tsunami sensor. The tsunami sensor is nearly identical to the above-mentioned.. The new system will also be linked to the Tokyo Headquarters through the telemetering. The laying of submarine cable and apparatus is scheduled to begin in August 1985.

Tsunamis from the Chilean Earthquake of March 3, 1985

Tsunami waves caused by the earthquake (magnitude 7.7 of March 3, 1985 near the coast of central Chile were recorded on the tide gages of throughout the Pacific coast of the Japanese Islands. The first waves of the tsunami reached Hokkaido and Northeastern Honshu about 23 hours after the shock. Some of the maximum wave heights are: 17 cm at Chichijima; 15 cm at Nemuro and Onahama; 13 cm at Owase; and 12 cm at Hachinohe (Figure 2). On the basis of teletyped message from PTWC at Honolulu, a tsunami advisory "TSUNAMI ATTENTION" had been issued two hours in advance. This advisory is for maximum wave height of less than several tens centimeters. Increasing public awareness of tsunami hazards demands detailed care in execution of information dissemination on the part of JMA.

USSR NATIONAL TSUNAMI WARNING SERVICE

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Oceanographic Committee of USSR

No substantial changes have occurred recently in the National Tsunami Warning Service of USSR.

Three local warning centers, situated in Petropavlovsk-Kamtchatskii, Uzhno-Sakhalinsk and Vladivostok, are responsible for tsunami warnings in the Far-Eastern coast of the USSR. Seismic recordings, determination of earthquake epicenter coordinates and magnitudes are made by three seismic stations involved in the operational tsunami warning service. These are Petropavlovsk-Kamtchatskii, Uzhno-Sakhalinsk and Kourilsk. Plans are being implemented to use seismic stations at Severo-Kourilsk and Vladivostok resulting in the improvement of the tsunami warning service for some areas of the Soviet Far East. Improvements are also expected in the determination of seismic parameters of potentially tsunamigenic earthquakes. Present seismic stations in the National Tsunami Warning Service are all equipped with long-period seismographs, and with appropriate devices for data processing and interphasing with communication circuits.

The following sea level measuring stations have been added in the Pacific Ocean and in the Seas of Okhotsk and Japan: Petropavlovsk-Kamtchatskii, Oust-Kamtchatsk, Bering Island, Severo-Kourilsk, Matya Island, Ouroup Island, Kourilsk, Uzhno-Kourilsk, and Nakhodka.

To check on the reliability of operational communications and in the development of effective operational procedures, periodic training exercises and test alarms have been held in the tsunami risk zone of the Far-Eastern coast of USSR.

Improvements to the National Tsunami Warning Service: A number of improvements have been accomplished. Applied research activities have continued to contribute towards the improved efficiency of the operational Tsunami Warning Service. Standard Operating plans have been developed to provide the population and organizations of the coastal regions of the Far East with prompt tsunami warnings. Work continues in upgrading equipment, and developments have been undertaken to automate all components of the Tsunami Warning Service. The operational use of deep water level recorders is being investigated.

Tsunami Events: There was no major tsunami events observed along the coast of USSR during the 1984-1985 period. The most notable tsunami was that caused by the earthquake on March 3, 1985 in Chile. USSR participated actively in the data exchange resulting from this event.

Tsunami Research Activities in USSR: Tsunami research in the USSR is directed both at the comprehensive analysis of the tsunami phenomena and at the development of tsunami protective measures for the preservation of life and property. Approximately a hundred specialists from a dozen institutes participate in these activities. The following is a summary of some of the research findings of the last few years:

Further development of tsunami generation theory confirms that tsunami wave generation occurs only in cases where a displacement of the basin bed takes place for a long period and if it exceeds the wave periods. Seismotectonic thrust movements long a seismic faults in the earthquake epicentral area are equal, upthrust and thrust, giving rise to a tsunami of uniform intensity. A thrust along a seismic fault produces a tsunami with a well defined orientationn and direction of propagation.

Efforts continue in deriving new differential equations for describing tsunami waves taking into account dispersion effects and wave non-linearity. Numerical methods for tsunami modelling have been improved. The calculation of the 1964 Alaska tsunami propagation from the generating area to the coast of the USSR has been completed.

Great emphasis has been placed on tsunami behavior on the shelf, in bays and straits, and on tsunami runup studies. Accurate analytical tsunami solutions for one- and two-dimensional cases have been obtained. Tsunami wave attenuation has been quantitatively related to wave intensity. A few schemes have been proposed for numerical calculation of tsunami runup over the shore in one- and two-dimentional cases. The scheme comparison showed that the available values of wave splash up and flow velocities differ within 20%.

Tsunami effects on engineering structures have been investigated by means of theoretical and hydraulic modelling. Damaging effects of erosion of important structures such as marine oil and gas platforms, caused by tsunami action, have been investigated with such models.

Tsunami mapping of the USSR coast has been continued on the basis of a two parameter model (mean tsunami frequency on the 200 mts isobath and local coefficient of wave intensification). A "key-actuated" model has been developed relating tsunami generation in the subduction zones of lithospheric plates.

Computer programs have been developed for processing in real-time seismic signals of major earthquakes at stations of the Tsunami Warning Service and for automated determination of the earthquake epicentres.

A minor Iturup tsunami was recorded near Shikotan island by means of an experimental cable tide gauge on March 24, 1984 (the second tsunami recorded by this tide gauge).

Experimental devices have been tested for recording tsunamis occurring in deep water by means of a ground buoy complex with operational data telemetry to shore, via radio.

IV - NEED FOR AND STRUCTURE OF FUTURE REGIONAL TSUNAMI WARNING CENTERS

NEED FOR AND STRUCTURE OF FUTURE REGIONAL TSUNAMI WARNING CENTERS

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Canadian Hydrographic Service

ABSTRACT

In the northern area of the Pacific, tsunamis can be verified for appropriate watch and warning action in less than 20 minutes. This results in the saving of life and property within the immediate source area of the tsunamigenic event and also provides the data needed to assess if a Pacific-wide tsunami will be generated.

Present operating limitations of the existing four national and/or regional warning centers prevent giving equivalent services to all countries within the southern Pacific.

Maintaining a proper network of reporting stations for seismic and tidal data, establishing real-time communication facilities, employing existing technologies and operating three stratigically located Regional Warning Centers will provide the information needed to issue warnings in less than 20 minutes.

The South Pacific Tsunami Warning Centers should be modelled similar to those in existence in the United States of America, the U.S.S.R. and Japan. It is suggested that new warning centers should also have the capabilities in disseminating and promulgating, within the area of responsibility, all tidal and seismic data as well as providing international data centers with the required information.

In addition, the communication channels of Tsunami Warning Centers could be utilized for the warning of dangerous water level changes caused by other meteorological events.

INTRODUCTION

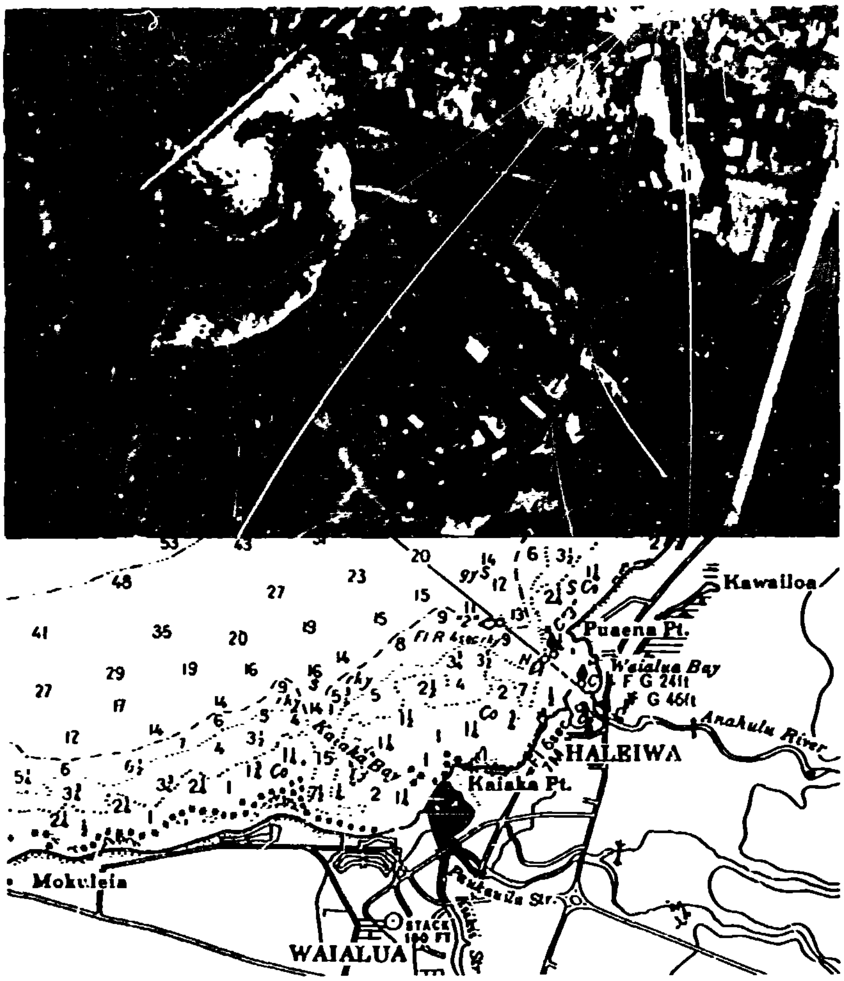
Over the past two decades all the coastal areas in the Pacific experienced a rapid growth in population and industrial and harbour facilities. A firm estimate is not available of the number of potentially endangered persons in each country bordering the Pacific, however many miles of coastline are exposed to tsunamis in North America, the east coast of Asia, the Pacific Islands, and South and Central America.

At least seven near-shore seismic events causing tsunamis, having occurred in the last ten years, resulting in loss of life and property (29 November 1975, Hawaii, 2 lives lost; 17 August 1976, Philippines, 8,000 lives lost; 19 August 1977, Indonesia, 189 lives lost; 18 July 1979, Indonesia, 540 lives lost; 12 September 1979, New Guinea, 100 lives lost; 12 December 1979, Colombia, an estimated 500 lives lost; and 26 May 1983, Sea of Japan, approximately 100 lives lost). Tsunami Warning Centers were unable to provide tsunami warnings to these areas in time to be useful. Losses such as these from future tsunamis can be minimized if a denser network of warning centers, reporting stations and better communications existed, and if better programmes of tsunami preparedness and education were in effect.

Tsunamis always produce a threat close by, but not always one far afield. Only if the energy produced is sufficiently great, will the resulting wave cross the open ocean as a very long and low amplitude wave, reappearing depending on the coastal bathymetry as a highly destructive wave thousand of miles away from its source.

The most destructive Pacific-wide tsunami of recent history was generated along the coast of Chile on May 22, 1960. No accurate assessment of the damage and deaths attributable to this tsunami along the coast of Chile can be given; however, all coastal towns between the 36th and 44th parallels either were destroyed or heavily damaged by the action of the waves and the quake. The combined tsunami

Present techniques of tsunami prediction are severely limited. The only way to determine, with certainty, if an earthquake is accompanied by a tsunami, is to note the occurrence and epicenter of the earthquake and then detect the arrival of the tsunami at a network of tide stations. While it *is* possible to predict when a tsunami will arrive at coastal locations, it is *not* yet possible to predict the wave height, number of waves, duration of hazard, or the forces to be expected from such waves at specific locations.



THE NOVEMBER 1952 TSUNAMI ON THE NORTH SHORE OF OAHU, HAWAII

During the last few years, new operational concepts have been developed for warning systems utilizing updated technology and instrumentation. The objective of these new operational systems are to reduce the time needed to evaluate the tsunami hazard, make decisions, and disseminate the warnings, on a Pacific-wide or on a regionalized basis. These new systems can and earthquake toll included 2,000 killed, 3,000 injured, 2,000,000 homeless and $550 million damage. Off Corral, the waves were estimated to be 20.4 meters (67 feet) high. The tsunami caused 61 deaths in Hawaii, 20 in the Philippines, and 100 or more in Japan. Estimated damages were $50 million in Japan, $24 million in Hawaii and several millions along the west coast of the United States and Canada. Wave heights varied from slight oscillations in some areas to ranges of 12.2 meters (40 feet) at Pitcairn Island; 10.7 meters (35 feet) at Hilo, Hawaii; and 6.1 meters (20 feet) at various places in Japan.

Destruction from tsunamis is the direct result of three factors: inundation, wave impact on structures, and erosion. Strong tsunami-induced currents have led to the erosion of foundations, the collapse of bridges and seawalls. Flotation and drag forces have moved houses and overturned railroad cars. Tsunami-associated wave forces have demolished frame buildings and other structures. Considerable damage also is caused by the resultant floating debris, including boats and cars which become dangerous projectiles crashing into buildings, piers, or other vehicles. Ships and port facilities have been damaged by surge action, caused even by weak tsunamis. Fires resulting from oil spills or combustion from damaged ships in port, or from ruptured coastal oil storage and refinery facilities, can cause damage greater than that inflicted directly by the tsunami. Other secondary damage can result from sewage and chemical pollution following destruction. Damage of intake, discharge, and storage facilities also can present dangerous problems. Of increasing concern is the potential effect of tsunami drawdown when receding waters uncover cooling water intakes associated with nuclear power plants.

More people are attracted to the sea shores for their livelihood and for recreational and other purposes. The damage caused by a tsunami now or in the future will be much greater than in the past, if existing technology is not utilized in providing the most effective and efficient warning system for those living along the shores of the Pacific.

use shore and off-shore based seismic and tsunami sensors transmitting data in real time, to the Pacific Tsunami Warning Center and/or to Regional Warning Centers throughout the Pacific making use of synchronous meteorological satellites for communication relay. The systems can also make use of conventional communication facilities and reduce the time necessary to communicate tide and seismic information, as well as to transmit warning messages. Utilizing such technology, the operational response of the Pacific Tsunami Warning Center and that of the Regional Tsunami Warning Centers could be greatly enhanced for the protection of life and property.

PRESENT TSUNAMI WARNING CENTERS

The Pacific Tsunami Warning Center:

In 1948 the Seismic Sea-Wave Warning System was put into operation at the Seismological Observatory near Honolulu. The Intergovernmental Oceanographic Commission (IOC) approved in 1966 the offer made by the United States of America to strengthen these facilities by establishing on a permanent basis the International Tsunami Information Center (ITIC). At the same time, the IOC established the International Coordination Group for the Tsunami Warning System in the Pacific (ITSU).

On the recommendations by this Group, the facilities at Honolulu have been identified as the Pacific Tsunami Warning Center (PTWC). Its main responsibility is to issue warnings to all participants having designated appropriate civil defense organizations within sixty minutes of a tsunamigenic earthquake.

Appropriate communications and computer facilities as well as trained staff are available on a 24-hour basis to carry out this task at the Center.

The Communications Plan of the Tsunami Warning System, Ninth Edition, September 1980, prepared by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Weather Service, gives information on the gauging and seismic stations in operation, the participating agencies, the procedures to be followed in the event of a Tsunami and other information of importance and interest.

The Present Warning Process:

The tsunami watch process is triggered by seismic signals received in almost real time at Honolulu from selected seismic stations, seismic observatories and Regional or National Warning Centers.

Tsunamigenic earthquakes occurring in the region of the North Pacific can be verified presently at the Pacific Tsunami Warning Center in Honolulu within 20 minutes. During this time frame all participating nations in the area are advised that a possible tsunami threat exists. However, the confirmation of the actual tsunami can only come from properly located and instrumented water level recorders. Within the North Pacific area several water level gauges have good communication links with Honolulu or other warning centers. Confirmation of a dangerous tsunami within 20 minutes is therefore only possible where these facilities exist and are being maintained for this purpose.

Present operating limitations prevent actual warnings to be disseminated in less than one hour to most countries within the Southwest Pacific and along the South American coast. However, given the technology, warning center distribution and communication facilities as available for the North Pacific, warnings to the population within the equatorial area and the Southern part of the Pacific could be activated also in less than one hour.

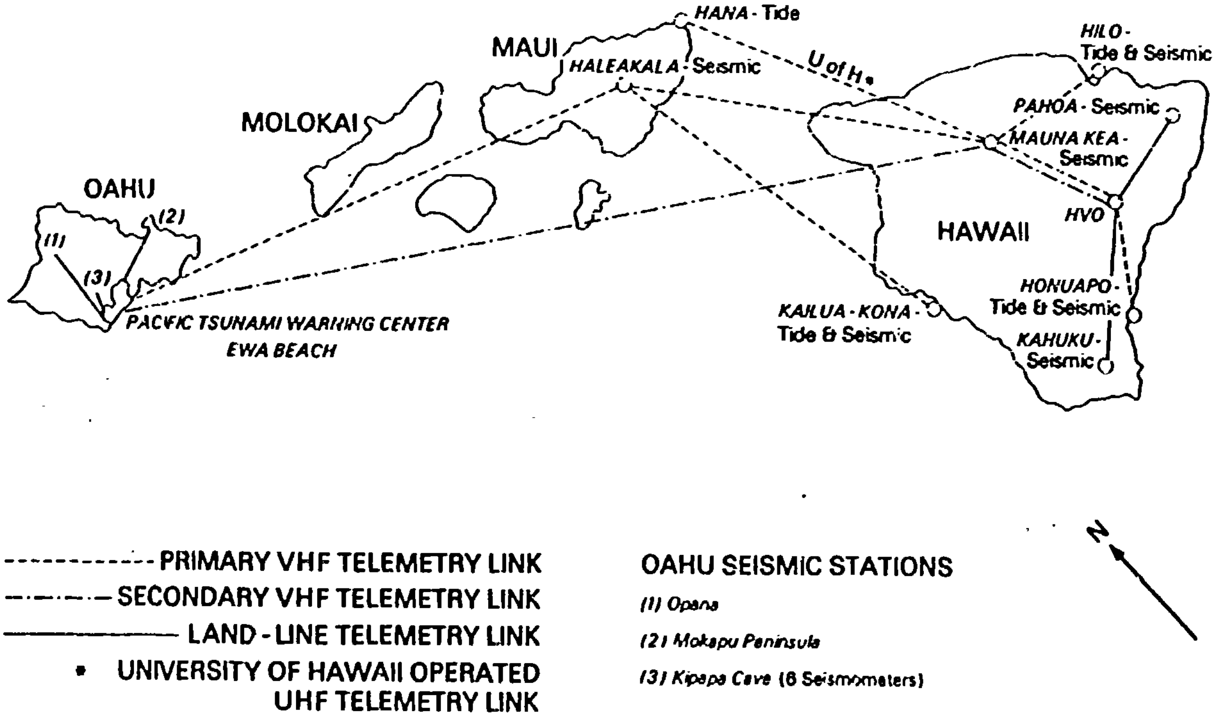
THE PACIFIC TSUNAMI WARNING CENTER

Regional or national warning centers are in existence within the United States of America, the Union of Soviet Socialist Republics and Japan. The Centers are located at Honolulu and Palmer (U.S.A.), Petropavlovsk-on-Kamchatka, Kurilskiye and Sakhalinsk (U.S.S.R.), Sapporo, Sendai, Tokyo, Osaka, Fukuoka and Naha (Japan).

The Hawaii Regional Warning Center

The Hawaii regional system entered into service in 1975 providing warnings for locally generated tsunamis for the people of Hawaii. When an earthquake of magnitude 7.5 or greater occurs in the Hawaiian region, the Pacific Tsunami Warning Center issues warnings to the threatened coastal areas of Hawaii through the Hawaiian Civil Defense and other designated agencies.

Telemetered data from a quadripartite seismograph and tide gauge system located on Oahu, Maui and Hawaii provides the essential data needed to make decisions on the issuance of warnings utilizing computer technologies.

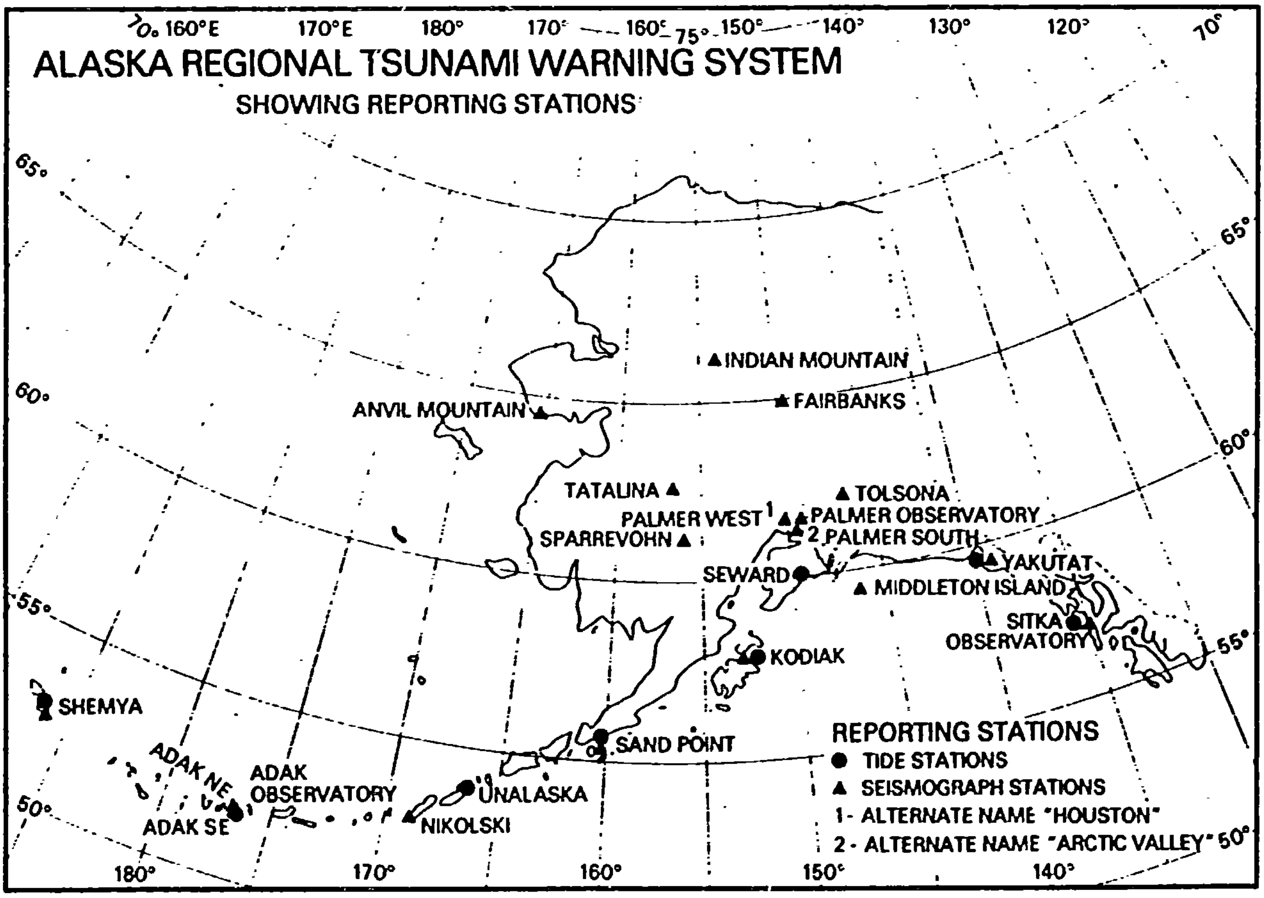


THE HAWAII REGIONAL TSUNAMI WARNING CENTER

The Alaska Regional Warning Center

This regional system has been operational since 1967 and represents a collection of sophisticated equipment and techniques available to seismologists and oceanographers. The Center at Palmer Observatory, north of Anchorage, is highly automated and linked to telemetering tide and seismograph stations from Sitka to Shemya. There are good communication links to Civil Defense units and emergency measures organizations within the area of jurisdiction.

Whenever a major earthquake of magnitude seven or greater occurs along the Pacific coast of Alaska, a tsunami watch is issued to the Alaskan, Canadian and Mainland U.S. Pacific coastal population through the appropriate Civil Defense authorities.



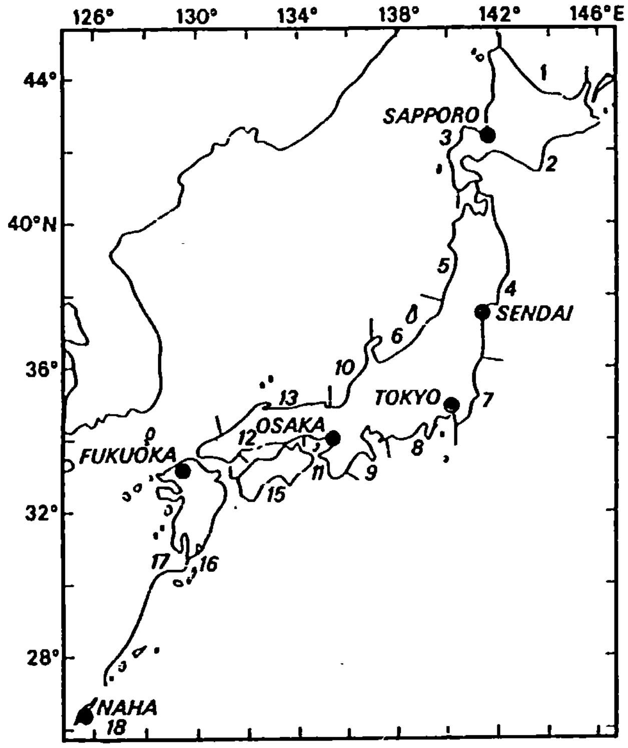
THE ALASKA REGIONAL WARNING CENTER

The Japanese Tsunami Warning Centers

The Tsunami Warning Service for Japan was established in 1952. Many seismic recorders and water level gauges are being used in the determination of tsunamigenic events. The Service employs up-to-date telemetry systems in order to obtain the information in almost real time. The Japan Meteorological Agency (J.M.A.) maintains six regional tsunami centers and designated Tokyo as the national center for Japan.

If a tsunami is generated within a 600 km radius of the coast of Japan, all centers will issue warnings through designated channels.

For tsunamigenic earthquakes outside this radius, the National Center will establish contact with the Pacific Tsunami Warning Center and will advise its Civil Defense agencies and others accordingly. In addition, tsunami-related information is exchanged with Khabarovsk, Palmer and Washington through an automated switching system.



Showing the assigned areas of the respective Tsunami Centers.

Centre	Coast
SAPPORO	1, 2, 3
SENDAI	4, 5
TOKYO	6, 7, 8, 9, 10
OSAKA	11, 12, 13, 14, 15
FUKUOKA	16, 17
NAHA	18

Closed circles show the Regional Tsunami Centers and a double circle shows the National Tsunami Center.

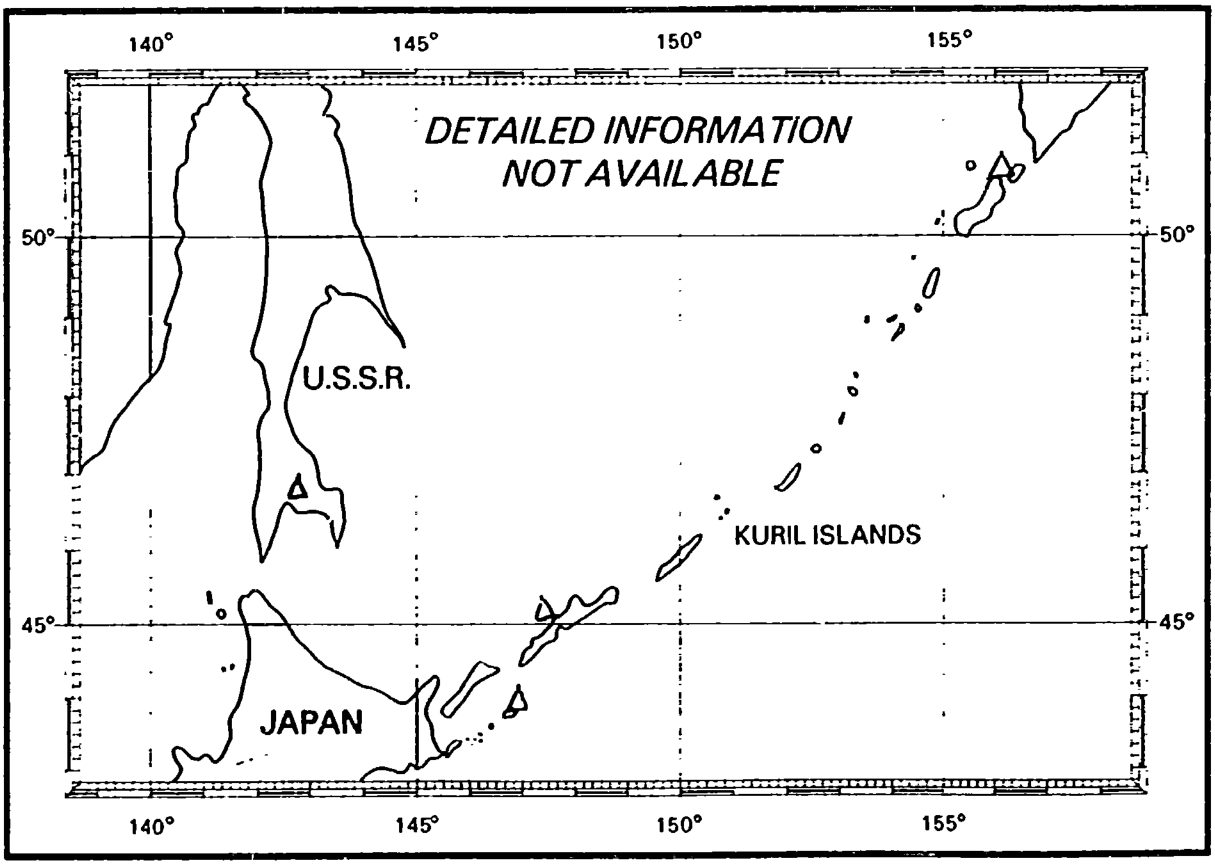
TSUNAMI WARNING SYSTEM OF JAPAN

The U.S.S.R. Tsunami Warning Center

The U.S.S.R. started implementing a Tsunami Warning System after the 1952 Kamchatka earthquake. Three specialized seismic tsunami stations were established. The overall responsibility of these stations is exercised by the Hydrometeorological Service of the U.S.S.R. with the assistance of the Academy of Sciences and several other institutions. Each Center has full authority to issue a warning in case of a tsunami threat and appropriate quarters are advised to evacuate affected population centers.

Special instruments are in operation to detect earthquake magnitudes of seven and larger as well as resulting tsunamis at distances between 150 and 2000 km off-shore.

Tsunami wave travel time charts and historical data are used in the warning process. Communication is maintained with the Pacific community through the Khabarovsk-Tokyo cable link.



TSUNAMI WARNING CENTERS OF THE U.S.S.R.

AREAS WITHOUT WARNING CENTERS

West Pacific

The greatest loss to life and property due to tsunamis during the last ten years occurred in Indonesia and the Philippines. In applying present technology in both Communication and Instrumentation, regionl or national warning systems could be established, which would enable appropriate Civil Defense Authorities, to issue Tsunami Warnings within twenty minutes of tsunamigenisis.

A warning system or systems in this area will only serve this particular region and any contribution to the Pacific-wide system is secondary. However, since the socio-economic development of the region is closely related to the mitigation of the effects of natural disasters and in order to minimize future loss of life and property, a modern warning system is a necessity.

South America

The west coast of South America is the site of the subduction of the oceanic Nazca Plate under the continental South American Plate. The result is a band of strong seismicity running the length of the continent and roughly paralleling the axis of the Peru-Chile Trench. Tsunamigenic earthquakes have occurred all along this zone. Since 1687, over 25,000 people have lost their lives due to tsunamis originating in this region. One of the largest tsunamigenic earthquakes of at least the last two centuries, the earthquake of 22 May 1960, produced motion of the sea floor along a stretch of the Chilean coast nearly 1000 km long and caused a tsunami which killed approximately 1000 people throughout the Pacific. Fortunately, such events have not occurred often. But the continued seismicity of the region and its history of frequent large earthquakes of the type which have produced tsunamis mean that this region continues to be a possible source of destructive tsunamis.

The Southwest Pacific

The Southwest Pacific Region is one of the most active and complex seismic areas of the world. Its seismicity is affected largely by the opposite motions of two separate plates: the Indo-Australian plate moving to the North-East, and the Pacific plate moving from the east to west. These plates are subducted in the areas of the Tonga Trench, Vitiaz Trench, and the New Hebrides Trench, and this subduction process results in large numbers of shallow to deep focus earthquakes in the southwest Pacific. In fact, the abundance of deep focus earthquakes in this region has attracted much scientific attention, to the point where shallow earthquakes have been ignored, largely because they have not been recorded outside the region.

For many years, the only seismological stations in the Southwest Pacific were those in Apia, Suva, and New Zealand. Recently the French have improved their network in New Caledonia and French Polynesia, and other countries have acquired a few new instruments. With the very few stations that have existed in the past, it has only been possible to locate the stronger events that are detectable by at least three stations in different countries. Moderate local earthquakes recorded by any one station were often ignored because they could not be located, thereby giving the false impression that most South Pacific countries are free of active fault zones. Recent studies have shown there are active seismic zones in Fiji, New Hebrides and Papua New Guinea, and a proper network of instruments are required to delineate seismic zones which may exist in other countries as well. Strong earthquakes have affected Tonga, Samoa, Kermadecs, Fiji, New Hebrides, Solomons, and Papua New Guinea in the past.

Because of the proximity of the various island groups in the region, tsunamis generated by a strong earthquake in one country can affect a neighbouring country within 2 hours.

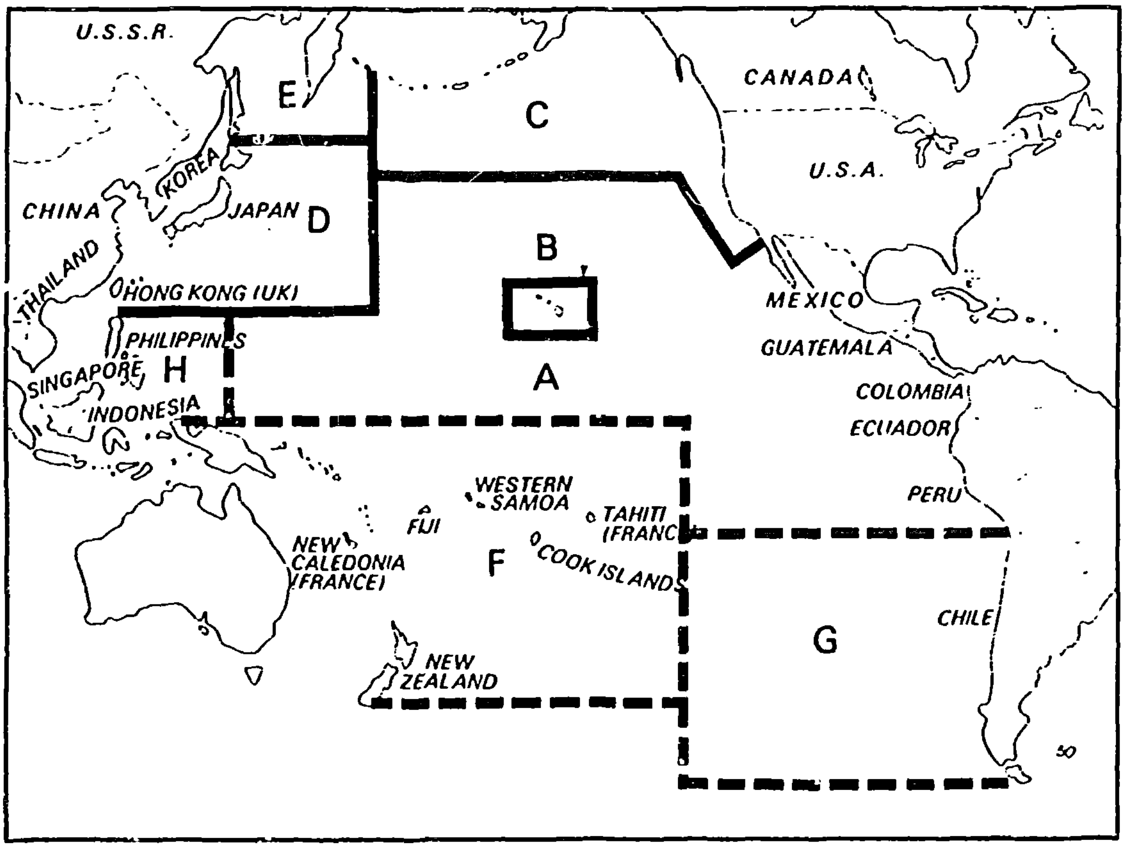
RECOMMENDATIONS

Three new warning centers for the Southwest Pacific, South America and the West Pacific, should be developed to reduce tsunami hazard in these regions. Communication facilities and instruments designed for real-time data acquisition and warnings combined with a well-designed contingency plan are prerequisites for these centers.

Each center would act on its own should local tsunamis threaten its area and maintain real-time contact with the Pacific Tsunami Warning Center in every case of tsunamigenesis.

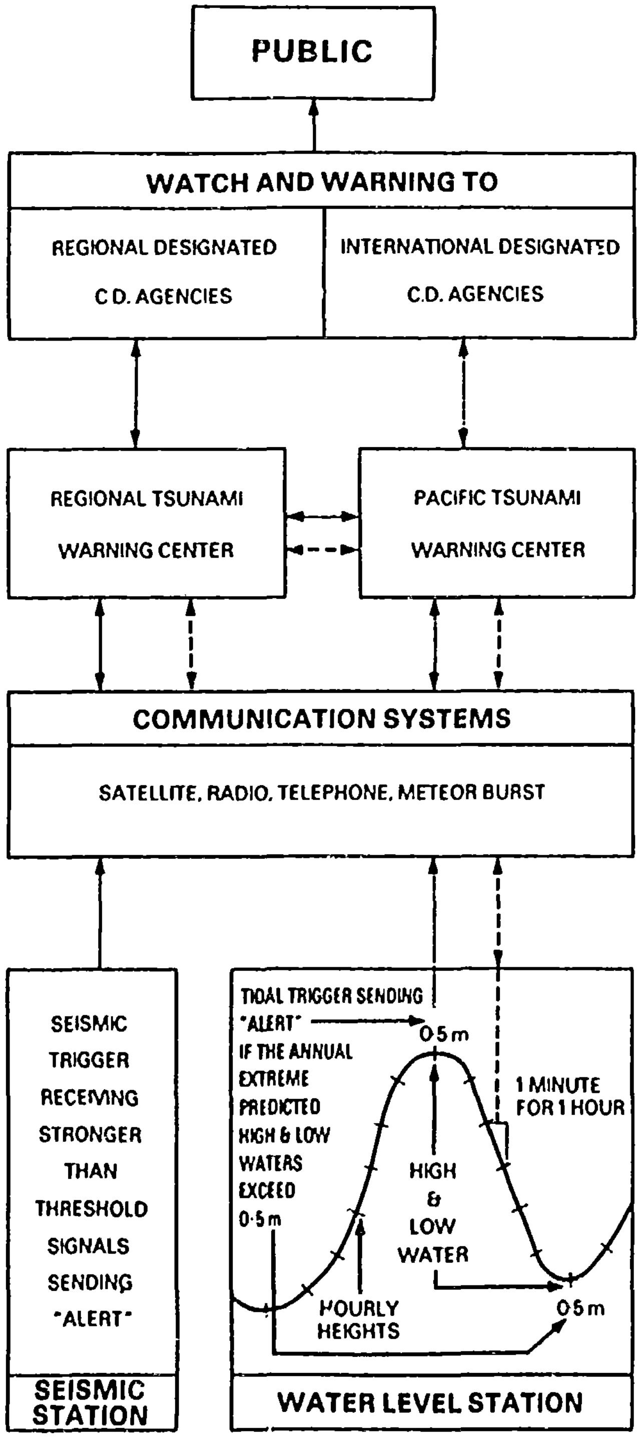
The centers should be modelled to those in existence in the Northern Pacific with the additional capabilities in disseminating and promulgating, within the area of responsibility, all tidal and seismic data as well as providing international data centers with the required information.

In addition, the communication channels of each Tsunami Warning Center could be utilized for the warning of dangerous water level changes caused by other meteorological events.



A PACIFIC TSUNAMI WARNING CENTER (PTWC)
B HAWAII TSUNAMI WARNING CENTER (U.S. NATIONAL TWC)
C ALASKA TSUNAMI WARNING CENTER
D JAPAN TSUNAMI WARNING CENTER
E U.S.S.R. TSUNAMI WARNING CENTER
Planned
- F SOUTH WEST PACIFIC TSUNAMI WARNING CENTER
- G SOUTH AMERICA TSUNAMI WARNING CENTER
- H WEST PACIFIC TSUNAMI WARNING CENTER

PROPOSED AREAS OF RESPONSIBILITIES FOR TSUNAMI WARNING CENTERS IN THE PACIFIC



PROPOSED DATA FLOW AND COMMUNICATION RESPONSIBILITIES

THRUST PROJECT

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1. INTRODUCTION

The Agency for International Development (AID), Office of U.S. Foreign Disaster Assistance (OFDA) is authorized by the United States Congress in Chapter 9 of the Foreign Assistance Act of 1961, as amended, to help alleviate suffering from disasters in foreign countries by providing emergency relief and strengthening the ability of developing nations to cope with disasters by increased reliance on their own resources. Helping host countries achieve adequate levels of preparedness and early warning capabilities represents OFDA's principal focus in disaster prevention and mitigation. Historically within the Pacific Basin, one of the most destructive natural hazards is the seismic sea wave, or tsunami, generated by large submarine earthquakes. Since 1850, more than 70,000 lives have been lost in the Pacific due to tsunami (1). Today, several million people live or derive livelihood in tsunami hazard zones in the Pacific.

Since 1965, Pacific nations subjected to tsunami hazards have mutually benefited from the United Nations organization International Coordination Group for the Tsunami Warning System in the Pacific. In April 1982, this group advanced the resolution that early warning systems be developed for areas exposed to tsunami generated by local earthquakes. The present study addresses the application of available technology, including satellites, for significantly improving early tsunami warning along vulnerable coastal zones in the Pacific Basin. Specifically, a program is described which will test and evaluate the utility of these technologies in tsunami hazard mitigation in developing nations.

In describing locally generated warning systems, two time periods are essential: the period, be it days, months, or years, prior to the tsunami (pre-event stage) and the first hours after tsunami generation (real-time stage). During the pre-event stage, attention focuses on determining the general extent of the tsunami threat in a coastal area and creating a viable emergency evacuation plan for implementation at the time of the disaster. During this time a program of public tsunami awareness and education can be undertaken which can save many lives during the first few minutes of a locally generated tsunami, when no mechanical warning system can be truly effective and a threatened population must rely on its informed instincts. Once a tsunami occurs (the real-time stage), a warning system capable of collecting seismic and water level data, analyzing them, and disseminating hazard information based on them is essential. Japan, USSR, and USA (Alaska and Hawaii) have regional warning systems capable of reacting to a tsunami and issuing a local warning about ten minutes after a local event (2). The other nations of the Pacific, many of which are developing nations, are not as fortunate and must rely on the Pacific Tsunami Warning System (operated at the Pacific Tsunami Warning Center (PTWC) in Honolulu, Hawaii) for warning messages. Present operating limitations prevent actual warnings from being disseminated to most countries in less than one hour from the generation of a tsunami (3).

A gap, therefore, exists in the present warning structure. Developing countries without a regional warning system cannot be alerted about tsunami originating close to their shores until an hour after generation. The purpose of this study is to examine existing U.S. technology to ascertain if an early warning system can be designed to fill this gap in nations with no regional or national warning system. Specifically, the objective is to design a system that can deliver earlier warnings to a developing country within the Pacific or directly to isolated population centers within ten minutes of tsunami generation.

Thus, the rationale for the study presented in this document is the transfer of existing U.S. technology to developing countries to supplement the Pacific Tsunami Warning System during the first crucial hour of a tsunami.

These technologies can be partitioned into three categories: data collection, data analysis, and information dissemination. Sections 2, 3, and 4 assess the existing technologies in data collection, analysis, and dissemination which are applicable to the warning system and most appropriate for transfer. Other U.S. technologies are available, but have certain drawbacks because they are not easily adaptable to the existing tsunami system.

A number of criteria were used in selecting technologies for use in early warning in local regions. Among these are reliability, compatibility, and availability. The selection criteria also balanced the benefit of the hazard reduction with cost of the system.

In Section 5, we present a conceptual system which synthesizes the technologies discussed in Sections 2, 3, and 4. Finally, a demonstration program is described in Section 6. The applicability of the demonstration program to many areas of the Pacific can be shown. Implementation, including a site survey and equipment installation in a test area, is a requisite step in developing a satellite-based network throughout the Pacific Basin with the potential of saving lives and protecting property from the hazard of locally generated tsunami.

2. DATA COLLECTION

Since the beginning of the Pacific Tsunami Warning System in 1949, the warning process has been initiated by seismic signals from large earthquakes. The instruments used to detect these signals were largely those developed for routine earthquake and tide monitoring programs. Recent significant advances in data collection technologies have occurred which could be applied to early tsunami warning (2). These include digital recorders, computers and microprocessor technology, and satellite telemetry. Some of these technologies have been used for experimental tsunami warning programs, nuclear-test monitoring, and earthquake prediction programs in developed countries. The technology is, therefore, available for use by developing countries for improving local warnings.

The following is a brief review of the present status of water level and seismic sensor technology relative to the tsunami early warning operations. For this review, the following criteria were selected in assessing current available instrumentation:

- Water level sensors should be capable of recording water level changes to an accuracy of 1 cm for wave periods ranging from 3 to 90 minutes. They should be able to remain on-scale during fluctuations of up to 7 meters beyond tidal ranges at shallow water locations. The sensors should be able to transmit, via satellite or hardwire to any location, digital data recorded at 30-second intervals independent of local power sources. The timing device for the system should be accurate to within one minute in one year.

- Seismic sensors should be capable of recording accelerations to within .01 g over a range of .1 g to 1.0 g. They should remain on-scale during accelerations up to 1.0 g. Data from these sensors should be digitally processed in real-time to activate a satellite transmission once a certain threshold has been exceeded. The sensor, processor, and transmitter should also operate independently of local power sources. The system timing device should have an accuracy of one minute in one year.

Equipment components available to create a data collection, processing, and transmitting platform (with possible U.S. suppliers) include:

1) Tide gage (Metercraft; Progress Electronics of Oregon; Handar Corp.)

2) Seismometer (Springnether; Kinemetrics; Geotech)

3) Microprocessors (North American Rockwell)

4) GOES receiver and transmitter (La Barge Corp; Motorola)

5) Solar panels with rechargeable batteries (Solarex)

Progress Electronics of Portland, Oregon, has stand-alone systems available which meet tsunami warning water level criteria. Synergetics

Corporation of Boulder, Colorado, has a stand-alone seismic system available for earthquake detection, processing, and transmitting from remote locations.

This evaluation leads to the conclusion that sensors can detect the important parameters for tsunami warning and can transmit raw or processed data via satellite. Indeed, some of these sensors have already been used in test modes for improving the tsunami system. In particular, data from coastal tide gages (bubbler type) and processed seismic data (short-period) have been transmitted via the Geostationary Operational Environmental Satellite (GOES) West system (4, 5). Data from other sensors, such as well-type tide gages, short period and long period seismometers, have been transmitted in analog and digital form to regional warning systems of Alaska, Hawaii, Japan, and USSR (6). At all of these centers, computer-assisted data analysis is either operational or in developmental stages (6). Thus, there are no known limitations on existing sensor technology for immediate application to a satellite-based early tsunami warning system.

One of the most exciting possibilities for improved early warning operations is the automatic triggering capability of these sensors. Previous U.S. application of satellite technologies to the tsunami operation have focused primarily on human-activated interrogation mode. For example, once an earthquake has been detected and located by PTWC, tide gages are manually interrogated for verification of tsunami existence and determination of severity. The principal drawback of this approach for early warning (10-60 minutes after generation) is the time delay encountered in detecting the earthquake, assessing data, and interrogating sensors. Currently, human-activated interrogating systems introduce serious delays of up to one hour, which may be critical for a developing country susceptible to a locally generated tsunami. It is recommended that new satellite-based technology be integrated with the sensor-activated mode to provide more rapid warning information to operational decision-makers and people in charge at the disaster site. This total system is described in more detail in Section 5.

In addition to real-time data collection, historical data on previous tsunami in a particular location are essential to determine placement of instruments, calibration of models, and formation of emergency planning. In particular, historical information of tsunami arrival times, run-up levels, and mitigation measures is necessary. Local bathymetric and topographic data are also required to support model studies in threatened areas.

3. DATA ANALYSIS AND MODEL STUDIES

This section addresses the data analysis, data products and modeling needed to provide the background for planning decisions, risk determination, and educational material development in support of awareness of primary tsunami hazards and response to natural or system warnings.

One of the principal tools for tsunami data analysis is the use of models of one type or another. These allow studies to be carried out during the periods between actual events. Equally important is applying existing and currently evolving techniques for modeling tsunami evolution for the improvement of both the tsunami warning and the hazard mitigation capabilities. A useful approach is the recognition that tsunami evolution can be described by three phases.

- generation and behavior in the immediate source area,
- propagation away from the source area and toward coastlines, and
- interaction (possibly destructive) with the environment near, at, and on the shorelines.

This three-phase structure helps to point out the different information requirements for tsunami warning procedures and for hazard mitigation planning.

Tsunami Warning

A system designed to warn people about a specific hazard should have several goals. It should be able to ascertain quite rapidly that a threatening hazard has developed, generate an assessment of the seriousness of the threat, and communicate this information to threatened populations in sufficient time for them to take action to save their lives and protect their property. A warning system must, in addition, be able to achieve these goals repeatedly and accurately in order to establish its credibility and thus maximize its effectiveness. In order to be an effective tool for saving lives and property, the ideal tsunami-warning system should be able either to generate on its own or to tap into established sources of information concerning all three phases of tsunami evolution.

Hazard Mitigation

The development of hazard mitigation plans takes place over a much longer time scale than the tsunami warning process. Such plans might concentrate on the most difficult phase of tsunami evolution -- the coastal interaction phase. These plans must take into account a wide variety of factors. These include questions such as which portions of a coastal area are or have been most severely threatened by tsunami? Where would the damage to life and property be most significant? What are the probabilities of such events occurring in ten years? fifty years? a century? What type of disaster relief preparations should be made? How effective would measures such as strict zoning, land use plans, increasingly stringent building codes, and coastal barrier construction be in reducing the hazard?

Tsunami Models

The next question to be addressed is how tsunami models could help fill requirements. Tsunami modeling, in simple terms, is an attempt to simulate or approximate the behavior of a physical phenomenon. Tsunami models of one or more of the three phases of evolution have been in use for the last several decades. These models can be grouped into three categories:

Hydraulic models are attempts to recreate in wave tanks and with physical models the processes observed in actual situations.

Analytical models reflect attempts to strip the complicated tsunami process down to its basic physical elements and translate these into tractable systems of equations. Functional solutions to these equations are then found. The goal is not to faithfully recreate observations, but rather to combine the various forcing mechanisms in an appropriate fashion, so that the model waves behave in a manner qualitatively similar to physical waves.

Numerical models begin with sets of equations similar to those used in analytical models. Computational, rather than functional, solutions are sought, usually by means of digital computers. These solutions should closely conform to observations.

All three types of models have been used successfully in examining the various aspects of tsunami evolution (7). Numerical models, because of their great flexibility and relatively low cost, seem to have the greatest utility for tsunami research (8, 9, 10).

Tsunami models can be quite useful in both hindcast and forecast modes. That is, they can be used either to reconstruct what happened during a historical event or to estimate what might possibly occur in the future. Both of these uses provide a strong foundation of basic information to draw upon for both long-term hazard planning and real-time warning.

In the hindcast mode, models can help to shed new light on what actually happens when a tsunami occurs. They can be used to fill gaps in areas where observational data is scarce. And they can be used to analyze ways in which protective measures could have helped to reduce damage and destruction.

If models are to be used in this mode, a detailed compilation and analysis of existing observational data must also be undertaken. The primary purpose is to provide as much data as possible for verifying and calibrating model results so that they conform closely to historic reality. A second purpose is to place the tsunami (both real and model) into their proper historical perspective in terms of frequency of occurrence and severity. This information would be valuable on both regional and basin-wide scales by depicting the nature of the threat for planning and education purposes.

In the forecast mode, models can be used to augment the historical data base to estimate threat levels due to tsunami which have not yet happened. This could include not only worst-case or once-in-200-year tsunami, but also less severe, but quite possible, events. They can also provide travel time information for augmenting existing charts.

In both modes, tsunami models can be applied to both long-term planning and real-time warning.

Hazard Planning

Models can provide information to eliminate many omissions in our existing knowledge. On a basin-wide scale they can be used to delineate areas of most severe threat due to tsunami generated in specific regions. On a finer scale they can be used to fill in gaps in tide gage coverage along coastlines for both historical and hypothetical events. This type of information can be used to develop threat levels and probability-of-occurrence estimates in Pacific coastal locations. Coastal models can be used to locate high-risk areas for flooding and guide both land use requirements and building codes. Highly detailed run-up models could even be used to develop scenarios for disaster preparedness exercises.

Real-Time Warning

Tsunami models can also play a key role in warning operations. If a warning system were able to rapidly acquire information on the location, magnitude, areal extent, and tsunami potential of an earthquake, an existing data base of similar cases could identify threat probabilities throughout the Pacific. The most useful product, in terms of determining appropriate response, would be to supplement notice that a tsunami has been generated with estimates of its severity.

Data Products

A useful product for public information could be a map illustrating the tsunami occurrences and effect within the Pacific Basin. This would summarize in a visual form the history of destructive tsunami on a Pacific-wide and local basis. A revised travel time chart for local and Pacific Basin tsunami could be prepared using new digital bathymetric data for any location.

In order to provide the data needed to support later modeling, analysis and dissemination activities, local coastal bathymetry and elevations, tsunami effects, run-up and arrival time data and information on local disaster warning infrastructure must be gathered.

4. DISSEMINATION OF INFORMATION

The Pacific Tsunami Warning System detects major earthquakes in the Pacific region, evaluates the earthquake tsunami potential in terms of epicenter and Richter-scale magnitude, determines if a tsunami has been generated, and issues appropriate warnings and information to minimize the hazards of tsunami. The international monitoring system is composed of twenty-two seismic stations and approximately 50 tide stations throughout the Pacific Ocean. The international warning system employs teletypewriter and voice communication links to acquire data and disseminate tsunami information to seventeen nations. Transmission times range from 10 minutes to one hour, depending on the efficiency of communication relay points. Regional warning systems for locally generated tsunami exist for Hawaii, Alaska, Japan, and USSR. These monitoring systems are real-time links from seismometers and tide gages to the respective centers (6). Local tsunami warnings in these systems may be issued on the basis of earthquake information alone.

In general, warnings delivered by these centers include earthquake locations (±50 km), earthquake Richter-scale magnitude (±.3), tsunami arrival (±20 min), and reports of tsunami wave heights as recorded by tide gages (6). The earthquake parameters and tsunami arrival times throughout the Pacific are usually disseminated by PTWC to the 54 international warning points within one hour after the occurrence of an earthquake. The time of receipt of tsunami wave reports at PTWC varies with the travel time of the tsunami from its origin to the tide gages, the dependability of equipment and observers, and the communication links.

Development of satellite communication offers significant opportunities for both collecting and disseminating warning information. NOAA's Geostationary Observational Environmental Satellite (GOES) provides a transmission pattern for the whole eastern Pacific (Figure 1).* The GOES operating system includes a data collection system (for use with sensors described in Section 2) that can receive information from a sensor and relay this information through the satellite to a central point for distribution. For Pacific-wide tsunami warning application, the data would be transmitted to the command and data acquisition station (CDA) at Wallops Island, Virginia, then retransmitted to the PTWC. The time of transmission from sensor to PTWC can be as short as one minute in "real time."

The GOES West operating system can also interrogate remote sensors by command initiation from CDA. In this mode, a coded address is initiated and transmitted via satellite in real-time to the platform.

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* Failure of the imaging scanner on the GOES West satellite Nov. 25, 1982, did not affect the communications capability. The following discussions about the GOES West are still valid.

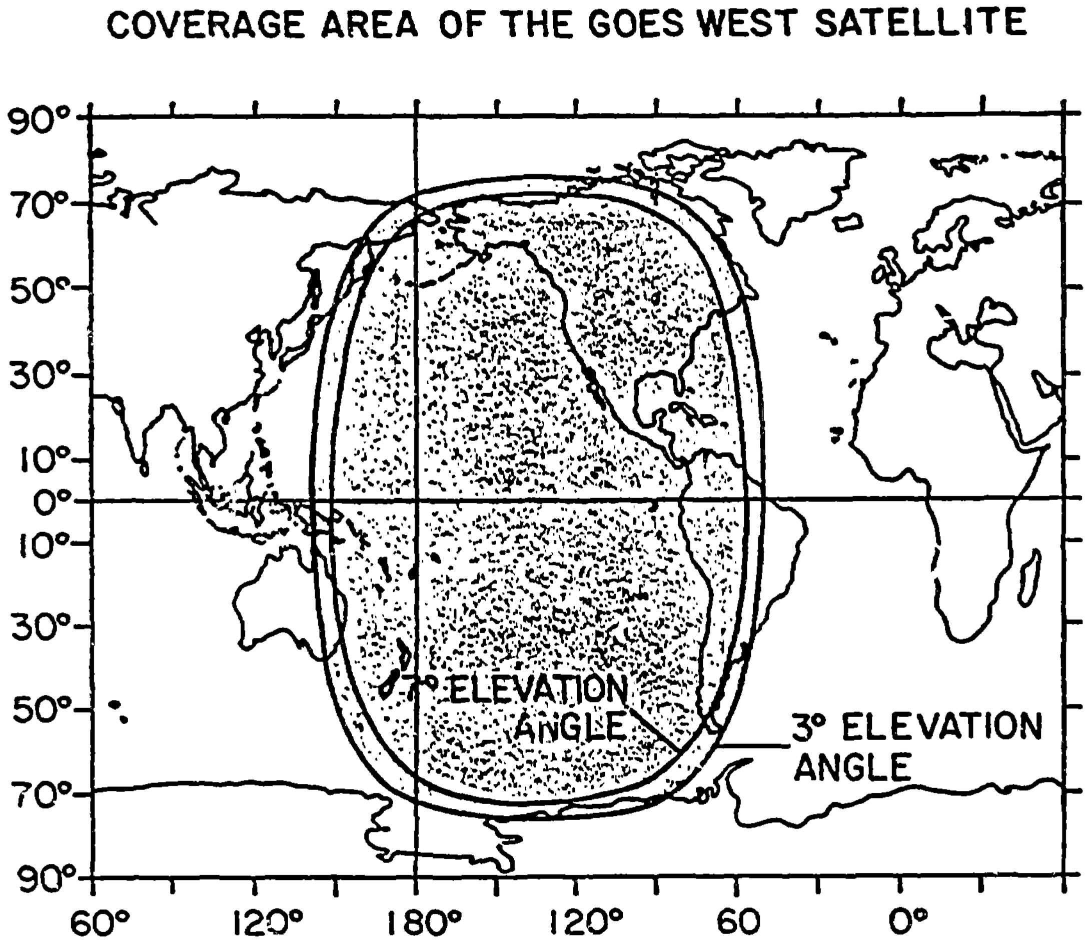


Figure 1. Coverage area of GOES West Satellite

The platform receives a command that activates a preprogrammed set of instructions. Normally, the command from the satellite is a 50-bit serial code containing an identifier, a platform number, a priority, a primary and secondary address, a standard validation code, and a time code. The interrogation code can serve as an early warning alert by substituting one of the normal codes through modification of the operating system at CDA (11). For more technical details of the GOES communication system, see Appendix B.

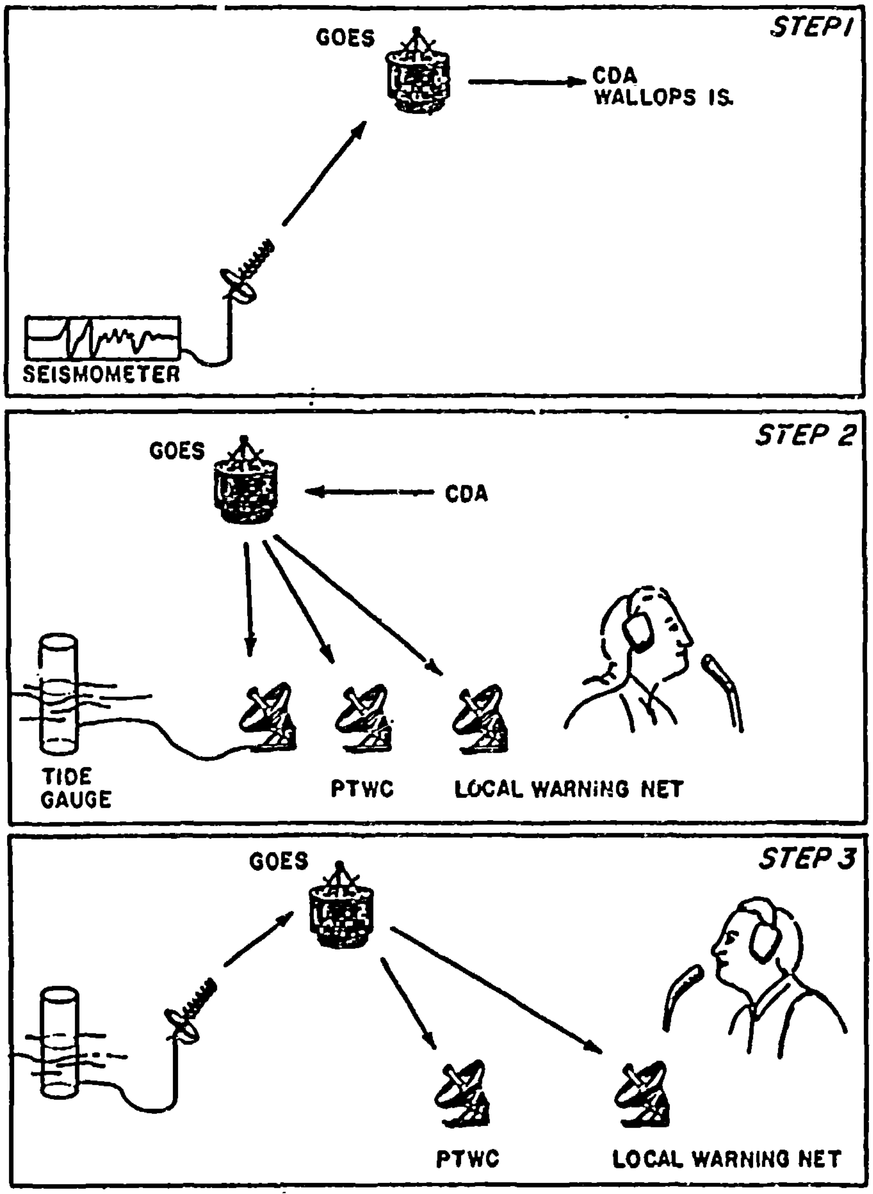
A Disaster Alert System

Ideally, for a disaster alert system, a comprehensive message describing the potential disaster conditions, parameters, and prognosis is desirable. But in real emergencies a minimum amount of factual material is available to issue a warning. The decision to extend this warning to a given population might require additional information not available from a warning service or possibly not available at all. An electronic device could provide a basic alert and a suggested course of action. Figure 2 shows a basic alerting system. The required elements are antennas, receivers, independent power sources, sensors and alarms. The antennas are a simple, harsh environment model that can endure a corrosive salt atmosphere and wide temperature variations. The receiver is a dual-conversion solid-state model with all of the electronics necessary to strip the coded information from the transmitted signal and, through the use of built-in microprocessors, to broadcast information. A receiver with provisions for receiving either normal or alert code must be used.

At remote sites, a set of solar panels would provide independent power for the data collection platform. In an operational system, the panels would be large enough to power the complete system and batteries capable of powering the system for several days to cover a period of power loss would be included.

Critical and threshold levels can be established which trigger a sensor's transmission to the satellite. GOES can then automatically transmit messages which notify authorities and trigger any one of a wide variety of automatic alarm devices (sirens, bells, voice broadcasts, etc.). Then incoming information can, for example, trigger the printing of messages, in the form of narrative sentences, previously stored in a microprocessor memory of the receiver. The microprocessor can also initiate alarm relay to remote locations. Verbal announcements stored in the microprocessor may be released in the local language and sirens sounded in any order or combination desired. This can all be accomplished automatically or under human control.

Thus, by utilizing existing technologies with slight modification, an early warning event-activated system can be installed in disaster-prone developing nations without regional warning systems. Such a system could reduce alerting time from one hour to as little as one minute. The time-saving alert coupled with a well-designed local contingency plan could save many lives.



Seismic sensor(s) or tide sensor(s) receive stronger-than-threshold signal, alerts GOES of pertinent data.

GOES automatically issues two messages. One instructs tide gages to begin transmitting data. The second alerts PTWC and the local warning net that an alarm has been tripped. Local authorities decide whether or not to issue a warning.

The gage data is transmitted to GOES and thus to both PTWC and the local warning net. Both organizations have additional information to supplement earlier warnings/watches.

Figure 2: Local tsunami warning network operations.

5. SYNTHESIS OF TECHNOLOGIES AVAILABLE FOR TRANSFER

The previous three sections have shown that the technology exists to improve estimates of tsunami hazards and to establish rapid dissemination of localized early warnings. Appropriate configuration of these elements will constitute a conceptual model that represents a significant advance in early tsunami warning. In terms of the previous three sections, the conceptual model can be described in the following fashion:

Data Collection

A. Pre-event: Historical data on tsunami run-up, times of arrivals and effects will assist in emergency planning and model verification. Bathymetric and topographic data are necessary inputs for model simulations.

B. Real-time: Data collection will be initiated by the triggering of seismic or water level devices of the tsunami system. Reports from water level sensors are still required to determine the existence and severity of tsunami. Both sensor types must be in communication with PTWC. It is desirable, but not necessary, that the sensors be directly linked to a local warning network in addition to the satellite link.

Data Analysis

A. Pre-event: Historical data analysis, coupled with numerical models, provides estimates of potential inundation levels for planning purposes. These investigations are essential to designate hazard areas and safety zones for disaster planning.

B. Real-time: Real-time data can be used to update warning information calculated in the pre-event data analysis. They can also be used to monitor and continuously refine warning information as the tsunami propagates throughout the Pacific.

Dissemination

A. Pre-event: Emergency preparedness will require the establishment of a local infrastructure to respond to a tsunami. Public education is the foundation of proper response to a tsunami alert. Dissemination of information on the procedures and dangers of tsunami will take the form of workshops, media coverage, school programs, and other vehicles to keep the public aware of the hazard.

B. Real-time: Or near-real-time dissemination of warnings for developing countries can be accomplished by the application of satellite technology as described in Section 4.

With the conceptual framework as a guide, a demonstration program could be implemented for one population center to demonstrate the utility of the system. This program is described in detail in Section 6. The products derived from this demonstration are transferable for use in the Japanese GOES system and the Indonesia PALAPA system, thereby providing a proven technology to other countries interested in tsunami hazard mitigation but outside the range of GOES West. Such a program will provide data to PTWC much more rapidly, thus allowing for earlier alerting of the Pacific System. It will also foster cooperation among agencies that have an interest in U.S. tsunami hazards mitigation.

This conceptual model should be considered a generalized framework. As such, it has inherent limitations because localized details have been omitted. Each application of this model must reflect the geophysical, oceanographic, and socio-political character of the specific site. The geophysical characteristics will determine seismic instrument design and placement; oceanographic characteristics will determine water level gauge placement and design; and socio-political characteristics will determine the emergency system design. The successful integration of these factors is a difficult task which must be accomplished on a case-by-case basis. The lack of a detailed elaboration of these factors is not meant to minimize their impact; such a discussion, however, is well beyond the scope of this feasibility study.

6. THRUST PROGRAM

The conceptual model described in Section 5 can quite readily be turned into a demonstration program -- Tsunami Hazard Reduction Utilizing System Technology (THRUST) -- to mitigate tsunami hazards in the Pacific Ocean. The first step of this program is to test the conceptual model described in Section 5 at one population center in a developing country.

The THRUST pilot study is subdivided into the three functional areas of data collection, data analysis, and information dissemination; each area is partitioned into pre-event and real-time frames. Thus, one could interpret the first row of the matrix as development of the emergency operating system that is activated by the real-time second row. Both time frames must be considered for a system that will reduce tsunami hazards.

During the pre-event stage a data base would be developed to provide historical information on tsunami run-up, arrival times and tsunami impacts. Additional data would be collected on the bathymetry of the local coastline, the topography of the land, and local tidal ranges. These data would be used to simulate historical tsunami events. The historical data would help validate and calibrate the numerical model while information on the physical morphology would be used to construct the model. Once the numerical model has been verified (simulations closely resemble historical data), then hypothetical simulations will be conducted for worst-case scenarios. The selection of scenarios will be based upon geophysical information relating to the most probable earthquake's areal extent, magnitude, and vertical displacement which could occur close to the test area. The combination of historical data and model simulations provides an extended data base from which to create emergency operating plans. Although this extended data base has drawbacks (it depends on the quantity and quality of the real data base), it represents the best technique of supplying data where none exists. From these data, zones of hazard and safety can be constructed and evacuation plans established. In many cases, these data can also provide building code guidelines.

An earthquake activates a seismic instrument. This instrument then transmits a signal to the GOES satellite system (satellite and CDA) that responds by automatically transmitting an alert code to an alarm device at the warning site designated by local authorities. The alarm device instantly responds by initiating a set of prerecorded instructions based upon the emergency plans established before the tsunami. A human will make the final determination about issuing a tsunami warning based upon predetermined criteria. Thus, a human will make the <u>decision</u>, and he will have enough information within 5 minutes of the earthquake to make such a decision <u>intelligently</u>. In addition to the early alert signal from the GOES satellite, other signals are sent to interrogate tide gages about the earthquake source. These water level data are sent to PTWC and to the local authorities for faster confirmation of tsunami activity. The impact of the THRUST program will be an early warning system for the local population near the source <u>and</u> faster dissemination Pacific-wide by PTWC.

In choosing population centers for a pilot demonstration, consideration was given to tsunami hazard potential, access to GOES West satellite, and national commitment to the program. Using these criteria, Valparaiso, Chile was selected for the pilot study.

The Pre-event work has been completed. This work included the development of a Chilean tsunami data base, a "Tsunami of the Pacific Basin" map, numerical modeling simulations, and the development and integration of a Standard Operating Plan.

The Real-time work includes the design, development and installation of the instrumentation. The installation of this instrumentation in Chile is expected to be completed in May 1986.

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REGIONAL TSUNAMI WARNING SYSTEM (THRUST)

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INTRODUCTION

One of the most destructive natural hazards within the Pacific Basin is the seismic sea wave, or tsunami. More than two million people support themselves or reside in the tsunami prone areas of the Pacific Basin. Since the early 1850's, more than 70,000 of these people have lost their lives due to the devastation of tsunamis (Iida *et al.*, 1967).

Developing countries within the Pacific Basin, with minimal or no regional warning system, cannot be alerted of tsunamis originating close to their shores. The present operating limitations of the existing Pacific-wide tsunami warning network (the Pacific Tsunami Warning Center (PTWC) near Honolulu, Hawaii, USA) allows a warning to be issued ½ to one hour after the generation of a tsunami. A gap, the ½ to one hour after tsunami generation, exists in the present warning structure.

The purpose of the THRUST (Tsunami Hazard Reduction Using Satellite Technology) project has been to examine existing technology and to ascertain if an early warning system can be designed that would fill the "gap" in nations with minimal or no regional warning system. Specifically, the objective is to design, assemble, test, install and evaluate a system that can deliver early warnings to a developing country (Bernard *et al.*, 1982).

The Valparaiso, Chile area was selected as the site in which the THRUST project will take place because of its great tsunami threat and its existing warning infrastructure.

THRUST SYSTEM

Warning systems can be divided into two time frames, the pre-event stage--the period (days, weeks, months, years, etc.) prior to the event (tsunami); and the real-time stage--the first hours after the event (tsunami generation). The pre-event time frame of this warning system determines the potential danger the event presents to that area and the solutions to these dangers. The real-time time frame's efforts are focused on the collection and analysis of seismic and water level data and the dissemination of the warning information.

The technologies that are being examined in THRUST can be categorized into three areas: data collection, data analysis, and information dissemination.

The THRUST system, being an early warning system, can be conceptually described as combining the time frames of a warning system with the areas of technology to form a working matrix. Utilizing Table 1 (below), we can describe the system in the following fashion (Bernard *et al.*, 1983).

THRUST SCHEMATIC PILOT STUDY

FUNCTIONAL AREA			
TIME FRAME	DATA COLLECTION	DATA ANALYSIS	DISSEMINATION
PRE-EVENT	DEVELOP TSUNAMI DATA BASE	EVALUATION OF HAZARD USING SIMULATIONS	DEVELOPMENT OF EMERGENCY OPERATIONS. PROCEDURES
REAL-TIME	SENSOR DEVELOPMENT INSTRUMENT + PROCESSING + TRANSMISSION	OPERATIONAL "PREDICTIVE" MODEL	INTEGRATION OF EARLY WARNING DEVICE INTO EMERGENCY SYSTEM

Table 1.

PRE-EVENT

Data Collection

This task consisted of compiling, cataloging and synthesizing all available data relating to tsunami effects in the Pacific Basin, concentrating on the country of Chile.

To date, three files utilizing this data have been assembled. The first file is a pre-twentieth century file that include 382 events (categorized into run-up heights, magnitudes, origin, etc.) of which 178 have caused death or destruction. The second file is a twentieth century file which includes 405 events (categorized as mentioned above). The third file is a file of all Chilean tsunamis since the 16th century. This file contains 249 events of which 34 have caused death or destruction.

Utilizing the above data files, a "Tsunami in the Pacific Basin" map has been assembled and published. This map details earthquake origin and magnitude, tsunami run-up height, related deaths, dollar damage, etc. of all tsunamigenic earthquakes in the Pacific Basin from 1900 to 1983. The data files have also been utilized for validating the numerical models and assisting in the development of the Standard Operating Plan.

Data Analysis

This task has produced computer simulations which have provided estimates of potential inundation levels, flood hazard areas, and worst case effects of observed and potential tsunamis.

The SURGE II model was applied to all modeling efforts (Reid *et al.*, 1977). A ½ km grid was utilized with a seafloor uplift (within the grid) being the source of the tsunami. These simulations provided information that the threat to Valparaiso from local tsunamis approaching from the west and/or northwest is quite great. Data obtained from the Chilean Navy Hydrographic Institute (IHA) in Valparaiso, Chile on the May 22, 1960 tsunami in Corral, Chile was utilized to verify the model (Hebenstreit, 1984a).

Results of these numerical simulations will be used to formulate the evacuation plan in the Standard Operating Plan (SOP) and for the development of the Real Time Processor (RTP).

Information Dissemination

This task includes the development of the Standard Operating Plan (SOP) for the city of Valparaiso, Chile. The purpose of the SOP is to achieve effective preparedness and to organize a coordinated program of tsunami warning dissemination which will ensure a prompt and flexible response by the local population, thus minimizing loss of life and property. Mr. Emilio Lorca, IHA, has assisted THRUST in formulating the SOP. Information obtained from the data files and numerical simulation were utilized to formulate an effective SOP.

REAL TIME

Data Collection

This task will coordinate the collection and dissemination of all data. The instruments for THRUST will utilize a satellite-based communications system, in the form of the Geostationary Operational Environmental Satellite (GOES) system. Utilizing the GOES system will allow the lag time between the event and the receipt of initial data to be reduced to the order of minutes--enough time to provide regional early warnings (see Figure 1).

After reviewing the requirements of the seismic system needed for THRUST, it was decided that strong motion triggers would be well suited for our needs. Two seismic triggers, made by Kinemetrics, will initiate the system when a seismic event occurs. One of the triggers will be in Valparaiso and the other will be in Santiago (see Figure 2).

Pressure digital water level sensors are best suited for this project because of their large dynamic range. Paroscientific Digiquartz pressure transducers will be used as the water level gauges. Both water level sensors will be placed on the concrete pier located in the Valparaiso harbor (see Figure 2).

The GOES radio sets that will be utilized by the THRUST system will be manufactured by Synergetics. These radio sets will be transmitters (TX) only. The radio sets will be connected to the seismic triggers and water level sensors. Kinemetrics True Time Receivers will be utilized as the

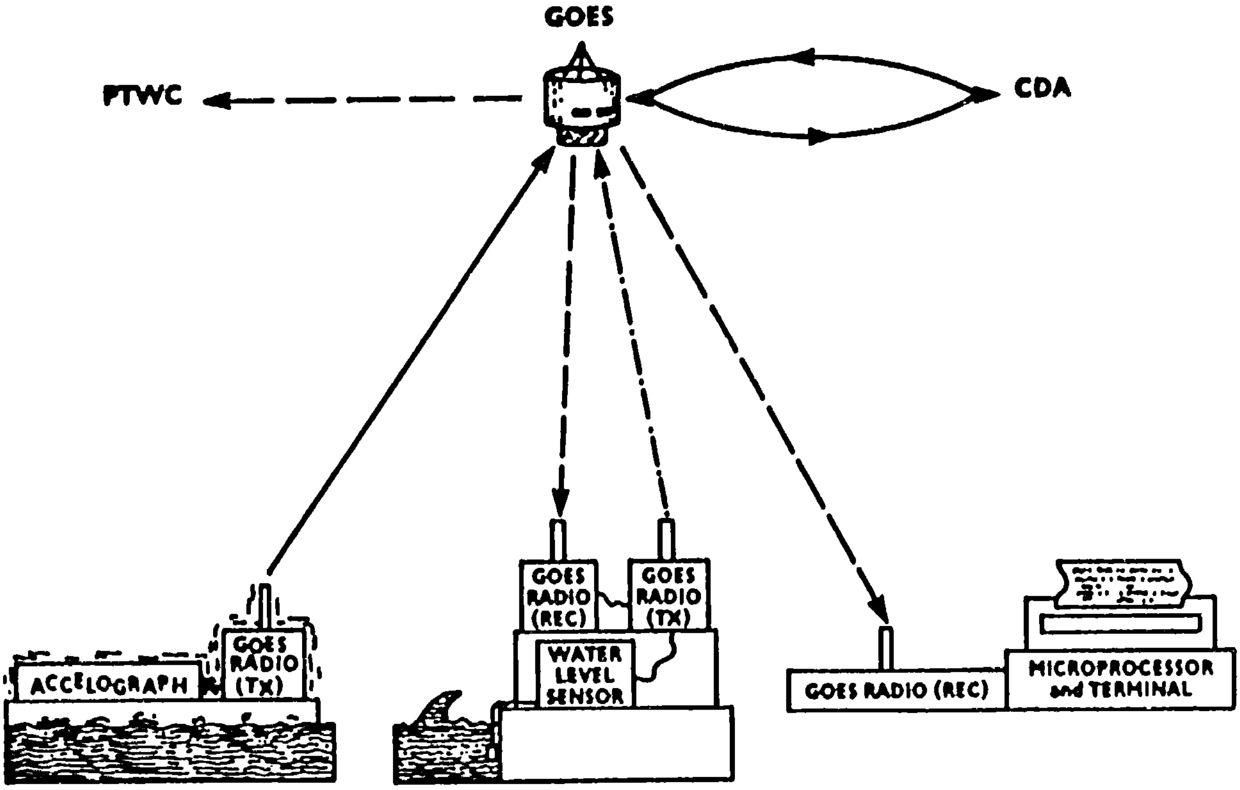
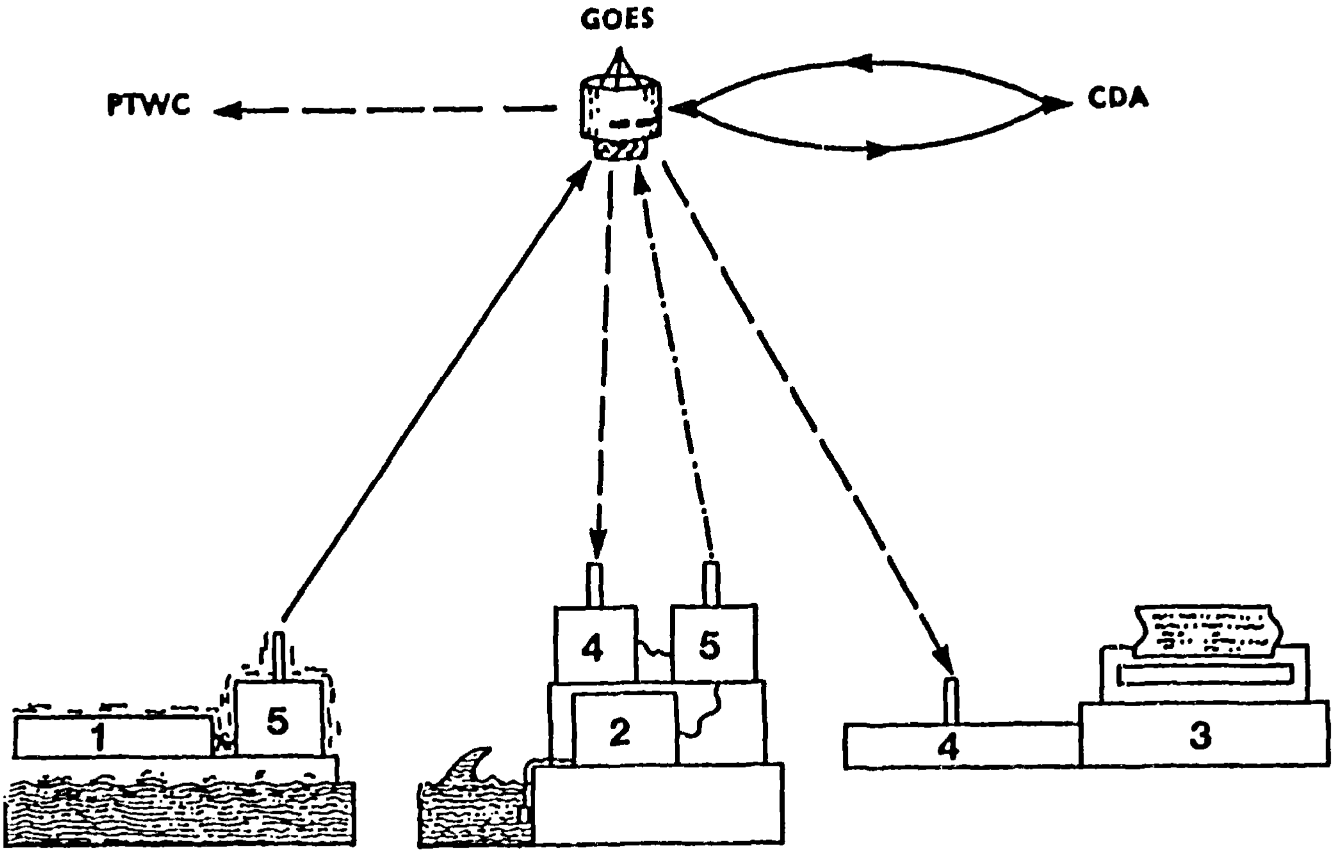


Figure 1.
THRUST instrumentation design.
CDA refers to Command Data and Acquisition.



INSTRUMENTATION:

1. Accelograph: Kinemetrics Vertical Seismic Trigger (VS-1)
2. Water Level Gauge: Paroscientific Digitiquartz Pressure Transducer (2100AS-002)
3. Microprocessor/Terminal: Commodor 64 with Dot Matrix Printer
4. GOES Radio Receiver: Kinemetrics True Time Receiver (468-DC)
5. GOES Radio Transmitters: Synergetics (3401A)

Figure 2.
THRUST instrumentation.
CDA refers to Command Data and Acquisition.

Commodore 64 with a dot matrix printer (see Figure 2). The RTP will be located at IHA in Valparaiso, Chile.

Procurement of the above mentioned items has been initiated. After PMEL receives all the equipment (Summer 1985) it will be assembled and tested for approximately 6 months. After a successful test, all equipment will be installed in Chile (May 1986) for one year of testing and evaluation.

Data Analysis

This task deals with the development of the Real Time Processor (RTP). The RTP is the first link between the THRUST instrumentation and the Chilean Tsunami Warning Center personnel. The RTP will consist of a microprocessor and a printer that will print a stored message (see Figure 3) when it receives an event alert signal through GOES from the seismic trigger. The RTP will:

1) Alert Warning Center personnel that the seismic trigger was turned on by an event;
2) provide some level of assessment of the tsunami threat;
3) remind Warning Center personnel of the procedures to follow (Hebenstreit, 1984b).

Information Dissemination

This final task deals with the transmission of warning information to threatened population areas. In this final step of the warning process, the incoming data and the accompanying analysis are used to determine which areas to warn, in what order to warn them, and what instructions to issue (SOP).

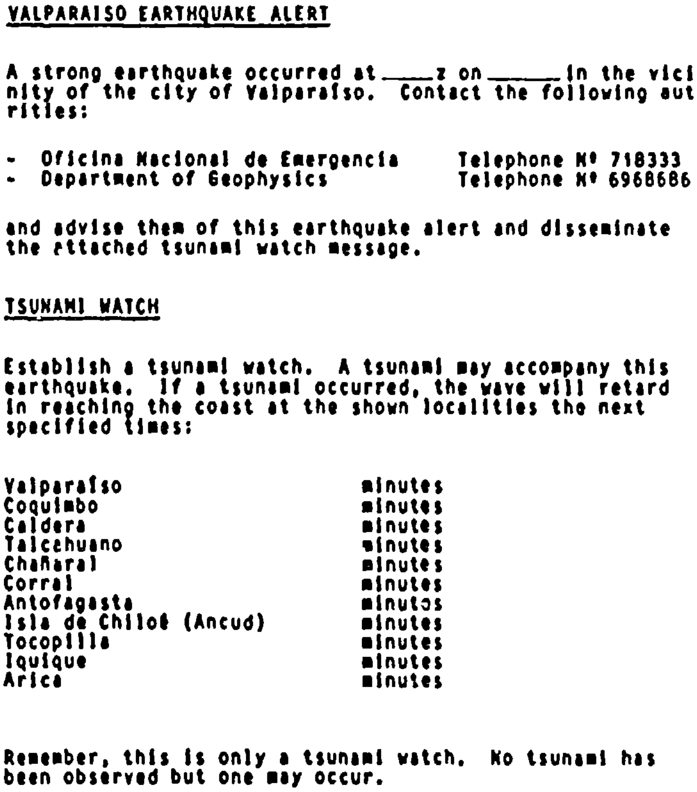
The THRUST project has received eight satellite addresses for the GOES System. Four of these addresses will be for the daily test made of the system. The remaining four will be for the standard operation of the system. NOAA, manager of the GOES system, has assigned THRUST a random report channel with very little usage for the demonstration of the THRUST system to ensure successful transmissions of messages.

Every seismic trigger (uplink) message, whether test mode or standard operation, will be sent through the GOES system four times to ensure the receipt of the message. Each message will be sent within a 15 second window with a 60 second delay after each window. Thus, a message could be received by GOES in as little as 15 seconds or as much as 7 minutes after the occurrence of the event. Upon receipt of this event triggered message, the GOES-CDA (Command Data and Acquisition) would be alerted that this is an emergency message and immediate action is to be initiated. This action (to be initiated within 1 minute) is a message sent back through GOES to turn on the water level sensors and the RTP (see Figure 1) (THRUST Pilot Study, 1984).

THRUST SCENARIO

Once the THRUST study has been installed and operating, a typical event scenario should occur in the following manner (see Figure 1).

An earthquake will activate the seismic trigger. This instrument then transmits four messages through the GOES system which responds by initiating an alert code back through the GOES system to the RTP located at the Hydrographic Institute in Valparaiso. The RTP instantly responds by initiating a prerecorded message based on the Standard Operating Plan and procedures established prior to the tsunami. The message format THRUST will use is similar to the following (THRUST Pilot Study, 1983):



VALPARAISO EARTHQUAKE ALERT

A strong earthquake occurred at ____z on ______ in the vicinity of the city of Valparaíso. Contact the following authorities:

- Oficina Nacional de Emergencia Telephone Nº 718333
- Department of Geophysics Telephone Nº 6968686

and advise them of this earthquake alert and disseminate the attached tsunami watch message.

TSUNAMI WATCH

Establish a tsunami watch. A tsunami may accompany this earthquake. If a tsunami occurred, the wave will retard in reaching the coast at the shown localities the next specified times:

Valparaíso	minutes
Coquimbo	minutes
Caldera	minutes
Talcahuano	minutes
Chañaral	minutes
Corral	minutes
Antofagasta	minutes
Isla de Chiloé (Ancud)	minutes
Tocopilla	minutes
Iquique	minutes
Arica	minutes

Remember, this is only a tsunami watch. No tsunami has been observed but one may occur.

Figure 3.
RTP message format.

In addition, The GOES alert code will initiate the water level sensors in the Valparaiso harbor to begin sending data via satellite to CDA. This information can then be accessed via telephone line.

Note that this process is entirely automatic and should take no more than 10 minutes to complete. But no real decisions have been made, except possibly a predetermined one to sound a general alert. Final authority to make decisions, to issue further alerts or sound the evacuation alarm, must rest with human officials. This task should be made simpler because of several factors. The decision makers will now be familiar with the historical and potential hazard analyses performed during the pre-event phase and will now be aware of the general type of threat the coast of Chile faces. Also, because of the Standard Operating Plan implemented during the project; IHA will have a set of procedures to follow and should not find it necessary to improvise. In addition, because of the public awareness program established during the project, the Chileans should be confident that the threatened population know how to respond to ensure their own safety. And lastly, the Chileans can be sure that the sensors and the real-time analysis package are providing them with the most up-to-date information available.

CONCLUSIONS

The goals of THRUST are to show that such a system can be built, to work with the Chilean government to integrate the technical system into its disaster control structure, and to train the Chilean personnel in the operation and maintenance of the system. Each phase of THRUST, then, will be conducted in conjunction with personnel from Chile. In this way the technology behind THRUST can be demonstrated to other tsunami-prone (and geophysical hazard-prone, in general) nations, while concurrently enhancing the technological capabilities of Chile. Successful completion of the THRUST project will not only enhance the tsunami protection of Chile but will, by adding additional input to PTWC, improve the protection of the entire Pacific community.

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V - OPERATIONAL PROCEDURES

TSUNAMI WATCH AND WARNING PROCEDURES

Gordon D. Burton, Pacific Tsunami Warning Center

From its inception, the Tsunami Warning System has functioned on an operational basis through the detection and evaluation of an earthquake to determine the probability of tsunamigenesis followed by the evaluation of sea level data for confirmation or negation of the actual generation of a destructive tsunami. Initially a Tsunami Advisory was issued based on the evaluation of the earthquake data, but this term was officially changed to Tsunami Watch in 1966. The decision to issue a Tsunami Warning was based on an evaluation of the sea level data obtained from the nearest tide stations.

This dual Watch/Warning concept remains in use at the Pacific Tsunami Warning Center (PTWC), although the Watch Bulletin has been modified to become a Regional Tsunami Watch Bulletin which officially only places those countries in a Watch status which fall within a 6 hour tsunami travel-time of the issuance of the Regional Tsunami Watch Bulletin. This paper will examine from an operational perspective the application of procedures for the issuance of the various PTWC Bulletins documented in the Communication Plan for the Tsunami Warning System, Tenth Edition.

To better understand operational procedures, imagine yourself as a watchstander at PTWC with the responsibility for responding to the seismic alarms and making the decision as to whether to issue an Earthquake Information Bulletin, a Regional Tsunami Watch Bulletin, a Tsunami Warning, or to simply work up the event and then take no further action. What criteria should be used in making such a decision?

Regional Tsunami Watch Procedures

A Watch has historically been used to notify TWS participants of the possibility of a tsunami and to advise that a tsunami investigation is underway. As such the initial Regional Tsunami Watch Bulletin is issued using only seismic information to determine the probability that a tsunami may have been generated. This is based on the earthquake location being coastal or near coastal, with a shallow depth hypocenter, so as to pose a potential tsunamigenic threat. As for size of the earthquake, the most commonly used measure is that of magnitude on the Richter scale (Ms), with a threshold value of 7.5 used to determine the need to issue a Watch. For events in Alaska, the Richter magnitude threshold is lowered to 7.0 as the basis for issuing a Watch.

The above standards provide the PTWC watchstander with a very quantitative and easily applied measure for making the determination on the operational requirement to issue a Regional Tsunami Watch Bulletin. The real question is how realistic are these standards in terms of addressing the true tsunami threat? This must be addressed from two perspectives: 1.) how accurate is PTWC in determining the location and size of the earthquake, and 2.) how accurate are the established threshold standards as a reflection of the true tsunamigenic potential of any given region?

With regard to the accuracy of PTWC's determination of earthquake parameters, a study has been done of all event workups since January 1983, the date when the satellite data communications circuit was established with the U.S. Geological Survey's National Earthquake Information Service (NEIC) to provide PTWC with real-time seismic data from the mainland. Using the parameters published by NEIC in the Earthquake Data Report (EDR) as the most reliable standard, PTWC's determination of epicenters varies in accuracy from within an average of 30 miles in the northern hemisphere to an average of 75 miles for the southern hemisphere. Richter magnitude (Ms) determinations vary, with 85% of all events determined by PTWC on an operational basis falling within 0.2 units of the Richter scale as published in the EDR. The determinations of epicenter location and earthquake size are operational problems for which an inherent error margin always exists, but PTWC's accuracies are as satisfactory as can be obtained on an operational basis and certainly meet the requirements for accurate evaluation of any significant earthquake in the Pacific basin.

The accuracy of earthquake magnitude threshold standards as a true reflection of the tsunamigenic potential of a region is a very different problem. The threshold values of 7.5 for the Pacific with 7.0 used for Alaska are based on the historical generation of tsunamis around the Pacific, with the operational emphasis being on the generation of destructive Pacific-wide tsunamis. The lower Richter value of 7.0 for Alaska is based solely on the tsunami of April 1, 1946, which was associated with a magnitude 7.4 earthquake.

How realistic are these threshold standards? On an overall basis for the entire Pacific, again with the emphasis on the generation of destructive Pacific-wide tsunamis as documented historically, the value of 7.5 seems remarkably good for the issuance of a Watch, particularly when considering the possible error range in determining the Richter magnitude. However, on an area-by-area analysis, it is quite easy to document numerous instances in which the threshold value of 7.5 is inappropriate for determining the probable generation of a tsunami, particularly one which may be destructive primarily in the near source region. It is operationally naive to assume that a magnitude 7.8 earthquake in the Tonga-Kermadec Trench has the same tsunamigenic potential as a magnitude 7.8 event off the coast of Chile. At the same time it is operationally naive to use the uniqueness of the 1946 Aleutian tsunami to establish a lower magnitude threshold for Alaska and ignore the similar uniqueness of the 1896 Sanriku tsunami in Japan which was also associated with a lower magnitude earthquake.

The geotectonics, and therefore the tsunamigenic potential, varies on an area-by-area basis around the Pacific. Operational procedures should reflect the probable tsunamicity of each region. An initial attempt in this direction has been implemented with the Regional Tsunami Watch system, which recognizes that not all tsunamis pose a Pacific-wide threat and therefore distant TWS participants need not be unduly placed in a Watch status until the true threat has been better determined. One operational weakness of this Regional Watch system has been the failure to develop improved threshold criteria on a regional basis for implementing the Regional Tsunami Watch procedures. At the present time, the PTWC watchstander is still using the same threshold criteria for issuing a Regional Watch as was used for previously issuing a Watch on a Pacific-wide basis.

Tsunami Warning Procedures

Again imagining yourself as the PTWC watchstander, what guidelines and criteria exist for making the decision to issue a Tsunami Warning Bulletin? The operational intent of a Tsunami Warning is to alert TWS participants of the generation of a destructive tsunami. The guidelines available to the watchstander for issuance of such a warning are very vague and only state that a Warning will be issued after confirmation has been received that a tsunami has been generated that poses a threat to the population in part or all of the Pacific.

The problem for the PTWC watchstander comes in determining what constitutes such a confirmation. Other than the earthquake size and location, the only data coming in to PTWC are reports from TWS tide stations. If a 20 meter wave is reported, the decision to issue a Warning may be quite simple, but what if only a 20 centimeter wave is reported? That may provide confirmation that a tsunami has indeed been generated, but does it constitute a potential threat? This becomes the age-old question of, "How big a wave is a tsunami?". This question has been left solely to the subjective judgment of the PTWC watchstander, and not all watchstanders have similar capabilities of experience, training, and judgment. Because of the location of the tide gauge relative to the coast as well as relative to the distance and direction from the tsunami source region, a 20 cm sea level fluctuation at one tide gauge may be insignificant, while the same measure may be extremely critical at another station.

There is no question PTWC will function properly for really destructive Pacific-wide tsunamis. However for the many tsunamis which are destructive in the near-source region and pose minimal threat to distant participants, the operational procedure of either issuing a Pacific-wide Warning or no Warning at all must be questioned. At present, no quantifiable standards exist to aid the watchstander in making the most important decision for which he is responsible.

Operational Analysis of Seismic Gaps

As mentioned earlier in the presentation on "Activities and Responsibilities of the PTWC", the PTWC staff are involved in a continuing operational evaluation of procedures based on presumed earthquakes occurring at selected locations around the Pacific. For the most part, these selected locations coincide with seismic gaps, areas designated as having a high probability for the future occurrence of large earthquakes.

The use of one such area as an example, the Kamchatka seismic gap, will illustrate the studies being conducted at PTWC. For a presumed earthquake along the coast of the Kamchatka peninsula, the travel-time contours of the seismic P-phase are mapped to display the availability of seismic data for the PTWC watchstander. Given a significant magnitude earthquake, the P-phase contours can be used to determine alarm activation at any seismic station, for example, 9 minutes for PTWC. The same P-phase contour chart provides information on what other seismic stations can be used to determine earthquake location and when that data will be available to PTWC. For a Kamchatka event, P-data will be available to PTWC from all real-time mainland stations within 12 minutes of the earthquake origin. P-data from real-time stations in Japan would be available to JMA within 6 minutes and to the Royal Observatory in Hong Kong and to Guam Observatory within 8-9 minutes. Given the response time of the PTWC watchstander in reporting to the office and computing the earthquake epicenter, a preliminary location will be available within 19 minutes or less after the earthquake origin.

In a similar manner, the seismic surface wave travel-times can be contoured to evaluate the availability of data needed to determine the earthquake magnitude on the Richter scale (Ms). For this particular event, the magnitude based on surface wave arrival at PTWC would be available 26 minutes after the origin. This would be the earliest time at which PTWC could determine the need to issue a Regional Tsunami Watch Bulletin.

In addition to preparing a seismic phase travel-time chart, a tsunami travel-time chart is contoured based on a presumed tsunami originating from the Kamchatka seismic gap. This chart graphicaly illustrates the tsunami arrival sequence throughout the Pacific and provides PTWC with an evaluation of when sea level data might be available from participating TWS tide stations. For this particular event, sea level data would only be available from three TWS stations 3 hours after tsunami generation. These would be Shemya and Adak in Alaska and Hachinohe in Japan. This does not constitute an optimal data base upon which the PTWC watchstander must determine the need to issue a Tsunami Warning Bulletin.

In an effort to improve PTWC operational procedures for a Kamchatka event, the historical earthquake and tsunami data are then summarized for the area. These data not only confirm that tsunami generation is a frequent occurrence along the Kamchatka coast, but that the tsunamis generated pose a threat to distant TWS participants as well as near the source. Moreover, using the historical data available, almost every earthquake of Richter magnitude (Ms) exceeding 8.0 has generated a potentially destructive Pacific-wide tsunami. For events between 7.5 and 8.0, no tsunamis were reported for many earthquakes, although tsunamis were reported for some events.

These historical data support the present seismic threshold of 7.5 used by PTWC for issuance of a Regional Tsunami Watch Bulletin, although consideration should be given to directly issuing a Tsunami Warning if the earthquake magnitude exceeds 8.0. A further analysis of the historical data, however, documents some events with a Richter magnitude between 7.0 and 7.5 which generated tsunamis which were recorded at distant stations, but were not destructive. PTWC's present operational procedures do not specifically address this type of problem, other than to have initiated a general investigation to determine the tsunami threat.

The historical data can also be used to determine quantitative thresholds for the issuance of a Tsunami Warning based on the response of particular tide stations to historical tsunamis. For a Kamchatka event, it can be determined that sea level fluctuations exceeding 50 cm at the three nearest TWS tide stations of Shemya, Adak, and Hachinohe generally have been associated with a Pacific-wide tsunami which had a destructive potential elsewhere. This 50 cm threshold at these tide stations can therefore be used as a quantitative value by the PTWC watchstander to determine the issuance of a Tsunami Warning. For Kamchatka events, therefore, this is an initial attempt to define the question posed earlier, "How big a wave is a tsunami?".

Operational Analysis of Historical Data

In close coordination with the International Tsunami Information Center

(ITIC), PTWC has been conducting a detailed analysis of historical earthquake and tsunami data on an area-by-area basis around the Pacific. The operational premise is that when the seismic alarms have been activated, and the location and size of the earthquake determined, the historical characteristics of that area can provide the PTWC watchstander with a preliminary evaluation of the tsunamigenic potential to be expected. This can be used not only on a short-term basis to permit the watchstander to more intelligently apply present operational procedures, but on a longer term basis to allow PTWC and ITIC to develop improved operational procedures which more accurately reflect the true tsunami threat from any particular region in terms of its near-source impact as well as far-field impact.

Several examples can better illustrate the use of historical data. For the coast of California, the historical data confirm the evaluation of a low tsunamigenic potential. No destructive Pacific-wide tsunamis have been generated in this region, with the 1906 San Francisco earthquake (Ms = 8.3) only resulting in a minor tsunami of 10 cm amplitude. The maximum tsunami run-up recorded along the California coast was less than 2 meters associated with the 1927 earthquake having a magnitude of 7.3 on the Richter scale. Using the historical data, the California coast can be characterized as a region of infrequent major or great earthquakes where any tsunamis generated tend to be minor or potentially destructive on a limited scale only in the near-source region. This is what might be expected of a tectonic regime dominated by horizontal surface displacements, with the primary tsunami generation mechanism probably associated with secondary slumping of sediments set off by the earthquake. One must now ask whether PTWC's present procedures are the best available for addressing the probable tsunami threat for this region. Is it realistic to place Mexico, California, Oregon, Washington, Canada, Alaska, and Hawaii in a Watch status for a magnitude 7.6 earthquake near the coast of California?

By contrast, we can study the historical data for the southern Kurile Islands and northern Hokkaido. The occurrence of major and great earthquakes is more frequent than for California, with at least 50 events of magnitude equal to or greater than 7.0 documented since 1900, with 36% having generated tsunamis. These tsunamis have frequently been destructive near the source region, and usually have been recorded on a Pacific-wide basis without being destructive. The historic data reveal further tectonic complexities of this area with the generation of destructive tsunamis associated with lesser magnitude earthquakes. For instance, the earthquake of 20 October 1963 had a Richter magnitude of 6.8, yet generated a tsunami with as much as 15 meters local run-up and minor waves recorded as far as Hawaii and Samoa. Using the PTWC procedures of initiating queries to tide stations only if the Richter magnitude exceeds 7.0 obviously does not adequately address the true tsunami threat from the southern Kuriles. With both Japan and the U.S.S.R. immediately threatened by tsunamis from this source region, PTWC's operational procedures might be reexamined as to how PTWC can provide optimal tsunami warning services to both near-source and far-field TWS participants.

Summary

PTWC's Watch and Warning procedures have essentially remained unchanged since the inception of the Tsunami Warning System, with the exception that the Tsunami Watch has been regionalized to cover only those countries included within a 6-hour tsunami travel-time. The threshold for issuance of a Watch remains the occurrence of an earthquake of Richter magnitude 7.0 for Alaska and 7.5 for the remainder of the Pacific. Issuance of a Warning is based on the judgment of the PTWC watchstander.

An operational analysis of the historical earthquake and tsunami data on a detailed area-by-area basis is being used to improve the implementation of Watch/Warning procedures through the better identification of earthquake magnitude thresholds as related to probable tsunamigenesis and through the analysis of historic tsunamis as recorded at individual tide stations. The goal is to improve tsunami warning services to TWS participants by using present procedures in a more optimal manner or by developing improved procedures where needed to address not only the probability of tsunamigenesis, but to also develop a predictive tsunami evaluation capability on both a near-source and far-field basis.

WATER WAVE REPORTING PROCEDURES

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International Tsunami Information Center

At the present time the Tsunami Warning System in the Pacific makes use of an international network of 24 seismic stations, 53 tide stations and 52 dissemination points in the Pacific Ocean Basin. A number of automated sea level monitoring gauges are also operated by the Tsunami Warning System in close cooperation with the University of Hawaii for the Integrated Global Ocean Services System (IGOSS) and for the IGOSS Sea Level Pilot Project (ISLPP).

These stations transmit data via satellite in real time to the Pacific Tsunami Warning Center (PTWC) in Honolulu. Although data from such stations is of great value in the assessment of potential tsunamis in the Pacific, the Tsunami Warning System relies heavily on the conventional tide gauges operated by Member States of the International Coordination Group for the Tsunami Warning System in the Pacific (ITSU).

The data from such stations is transmitted primarily by satellite or by conventional means. However, tsunami detection and reporting at such stations is the responsibility of the local authorities operating these important tide gauge stations. For each such station, observers and substitute observers are assigned with the responsiblility of maintaining the stations, changing the records, calibrating the instruments, and reporting any unusual water level activity related to a tsunami.

A publication entitled "Wave Reporting Procedures for Tide Observers in the Tsunami Warning System" was prepared in 1975 by the Intergovernmental Oceanographic Commission and distributed to Member States of ITSU for use by designated tide observers. Also the manual was distributed to several other non-member states and governmental and non-governmental agencies which also participate in the Tsunami Warning System. At the present time, this manual is undergoing revision and a new edition reflecting changes will soon be published and distributed by IOC.

The purpose of the publication is to provide general information and specific instructions to assist tide observers in reporting properly tsunamis to PTWC in Honolulu. The manual provides general information related to the nature and description of tsunamis, the Tsunami Warning System, and the Plan of Communications being used for data acquisition and tsunami watch and warning dissemination. Specifically, the publication defines the duties and responsibilities of observers and safety measures to be taken to avoid risks in the event of a large tsunami.

Furthermore, the manual outlines the types and formats of messages that are being exchanged between PTWC and observers during a tsunami investigation as well as the types and formats of monthly communication tests. Finally, the manual covers specific wave reporting procedures when a station is alerted of a potential tsunami arrival or when the station responds on its own when a tsunami event is either observed or activates an alarm at the station.

The procedures illustrate with numerous graphical examples the types of initial wave activities that may be observed at different stations emphasizing particularly slope changes of the water level recordings in relation to time and height scales. The procedures caution for proper interpretation of the tide gauge records differentiating from background oscillations caused by wind waves and seiches which have different heights and frequency ranges than tsunami waves. Finally the procedures designate periods and frequency of observations and message format for reporting sea level fluctuations caused by a tsunami.

The following are graphical examples of tide gauge recordings of normal tides which may include wind induced waves, records showing windwaves and seiche oscillations and, finally, examples of initial sea level change due to a tsunami followed by subsequent sea level oscillations manifested by continuing tsunami activity. Figures 1, 2, 3, 4, are such examples. Figures 5 and 6 are examples of actual historical tsunamis as recorded by tide stations in the Pacific Tsunami Warning System.

Reference: Intergovernmental Oceanographic Commission (IOC). Wave Reporting Procedures for Tide Observers in the Tsunami Warning System. Manuals and Guides 6. Paris, France: UNESCO, 1975.

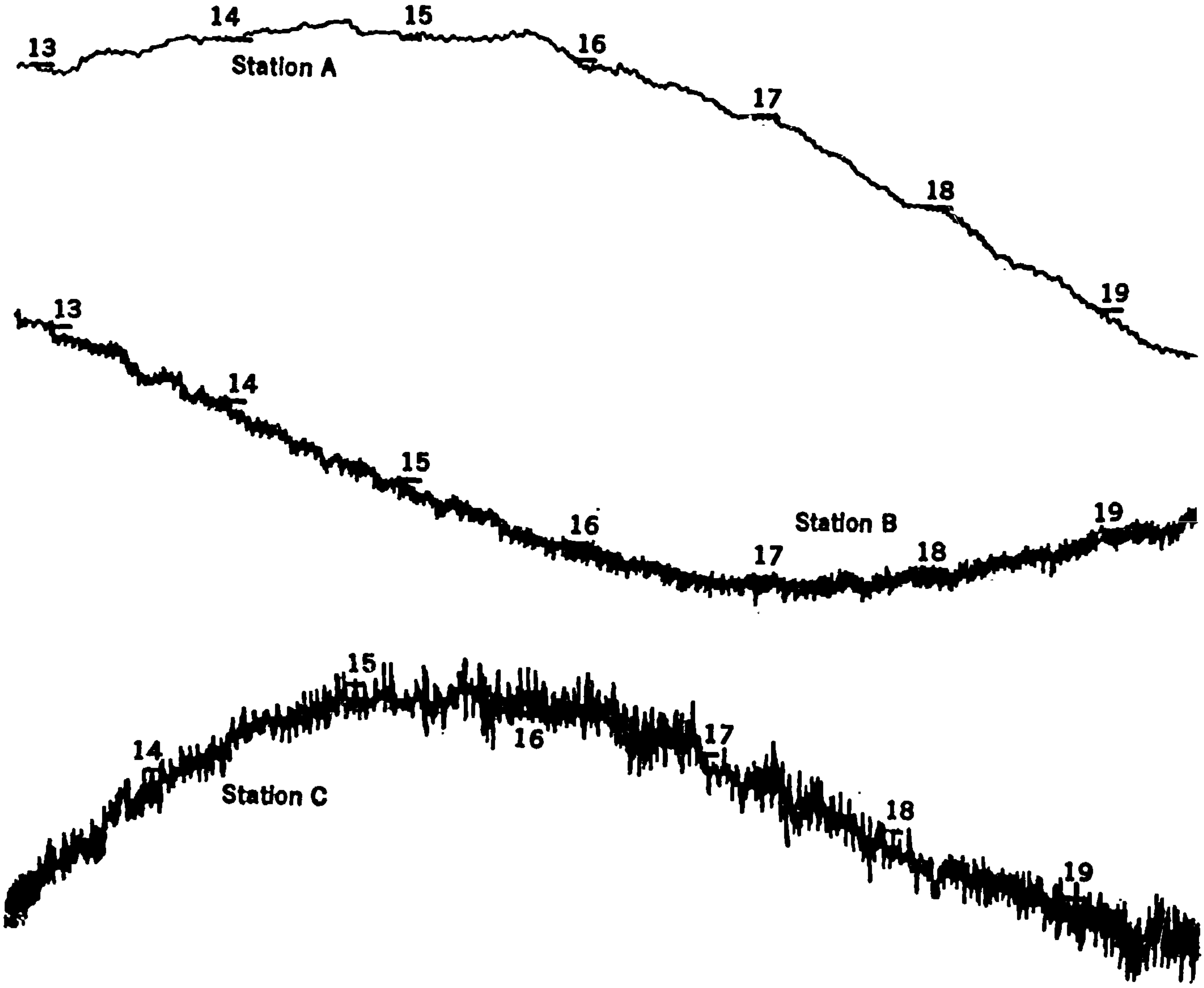

Figure 1. Examples of normal tide gauge records showing wind waves.

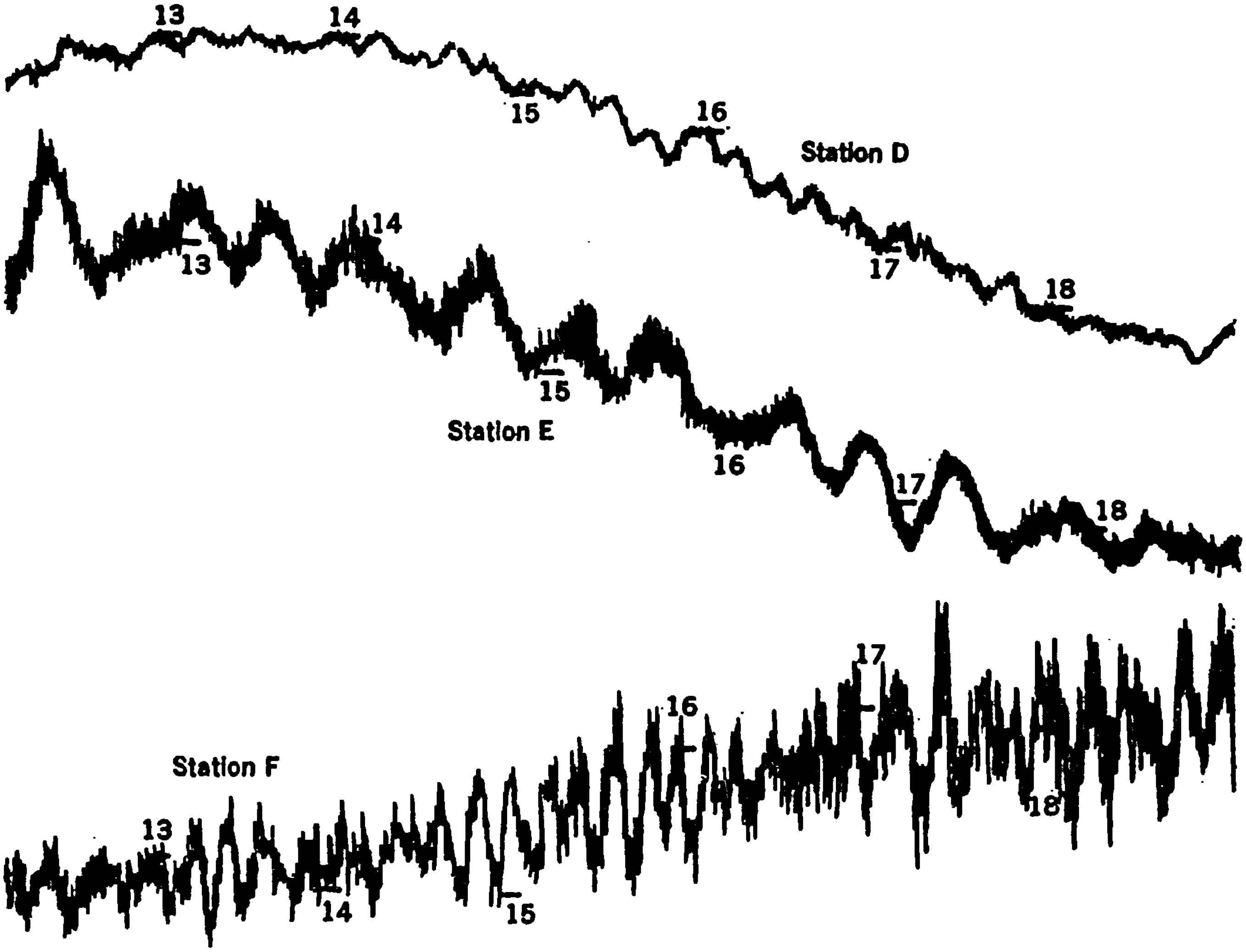

Figure 2. Examples of tide gauge records showing wind waves and local seiche oscillations.

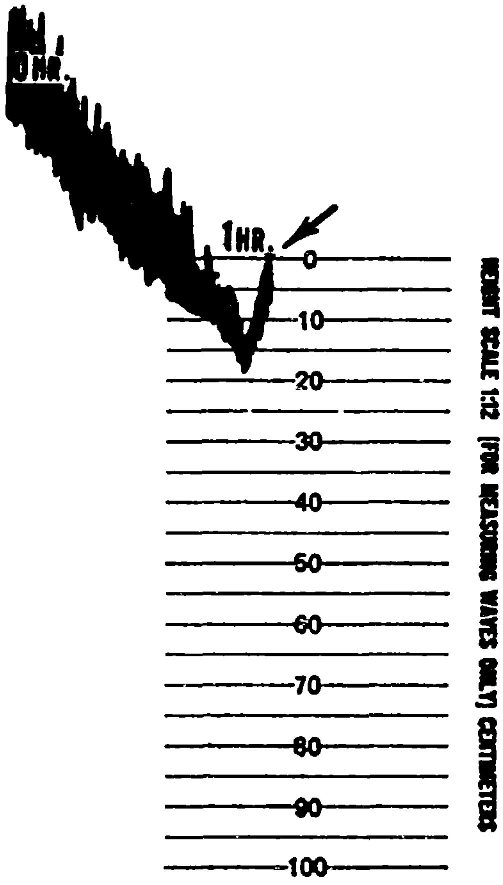

Figure 3. Example of initial tsunami disturbance as recorded at the Santa Monica tide gauge.

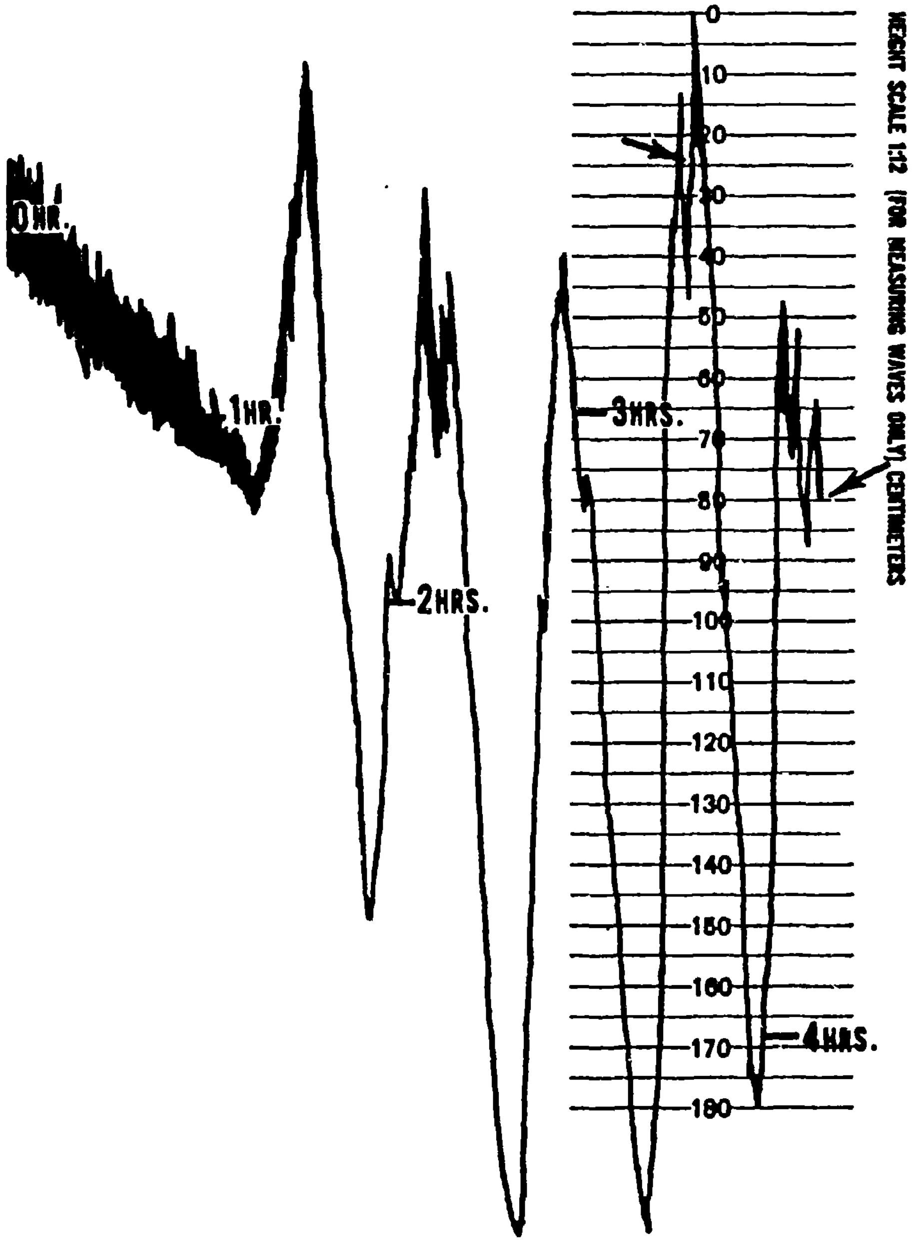

Figure 4. Subsequent tsunami oscillations as recorded by the Santa Monica tide gauge.

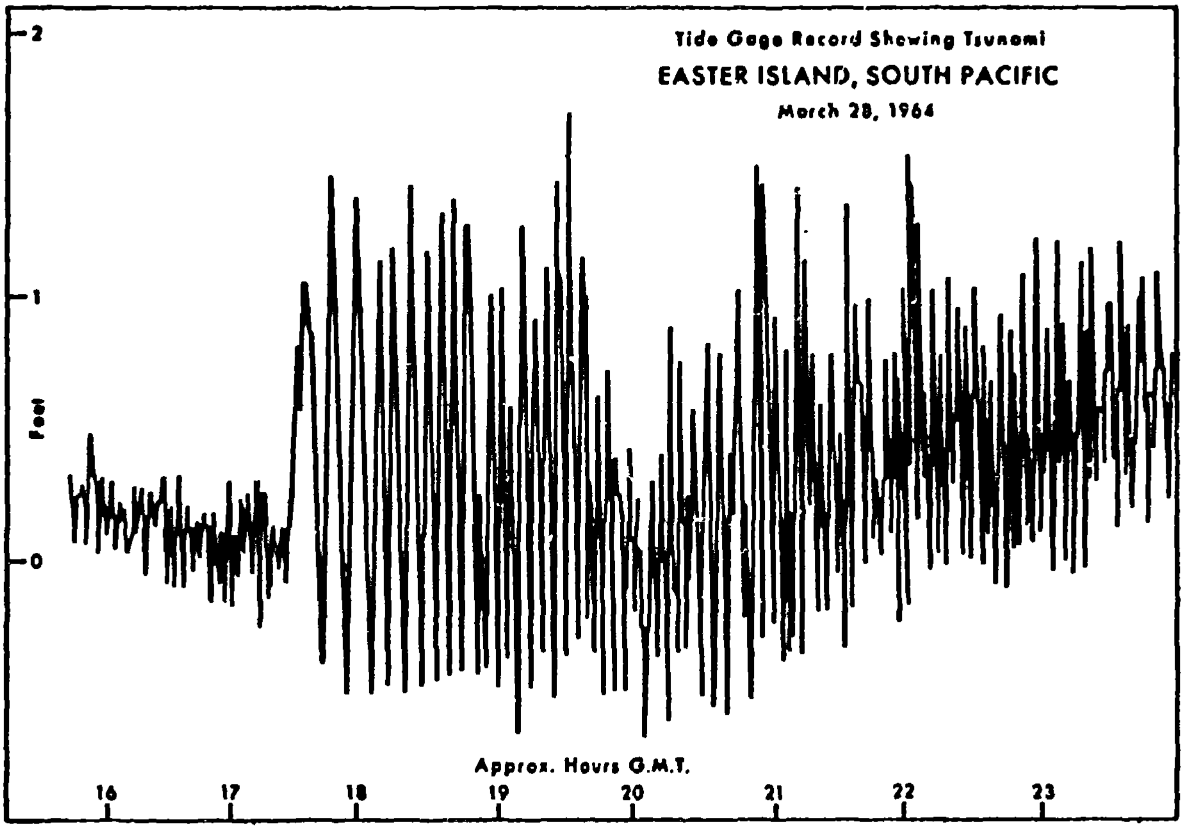

Figure 5. Example of tsunami as recorded by tide gauges at Easter Island.

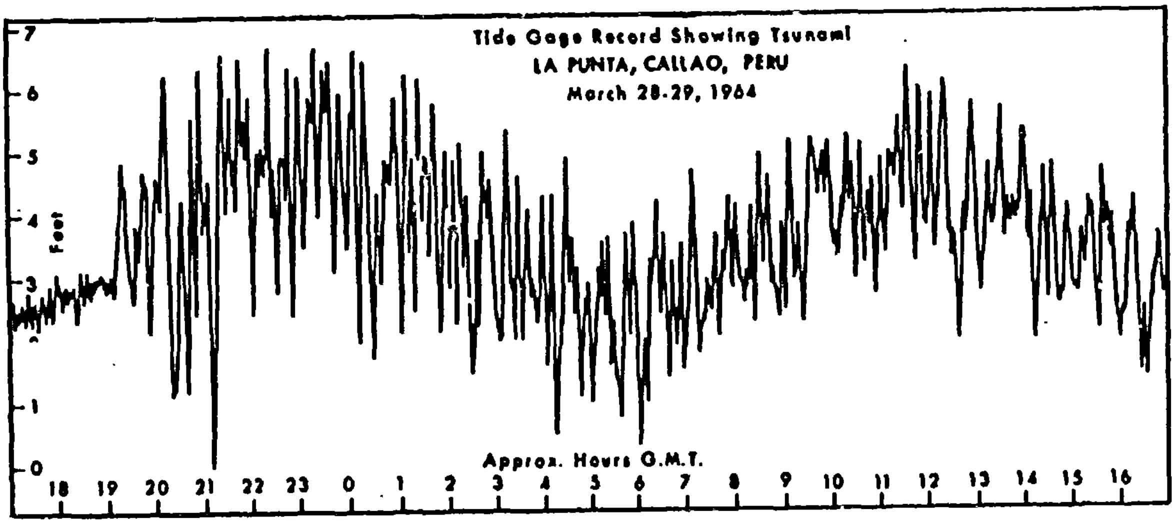

Figure 6. Example of tsunami as recorded by tide gauges at Callao.

COMMUNICATIONS

Richard H. Hagemeyer
U.S. National Contact, ITSU

I will be talking this afternoon on communications as it relates to the Pacific Tsunami Warning System. I don't intend to talk forever but I do have a number of points which I wish to cover. These will include: 1) some background and the tsunami communications system as it exists now; 2) what I perceive to be some generic deficiencies in the present system (Edition 10 of the Communications Plan); 3) how these surfaced following the March 3, 1985 Chilean earthquake; and 4) some of the things that I think can and should be done to impove the functioning of the present Plan.

In the National Weather Service we liken the process of producing and delivering a forecast or warning to the user as a five link chain. We consider each link to be as important as the next and realize that the failure of any one link is, in effect, the same as the failure of the entire chain. These links are labeled DETECTION, COMMUNICATIONS, GUIDANCE/FORECASTING, DISSEMINATION, and USER RESPONSE. Here COMMUNICATIONS means the transmission of the fact of detection to the FORECASTING/GUIDANCE function and DISSEMINATION means the transmission of the end product to the user. It appears that we will be covering all of these aspects during the course of this Workshop. Within the context of the Communications Plan and this presentation "Communications" will encompass both of these.

In order to look at the Communications Plan, we should first consider the nature of the communications that take place within a Tsunami Warning System. These are best categorized as non-operational and operational, with the operational communications including:

1. Data acquisition or data exchange, primarily for tidal or seismological stations;

2. Dissemination of information, i.e., Watches, Warnings, or Information Bulletins; and

3. Routine testing of the Communications System.

For data communications, the Alaska Tsunami Warning Center (ATWC) and the Pacific Tsunami Warning Center (PTWC) use a combination of telephone lines, VHF and microwave to receive seismic and tide data from locations within their regional areas of responsibility. Commercial satellite communication is used by both Centers through a seismic data exchange with USGS/National Earthquake Information Center (NEIC). In this way ATWC obtains real-time seismic data from stations along the West Coast and PTWC obtains real-time seismic data from a network of stations extending from the Eastern U.S. to the Western Aleutians. Beyond the local area the acquisition of tide data in order to confirm the generation of a tsunami is, compared to the acquisition of seismic data, still pretty much in the dark ages. Until just recently PTWC has had to depend exclusively on telephone/telegram/telex for the collection of remote tide information. During 1985 we have begun the establishment of a number of satellite reporting tide stations - this will be discussed in some detail in the section on improvements.

Except for telephone communication with Civil Defense staffs in their respective areas of regional responsibility, hardcopy communication via various teletype circuits remains the primary method of communicating tsunami information to TWS participants throughout the Pacific. Facsimile communications, such as RAPICOM, have been investigted, but at this time do not appear to satisfy the necessary operational requirements for disseminaticn of tsunami information.

NEED FOR A COMMUNICATION PLAN

On an operational basis when a major earthquake has occurred, communication becomes critical and is the heart of the Warning System. Seismic data must rapidly be obtained to locate and evaluate the earthquake. Sea level data must be rapidly obtained to confirm or negate the generation of a tsunami, and to provide data for evaluation of the tsunami threat. Upon completion of an evaluation of the data by the Warning Center, information must be rapidly disseminated to all participating agencies.

When operational communications are involved, human lives are involved and time cannot be wasted looking for information. There is a need for documentation which lists all the active participants in the System who either provide data or information to the Warning Center or who receive information disseminated by the Warning Center, and the methods by which such communications are accomplished. The primary purpose of such a document is to address those stations where interactive participation is required to provide data to the Warning Center or where participants are responsible for enacting immediate disaster mitigation measures based on the information received from the Warning Center. As such, the document must be accurate and current in content to be useful.

Within the Tsunami Warning Service this document is call the Communications Plan and it covers the data collection and watch/warning dissemination of both PTWC and ATWC.

This, or any communications plan, to be useful must have several characteristics:

a. The listings must be accurate and current;

b. Stations and agencies listed must provide 24 hour-a-day capability;

c. The listings for data sources (i.e., seismic and tide stations) should document the method by which each station communicates to the Warning Center;

d. The listings for dissemination agencies should document the method by which the Warning Center transmits information to that agency;

e. When available, alternate methods of communication should be listed;

f. The number of listings and the methods of communications used must reflect a realistic and achievable capability that can be met by the Warning Center on an operational basis.

Because of the widespread dissemination of the NWS Communications Plan on an international basis, the Plan has been extended to include some summary information on operational procedures by the Centers as well as general information of the nature of tsunamis. In this manner the Plan provides basic information that might otherwise be included in an Operations Manual devoted to the strictly operational aspects of a Warning System. Communication may be the most critical element of an operational system, but the Communciation Plan does not attempt to address all aspects of operations. At present, there is no comprehensive Operations Manual as such for the Tsunami Warning System. Operational information contained within the Communication Plan is supplemented by other sources, such as the manual, "Wave Reporting Procedures for Tide Observers in the Tsunami Warning System."

GENERIC DEFICIENCIES

There are two areas of what I consider to be generic deficiencies in the current Communciations Plan. The first of these is the almost exclusive dependence on commercial telephone or telegram/telex for the acquisition of confirming tide information. The first place that we would look for these data would be in the area of origin and this is the place most likely impacted by the potentially tsunamigenic earthquake. There is a high probability that the earthquake will destroy or badly damage the infrastructure and this will severely complicate the process of getting data out of the source region. (This is what happened in Chile during the March 3, 1985 earthquake). The second deficiency is in the international dissemination of information generated by the Centers. The number of locations where there is a two-way exchange of data are extremely limited. There are a number of other locations to which watches, warnings, etc., are sent but since there is no arrangement for acknowledgement the responsible Center has no way of knowing if the message reached its destination. Further there are some areas of potential impact, Tuvalu and Kiribati for example, that to our knowledge receive no information. A further observation might be made that there are members of ITSU who, for all practicable purposes, are not participants in the System.

PROBLEMS RELATED TO THE MARCH 3, 1985 EARTHQUAKE

The March 3, 1985 Chilean earthquake presents an interesting casebook study of what can go wrong with the present communciations system when the infrastructure is disrupted by the earthquake. The earthquake occurred at 032247 UTC and PTWC efforts to reach Valparaiso were unsuccessful as were immediate efforts to get data out of Peru. It was not until 040249 UTC, Mr. Emilio Lorca, through perseverence and a lot of luck was able to get through to PTWC with tide information. (If you want to hear an interesting and sometimes hair raising story ask him about what happened). Regular communications were not re-established with Valparaiso until almost 22 hours after the earthquake, so if Mr. Lorca had not gotten through to PTWC at the time he did, we would have had to wait until 041030 UTC for fsunami confirmation. That is the time when any generated waves would have reached Tahiti. If the initial evaluation of the earthquake had been 7.5 or above in magnitude and PTWC had issued a Watch, then the initial watch area would have been expanded, hour by hour, and would have included parts of the Tuamotos and half way up the coast of Mexico by the time Mr. Lorca made contact with PTWC. If that contact had not been made then by the time first confirmation was available from Tahiti the watch area would have included New Zealand, Samoa, New Caledonia, Papua New Guinea, the U.S. West Coast, Canad, and Hawaii. With the ETA in Hawaii less than three hours after Tahiti the Hawaii Civil Defense would have declared a warning and begun evacuation. Fortunately the initial magnitude determination was a marginal 7.4 and a watch was not issued.

IMPROVEMENTS TO THE SYSTEM

The first thing that needs to be done is to establish a reliable method of receiving tide data that basically is independent of the infrastructure at the tide gauge's location. One method of doing this would be the use of strategically located ocean bottom pressure systems that are capable of sensing the passage of a deep ocean tsunami wave and transmitting that information to the Centers responsible for issuing Watches and Warnings. There is an ongoing program within the U.S. directed at developing and deploying these devices. A second method involves the use of satellites for data relay. this would consist of Data Collection Platforms (DCPs) containing a microprocessor which is programmed for a multi-channel input to sample sea level every five seconds and to average and store the data over four-minute intervals. The data are then transmitted by the U.S. Geostationary Operational

Environmental Satellite (GOES) to PTWC. GOES transimissions are normally made every four hours to provide a continuous record of sea level activity for the preceeding interval. The DCPs also have the capacity to be programmed as event detectors and to commence random transmissions on the GOES emergency channel whenever the sea level thresholds characteristic of a tsunami are exceeded. These latter transmissions are made in a near real-time mode (3 to 5 minutes). Within the last year DCPs programmed as event detectors have been installed at Rarotonga, Cook Islands; Baltra Island in the Galapagos; La Libertad, Ecuador; and La Punta, Peru. These were installed as a part of a cooperative effort between the National Weather Service, the University of Hawaii, and Oregon State University. In addition to the tsunami function they also transmit data to meet the needs of the National Science Foundation Sea Level Network, TOGA, and the Integrated Global Ocean Services System (IGOSS) Sea Level Pilot Project. In addition, 5 existing or new DCPs installed and operated by the University of Hawaii have been reporgrammed to provide sea level data to PTWC, but do not function as event detectors. These DCPs are located at Majuro in the Marshall Islands; Nauru; Kapingamarangi Atoll; Rabaul on New Britain; and Honiara on Guadacanal. This represents a good beginning but the numbers should be substantially increased for optimum tidal data coverage.

The second thing that needs to be done is to expand the areas covered by the current Watch and Warning distribution system. This should encompass the inclusion of locations not now receiving tsunami messages, the establishment of a "feedback" mechanism on message receipt, and the more active participation in the TWS by members of ITSU who are not now doing so.

Recent experience has shown that a person-to person exchange is one way that can be used to improve communications within the TWS. This can be done as a part of the IOC sponsored Visiting Scientist program or through travel by staff members of the Centers. Both have been used this past year to very good effect.

I hope that through these remarks I have enlightened you, may be somewhat raised your level of interest in this aspect of the TWS, and possibly encouraged you to take a more active role in improving this aspect of our system. Thank you.

VI - TSUNAMI PREPAREDNESS

TSUNAMI HAZARD ANALYSIS, TSUNAMI HAZARD PLANNING, PROTECTION MEASURES, TSUNAMI EXERCISES AND PUBLIC EDUCATION

G. Pararas-Carayannis
International Tsunami Information Center

INTRODUCTION

It has been clearly documented that tsunami have had a very important and long-term socioeconomic impact on the communities of the Pacific and on our society in general (Pararas-Carayannis, 1983). However, the historical record does not prepare us for the potential damage that can now be caused by tsunami in the coastal areas of many developing or developed coastal countries where development has taken place in the last 20 years. It is expected that future tsunamis will have a much more severe social and economic impact than that of past events. Thus, assessing the tsunami hazard and preparing for such future events is very important.

Tsunami hazard analysis precludes a good understanding of what tsunami events have occurred in the past, and how often and to what extent these events have affected the region under study. In the absence of adequate historical data, physical and computer tsunami models can be utilized to define quantitatively the tsunami hazard for proper planning and adequate preparedness. Preparedness involves proper hazard planning, protection measures for the safety of the public, and comprehensive educational program which includes exercises and public education.

TSUNAMI HAZARD ANALYSIS

The risk potential of tsunamis is of extensive interest to governmental, nongovernmental agencies, and to industries and the public in general. Management of the tsunami hazard precludes analysis of the risk in planning for mitigation, and good perception of the risk by those responsible for the protection of public safety and property. It is important that the hazard is evaluated properly and that the potential threat is correctly estimated. Underestimating the tsunami threat can be both expensive and counterproductive. Reduction of the tsunami risk is the responsibility of government agencies and any misconceptions related to its proper assessment can produce the potential for unnecessary deaths and destruction.

In most communities tsunami hazard mitigation strategies are applied on an ad hoc basis in an uncoordinated manner, usually following the occurrence of an actual event. Such strategies can be far more effective, however, if they are implemented before the occurrence of a catastrophic tsunami. The success or failure of any safety program rest on a valid appreciation of the distribution of the tsunami risk. For this reason a specific regional risk assessment must be undertaken to determine how the tsunami hazard differs in its spatial distribution and potential severity of impact. Risk is not an absolute and can be reduced by proper planning, proper public education, and proper land use.

Historical Studies: Studies of historical tsunamis of local and distant origin is the first priority in the analysis of the tsunami hazard. The seismicity of the region should be studied in order to establish the potential threat from locally generated earthquakes. Analysis of the seismicity of the region should go back in time as far as possible, and a historical tsunami data base should be developed consisting of all collected information. Similarly, tsunamis from distant earthquakes should be evaluated by careful review of historical information, films, photographs, newspaper articles and diagrams available from government and university archives, newspaper files, television studios, church groups, and private collections. Such information may contain data which may shed light in the spatial difference in the distribution of the tsunami impact of past events which in turn may allow the zonation of the hazard.

It is possible that major damaging events may not have occurred locally during the period of record taking. However, it may be possible to obtain eye-witness accounts of past events as remembered by older residents passed down by word of mouth. Such information may be great value particularly those in which the person interviewed was a victim or nearly so of the disaster and remembers with clarity the event. Similarly, legends of a tsunami catastrophe may have survived. However, such accounts may be distorted and should be evaluated carefully in identifying the potential tsunami risk and its recurrence frequency.

Tsunami Hazard Frequency: The next most important information needed in the tsunami hazard analysis is the recurrence frequency of tsunamis. Assuming that the historic record is long and there have been many years of direct observations it is possible to establish the frequency of tsunami events. However, if the historic record is limited, planners cannot rely on such short record alone to evaluate the tsunami hazard. Large catastrophic events may take place so infrequently in any one location that there may be no locally available data on which to predict risk and produce a zonation of the hazard. This should not be misinterpreted to mean that there is no danger. A statistical approach may be the only way for the prediction of the spatial distribution of the tsunami disaster. The statistical distribution in the occurrence of extreme events has been treated by Gumbel (1958). In this, he suggests that the recurrence intervals of exceptionally large phenomena bear consistent relationships to their magnitude expressed in either arithmetic or logarithmic terms. Thus, 50 years of data can be used to extrapolate and determine the once-in-a-thousand-year event. Of course this approach is rather vague as the confidence limits are usually so large so that the resulting estimates of recurrence are largely meaningless. On this basis it is very difficult to accept the statistics of extreme events as the basis for planning. In such cases one may have to resort to tsunami modelling studies as described in the following section.

Physical Modelling: In the absence of historical information, the tsunami disaster may be simulated by making scale models of coastlines and introducing scale models of buildings and other aspects of land use into physical models. Then the tsunami may be produced with appropriate wave generators and its impact can be photographed, measured, and recorded. Such models have been made, for example, for Hilo Bay by the U.S. Corps of Engineers and in close cooperation with the University of Hawaii. Many other hydraulic models have been built to assist in predicting the potential of the tsunami disaster. Such models are expensive to construct and to scale down in size both geometrically and kinematically. However, physical models have been very useful for important coastlines where important engineering structures have been built.

Computer Modelling: Computer models permit relatively accurate predictions of the potential tsunami inundation and can be invaluable in the management of the tsunami hazard. The construction of such models involves four common elements. The first of these elements is an initial analysis of the physical characteristics of the tsunami hazard. This permits the subsequent development of the mathematical model which is capable of forecasting the severity of the tsunami impact for different events approaching the coastline under study from different directions. Such an approach leads to the development of the spatial pattern of impact intensity which in turn can be used for the microzonation of the tsunami hazard. Most numerical models deal primarily with the extent and height of tsunami inundation leaving all other engineering interpretations to planners and engineers. From such models the extent of damage can be estimated and evacuation limits can be established to minimize deaths and injuries. This information is normally presented in a map form with tabulations so that both the spatial distribution of the tsunami risk and its gross impact can be established.

Zonation of the Tsunami Hazard: The final product of the historical studies of the recurrence frequency, and of the Hydraulic and Numerical Modelling, is a representation of the spatial variations of the tsunami hazard along a given coastline where expected tsunami height can be quantified and evacuation limits designated. These are prerequisites for proper planning. Because of the extreme selective nature of tsunami destruction along given coastlines, a microzonation map of the tsunami hazard may be required which will be of great usefulness in planning and management of the hazard. Similarly, the total risk at any point can be established by such studies, as well as the probability of occurrence for insurance purposes. The production of large scale maps depicting variations in the degrees of tsunami risk are invaluable tools in the disaster planning process. In this way, high risk areas can be avoided or used for low intensity development only.

In producing maps of the tsunami hazard, attention should be paid to scale requirements so that the significance of the hazard can easily be identified and correlated to prominent landmarks. Such maps should be sufficient for precise planning of land use and should include vertical and horizontal parameters of scaling that are sufficiently large. For example, the tsunami inundation maps that had been produced for Hawaii have been made at scales of 1:63,360, and 1:24,000 respectively. All that can really be suggested is that the selected scale be large enough to make full use of the available data and thus permit individual sites and structures to be identified, if possible. It should not be so large, however, that it gives an invalid impression of precision in areas where the information does not warrantee such a position. Figure 1 (below) is an example showing potential tsunami inundation maps for Hawaii.

TSUNAMI HAZARD PLANNING AND PREPAREDNESS

There is very little that can be done to prevent the occurrence of a tsunami. In the past, before tsunami warning systems were established, there was a passive approach to this type of hazard. But while these natural disasters cannot be prevented, their results, such as loss of life and property, can be reduced by proper planning and preparedness.

The tsunami hazard is not frequent and when it does occur its destructiveness varies from place to place. With proper planning it is a hazard that can be dealt with effectively, and its effects can be considerably mitigated. No matter how remote, the likelihood of a tsunami should be considered in developing plans for public safety and land use management. While some degree of risk is acceptable, government agencies should promote new development and population growth in areas of greater safety and less potential risk (Pararas-Carayannis, 1983). Such government agencies should formulate land-use regulations for a given coastal area with the tsunami risk potential in mind, particularly if such an area is known to have sustained tsunami damage in the past.

Tsunami Hazard Planning and Preparedness require proper hazard analysis as outlined previously. This is fairly simple for certain regions of the Pacific and very difficult for others. Once the historic record of tsunami activity has been examined and proper studies have been completed, only then, fundamental questions of preparedness can be addressed, such as: What safety measures can be taken by authorities in protecting the coastal population and vital coastal resources, industries and structures? How can the risk of the tsunami hazard be minimized? Are public safety personnel properly trained to deal with the disaster? Are relief facilities adequate to respond in an emergency situation? What level of risk is acceptable? .

Public Safety: Public safety should be the primary consideration. Government agencies have the responsibility of evaluating the tsunami hazard in accordance with the methodology described and establishing adequate warning procedures to protect the communities under their jurisdiction. It is difficult to establish acceptability of the tsunami hazard in terms of risk to life. It is the responsibility of the planners to establish standards of an acceptable personal risk and ratio of injury to fatality. From a moralistic point of view any loss of life is unacceptable whether directly or indirectly associated with the potential hazard.

Protection of Property: The level at which property risk becomes unacceptable will generally depend upon the socioeconomic cost of the disaster and of the size of the benefits accruing from the property in question. For example, loss of agricultural property and land use may be more acceptable than loss of a nuclear power plant. For such reasons, high risk standards may be required for certain lifeline facilities since this often imposes a great social and economic disruption cost, should they fail. Examples of this type of land use may include communication centers, chemical factories, nuclear power plants, and other important engineering structures. Any unnecessary risk to such unique and vital or dangerous properties may result in enormous secondary damages in case of failure (Pararas-Carayannis 1976). For this reason risk should be decreased to the greatest technologically feasible extent by proper design and land utilization. Other lifeline facilities may bear substantial social costs, such as loss of important facilities, as hospitals, fire stations, or police services. Such services are vital in disasters and their facilities should be appropriately protected to guarantee their ability to function during periods of emergency.

Warning Procedures: The key element to a tsunami safety program is a tsunami warning system. For areas where such a system is not functioning it should be established to allow for the monitoring of potential tsunami disasters and for the issuance of warnings. Civil Defense Agencies should establish plans for evacuation or other preventative measures to be taken when a tsunami danger arises. Present tsunami protective measures involve primarily existing tsunami warning systems which employ advanced technological instrumentation for data collection and for warning communications. Many developed nations of the Pacific have developed sophisticated warning systems and have accepted the responsibility to share tsunami warning information with other countries of the Pacific.

Tsunami Exercises and Public Education: A program of public education is the minimum requirement to minimize loss of life. Warning procedures should be established, and once established, they should be reviewed frequently to define and determine better respective responsibilities between the different government agencies at all levels. These agencies should publish proper training for public safety personnel and for the citizens in general. Tsunami exercises should be held frequently. Warning procedures are inevitably more successful if community awareness has been heightened and a disaster plan drawn up to ensure that all necessary tasks are accomplished with a minimum of delay or confusion during a tsunami disaster. To accomplish this objective a comprehensive program of public education is necessary.

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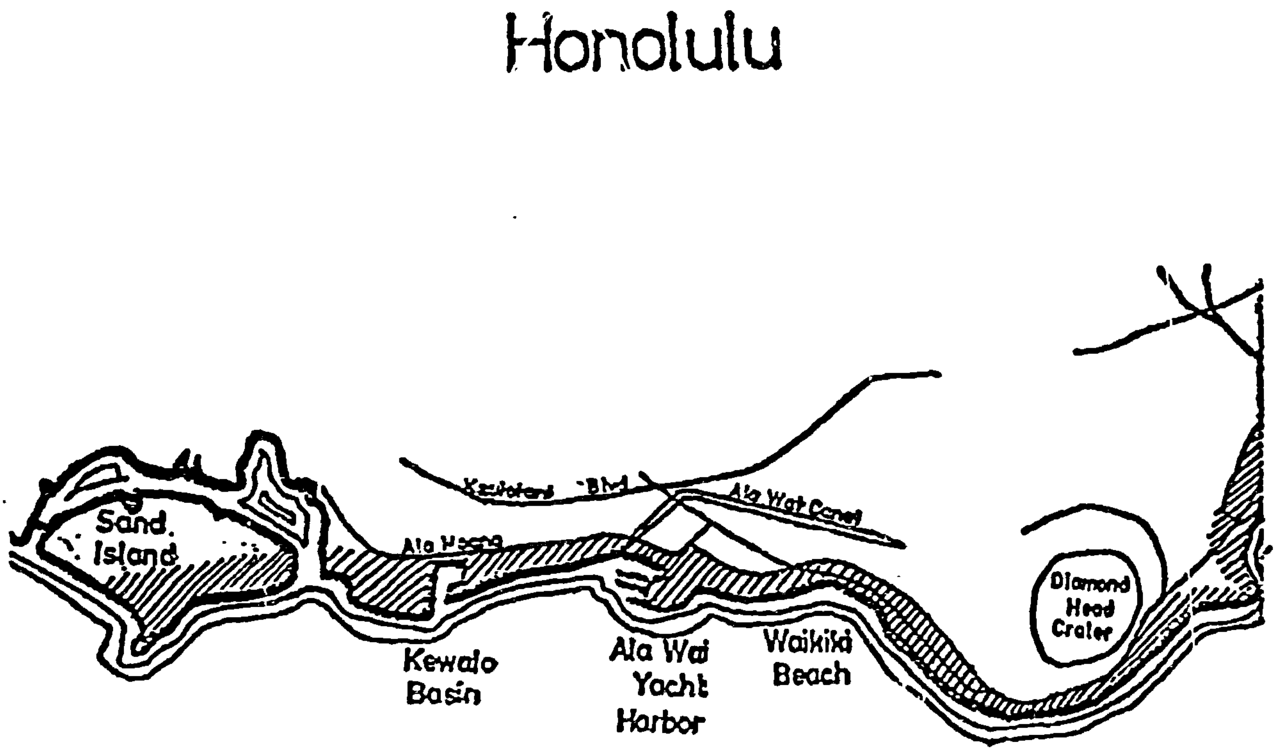

Figure 1. Tsunami inundation map for Honolulu, Hawaii.

INVESTIGATION FOR TSUNAMI HAZARD MITIGATION IN DEVELOPING COUNTRIES

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SYNOPSIS

Two previous studies made in Perú on seismic microzonation and vulnerability of Metropolitan Lima (ML) had shown the necessity to investigate the tsunami effects on the 100 kms of ML sea shore. The run up, inundation zones, and the arrival time of nearly generated tsunamis were found for urban planning purpose - and to prepare realistic evacuation plans for people living in inundation built up areas. To verify the soundness of the used method and the assumed nypothesis, the numerical results were check with actual records and historical data. The comparison was very satisfactory in spite that the method used was practical and unsophisticated, and may be useful for developing countries located - around the Pacific basin.

INTRODUCTION

For developing countries located in disaster prone areas, planning for mitigating their effects is a must, to give good use of the scarce economic resources and to avoid catastrophic - losses, a during the 1970 Perú earthquake when 67,000 lost their - lives and the material loses amounted more than USD 500 millions, and the 1983 torrential rain originated by el Niño phenomena when the losses were about USD One Billion in Perú, marking worse the - country difficult economic situation.

But realistic physical planning requieres a detailed knowkedge of the natural conditions existing at the area to be occupied by settlers to located important engineering projects.

According to this premise during the 70's a microzonation study method was developed in Perú (1)*, in which not only the relative seismic wave amplification was taken into account, but also all types of natural disasters menacing the area of interest as inundations, land slides, etc. At the end of that decade the method was simplified to be use in planning of small to medium size human settlements (2)

To apply the microzonation method to low coastal areas, where tsunamigenic earthquake occurs, it is apparent that tsunami run up and delimitation of the inundation areas are needed.

On the other hand, from 1973 to 1978, a vulnerability study of Metropolitan Lima was made under the auspice of Perú Civil Defense (3). From that investigations it was concluded that the most critical areas were the city old sections, where there are numerous overcrowded adobe constructions built before 1940. In Callao the nearby seaport, the old section is located in tsunami inundation area. Persons trapped under the debris of those constructions may not be rescued on time if the area is attacked by tsunamis generated near the coast. For evacuation plans or rescue works, the time elapsed between the ocurrence of the tsunamigenic earthquake - and the arrival of the first tsunami wave to coast, is critical.

In due of these necessities, tsunamis investigations were made in Perú under UNDRO auspice during 3 years (1981-83), resulting mainly in a Civil Engineering thesis (4) and a special report to UNDRO and the Peruvian government (5). To the international community the studies were reported in two papers: During the 8th World Conference on Earthquake Engineering (San Francisco, CA, 1984) (6), in which emphasis was given to the physical planning of settlements near the sea shore; and in this paper, where tsunami investigation itself is of prime concern, so that the author who is a new comer in this field, may receive suggestions and criticisms from the tsunami experts attending this event, and may be useful to other developing countries with similar problems.

TSUNAMI INVESTIGATION IN PERU

Tsunami has caused one of the worst natural disasters in the Peru's history. In October 1746, tsunami waves generated by a near origen 8.4 magnitude earthquake, razed Callao, killing 4800 of its 5000 inhabitants. In the western coast of South America, most of the destructive tsunamis had been generated at the trench extending from Callao-Perú to Valparaiso-Chile. Outside of that area, tsunamis have been reported in only two locations in southern Chile, in 1960 and in Tumaco-Colombia, in 1906 & 1979.

This study was concentrated in the 100 kms of Metropolitan Lima coast, the country most important, extending from Ancón to Pucusana. Callao is located about the center of that stripe. There, distant tsunami have caused negligible damages on inland infraestructure in the last 4 1/2 centuries, in contrast with the Hawaiian Islands where tsunamis generated in the Pacific basin is received directly in some point of theirs 360° of coast, and most of the damages had been caused by distant tsunamis.

It seems to be that because of the orientation of the studied coast, tsunamis generated from southern Chile, along the western coast of the Americas, Kamchatka and Japan have negligible effects there. For example, the 1960 Chile tsunamis did not cause noticiable damages in Perú, but caused heavy destructions in Hawai and northern Honshu in Japan.

Due to the orientation of the Kermadec-Tonga trench in relation to the peruvian coast, tsunamis generated therefore may cause damages in the studied area, therefor special care should be taken if warning is issued for tsunamis originated there.

Historical information show that destructive tsunamis that have affected the peruvian coast had their origin east of the Perú-Chile trench. i.e., between that trench and the coast. On the other hand, there are tsunami refraction charts of distant tsunamis and other useful informations developed by a well organized scientific community. In contrast, very few investigations have been made in developing countries located in the Pacific basin on tsunamis with near origin. For these reasons, this study pay more attention to tsunamis coming from near source.

Since this investigation is a consequence or continuation of two previous studies, its objectives were clear:

- Delimit the tsunami inundation areas of the 100 kms of the Metropolitan Lima coast. The present population of Lima is 5 millions. At the beginning of the next century, only 20 years away, the population will increase to about 10 millions. Thousands will settle along the coast. To protect those people and their investment, it is necessary to take in consideration tsunami inundation in the urban planning and design. A large population requieres an extense recreational area. A stripe parallel to the sea shore is appropriate for that use. Its width is one of the information found in this study.

- The arrival time of the first tsunami wave originated near the Lima coast must be determined to prepare realistic evacuation plan for the people living in tsunami inundation area, being critical La Punta, a low lying 2.4 km long peninsula.

Conscious of the limitation existing in a developing country, the investigation method used was practical and direct, however it requires engineering judgement and the numerical results need to be compared with actually recorded tsunamis, earthquake data and historical information to verify the soundness of the method used and the assumed hypothesis.

For determining the tsunami run up, the Yamaguchi formula was used the disturbed ocean bottom was assumed to be an ellipse which was used, as original shape of the wave front. The size of the major and minor axes were fixed as function of the - earthquake magnitude according to the Iida criteria. The sea bottom countours information was provided by the Dirección de Hidrografía y Navegation, DHINA, of the Peruvian Navy. The boundary of the - inundation areas were determined using the japanese experience(7). For most of the places it was assumed that the wave height decline with a slope of 1% as forward inland.

To select the most probable location and orientation of the sea bottom disturbed area, the isoseismal lines of past earthquakes weve examined together with the boundary and interface between the Nazca and Southamerican plates. It was specially useful the epicenters of the 1966 and 1974 Perú earthquakes, which were considered to be reliable data. By drawing a straight line across those two points, it was found to be parallel to the coastal line. This result is solid with the former data.

The refraction drawing of the 1966 (M= 7.5 ,78.6°W, 10.7 S) and 1974 (M= 7.5, 77.8° W, 12.3°S) earthquakes were made using known method (8). The location of their epicenters were used as origen of the ellipses with the major axis parallel to the coastal line. Figs 1 &2 show the refraction curves of the 1966 tsunami and the one recorded at La Punta- Callao, with the earthquake local time mark ($16^{h}\ 41^{m}\ 58^{s}$) and the arrival local time of the first tsunami wave ($17^{h}\ 36^{m}$), giving a difference of 54^{m} . From the drawing, that difference is also 54^{m} . In general it is not expected such an agreement. It was considered that the result shows that the method, hypothesis and data used were sounds.

The 19[illegible] earthquake had just its epicenter offshore in front of Lima, i.e, the most unfavorable location to give the minimun arrival time to its coast. The difraction drawing and the recorded tsunami at La Punta- Callao, were given in Ref. 6. The travel time are respectivaly 25 m and 21 m. The october 1746 tsunami arrived to Callao 30 m after the earthquake. Three different methods gave acceptable results. Considering wider disturbed area for larger earthquake magnitude, but limited by the interface wide of corresponding interacting plates, it was recommended to take 20 minutes for preparing the evacuation plan for the area.

It was also prepared a chart for a fast estimation of the arrival time of the first tsunami wave to any coastal point of ML as function of earthquake magnitude and the parameters discussed before (5).

According to the sea bottom topography, the tsunami run up were calculated for different point of the 100 km ML coast ranging from 6.7 m in Pucusana in the south, to 3.2 m in Ancón in the north, and 7 m for La Punta- Callao.

An investigation made for the area by Hebenstreit and Whitakert (9) gives 9 m for La Punta- Callao, for the case of sea bottom instantaneous and uniform uplift and 3 m. in case of variable uplift, but with the source rather north from Lima. If the first hypothesis is compared with actual facts is possibly a bit conservative. The 1746 tsunami reached to a point 1.3 km inland where the elevation is 6 m over the sea level. Some people survived on the top of a thick defense wall located near the shore and 7 m over the sea level.

Taking in to account all these informations the inundation area for La Punta- Callao was delineated.

In the same way the inundation areas of towns located at ML shore and some areas to be occupied by settlers in a near future were drawn. General recommendations were given for urban planning and design to mitigate the tsunami destructive effects in the studied area (6).

WORKS IN PROGRESS

The works on tsunamis are being continued in two directions : public education, by spreading basic knowledges on tsunamics, the investigation results and the evacuation plan, and, detailed studies of La Punta- Callao inundation built up areas and Punta Negra, for physical planning for hazard mitigation.

Public education and evacuation plan.

For preparing a realistic evacuation plan for people living in tsunami inundation areas, it is necessary to have reliable data and the full cooperation of the involved persons. To do so, tsunami basic informations key numerical results of the investigation made for the area, and the prepared plan, have to be of their knowledge.

In coordination with Perú National Committe of Civil Defense and the auspice of UNDRO, two types of publication have been prepared:

- A 91 pages report (5), which includes: tsunami related problems in ML, general information on tsunami, method used in the investigation, numerical results and graphics for the 100 Kms of ML coast, inundation and shelter areas, and evacuation routes for each studied locality, together with the evacuation plan. This publication will be delivered to local authorities : municipal, civil defense, navy, police. Private clubs and organizations. Shool teachers and the most educated people of the community who may take the leadership in case of emergency.

- A 8 pages pamphlet, in wich minimum requiered information is included, so that in case of emergency people may react rationally and in a flexible way, according to the circunstances that may be somehow different to the prepared evacuation plan. This publication is to be hand over to all families living in the tsunami inundation areas. The distribution of these publication will be complemented by lectures in the respective localities.

Physical planning for tsunami hazard mitigation.

General recommendations have been given for physical planning of the studied area (6), but application for specific area requieres a more detailed investigation. For this purpose two locations have been selected : La Punta - Callao, where a large population live in the tsunami inundation area, including a relative extense area covered by old adobe constructions, and Punta Negra a small town located 48 kms south from Lima. This town was choosen because it was considered to be appropriate for a pilot study , and later used as model solution for settlements along the 100 kms of ML coast, where hundred of thousands of new inhabitans is going to live in the next 20 years.

To get support for this project a proposal have been prepared together with Urban Regional Reserarch (URR) of Seattle, Washington and submited to USAID by the Perú National Council of Science and Technology* URR have experienced in physical planning for tsunami hazard mitigation in the Hawaiian Islands and Alaska. At the mean time necessary basic informations are being collected in coordination with URR. (* CONCYTEC)

ACKNOWLEDGEMENT

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To the authorities of UNI, Peru Civil Defense, and DHINA for the facilities given during the investigations.

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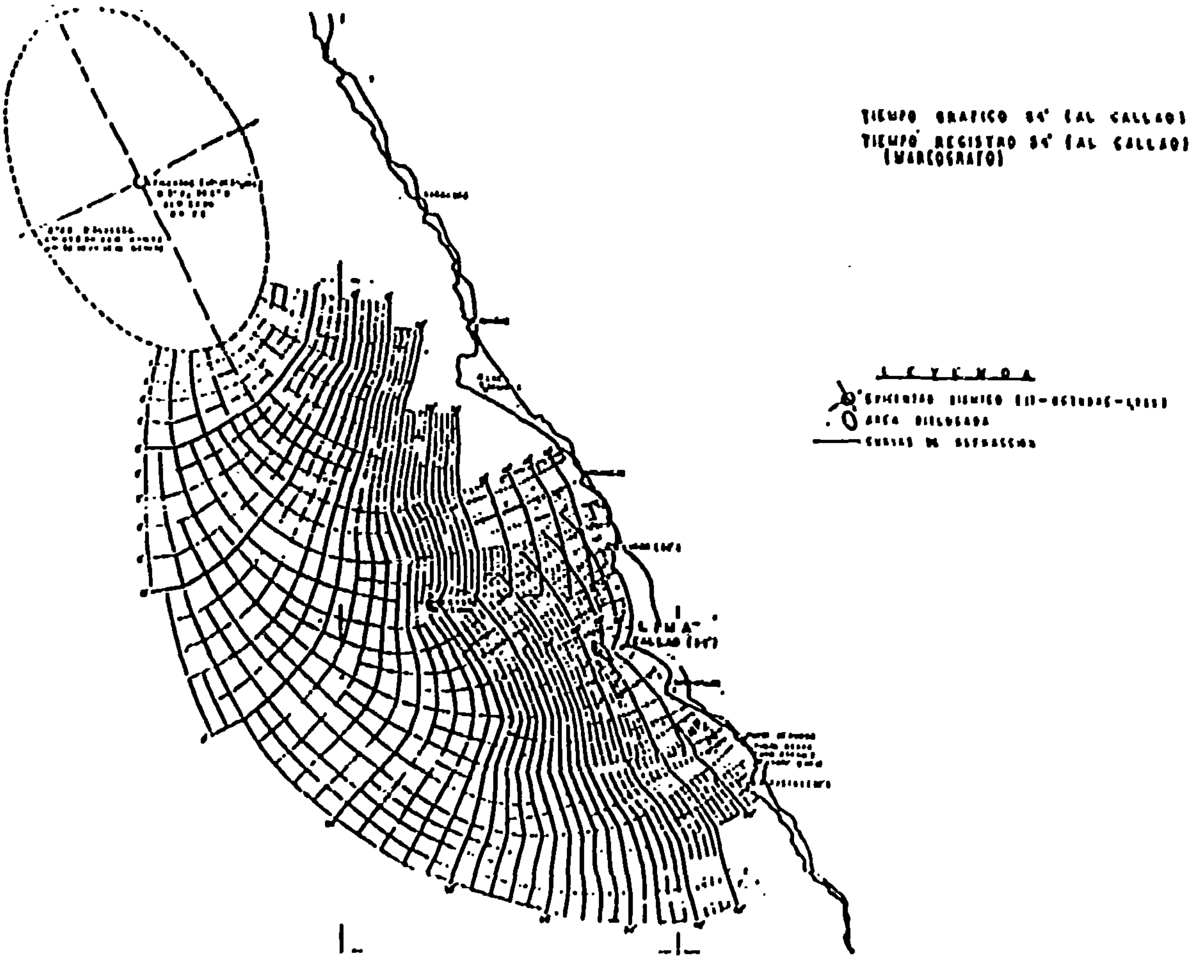


FIG. 1 .-October 17, 1966 tsunami refraction diagram.

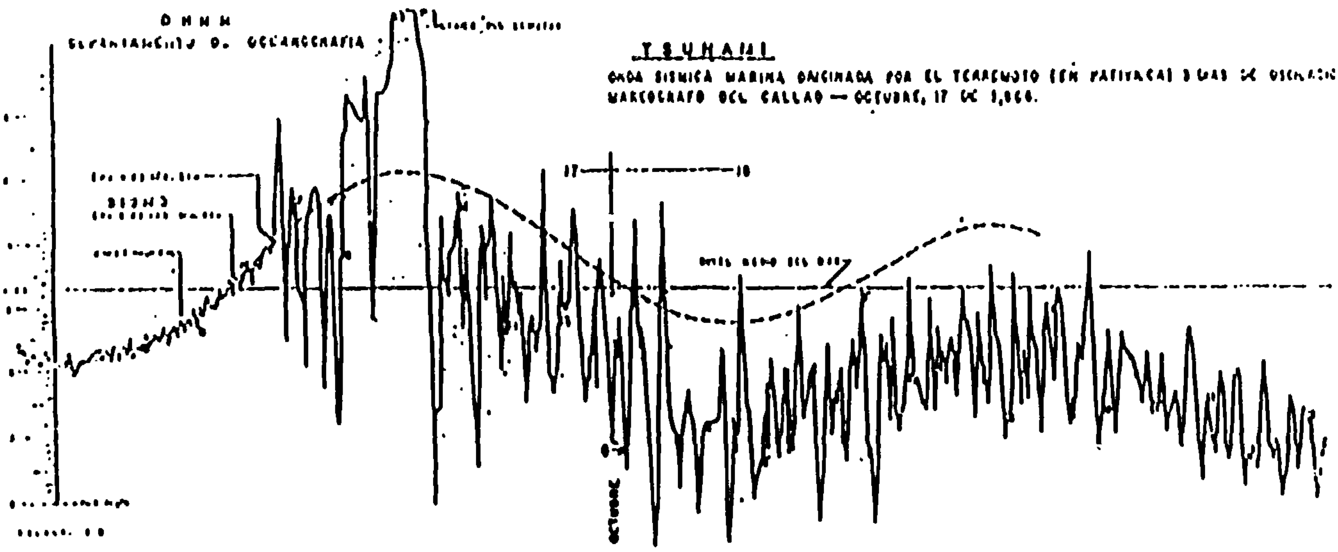
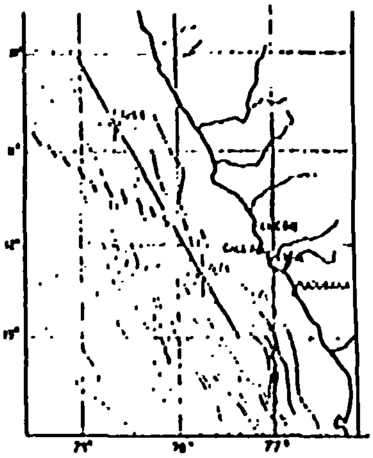
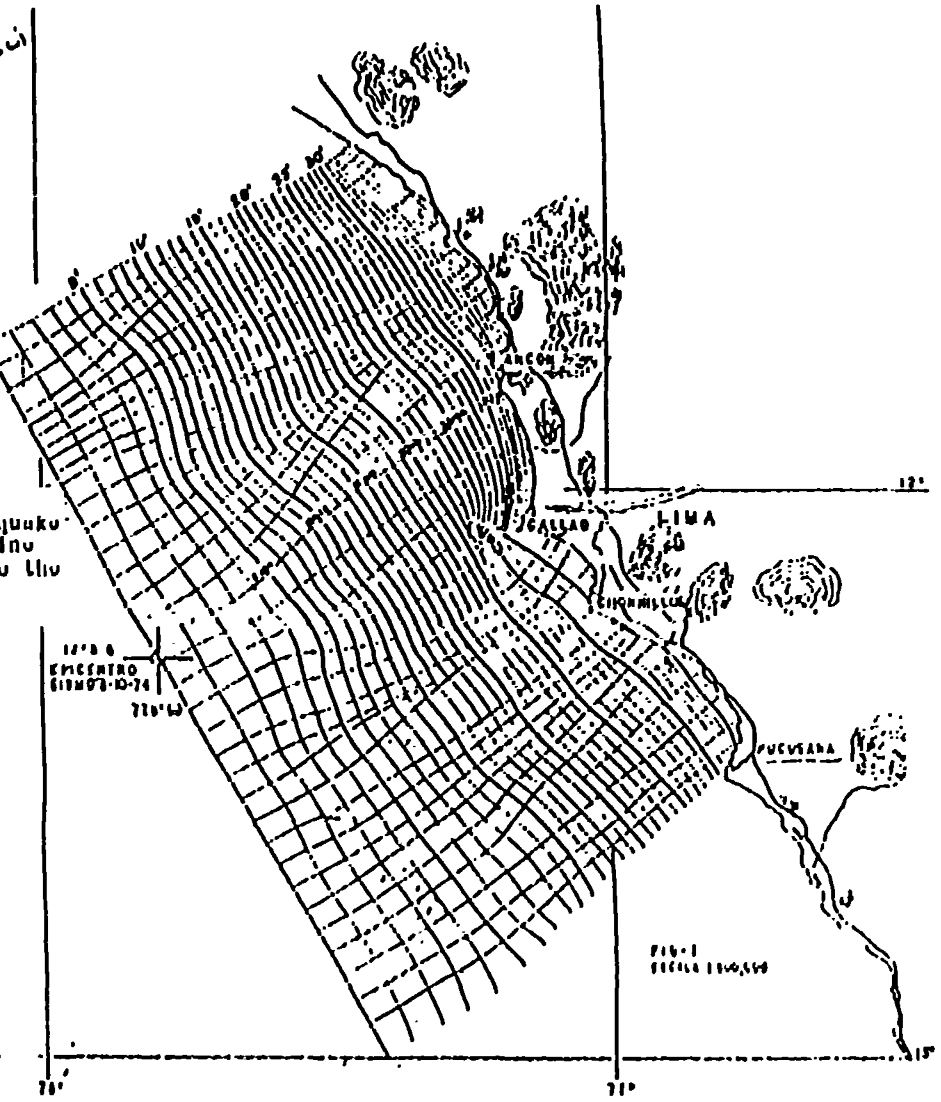


FIG. 2 .- October 17,1966 tsunami. Tide record in La Punta-Callao (Courtesy of DHINA of the Peruvian navy).

FIG. 3a.-1966 & 1974 earthquake epicenters. Note that the line across them are parallel to the coastal line.





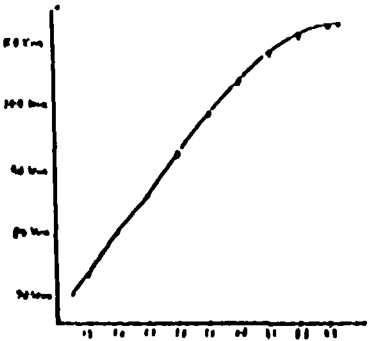


FIG. 3c.-Lenght of the ellipse minor axis b as function of the earthquake magnitude.

FIG. 3b .- Chart for fast estimation of the minimum arrival time of the first tsunami wave as function of the assumed earthquake magnitude to any point of ML between Ancón & Pucusana.

1.- Select the point of interest on the coast in Fig. 3b and draw a perpendicular to the line of epicenters.

2.- From Fig. 3c, according to the assumed earthquake magnitude, obtain b

3.-From the intersection of the perpendicular and the line of epicenters, return b/2 in the direction of coast.

4.- From the total time subtract b/2. The difference gives the minimum arrival time to the selected point

VII - TSUNAMI RESEARCH

STATUS OF TSUNAMI RESEARCH

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I. INTRODUCTION

This is a brief review of the status of tsunami research. The review is not meant to be comprehensive, but deals only with those topics in which the author has a direct interest. Section II deals with phase dispersion (also referred to as frequency dispersion) and amplitude dispersion (also known as nonlinear effects). In Section III the energy relationship between earthquakes and tsunamis is considered. Then, some aspects of tsunami generation and propagation using the so-called Boussinesq Equations are considered. The influence of ocean bottom topographic features on tsunami travel is also considered. An explanation is provided for the slower than expected travel of tsunamis in shallow coastal inlets.

Section IV deals with tsunami forerunners, especially whether the so-called lateral waves can be used to account for forerunners. Section V is concerned with the possible tsunamis that will be generated if the predicted large earthquakes occur in various seismic gaps.

II. DISPERSION

Tsunamis belong to the class of long gravity waves for which the horizontal length scale is very much greater than the water depth. There are three regimes of approximation for the Long Wave Theory (Murty, 1977):

a) Linear equations,
b) Finite-amplitude equations, and
c) Kortweg-de Vries (KdV) type equations.

The following three characteristic lengths determine which of the above three regimes is appropriate:

a) Water Depth D,
b) Wave Length λ,
c) Wave Amplitude η,

From these three characteristic length scales, the following three dimensionless parameters can be defined:

$$\epsilon \equiv \frac{\eta}{D}, \quad \mu \equiv \frac{D^2}{\lambda^2}, \quad U \equiv \frac{\eta\lambda^2}{D^3} \qquad (1)$$

where U is known as the Ursell Parameter. This Parameter expresses the relative importance of amplitude dispersion (nonlinear effects) versus phase (frequency) dispersion.

In the linear periodic wave theory, frequency ω is given by:

$$\omega^2 = gK \tan \; (KD) \qquad (2)$$

where g is acceleration due to gravity, K is wave number. Then the phase velocity C is given by:

$$C = \frac{\omega}{K} \qquad (3)$$

For very long waves tank (KD) can be approximated by the leading term in its expansion. Then from (2) and (3)

$$C = \sqrt{gD}\left\{1 - \frac{2\Pi^2}{3} \cdot \frac{D^2}{\lambda^2}\right\} \qquad (4)$$

where $K = 2\Pi/\lambda$

From equation (4) it can be seen that long waves travel with a speed mainly determined by water depth, but subject to a small negative correction proportional to μ. Two wave components with a slightly different value of μ will tend to separate as they travel. This μ is a measure of the frequency dispersion.

To understand the other type of dispersion, consider the formula for the celerity of a solitary wave

$$c \sim \sqrt{gD}\left(1 + \frac{\epsilon}{2}\right) \tag{5}$$

The celerity is approximately given by $\sqrt{gD}$ but is subject to a small positive correction,.proportional to the relative amplitude ϵ. Thus ϵ is a measure of the amplitude dispersion.

One can distinguish among the following three regimes for U:

U	$\ll 1$	Amplitude dispersion can be ignored. Linear long wave theory is valid.
	$O(1)$	Both amplitude and phase dispersions are important. The Boussinesq Equations are appropriate. Under certain conditions these equations reduce to the KdV equations.
	$\gg 1$	Amplitude dispersion dominates. Finite-amplitude, non-linear, long wave theory is appropriate.

In tsunami studies both linear and nonlinear long wave equations have been used. However, for tsunami travel over the continental shelf, neither the linear nor the nonlinear forms might be relevant. One might have to use intermediate type Boussinesq Equations.

The reduced form of the Boussinesq Equation, in dimensionless form is:

$$\frac{\partial \eta}{\partial t} + \frac{\partial \eta}{\partial x} + \frac{3}{4}\;\frac{2}{\partial x}(\eta^2) + \frac{1}{6}\mu\frac{\partial^2 \eta}{\partial x^3} = 0 \tag{6}$$

This equation can be used to understand the interaction between amplitude and phase dispersions. To examine the properties of this equation, drop the numerical factors, and rewrite it as follows:

$$\frac{\partial \eta}{\partial t} + \frac{\partial \eta}{\partial x} + \epsilon\eta\frac{\partial \eta}{\partial x} + \mu\frac{\partial^3 \eta}{\partial x^3} = 0 \tag{7}$$

This equation is suitable for initial value problems in which

$$\eta(a,0) = F(x) \tag{8}$$

is prescribed. Both amplitude and phase dispersions will tend to distort the wave forms. However, there might be situations when both effects cancel each other for special wave forms. In this case the solution is:

$$\eta = F(x - C \cdot t) \tag{9}$$

where C is the speed of propagation of the waves.

From (7) and (9), after introducting $\zeta = 0$ and integrating with respect to x, we get

$$(1 - C)F + \frac{1}{2}\epsilon F^2 + \omega \frac{\partial^2 F}{\partial x^2} = 0 \tag{10}$$

Multiply this with $\partial F/\partial x$ and integrate again with respect to x to give

$$\frac{1}{2}(1 - C)F^2 + \frac{1}{6}\epsilon F^3 + \frac{1}{2}\mu\left(\frac{\partial F}{\partial x}\right)^2 = B \tag{11}$$

where B is a constant of integration.

Equation (11) can be solved in terms of elliptic functions. Since these functions are represented by "Cn" the name "cnoidal waves" was coined to refer to the solutions of (10). For B - 0 the solution of (11) is

$$F = \frac{P}{\cosh^2(Qx)} \tag{12}$$

where

$$P \equiv \frac{3(C-1)}{\epsilon} \qquad \text{and} \qquad Q \equiv \frac{1}{2}\sqrt{\frac{C-1}{\mu}} \tag{13}$$

This is the solution for the so-called solitary wave. For this case, the Ursell Parameter becomes:

$$U = \frac{\epsilon}{\left(\frac{3}{2}\mu\right)}$$

which is independant of C and P. From (10) the speed of propagation of the solitary wave is given by

$$C = 1 + \frac{1}{2}\epsilon\eta + \frac{\mu}{\eta}\frac{\partial^2\eta}{\partial x^2} \tag{14}$$

III. GENERATION AND PROPAGATION

Table 1 compares earthquake energy versus tsunami energy for some typical cases. It can be seen that approximately a tenth of the earthquake energy goes in generating tsunamis.

TABLE 1

EARTHQUAKE ENERGY VERSUS TSUNAMI ENERGY

Earthquake	Richter Magnitude	Seismic Wave Energy (10^{23} ERGS)	Tsunami Energy (10^{23} ERGS)
Chile, May 22, 1960	8.5	35.3	3.0
Sanriku, March 1, 1933	8.3	17.8	1.7
Nankaido, Dec. 20, 1946	8.1	8.9	0.8
Tokachi, March 4, 1952	8.1	8.9	0.8
Tonankai, Dec. 7, 1944	8.0	6.3	0.79
Aomori, Feb. 10, 1945	7.3	0.56	0.004

The initial value problem for surface waves is known as the Cauchy-Poisson (C.P.) Problem. Usually the following two initial states are considered:

(a) initial elevation of the free surface with no motion,

(b) initially a horizontal surface with an initial distribution of surface impulse.

Earlier we mentioned that the KdV Equations are applicable for propagation in one direction only. For the general case, one has to use the Boussinesq Equations

$$\frac{\partial w}{\partial t} + (w \cdot \nabla)w + g\nabla\eta = \frac{1}{2} h\nabla(\nabla \cdot h \frac{\partial w}{\partial t} - \frac{1}{6} h^2 \nabla \left(\nabla \cdot \frac{\partial w}{\partial t}\right) \qquad (15)$$

$$\frac{\partial \eta}{\partial t} + \nabla\left\{(h+\eta) w\right\} = 0 \qquad (16)$$

where w is the vertically averaged horizontal velocity vector, η is the surface displacement, h is the water depth and ∇ is the gradient operator in the plane of the sea surface.

Hammack (1973) distinguished between impulsive and slow (or creeping earthquakes) through dimensional analysis. The following five parameters are relevant:

(a) Amplitude of vertical displacement of the ocean bottom y_o
(b) Duration of displacement t_c
(c) Horizontal size of displacement B
(d) Water depth D and
(e) Acceleration due to gravity g

These five independent variables are available to scale the dimensional variables of the problem.

The dependant variable which is the water surface displacement can be written as:

$$\eta = f(y_o, t_c, B, D, g) \tag{17}$$

since these five independant.variables involve only two physical dimensions (length and time), according to the Buchingham II-Theorem, the normalized water surface displacement hsould be a function of $5 - 2 = 3$ dimensionless ratios. A possible choice is

$$\frac{\eta}{y_o} = f\left(\frac{y_o}{D}, \frac{B}{D}, t_c\sqrt{\frac{g}{D}}\right) \tag{18}$$

where y_o/D is the amplitude scale of bed displacement, B/D is the size scale and $t_c\sqrt{\frac{g}{D}}$ is the time scale. One can distinguish between

$$t_c\sqrt{\frac{g}{D}} \begin{cases} \ll 1 & \text{impulsive earthquakes} \\ \gg 1 & \text{creeping earthquakes} \end{cases}$$

In tsunami studies, mostly we are concerned with impulsive quakes.

The typical forms of bed displacement used are the following:

Exponential Time Displacement

$$y(x,t) = y_o\left(1 - e^{-at}\right) H\,(B^2 - x^2) \qquad \text{for } t \geq 0$$

The heaviside step function H (B^2-x^2) is defined as

$$H\,(B^2-x^2) = \begin{cases} 1 \text{ FOR } B^2-x^2 > 0 \\ 0 \text{ FOR } B^2-x^2 < 0 \end{cases}$$

The other form, known as half sine time displacement is

$$\eta(x,t) = \eta_0 \left[\frac{1}{2}\left(1 - \cos\frac{\pi t}{T}\right) H(T-t) + H(t-T)\right] H(B^2-x^2)$$

for $t \geq 0$

Here

For $t<T$ $H(T-t) = 1$ AND $H(t-T) = 0$

For $t>T$ $H(T-t) = 0$ AND $H(t-T) = 1$

Tsunami travel time curves are generally constructed using the so-called Green-Du Boys formula for long gravity waves

$$C = \sqrt{gh}$$

where C is the speed of propagation, g is acceleration due to gravity and h is the average water depth. Megoldrick (1968) considered ocean bottom with sinusoidal undulations, and in the framework of the linearized shallow water theory he showed that in most cases the bottom irregularity slows down the long waves. However, if the wave length is of the same order as the scale of the bottom features, then the above formula is not valid and in a certain region, instead of retardation, the waves travel faster than predicted by the Green-DuBoys formula. In other words, the waves gain more time while travelling over the troughs of the bottom undulations than they lose while propagating over the crests.

The travel-time charts that are in use now were constructed in the late 1940's, and it is claimed that these charts are accurate to within ± 1.5 minutes for every hour of tsunami travel. This might be true in deep water, but it is not clear what the accuracy is on the shelf, and particularly in shallow coastal inlets. Also one should be able to construct better travel-time charts making use of the hydrographic and bathymetric data available since the 1940's. For techniques of representing the bottom features, see Katz (1963 a,b) and Fox and Hayes (1985).

For the Chilean earthquake tsunami of May 1960, the travel-times computed from the long wave formula do not agree with the observed travel times at some stations in the Queen Charlotte Strait on the west coast of Canada. For these stations there was about two hours of delay in the arrival of the tsunami (Loucks, 1962). Making use of a concept that in shallow water the propagation of a long gravity wave is governed predominantly by friction (le Blond, 1978), Murty (1983) suggested an explanation to account for these delays.

VI. TSUNAMI FORERUNNERS

Figure 1 shows the tsunami records at Tofino, British Columbia, and Crescent City, California, for the Chilean earthquake tsunami of May 1960. The tsunami forerunners are indicated by the arrows. Murty and Loomis (1983) suggested that these might be explained in terms of the so-called lateral waves (King and Le Blond, 1982).

King and Le Blond (1982) introduced the term "lateral wave" to describe a wave that arises at a depth discontinuity in the ocean such as at the boundary between a continental shelf and the deep ocean. Figure 2 shows schematically a continental shelf sloping to a deep ocean. The blackened area represents the region of tsunami generation due to a submarine quake on the shelf. The direct wave travels entirely in shallow water, where as part of the energy from the source is radiated into deep water. From the deep water wave travelling along the edge of the shelf on the deep water side, energy is continuously diffracted back onto the shelf and the coast, and this wave motion constitutes the lateral wave.

The path taken by the direct wave is entirely in shallow water whereas for the lateral wave, a substantial part of the travel occurs in deep water. Thus the lateral wave can arrive at coastal locations even before the arrival of the direct wave. The difference in the time interval between the arrival of the lateral wave and the direct wave at a given coastal location increases with the distance of the station from the tsunami source.

Murty and Loomis (1983) extended the work of King and Le Blond (1982) in several ways. Firstly, instead of using ray techniques, numerical simulation was used. The earlier case of a shelf of uniform depth meeting the deep ocean through a depth discontinuity is extended to the case of a sloping shelf. Thirdly, some attempts were made to identify the lateral waves with tsunami forerunners.

Figure 3 shows the results of numerical simulation for the Hawaiian Islands region. The abcissa is the time in minutes that elapsed after the impulsive generation of the tsunami. The computed water levels are shown as a function of time at various distances from the source. Along the ordinate, the location marked by zero is the tsunami source. The disturbance at the source as a function of time is also shown. The scale for the amplitude of the disturbance at the source is also indicated. Although the 5 m amplitude shown is exaggerated, since the problem considered is linear, the results could be deduced for any other amplitude. In Figure 3, V_1 is the lateral wave, V_2 is the first significant crest of the tsunami and V_3 is the wave with the maximum energy (amplitude).

V. TSUNAMIS DUE TO PREDICTED LARGE EARTHQUAKES IN SEISMIC GAPS

Gvishiani and Soloviev (1984) studied the Pacific coast of South America between the equator and 40 degrees S and classified the coastline according to the potential for occurrence of earthquakes with magnitudes greater than 7.75. Kim and Shimizu (1982) numerically simulated the tsunami that will result from a predicted large earthquake in the Tokai district of the southern coastal area of central Japan.

Weichert and Rogers (1985) suggested that the Vancouver Island area on the Pacific coast of Canada is due for a major earthquake. The last time there was a major earthquake in this areas was on June 23, 1946. A small local tsunami was generated in the Strait of Georgia (Rogers and Hasegawa, 1978).

Another important seismic gap is in the Shumagin Island area of the eastern part of the Aleutian Islands chain (Figure 4). It was suggested that a major earthquake will occur here within the next two decades (Jacob, 1984). It is expected that this earthquake will be at least as large as the Alaska Earthquake of March 1964. Although the direct effects of the earthquake itself will be confined mainly to the Alaska and Aleutian Islands area, the indirect effect, i.e. the resulting tsunami, is expected to travel Pacific Ocean-wide and cause great destruction.

Kowalik and Murty (1984) numerically simulated this tsunami. The equations of motions and continuity in a spherical polar co-ordinate system are (e.g. see Murty, 1984)

The equations of motion and continuity in a spherical polar coordinate system are [e.g., see Murty, 1984]

$$\frac{\partial U}{\partial t} - fV + \frac{KU}{H} + \frac{g}{R\cos\phi}\frac{\partial \eta}{\partial \lambda} = 0$$

$$\frac{\partial V}{\partial t} + fU + \frac{KV}{H} + \frac{g}{R}\frac{\partial \eta}{\partial \phi} = 0$$

$$\frac{1}{R\cos\phi}\frac{\partial}{\partial \lambda}(HU) + \frac{\partial}{\partial \phi}(HV\cos\phi) + \frac{\partial \eta}{\partial t} = 0$$

Here λ is the east longitude, ϕ is the north latitude, R is the radius of the earth, f is the coriolis parameter, g is gravity, (λ,ϕ) is the water depth is the equilibrium state and is the deviation of the free surface from the equilibrium level; here U and V are the east and north components of the depth-averaged currents, t is time and K is a linear bottom friction co-efficient.

In this deep ocean model, they have not included the nonlinear advective terms and the horizontal frictional terms, since these terms are expected to make no significant contribution. As for the boundary conditions, a radiation condition was used at the open boundaries and at the shore the normal velocity is equated to zero. The grid scheme and the finite-difference forms used here are similar to those in Ramming and Kowalik (1980). The model is calibrated against tides and storm surges in the polar regions (Kowalik and Matthews, 1982). Since tsunamis are long gravity waves such as tides and storm surges, the model calibration is believed to be valid for tsunamis also.

Figure 5 shows the tsunami source area and the travel times in seconds of the leading wave. Figure 6 shows the deep water amplitudes. Note that a major portion of the tsunami energy is directed toward the Hawaiian Islands. Other areas which have major impact will be Alaska and the west coast of the North American continent (note that this model only includes the area bordering the northeast part of the Pacific Ocean). Little energy will enter the shallow Bering Sea. In Figure 6 the tsunami amplitudes shown are for the deep water. They can be amplified many fold on the continental shelf and in some coastal inlets.

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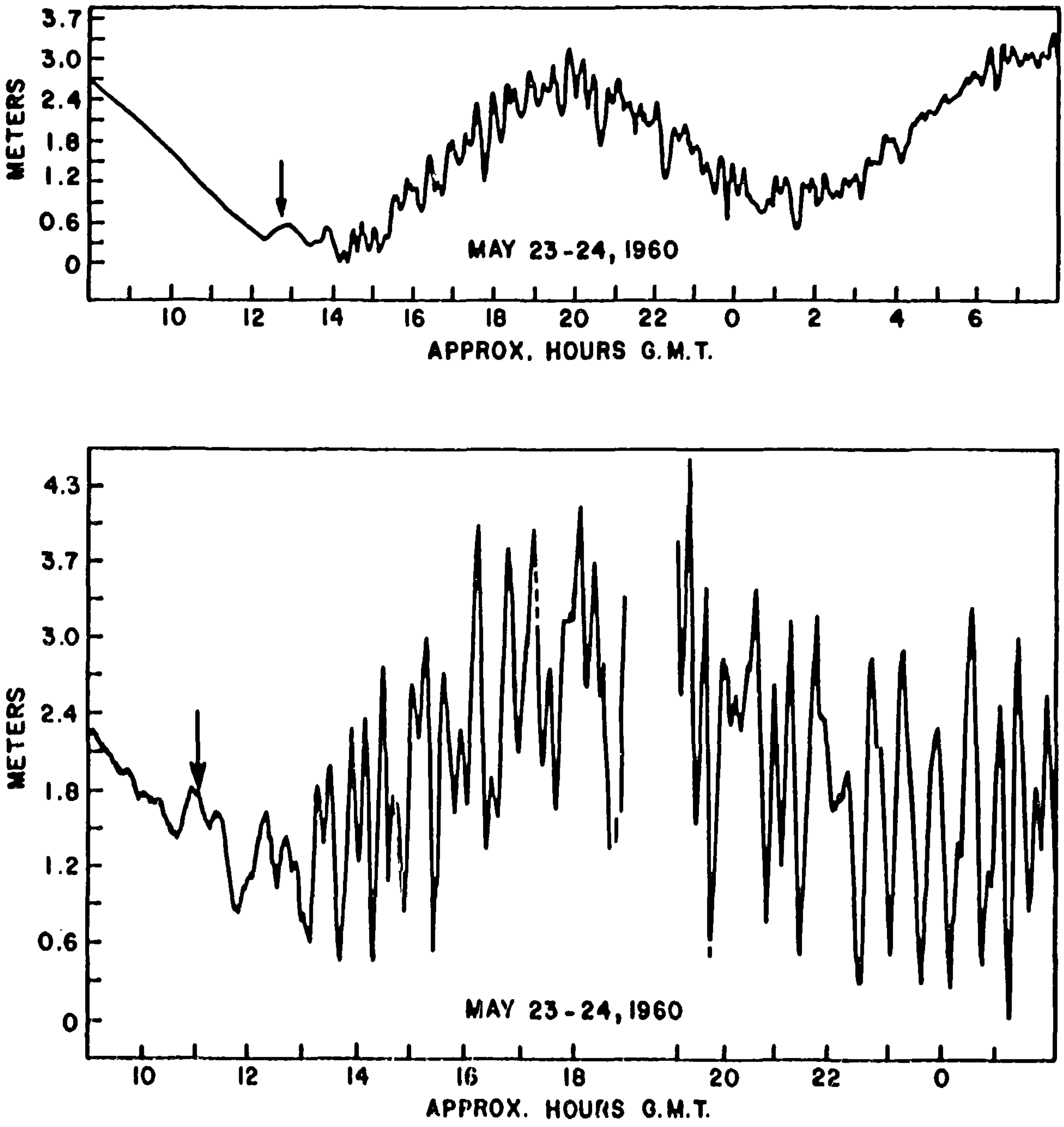


Figure 1

Water Level Records at Tofino, British Columbia (Top) and Crescent City, California for the Chilean Earthquake Tsunami of May 1960.

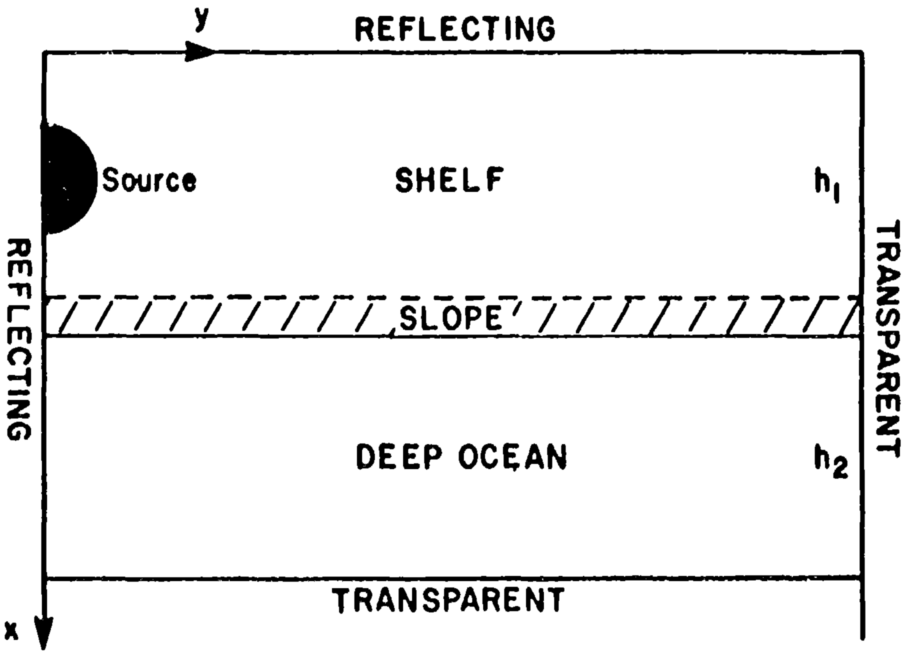


Figure 2

Schematic Representation of a
Continental Shelf, Slope and Deep Ocean

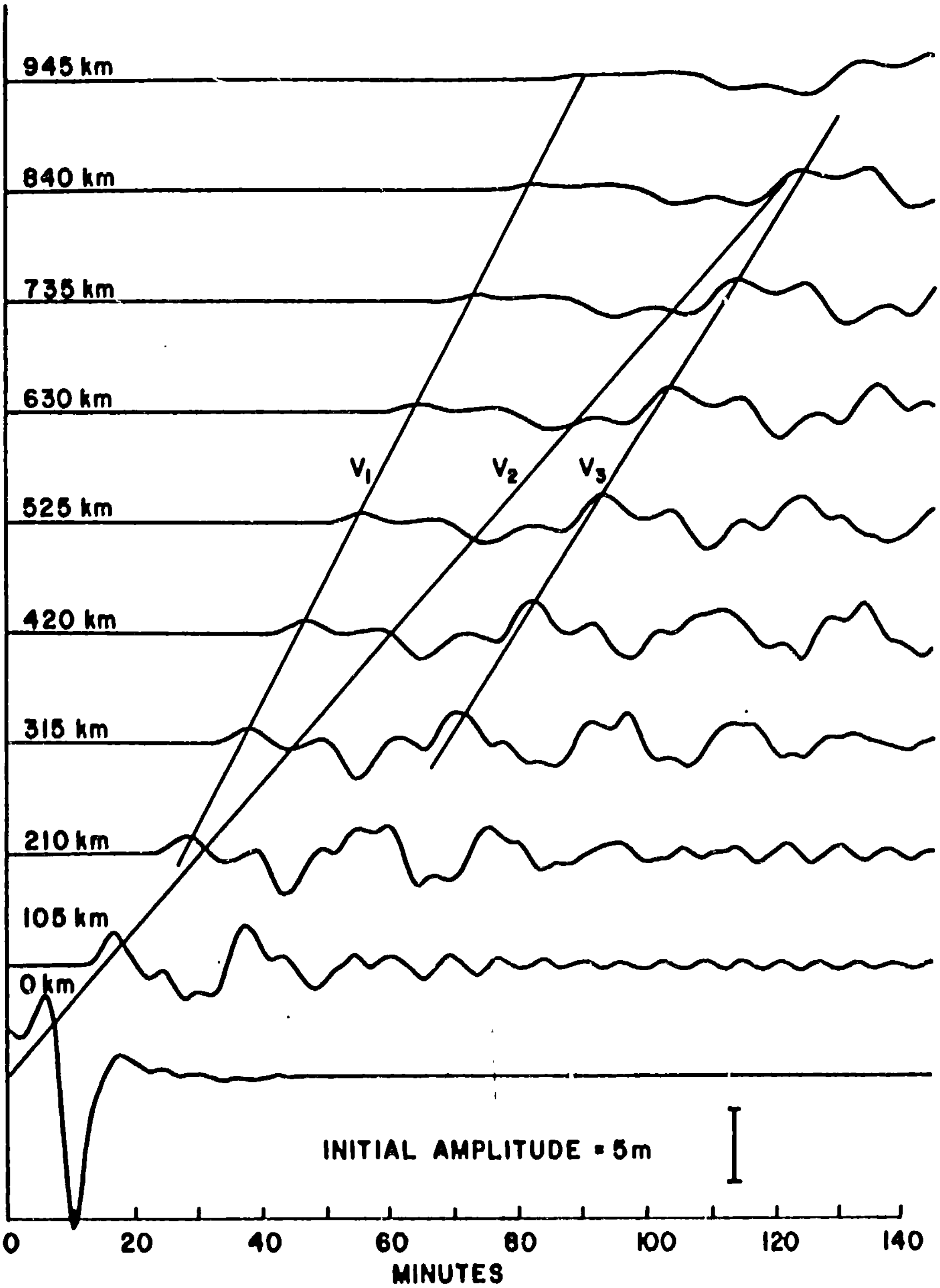
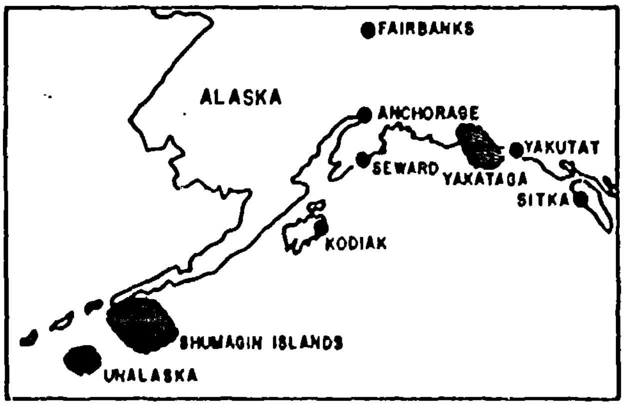


Figure 3

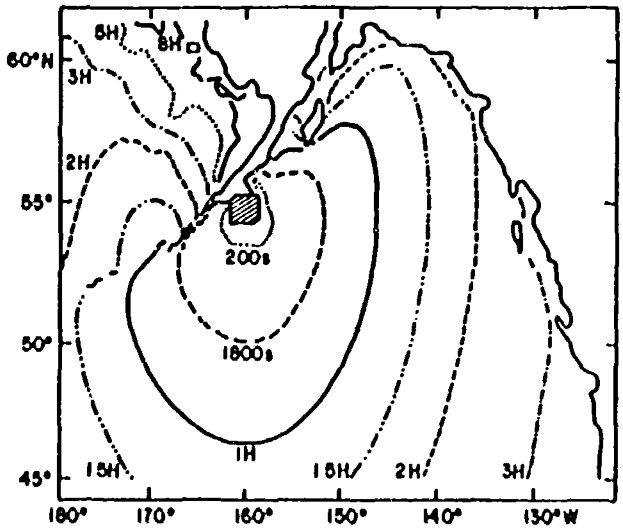
Lateral Wave Computations for the Hawaiian Islands



[illegible]. Seismic gaps in the Alaska-Aleutians area.

Figure 4

Seismic Gaps in the Alaska and Aleutian Islands Area

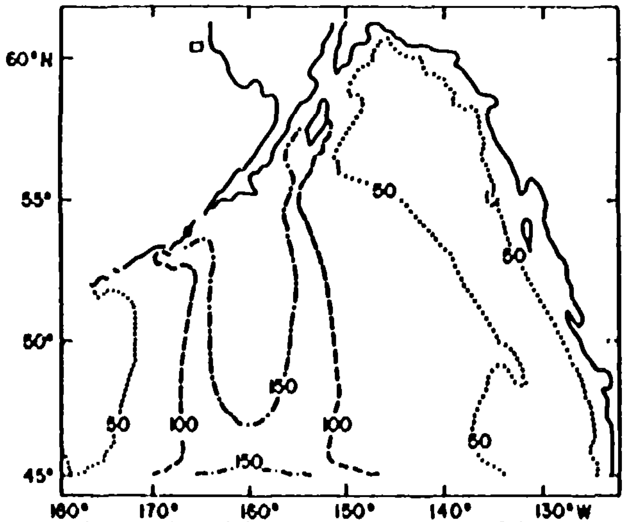


[redacted] Tsunami travel-time contours. The dark area shows the source region.

Figure 5

Tsunami Travel Time Contours

The Hatched Area Shows the Tsunami Source Region
in the Shumagin Seismic Gap



[redacted]. Distribution of the maximum amplitude of the tsunami (cm).

Figure 6

Distribution of the Maximum Tsunami Amplitude in Deep Water

THE USE OF NUMERICAL TSUNAMI MODELS IN OPERATIONAL WARNING ENVIRONMENTS

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1. INTRODUCTION

A great deal of effort in the past two decades has gone into the development, testing, and application of computer models of tsunamis. Although such models have been used extensively for research, very few attempts have been made to integrate them into tsunami warning operations. Early models, and many of the more complicated present day codes, were programmed to run on mainframe and super computers. Such machines have rarely been available to warning centers on a regular basis, and little pressure has existed to prod the development of real-time operational models. The recent proliferation of mini-computers and extremely powerful micro-computers has served to revive interest in operational models. The purpose of this paper is to lay out, in a non-technical fashion, some of the factors that must be considered when contemplating the feasibility of operational models. It will also discuss the types of tasks that existing models can and cannot be expected to perform. And, finally, it will give some indication of potential future uses of operational models.

2. FACTORS GUIDING MODEL DEVELOPMENT

Any numerical model, and especially one which may eventually be applied operationally, results from the interplay of three main factors:

- Physical/mathematical factors
- Computational factors
- User needs

Let us examine each of these in turn.

3. PHYSICAL/MATHEMATICAL FACTORS

The first step in building a numerical tsunami model is to develop the set of equations necessary to describe the interplay of the forces important in the process being modeled. Many possible physical forces can act on tsunamis, but not all of them are equally important. Table 1 lists some of the forces which could be taken into account and a general idea of their significance to various phases of tsunami evaluation.

Once the forces deemed most appropriate have been selected, they then must be coupled together into the desired set of equations. Each application will probably require a slightly different balance of forces, and thus slightly different equations. For example, an open-ocean propagation model will use Coriolis and pressure gradient terms, but probably not vertical accelerations and bottom stresses; conversely, a limited embayment model will need to take into account bottom stresses and, possibly, vertical accelerations, but not Coriolis forces.

Once the equations have been developed, initial and boundary conditions must be imposed in order to obtain unique solutions. Table 2 lists various options for these conditions. Again, the type of simulations desired govern the choices. A generation model will use a specified initial sea surface displacement based on sea floor motion as initial conditions, while a harbor model will probably start with the basin at rest.

The point here is that numerical models can be formulated in a number of different ways depending on the mixture of physical forces deemed appropriate to the problem at hand. This means that the operational user must be aware of the choices made in developing a model before deciding how useful its products can be.

4. COMPUTATIONAL FACTORS

Once the model equations have been settled upon, the next task is to get the computer to produce solutions. A number of techniques exist to accomplish this. Two of the most common are the finite-difference and finite-element techniques. Both methods produce realistic results and, at present, neither method seems clearly superior to the other.

In the finite-difference technique, the partial differentials in the model equations are approximated by linear differences of the dependent variables in time and space and solutions are obtained by carrying out the differences. A variety of well-established, fully tested algorithms have been used to obtain finite-difference solutions to tsunami equations. These methods can be computationally quite efficient (i.e., cheap) in certain types of problems.

Finite-element models have only recently been applied to tsunami problems, although they have been in use for a number of years in other fields. The technique involves a recasting of the model equations in variational form so that some quantity or quantities can be subject to a constraint. The set of independent variables which most closely satisfies the constraint is the approximate solution to the problem. One major advantage to this method is the extremely high spatial resolution possible in the solution grid.

TABLE 1

Some Physical Factors to be Considered in Numerical Model Development

Factor	Importance
Horizontal Pressure Gradient	High for all cases
Earth's Rotation (Coriolis)	High for long distance (basin scale) propagation; low for short scales
Bottom Stress (Friction)	Probably low for deep water waves; high for shallow water and runup
Horizontal Advection	Important, but tricky to implement
Vertical Acceleration	Very low for deep water waves; probably high for shoaling waves, but expensive to include
Bottom motion	Only for models including generation
Tidal forces	Probably not necessary at any scale, but tidal phase can be crucial in estimating inundation levels

Sample

TABLE 2

Typical Initial and Boundary Conditions

Initial Conditions	Implications
Rest	Water in basin not moving yet
Imposed Displacement	Earthquake has already occurred, but waves have not left source
Moving Seafloor	Earthquake begins to perturb sea surface as simulation begins

Boundary Conditions	Implications
Reflection	Waves strike wall at boundary and reflect completely back into grid. Usually used at land/sea boundaries, but can be used on seaward boundaries if source motion is inside model grid
Radiation	Most (ideally, all) wave energy reaching boundary passes through without reflection. Used for seaward boundaries
Forced	Wave height specified as a function of time along seaward boundary. Used in cases where waves arrive from outside the grid.
Moving	Waves can push on past initial boundary to form new limits. Used to simulate flooding on dry land.
Far-Field	Wave elevation reduces to zero far from the region of interest.

The choice of a solution technique is an important one for the modeler -- and the pros and cons of various methods can be quite fascinating. However, from an operational standpoint, the overriding computational factor is cost. The basic fact of life is that everything involved with computers -- the computer itself, the computer time, the computer programmer's time -- is expensive. The agency desiring to integrate a modeling capability into an operational warning system must decide whether to use existing computer facilities (if any) or add to them (by purchase or lease). Or should it buy computer time from a remote installation? Should the agency develop its own model and accept the resulting costs in personnel time? Or should it contract for the development of a model specific to the system's needs? Or borrow and modify an existing model?

All of these options carry a price tag which must be realistically evaluated in light of existing and potentially available resources.

5. USER NEEDS

The question of user's needs is intimately tied to the question of what existing models can and can't do. The first thing a prospective user must be aware of is that, at present, numerical models <u>cannot</u> reliably predict tsunami behavior in real time in any great detail. This is partly due to the fact that details of the source motion are usually quite hazy until long after the event and partly due to the fairly long computation times required for a detailed simulation. Also, existing models can rarely reproduce earlier tsunamis in exact detail, again largely because of the sparseness of detailed data on both the nature of the source and the effects at the coastline.

On the other hand, a great deal of research and development has gone into tsunami models and they can function quite well in a number of areas. For example, if the details of the source motion are known, existing models can do a good job of simulating waves in the source area. They are also quite well-suited for estimating such factors as travel times from a source, directionality of wave energy radiation, and general threat level. As more research is done in the areas of runup processes and wave-structure interactions, the capabilities of existing models to simulate these processes are continually improving.

6. POTENTIAL USERS OF NUMERICAL MODELS

The choice of whether or not to augment an existing operational system by adding numerical modeling capabilities revolves around the three factors: what kinds of processes can models simulate, how much will it cost, and do models exist that can meet present and projected needs. As with any choice of this nature, compromises need to be made. Highly detailed models, which include all of the physical processes shaping tsunami behavior, can be relatively accurate in their predictions but quite expensive to run on large mainframe computers. Less sophisticated models may cost considerably less, but produce only moderately accurate predictions. The ideal solution may fall somewhere in the middle.

Given the complexity of the issues involved, why should an operational system consider adding numerical modeling capabilities. Can they play any sort of useful role? The answer is that numerical models can be quite valuable in two modes: pre-event mode and real-time mode.

In the pre-event mode, models can be used to develop threat assessments prior to actual events. For example, if an earthquake occurs in an existing seismic gap, how would a tsunami be likely to threaten my coastline? Are some locations subject to more of a threat than others? Models have also been used to examine the effectiveness of protective barriers, evacuation plans, and relief infrastructures. They can also be used quite effectively to provide detailed scenarios for test exercises.

In the real-time mode, models can rapidly produce relatively accurate travel-time estimates. Tohoku University in Japan is developing a super-computer-based system for real-time predictions of wave height. On a lesser scale mini- and micro-computer based models will probably soon be capable of producing very rough wave height estimates within an hour or so after an earthquake.

7. THE FUTURE

The key to unlocking the full potential of numerical models in an operational setting lies not so much in the models themselves as in the warning systems. The types of information and the speed with which they are obtained are the dominant factors.

If the time it takes to accurately locate potentially tsunamigenic earthquakes can be reduced, then travel-time estimates can be produced much more rapidly. If information about the size of the source can be obtained quickly, then rough wave height and direction estimates would be possible in real-time. And if confirming water-level observations can be acquired quickly, then refined wave height estimates are completely possible.

SEISMOLOGICAL AND HYDROPHYSICAL FOUNDATIONS OF SHORT-TERM TSUNAMI PREDICTION

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Tsunamis occur in all oceans but principally in the Pacific. The distribution of tsunami sources is shown on Figure 1. Large tsunamis are responsible for extensive loss of lives and destruction to property. Tsunami prediction is of vital importance for the safety of the population living on the coastal areas in the Pacific and elsewhere.

Tsunami prediction in terms of a time scale will be discussed. Long-term prediction is based on estimating the probability of water inundation of different heights at given points on the shore. Such estimates of the tsunami risk are very important in order to make use of all the coastal zone.

Under intermediate-term prediction, estimates can be made of the origin times of large underwater tsunamigenic earthquakes. There are examples of successful predictions of some earthquakes based on the theory of seismic gaps or on other models. However, such predictions are not used routinely.

Just after a strong earthquake occurs, short-term tsunami prediction is used to determine whether a tsunami has been generated or not. All major Tsunami Warning Systems operating in the Pacific Ocean by the USA, Japan and USSR try to do short-term predictions. These Tsunami Warning Services were established after the big Aleutian tsunami of April 1, 1946, the Hokkaido tsunami of March 4, 1952 and the Kamchatka tsunami of November 4, 1952. The physical foundations of short-term tsunami prediction have not changed significantly in the last 30 or 40 years.

For local tsunamigenic sources in Alaska, Aleutian Islands, Kamchatka, Kurile Islands and Japan, the possibility of tsunami generation is estimated on the basis of only two criteria: location and magnitude of the earthquake.

Tsunamis are generated by sudden displacements of the ocean floor in a vertical or horizontal direction during an earthquake centered under the floor. The extent of the deformation of the ocean floor, the length of the rupture along the fault, the depth of the earthquake focus and other source parameters, determine the intensity of the tsunami.

The magnitude of an earthquake is an approximate measure of only one source parameter and relates to the energy released. The general understanding of an earthquake's magnitude is very simple. It is determined by measuring the seismic wave amplitude A, or velocity of ground oscillations A/T, at an epicentral distance Δ. The measurement of the seismic wave amplitude at any station must be correlated to the amplitude of the wave at the source and this value is approximately equal to the dimensions of the displacement along the seismic fault.

The assumption is made that the form of the amplitude curve does not depend on the energy of the earthquake. This is not quite correct but it is very convenient for practical purposes because on a semilogarithmic scale, when instead of A or A/T their logarithms are plotted, the amplitude curves of all earthquakes become parallel. The distance between them denotes the logarithm of the ratio of dislocations of seismic sources. A zero magnitude is assigned through special definition to a very small underground shock which could be determined by the most sensitive seismic instrument. And the formula for magnitude M is: $M = \log(A/A^*)$ or $M = \log(A/T) - \log(A/T)^*$, where $\log A^* = f(\Delta)$ or $\log(A/T)^* = \varphi(\Delta)$ are so called calibrating curves, that is amplitude curves for earthquake with $M = 0$. Though the idea of magnitude is very simple its practical application encounters difficulties due to anomalies in the density of the Earth and the variety of instruments used in measurements.

Several types of seismic waves following different travel paths are recorded at a distant station. The principal ones are the longitudinal P and shear S waves, propagating through the Earth's interior and the Rayleigh and Love waves propagating along the Earth's surface. The simplest amplitude curves with minimal dispersion are curves of the surface waves (Figure 2). This is the main reason why this type of magnitude M_{LH}, is usually determined by the tsunami warning systems operating in the Pacific. Amplitude curves of P and S waves are more complicated (Figure 3) and their dispersion is greater by approximately 1.5. But these waves travel faster, and magnitudes M_p and M_s can be determined somewhat earlier than the magnitude M_{LH}.

Even application of the simplest magnitude scale M_{LH} needs some caution especially in the Pacific region. The amplitude of the surface waves depends on the velocity section of the uppermost Earth layers. When the differences in the velocities of seismic waves in the crust and in the upper mantle of the Earth are small, the penetration of the energy of surface waves is deeper and the amplitude of the surface wave appears smaller. It is along the boundaries of the Pacific oceanic plates with the continental plates that these effects become more pronounced and special corrections to magnitude must be applied (Figure 2).

Since seismic waves propagate 15-30 times faster than tsunami waves, by recording the waves of an earthquake it is possible to evaluate the possibility of tsunami generation before the tsunami waves arrive.

This is very important for short-term tsunami prediction, but the method described is of purely statistical nature.

The efficiency of this method has been investigated quantitatively and some ideas on tsunami intensity have been developed. A scale of tsunami intensity was amended by K. Iida and S. Soloviev (1978), from a scale of tsunami magnitude proposed originally by A. Imamura. For most tsunamis we know only their manifestations on the coast but we have no data on tsunami parameters in the open ocean. Thus, we scale coastal manifestations according to an intensity scale by using conditionally the maximum observed value at a point on the shore that is nearest to the tsunami source, and by assigning a tsunami intensity at the source itself based on this value.

The tsunami intensity i is determined approximately as:

$$i = \log_2 h^{vis}_{max} = \log_2 h^{vis}_{av} + 1/2 = \log_2 h^{mar}_{max} + 1/2 = \log_2 h^{mar}_{av} + 1.$$

(Soloviev, 1978)

Here h^{vis} and h^{mar} are the rises of water level on the coast in meters, determined from visual observations and tide gauge records respectively; h_{av} and h_{max} are the average and maximum rises of water level along a section of the coast. The generalized intensity, characterizing the tsunami source, is denoted as I. In Table 1 the scale with its descriptive part is shown. Numerous independent determinations of intensities (or magnitudes) of tsunamis have shown that errors of I estimations are not greater than 1/2 degree (Soloviev, 1979).

Detailed catalogues of earthquakes and tsunamis in the Pacific have been compiled by the author and assistants, with homogeneous estimates of earthquake magnitudes M_{LH} (further denoted as M) and tsunami intensities, I (Soloviev, Go, 1974, 1975).

Earthquakes and tsunamis recurrences in the Pacific have been computed. They are shown on Figures 4 and 5. The thickness of belts in these figures is proportional to the frequency of tsunamis.

Comparison of two methods of computing recurrence frequency has shown that the probability of tsunami excitation is not the same for different seismic zones of the Pacific. For an earthquake with a given magnitude it turned out to be minimal for typical zones of island arcs and for Central America (double hatched belts) and maximal for zones of block tectonics such as the shelves of Japan Sea, south-west Philippines, Sulawesi and Kalimantan Islands in Indonesia (horizontally hatched belts). Zones of intermediate type are shown by inclined hatching. When passing from a zone of one type to the next one, the probability of tsunami excitation rises by a factor of two. (Soloviev, 1972).

In order to take into account the effect of tectonic structure of the zone, the parameter of tsunamigeneity T, has been introduced:

$$T = \frac{n(o)}{N(7\tfrac{1}{2})},$$

which is equal to the ratio of the frequency of tsunamis with intensity I = 0, to the frequency of earthquakes with magnitude M = 7 1/2.

The efficiency of the seismological method of tsunami prediction has been investigated as follows: The probability P for tsunami of intensity I appearing on the shore, is the product of two probabilities P_1 and P_2. The first one is the probability for an earthquake capable of generating a tsunami of any intensity. The second probability is the distribution of tsunamis according to their intensities (Soloviev, 1972). Normal laws of distributions have been used for smoothing the empirical data. Accordingly, the following have been obtained:

$$P(I,M,T) = P_1(M,T)_{I \geqslant -5} \cdot P_2(I,M,T)$$

$$P_1(M,T) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{2.5(M-7.63+1.23\log T)} e^{-\frac{y^2}{2}} . dv$$

$$\bar{I} = a + bM$$

zones	a	b
island arcs	-19.2	2.58
intermediate	-10.9	1.62
block tectonic	-4.72	0.83

$$\log a = 1.04 - 1.03 \lg T$$

$$\log b = 0.22 - 0.83 \lg T$$

$$\bar{I} = -11.0 T^{-1.03} + 1.66 T^{-0.83} M$$

$$\sigma = 4.44 - \log T - 0.4M$$

$$P_2(I,M,T) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2\sigma^2}(I - I)^2}$$

The results which have been obtained have been used for estimating the efficiency of the seismological magnitude method of short-term tsunami prediction (Table 2). The situation is obvious. The higher the threshold value of the magnitude used to issue a tsunami warning, the greater will be the number of tsunamis missed and the smaller will be the number of false warnings, and vice versa. Calculations have been carried out for two zones: 1) Kamchatka and Kurile Islands, and 2) Japan Sea, and for two classes of tsunamis: 1) I $\geqslant$ 0, 2) II $\geqslant$ 1.

For zones in the Pacific coast of Kamchatka and Kurile Islands, the magnitude threshold value is equal to $M_{LH} = 7$. Thus it can be concluded that no large tsunami can be missed but the number of false alarms may be as high as 80%. Analysis of the performance of the Soviet Tsunami Warning System gives somewhat different estimates but it does not change the basic assumptions. Earthquake magnitude alone is not a sufficient parameter for reliable short-term tsunami prediction.

Therefore, one should look for alternate actions. Theoretically it is possible to use other seismic source parameters that affect crustal deformation, as, for example, the depth of the earthquake source. Theoretical and empirical investigations show that the probability of tsunami excitation decreases with increase in the depth of earthquake focus (Figure 6). Unfortunately we do not have rapid methods for determining reliably the depth of the seismic hypocenter. Other methods exist for determining fault length and degree of displacement caused by an earthquake. However, we do not have presently reliable rapid methods of determining the source mechanism with data from one or few seismic stations. Recent investigations by V.K. Gusyakov and L.B. Chubarov (1984) have shown that the intensity of tsunamis generated by very gentle thrusts is approximately the same and only the horizontal shift reduces the tsunami intensity.

In the past five years a number of studies in the USSR have led to the discovery of some new tsunamigenic features of earthquakes. These are: the time of buildup of oscillations in P-waves up to a maximum; the relationship between the low-frequency and the high-frequency part of the spectrum of long-period P-waves and Rayleigh waves; the duration and the mean rate of rupturing in the earthquake fault, as determined by A.V. Vvedenskaya's technique; the total duration of P-waves; the corner point of the P-waves spectrum, as found by the Brune method; the period of the P-waves spectrum maximum, and some other features.

Among the aforementioned parameters the one which is most easily and quickly determined is the time of buildup of oscillations up to a maximum in P-waves (τ_m). This time was found to be a feature of the tsunamigenity of an earthquake for a different frequency pass band of the seismograph, at least under a variation of the period of maximum amplification of the instrument from 1 to 20 seconds. The parameter (τ_m) was found to be sensitive to the tsunamigenity of an earthquake under different epicentral distances: from near to teleseismic ones (Figure 7).

The efficiency of a tsunami forecast using the parameter τ_m and the earthquake magnitude, was compared for teleseismic distances for the records of long-period and short-period seismographs and was found to be approximately similar. Both of these parameters were found to be stochastically interrelated with the correlation coefficient in the order of 0.3. This is explained by a statistical dependence between the length of the fault in the earthquake source, and the amount of crustal displacements along the fault.

If the parameter τ_m is "corrected" for the earthquake magnitude, it ceases to be sensitive to tsunamigenity of the earthquake. Nevertheless, the joint application of the parameter τ_m and the earthquake magnitude, increases the efficiency of the tsunami forecast. Some numerical experiments with past tsunamis even show that the joint use of magnitude and some additional features of tsunamigenity can reduce the number of false alarms to 5-10% (Soloviev, Burymskaya, 1981).

Regardless of the reliability of new seismic methods for tsunami prediction, these will remain always of purely statistical character. Meanwhile it is possible to apply other methods for short-term tsunami prediction on a purely deterministic basis. However, from the technical point of view, these methods are difficult and expensive. For example, it is possible to register tsunamis in real time, in the open ocean with the help of bottom sensors. Physically such possibilities result from the nature of tsunamis being very long gravity waves. Long periods of the tsunami waves at first lead to the very slow alteration of water elevation. Contrary to short period wind waves, long period tsunami waves result in gravitational changes which affect the entire water column all the way to the ocean floor. A bottom sensor measuring the hydrostatic pressure of the water column is able to detect the passage of tsunami waves. The water particle motion of a long period wave, such as tsunami is by far greater in a horizontal than in a vertical direction. The ratio of the horizontal to vertical axes of orbital movement of water particles of tsunami waves is approximately equal to $T/2\pi\cdot\sqrt{g/H}$, where T is the period of the waves and H is depth of the ocean. In shallow water, this ratio increases tremendously. Thus tsunamis are not only water waves, but also mighty currents encompassing the entire water layer from the surface to the bottom, except for a very thin boundary, the turbulent near-bottom layer, with thickness of about 2 meters. Thus, a near-bottom sensor of currents can also detect tsunami passage. Other sensors can be also sensitive to tsunami passage as will be shown.

As an illustration to the previous discussion the correlation between initial water elevation in the source region A, in meters, the water depth H, in meters, and the current velocity in meters/second, for some large tsunamis are shown in Table 3.

Experiments of deep-water tsunami recordings were started in the 1960's at the Hawaii Institute of Geophysics by Dr. M. Vitousek and others. Such hydrophysical methods of tsunami prediction were described in the literature (Soloviev, 1968), and were implemented by the author at the Hydrophysical Observatory on Shikotan Island -- one of the extreme south-east islands of the Kurile arc. Experiments were started in 1964-1965. Interesting series of experiments was carried out in 1969-1970 (Zhak, Soloviev, 1971). Two instruments were placed on the ocean bottom in depths of 60 and 120 meters at a distance of 10-20 km from the shore and were connected to the observatory by cables. These instruments were equipped with pressure sensors, current meters, and with sensors recording temperature and electromagnetic effects. They were placed at an elevation of 1-3 meters above the bottom.

Pressure sensors used were of the vibrotron type (DDV-20B). The frequency range of measurements was equal to 0-10 cycles/second, and the dynamic range was from 0-20 atmospheres. Short-period variations of hydrostatic pressure (up to 1 hour) could be measured with the error reduced with the help of special scheme to 1.5 centimeters in the entire water column. A piezoceramic transducer was also used to measure the derivative of water elevation. Its accuracy for periods of tsunami waves was about 5%. Comparison with records of coastal tide gauges showed that the bottom instruments registered tides and swell without distortion.

During six months of continuous operation of the bottom instuments about 60 weak solitary waves with periods 10-100 minutes were recorded. More than ten of them were caused probably by local earthquakes because the times of their appearance on the record coincided with calculated times of tsunami propagation and with signal forms similar to those predicted theoretically (Figure 8). Passage of these small tsunamis disturbed all the hydrophysical parameters under measurement. For example changes of temperature reached one degree. The amplitude of the swell rose in many instances. The turbulence in the near bottom layer intensified. Reestablishment to the undisturbed state required 4-8 hours.

From 1964 to 1979, nineteen other similar bottom hydrophysical cable systems were installed near Shikotan Island and at other points of the Kuriles and at Sakhalin Island (Soloviev, 1981). But these installations were temporary because cable lines (of geophysical logging type) were laid out without special engineering protective measures and sooner or later were destroyed (and most frequantly by spring-floating ice). Their operational periods ranged from several weeks to one year, and during this period no confirmed tsunamis were recorded.

The first big success was achieved in 1980 (Dykhan el al, 1981). A new system equipped with a pressure sensor was installed in the summer of 1979 at a depth of 113 m and 8 km from the south-east corner of the island (Figure 9) and connected with the Hydrophysical Observatory by 20 km long cable line. Variations of pressure were translated into frequency-modulated electric signals which were recorded in analog form with the help of special devices in three frequency pass-bands: that of wind waves, swell, and tsunamis and tides.

On February 23, 1980, at 05^h50^m GMT an earthquake with magnitude M = 7.0 occurred south-east of Shikotan Island (Figure 9). It was felt from Hokkaido to Iturup Islands and its intensity on the Shikotan Island was equal to 6-7 degrees. A tsunami warning was issued by the Soviet service and in fact a small tsunami was generated. The tsunami was recorded by the coastal tide gauges from Hachinohe, Honshu Island, in the south, to Iturup Island, in the north. A relatively large length of tsunami registration was due to the orthogonal orientation of the tsunami source to the island arc. The tsunami was recorded also by the bottom sensor (Figure 10) one hour ahead of its arrival at the nearest settlements. A maximal height of 7 cm was recorded by the bottom sensor and the passage of tsunami over the sensor was observed at the Hydrophysical Observatory.

The striking peculiarity in the set of mareograms that were obtained was that the record at Yuzhno-Kurilsk situated on the shore which was facing the tsunami source was almost identical to the record of the bottom instrument which was located very close to the tsunami source. One can suppose that these records reflect the initial form of the tsunami at its source or that both records were distorted equally during tsunami propagation. Another record obtained at Malo-Kuril'skoe, on the NW side of the Shikotan Island, was of quite different character and represents mainly seiches at the Malokuril'skaya Bay.

Spectral analysis of the record of the bottom tide gauge indicates that there is perhaps some influence of spectral properties of the shelf on the tsunami marigrams. The current spectrum of oscillations recorded by the bottom sensor was calculated with the help of the Kaiser-Bessel time window with the width of 3 hours and consequent shifts of 20 minutes. A time spectral diagram shows (Figure 11) that the energy of oscillations is concentrated in narrow frequency bands with predominant frequencies of 1.1 cycle/hour (T = 50 minutes), 2.4 cycles/hour (T = 25 minutes) and T = 4 cycles/hour (T = 12 minutes). Attenuation of oscillations on long periods is small and the quality factor is equal to 10-20. Maxima on the main periods repeat each 6 hours. This is perhaps the result of energy trapped by the shelf. In Figure 11 the monochromatic oscillations falling normally on the shelf are shown. Maxima of the curve correspond fairly well to observed maxima. The real bathymetry of the shelf in the southern part of the Kurile Island arc was used in the calculations. The oscillations with a period of 50 minutes can be regarded as the main seiches (leaky mode) for that part of the arc.

A similar case of remote tsunami registration occurred on March 24, 1984 after the occurrence of an earthquake with magnitude M = 7.1 near Iturup Island. A small tsunami was again generated and was recorded by coastal tide gauges on Iturup, Kunashir and Shikotan Islands as well as by the bottom tide gauge installed near Shikotan Island. The height of the waves was again equal to 7 cm and their spectral composition was similar to that described for the tsunami of 1980. A third tsunami recorded with the help of the Shikotan temporary bottom installation was the Chilean tsunami of March 26, 1985.

In summarizing the results, the author concludes that the bottom cable systems provide the most promising means for tsunami detection by warning systems, such as that operating in the Soviet Union. Bottom sensors of hydrostatic pressure and near bottom currents installed at 50-100 kilometers from the most important settlements could detect tsunamis approximately one hour before the waves reach the shore.

The installation of permanent deep water sensor network is, of course, difficult and expensive. However, there have been two experiments where such instrumentation was employed. The first one operated between 1966-1971 in the Pacific, 200 kilometers west-north-west from San Francisco, and was equipped with a vibrotron, a long period hydrophone, and many other sensors. No data on tsunamis were published, though such large tsunamis as from the Peruvian earthquake of October 17, 1966 and the Honshu earthquake of May 16, 1968 must have been recorded by this installation. Another tsunami sensor was laid in 1978 at Cape Omae, on the south coast of Honshu Island, 200 kilometers to the south-west of Tokyo. The length of cable to the off-shore installation was 150 km. The cost of each system was estimated to be approximately one million dollars.

Warnings are issued by tsunami warning systems to coastal settlements usually via radio or cable communications. However, there are often cases when communications between the warning center and the settlements are not continuous. Such may be the case for small isolated hydrometeorological stations and other observational posts situated on small islands in the central part of the Kurile arc. For such cases it is necessary to find the correlation between the intensity of felt earthquake and the probability for tsunami occurrence. Such investigations have been carried out by the author and Dr. L.N. Poplavskaya (Soloviev, Poplavskaya, 1982) for the Kurile Islands and Kamchatka. It must be noted that for the central part of the Kurile island arc, warnings cannot be disseminated because tsunamis may reach the coast 5-10 minutes after the earthquake.

Observations on the macroseismic effects of earthquakes and on tsunamis for the period 1952-1976 were analyzed. A total of 1516 observations on local seismic intensities and 124 observations on local tsunami intensities were used. The statistical method was the same as for the correlation of earthquake magnitude and tsunami intensity. The general probability for tsunami of local intensity i to occur after an earthquake of local intensity I is assumed to be the product of the two probabilities $p_1(I)$ and $p_2(i)$. The first one is the probability for tsunami of any local intensity to be observed after an earthquake of a given local intensity I. The second probability is the distribution of local tsunami intensities i for a given local seismic intensity I. According to observational data, both probabilities are very close to normal laws of distribution.

For the first probability, empirical data was averaged for local seismic intensity or to zero point of the Gauss curve equal to 6.2 degrees and to dispersion of the curve equal to 0.9 degrees. For the second probability, both the average local tsunami intensities $\bar{i}$ and their dispersions $\sigma\bar{i}$ proved to be dependent on the local seismic intensity I.

This empirical dependence can be seen in Table 4. The bigger the local seismic intensity I, the bigger the average tsunami intensity $\bar{i}$, and the smaller is its dispersion σi. In Table 5 the first probability shown is the probability for a tsunami of any local intensity to occur after the earthquake of the given local intensity I.

The general probability is the product of two partial probabilities and is shown in graphic form in Figure 12. The horizontal axis is the local tsunami intensity i, the vertical axis is the probability of observing a tsunami of this intensity, and the figures above the curves indicate the local seismic intensity I (according to a 12-degree scale).

It can be concluded that when an earthquake is felt on the Pacific coast of the USSR with intensity $I \leq 5$, observations of sea level are urgently needed. For earthquakes with felt intensity 6 or greater, the population must evacuate dangerous coastal areas.

Other possible ways of tsunami detection must be mentioned. Other physical processes in the source region of strong underwater earthquakes could be investigated. Preliminary analysis shows that strong bottom oscillations with velocities in the order of 1 meter/second and greater must generate shock waves which could cause cavitation of the water surface. A sudden whitening of significant strip of water surface in an seismoactive zone which can be observed, for instance, from space can indicate the occurrence of a strong underwater earthquake with possible tsunami generation.

In addition, propagation of strong acoustic waves leads to adiabatic warming of the water in the source region probably by $0.1\text{-}0.5^{\circ}$. Current technical means allow the detection of such temperature changes from satellites (Garber, Soloviev, 1982).

It has been postulated that a tsunami cannot be observed in the open ocean by ships. According to views of S.S. Ivanov (1985) it is possible to observe tsunamis if special shipboard instrumentation is used. Oscillations of the water surface by tsunami waves produce corresponding vertical acceleration. For such typical parameters of strong tsunami in tho open ocean with a height of 1 meter and period of 15 minutes, acceleration can be of the order of 8-30 mGal, depending on the profile of the wave. Such accelerations could be easily registered by modern shipboard gravimeters with measurement errors of about ± 1 mGal. Double integration can provide the vertical profile of the wave which has passed beneath the ship.

In summary it is possible to conclude that the investigation of the tsunami phenomenon in recent years has been so intensive and fruitful that we have now the necessary theoretical and empirical data for the creation of a reliable service for short term tsunami prediction.

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Table 1

Scale of Tsunami Intensity I

I	Description of Tsunami
4	Disastrous. Partial or complete destruction of man-made structures for some distance from the shore. Flooding of coasts to great depths. Big ships severely damaged. Trees uprooted or broken by the waves. Many casualties.
3	Very large. General flooding of the shore to some depth. Quays and other heavy structures near the sea damaged. Light structures destroyed. Severe scouring of cultivated land and littering of the coast with floating objects, fish and other sea animals. With the exception of big ships, all vessels carried inland or out to sea. Large bores in estuaries. Harbour works damaged. People drowned, waves accompanied by strong roar.
2	Large. Flooding of the shore to some depth. Light scouring on reclaimed ground. Embankments and dykes damaged. Light structures near the coast damaged. Solid structures on the coast lightly damaged. Big sailing vessels and small ships swept inland or carried out to sea. Coasts littered with floating debris.
1	Rather large. Generally noticed. Flooding of gently sloping coasts. Light sailing vessels carried away on shore. Slight damage to light structures situated near the coast. In estuaries, reversal of river flow for some distance upstream.
0	Slight. Waves noticed by those living along the shore and familiar with the sea. On very flat shores waves generally noticed.
≤ -1	Very slight. Wave so weak as to be perceptible only on tide gauge records.

Table 2

Estimation of the Efficiency of the Magnitude Method of Predicting Tsunami Danger

Kuril-Kamchatka (T:F:U)			The Japan Sea (T:F:U)		
M_{tr}	I	II	M_{tr}	I	II
8.9	1:0:40	-	8.3	1:0:50	-
8.8	140:1:2400	-	8.2	1:0:20	-
8.7	80:1:800	-	8.1	1:0:12	-
8.6	50:1:250	-	8.0	1:0:8	-
8.5	40:1:180	17:1:250	7.9	50:1:250	13:1:130
8.4	25.1:80	10:1:65	7.8	30:1:120	12:1:65
8.3	15:1:40	7:1:25	7.7	20:1:60	8:1:30
8.2	10:1:20	5:1:12	7.6	12:1:30	6:1:15
8.1	7:1:9	3.5:1:6	7.5	8:1:15	4:1:8
8.0	5:1:5	3:1:3	7.4	6:1:8	3:1:4
7.9	3:1:3	4:2:3	7.3	4:1:4	2:1:2
7.8	2.5:1:1.5	2:1.5:1	7.2	3:1:2	2:2:2
7.7	2.5:1.5:1	2.5:2.5:1	7.1	2:1:1	2:2:1
7.6	4:3:1	4:5:1	7.0	3:2:1	3:3:1
7.5	5:5:1	6:10:1	6.9	4:3:1	4:6:1
7.4	8:10:1	11:22:1	6.8	5:6:1	6:12:1
7.3	12:24:1	20:52:1	6.7	8:12:1	10:24:1
7.2	24:54:1	40:140:1	6.6	12:24:1	17:53:1
7.1	50:140:1	130:570:1	6.5	20:50:1	30:110:1
7.0	150:550:1	-	6.4	40:120:1	65:330:1
			6.3	75:300:1	160:1000:1
			6.2	200:1000:1	-

T = alarms with tsunamis (true alarms)

F = alarms without tsunamis (false alarms)

U = tsunamis without alarms (unpredicted tsunamis)

M_{tr} = the threshold value of magnitude

In the version I the destructive tsunami was assumed to have I 0; in the version II it was assumed $I \geq 1$.

Table 3

Velocity of Currents, m/s, on Different Water Depth, H, m, for Different Initial Water elevation, A_0, m, on the Depth H = 6000 m

A_0, m H, m	0.5	1	2	4	8
6000	0.13	0.25	0.51	1.01	2.03
5000	0.15	0.29	0.58	1.16	2.33
4000	0.17	0.34	0.69	1.38	2.75
3000	0.21	0.43	0.85	1.71	3.42
2000	0.29	0.58	1.15	2.32	4.63
1000	0.50	0.97	1.95	3.90	7.79
500	0.82	1.64	3.28	6.55	13.10
200	1.63	3.26	6.51	13.02	26.05
100	2.74	5.48	10.95	21.90	43.81
50	4.61	9.21	18.42	36.85	73.69

Table 4

Mean Intensities $\bar{i}$ and Dispersions $\sigma_{\bar{i}}$ of Normal Tsunamis Distributions Corresponding to Different Local Seismic Intensities I

I	$\bar{i}$	$\sigma_{\bar{i}}$	Quantity of Data, n
3	-1.5	3.0	18
4.5-5	-1.0	1.8	16
5.5-6	0.1	1.4	21
6.5-7	2.0	1.9	46
7.5	1.9	0.9	16

Table 5

Probability of Tsunami Occurrence p(I) After Earthquake Felt With Intensity I

I	p(I)	I	p(I)
3	0.00019	6-7	0.62930
3-4	0.00135	7	0.81327
4	0.00734	7-8	0.92507
4-5	0.02938	8	0.97725
5	0.09176	8-9	0.99477
5-6	0.21770	9	0.99906
6	0.41294	9-10	0.99988

Captions to Figures

Figure

1 Sources of the largest known tsunamis in the world ocean. Circles - tsunamis of seismic origin. Squares - tsunamis, generated by ocean bottom relief changes due to volcanic eruptions. Triangles - tsunamis of volcanic origin. Big circles and squares - tsunamis with intensity $I = 3-4$, smaller ones - with intensity $I = 2-3$. Zones of small tsunamis generation are hachured. (Soloviev, 1981).

2 Amplitude curves for surface waves. 1-3 - curves for earthquakes of the Kurilo-Kamchatskaya zone calculated on the basis of the Far Eastern station data; 1-2 - experimental curve and area of standard errors; 3 - curve, smoothened by the expression $\lg(A/T)^{*}=\mathrm{const} - k\lg\Delta$; 4 - standard curve for continental earthquakes and continental stations (results by S.L. Soloviev and O.N. Solovieva).

3 Amplitude curves for P and S waves of earthquakes in the Kurilo-Kamchatskaya zone according to the Far Eastern stations observations (results by S.L. Soloviev and O.N. Solovieva).

4 Scheme of earthquakes recurrence in the Pacific. 1-11 - quantity of earthquakes with $M=7.5\pm0.15$ during 100 years in the zone with length equal to 1000 km (A): 1 - $A>12$; 2 - $12\gtrsim A>8$; 3 - $8\geq A>5.7$; 4 - $5.7\geq A>4.0$; 5 - $4.0\geq A>2.7$; 6 - $2.7\geq A>1.9$; 7 - $1.9\geq A>1.4$; 8 - $1.4\geq A>0.9$; 9 - $A=0.8-0.9$; 10 - $A = 0.6-0.7$; 11 - $A\leq0.5$; 12-15 - range of sources depths: 12 - 0-60 km; 13 - 70-150 km; 14 - 160-320 km; 15 - $\gtrsim$330km (Soloviev, 1972).

5 Scheme of tsunamis recurrence in the Pacific. 1-7 quantity of tsunamis with $I = 0.0\pm0.5$ during 100 years in the zone equal to 1000 km (a): I - $a\gtrsim5.0$; 2 - $a = 4.0-4.9$; 3 - $a = 3.0-3.9$; 4 - $a = 2.0-2.9$; 5 - $a = 1.0-1.9$; 6 - $a = 0.5-0.9$; 7 = $a\leq0.5$; 8 - the maximal tsunami intensity observed in the zone; 9-11 - the tsunamigenity factor of zones T: 9 - $T<1$; 10 - $T>1$; 11 - $T\simeq1$ (Soloviev, 1972).

6 Dependence of tsunamigenity of earthquake on its magnitude M and source depth H. 1-3 - tsunamigenic earthquakes: 1 - in the south part of Kurile Islands; 2 - in other zones of Western Pacific; 3 - tsunami of intensity $I\gtrsim0.5$; 4 - non-tsunamigenic earthquakes. a - proposed boundary dividing tsunamigenic and non-tsunamigenic earthquakes; b - boundary, proposed by K. Iida in 1963; c - boundary, proposed by A.I. Ivashchenko and Ch.N. Go in 1973 (Soloviev, Tulupov, 1981).

7 Records of the longitudinal waves of earthquakes, which generated tsunamis (on the left) and which did not cause them (on the right) obtained with the help of the long-period seismograph of observatory "Obninsk." Onsets of P-waves are shown by arrows. Magnitude of all the earthquakes is approximately the same and equal to $M = 7.0 - 7.2$. The longitudinal waves of tsunamigenic earthquakes have larger period. Besides they have the first peak smaller than the second one and the second smaller than the third one. For non-tsunamigenic earthquakes maximal oscillations coincides with the first or the second peak, according to R.N. Burymskaya (Soloviev, 1981).

8 Some results of remote registration of hydrophysical fields near the Shikotan Island in 1969-1970. The direction of registration is shown by horizontal arrows. a,b - pressure variations on 120m depth, caused by tidal changes of water level, swells and solitary waves of tsunami type (marked by the vertical arrows); c - time derivative of hydrostatic pressure on 60 m depth; the passage of small tsunami was recorded, accompanied by intensification of swell and appearance of a typical trend of the instruments record caused by temperature step-like change and subsequent recovery of temperature balance; d - current velocity variations on 60 m depth; at the bottom of figure - temperature jump caused by the passage of small tsunami type wave. (Zhak, Soloviev, 1971).

9 Source of earthquake of February 23, 1980. 1 - earthquake epicenter; 2 - preliminary outline of the earthquakes source according to the epicenters of first aftershocks; 3 - bottom tide-gauge (Dykhan et al, 1981).

10 Records of tsunami of February 23, 1980: a - obtained with the help of bottom tide gauge; b - with the help of coastal tide gauge in Yuzhno-Kurilsk; c - with the help of the tide gauge in Malokurilskaya Bay. Arrows mark proposed arrivals of tsunami. Tide oscillations are removed (Dykhan et al, 1981).

11 Spectrum of tsunami of February 23, 1980 and its interpretation. a - time viariations of the energy spectrum of water level oscillations on the shelf during tsunami: 1 - maximum of spectrum, 2 - intensity from 0 to -10 dB, 3 - from -10 to -20 dB; 4 - less than - 20 dB; b - amplification factor (γ) of the Shikotan Island's shelf for the wave, propagating from the ocean normally to the shore (Dykhan et al, 1981).

12 Probability p of tsunami with intensity i to appear after felt earthquake with different strength (earthquake intensity is shown by numerals near curves) (Soloviev, Poplavskaya, 1982).

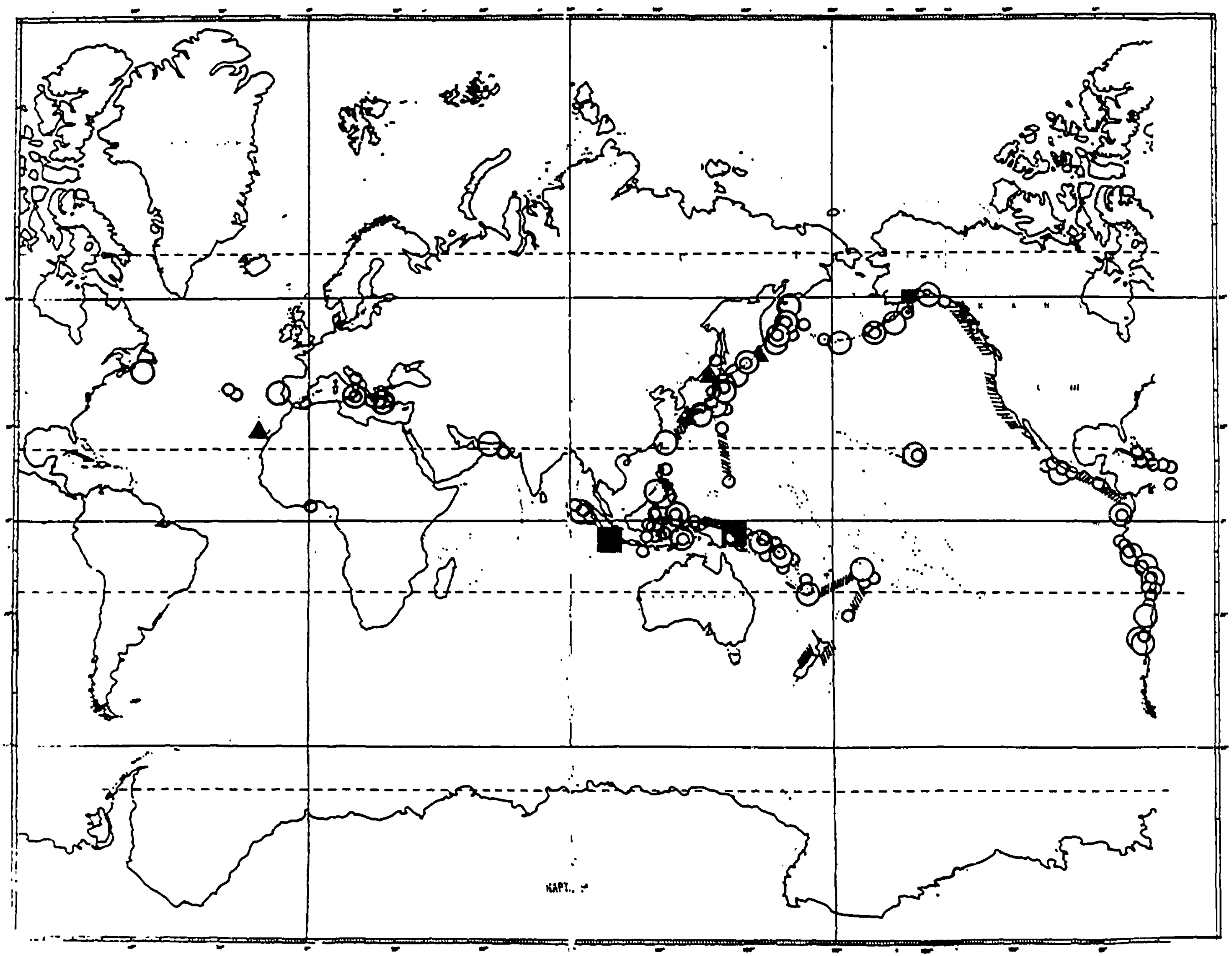
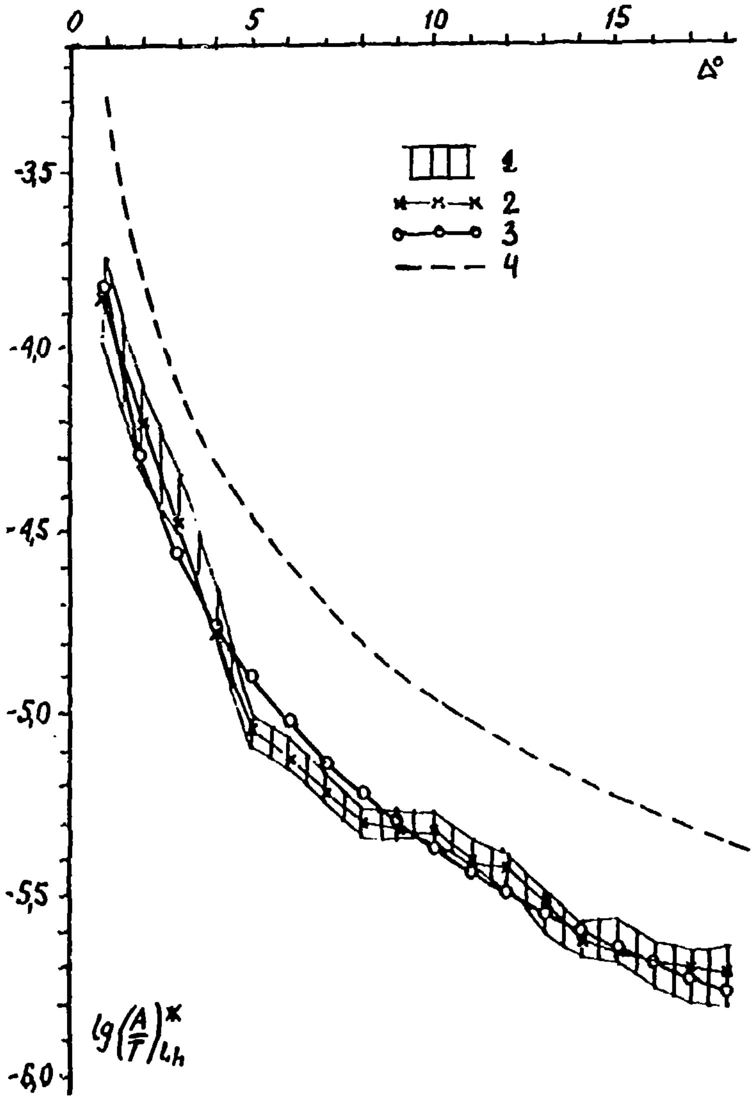


Figure 1



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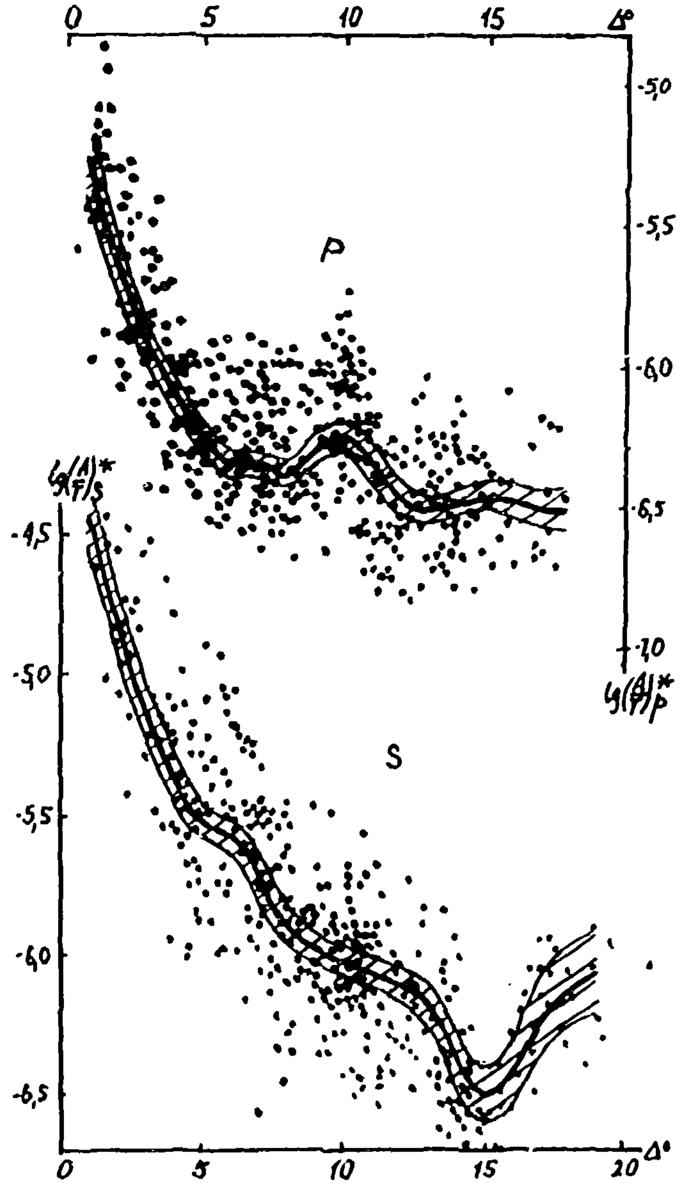

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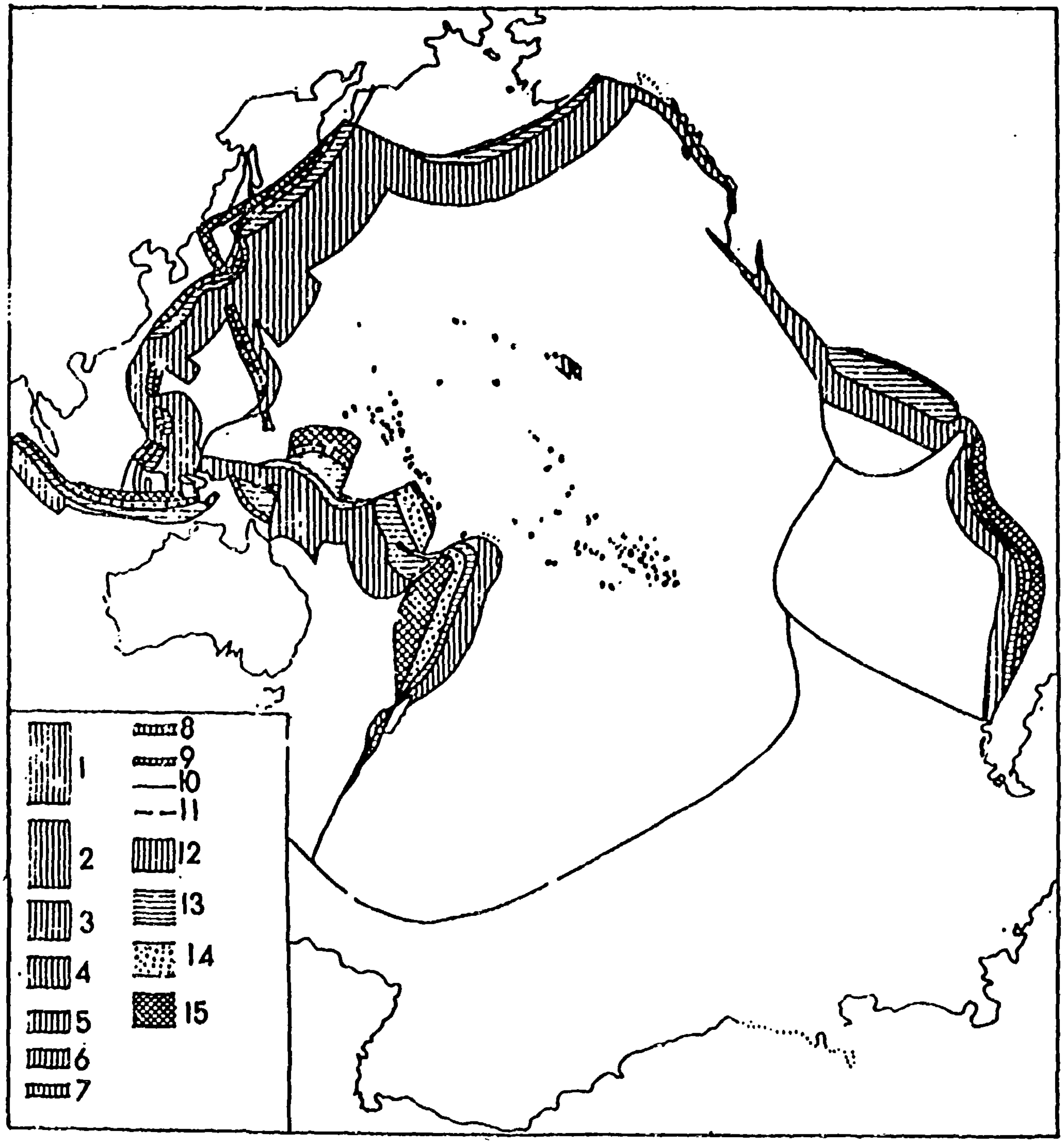

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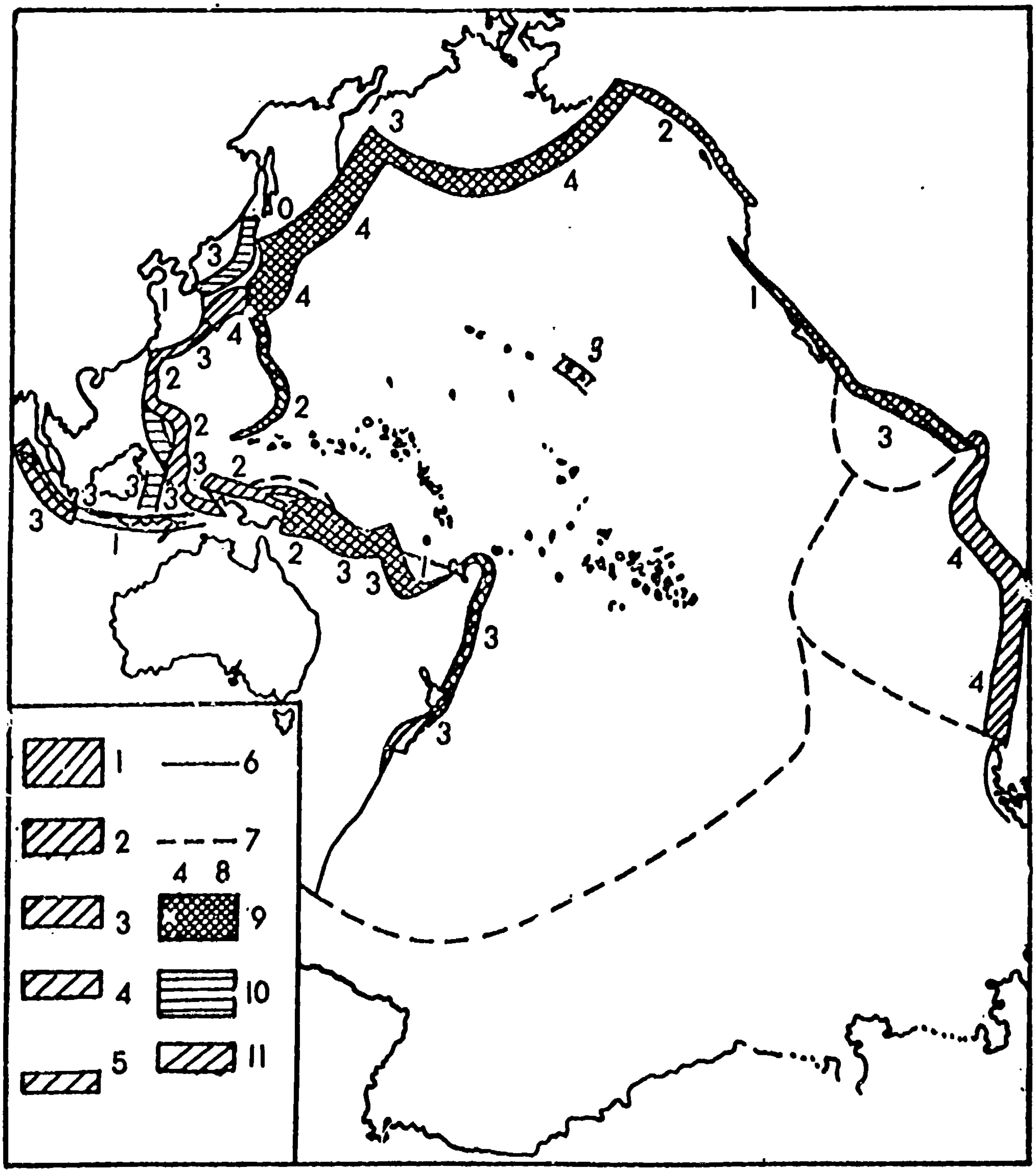

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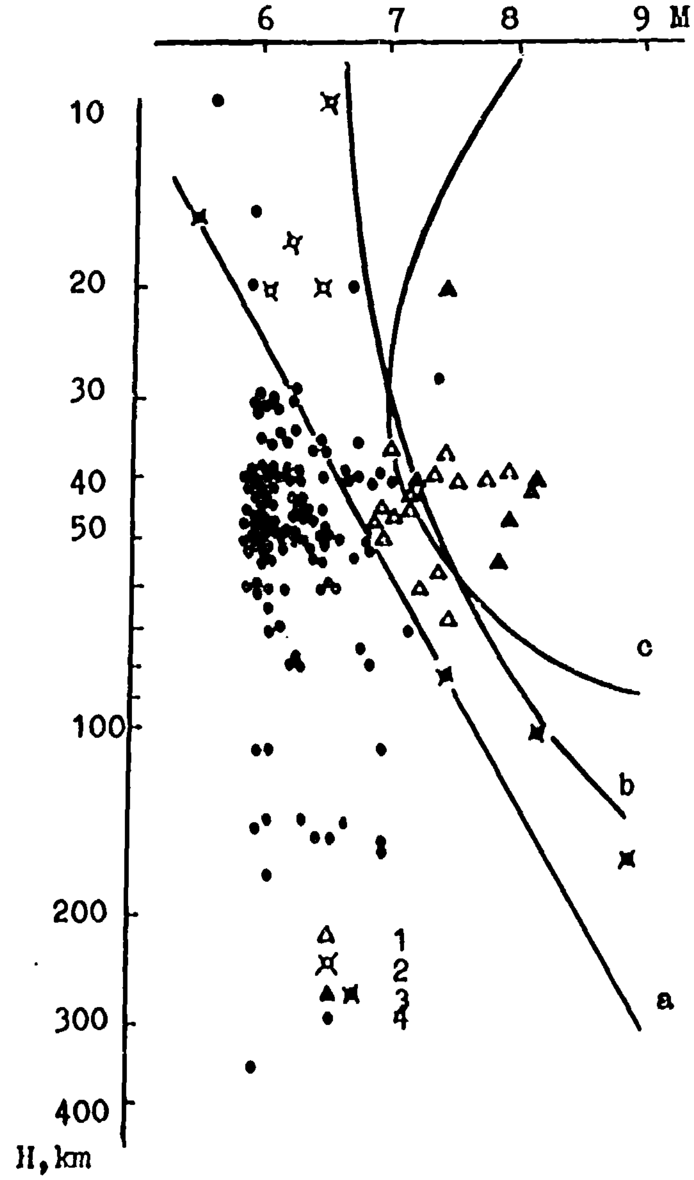

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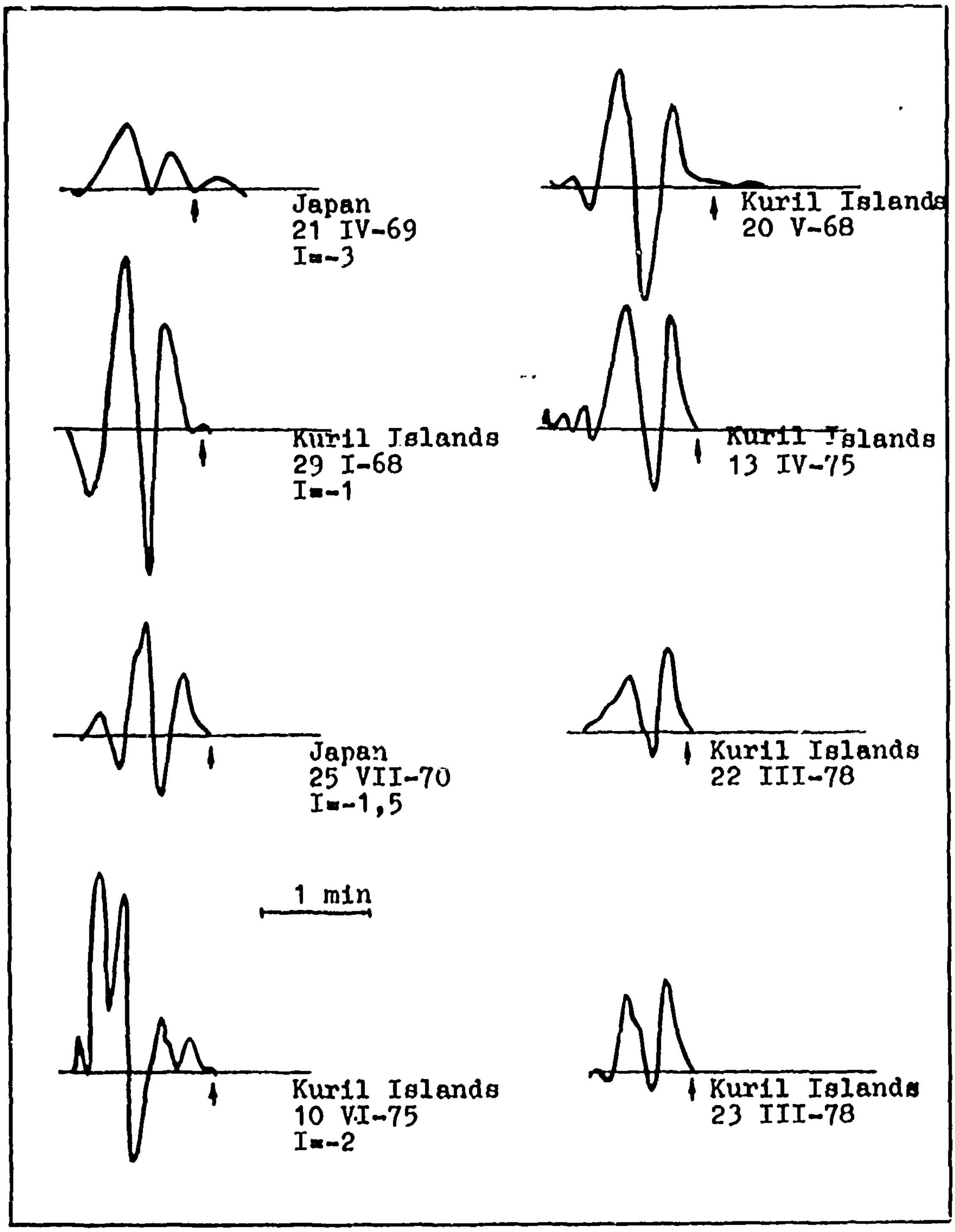
Japan
21 IV-69
I=-3
Kuril Islands
20 V-68
Kuril Islands
29 I-68
I=-1
Kuril Islands
13 IV-75
Japan
25 VII-70
I=-1,5
Kuril Islands
22 III-78
1 min
Kuril Islands
10 VI-75
I=-2
Kuril Islands
23 III-78

Figure 7

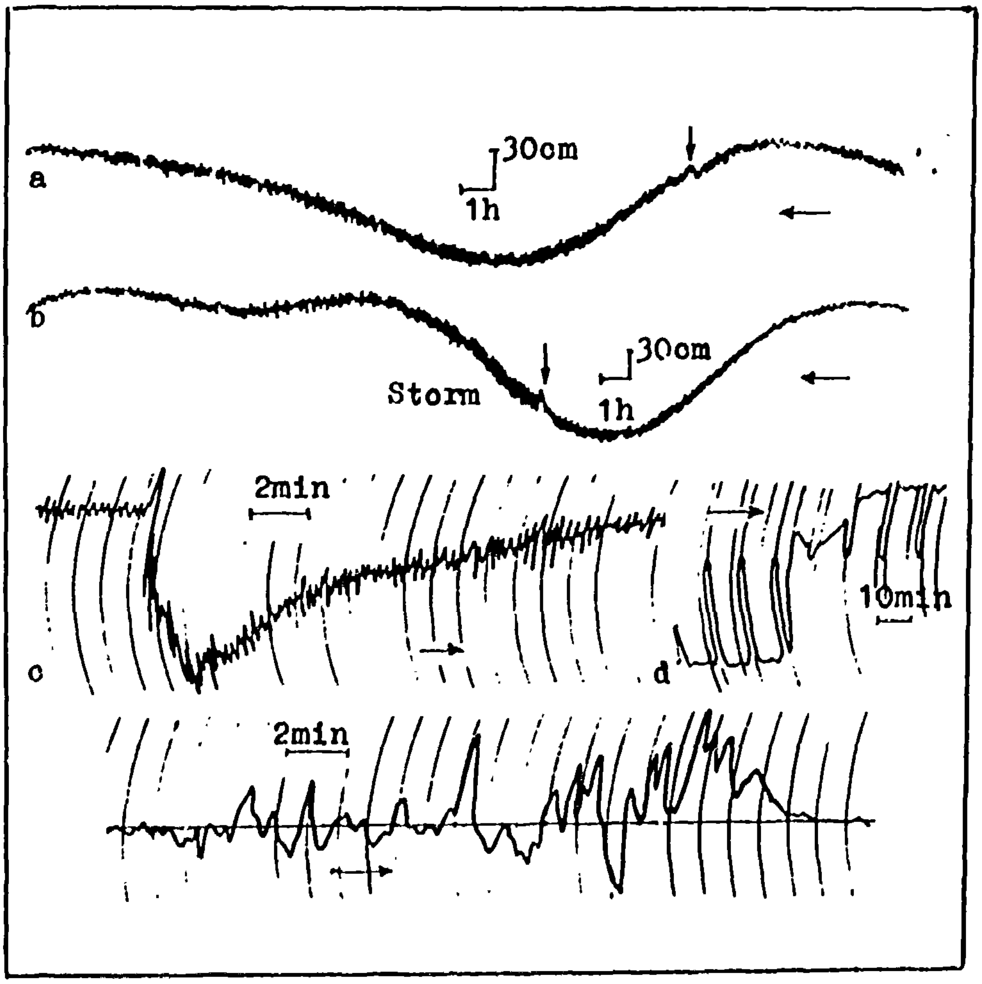

Figure 8

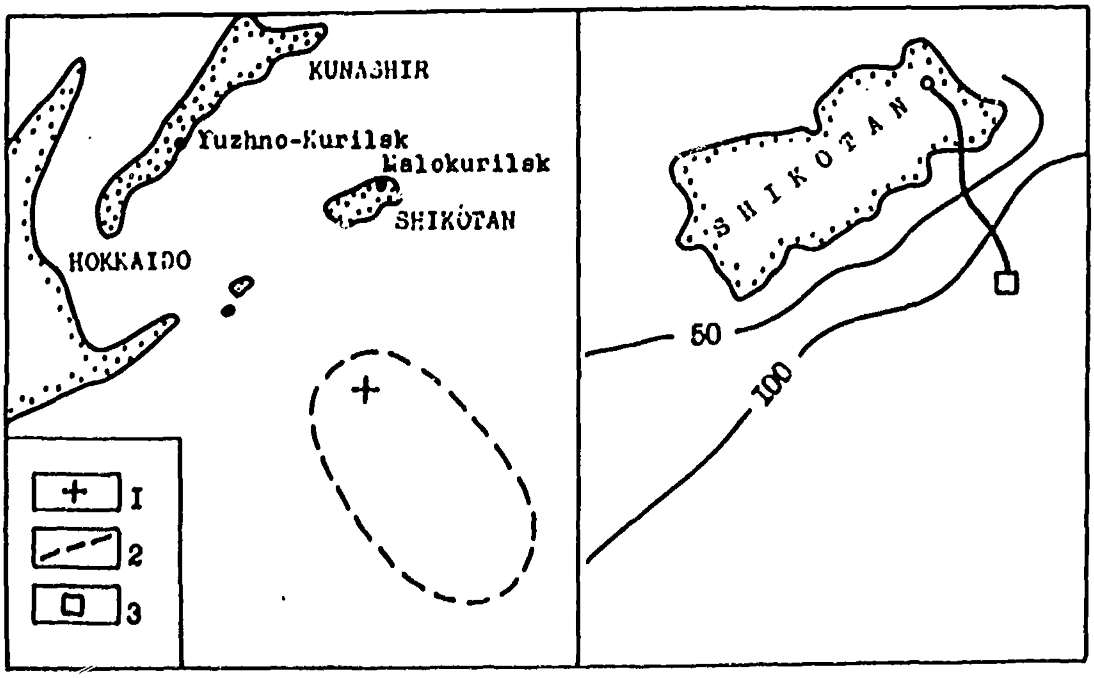
KUNASHIR
Yuzhno-Kurilsk
Malokurilsk
SHIKOTAN
HOKKAIDO
1
2
3
SHIKOTAN
50
100

Figure 9

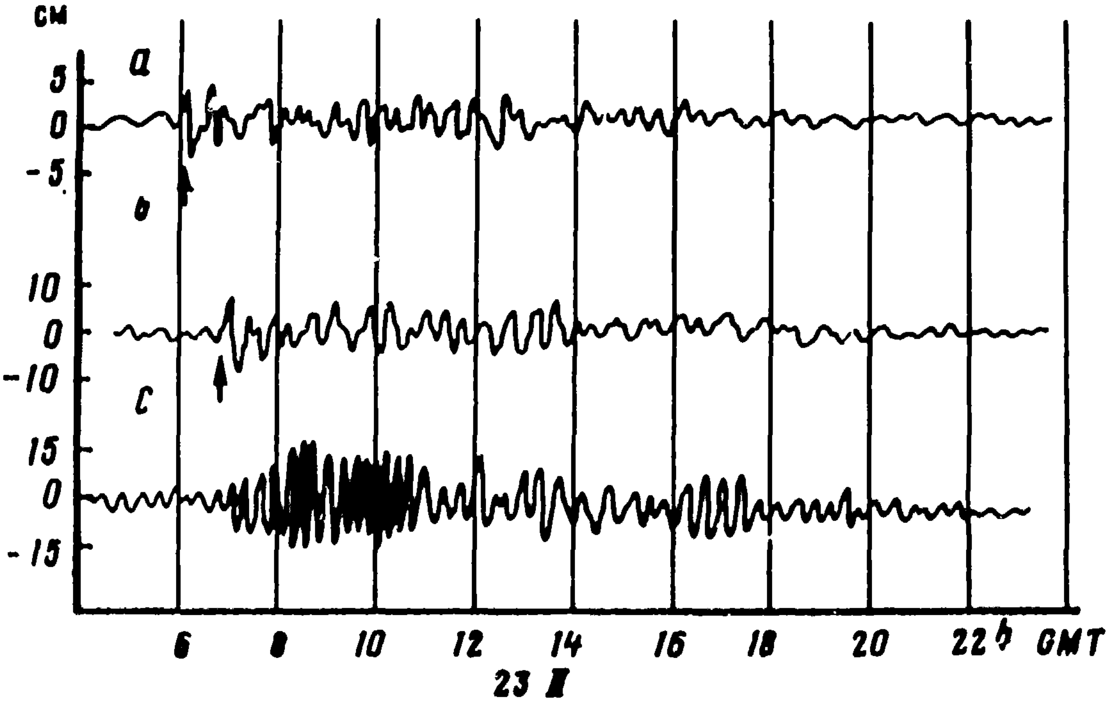

Figure 10

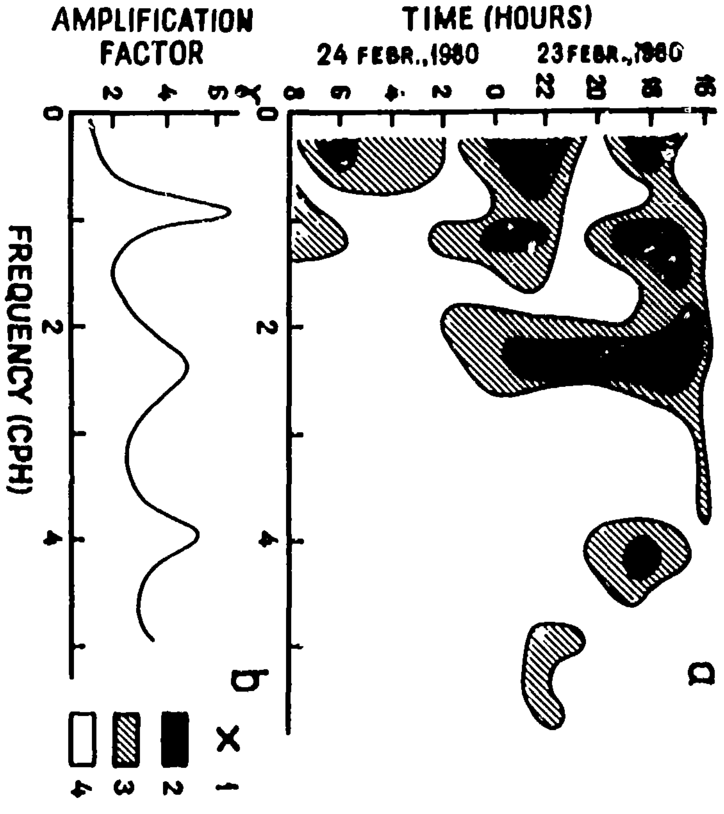
AMPLIFICATION FACTOR
TIME (HOURS)
24 FEBR.,1980
23 FEBR.,1980
8
6
4
2
0
22
20
18
16
2
4
6
X
0
2
4
FREQUENCY (CPH)
a
b
X
1
2
3
4

Figure 11

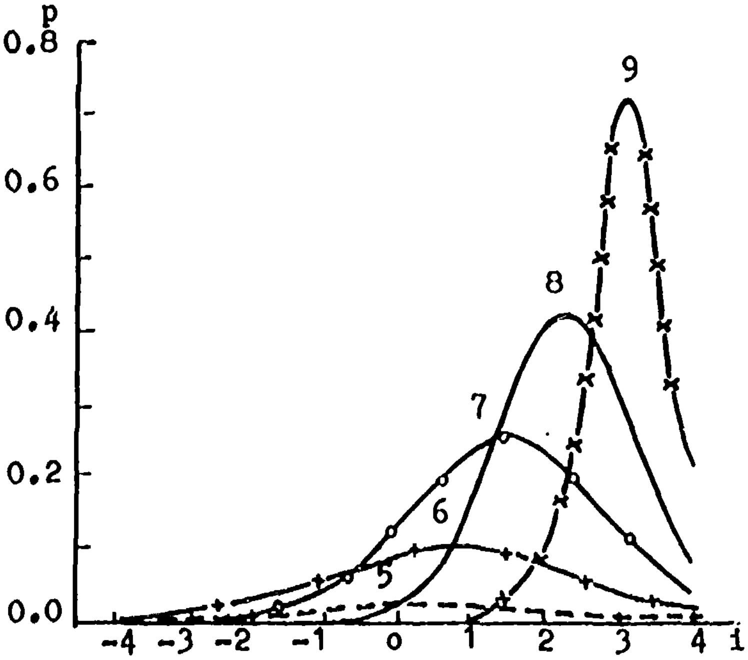

Figure 12

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32 Suppl.	Papers submitted to the UNU/IOC/Unesco Workshop on International Co-operation in the Development of Marine Science and the Transfer of Technology in the Context of the New Ocean Regime Paris, 27 September-1 October 1982	IOC, Unesco Place de Fontenoy 75700 Paris, France	English
33	Workshop on the IREP Component of the IOC Programme on Ocean Science in Relation to Living Resources (OSLR) Halifax, 26-30 September 1983	IOC, Unesco Place de Fontenoy 75700 Paris, France	English
34	IOC Workshop on Regional Co-operation in Marine Science in the Central Eastern Atlantic (Western Africa) Tenerife 12-17 December 1983	IOC, Unesco Place de Fontenoy 75700 Paris, France	English French Spanish
35	CCOP/SOPAC-IOC-UNU Workshop on Basic Geo-scientific Marine Research Required for Assessment of Minerals and Hydrocarbons in the South Pacific Suva, Fiji, 3-7 October 1983	IOC, Unesco Place de Fontenoy 75700 Paris, France	English
36	IOC/FAO Workshop on the Improved Uses of Research Vessels Lisbon, 28 May - 2 June 1984	IOC, Unesco Place de Fontenoy 75700 Paris, France	English
36 Suppl.	Papers submitted to the IOC-FAO Workshop on Improved Uses of Research Vessels Lisbon, 28 May-2 June 1984	IOC, Unesco Place de Fontenoy 75700 Paris, France	English
37	IOC/Unesco Workshop on Regional Co-operation in Marine Science in the Central Indian Ocean and Adjacent Seas and Gulfs Colombo, 8-13 July 1985	IOC, Unesco Place de Fontenoy 75700 Paris, France	English
38	IOC/ROPME/UNEP Symposium on Fate and Fluxes of Oil Pollutants in the Kuwait Action Plan Region Basrah, Iraq, 8-12 January 1984	IOC, Unesco Place de Fontenoy 75700 Paris, France	English
39	CCOP (SOPAC)-IOC-IFREMER- ORSTOM Workshop on the Uses of Submersibles and Remotely Operated Vehicles in the South Pacific Suva, Fiji, 24-29 September 1985	IOC, Unesco Place de Fontenoy 75700 Paris, France	English
40	IOC Workshop on the Technical Aspects of Tsunami Analyses, Prediction and Communications Sidney, B.C., Canada, 29-31 July 1985 (in press)	IOC, Unesco Place de Fontenoy 75700 Paris, France	English
40 Suppl.	IOC Workshop on the Technical Aspects of Tsunami Analyses, Prediction and Communications Sidney, B.C., Canada, 29-31 July 1985 *Submitted Papers*	IOC, Unesco Place de Fontenoy 75700 Paris, France	English