



WEATHER BUREAU
Western Region
Salt Lake City, Utah
February 1970

Tsunami

Richard P. Augulis



Technical Memorandum WBTM WR-48

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION



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**Revised



A western Indian symbol for rain. It also symbolizes man's dependence on weather and environment in the West.

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ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
WEATHER BUREAU

Weather Bureau Technical Memorandum WR-48

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Richard P. Augulis
Meteorologist
Scientific Services Division
Western Region Headquarters, Salt Lake City, Utah



WESTERN REGION
TECHNICAL MEMORANDUM NO. 48

SALT LAKE CITY, UTAH
FEBRUARY 1970

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TSUNAMI

I. INTRODUCTION

The tsunami is an ocean wave generated by seismic activity--eruption of volcanoes, slippage of faults, submarine landslides, etc. The tsunami is usually unnoticeable in midocean, but when finally striking land its destruction can be considerable.

It is the purpose of this Technical Memorandum to acquaint Western Region personnel with some basic theoretical concepts and operational problems associated with the tsunami. The U. S. Coast and Geodetic Survey, an agency of the Environmental Science Services Administration (ESSA) is responsible for issuing tsunami warnings. Although the Weather Bureau is not directly involved in tsunami warnings, requests for assistance to fulfill some public service requirements during such a warning might be solicited by the Coast and Geodetic Survey, local law enforcement, or Civil Defense agencies. It is important during these and other circumstances that Weather Bureau personnel have some knowledge of tsunamis. With approximately 8,900 miles of tidal shoreline in the Western Region susceptible to tsunami inundation, the aforementioned requests might not be infrequent.

Tsunamis have affected man ever since he began settlement of islands and the continental rims of oceans. Scientific research has increased his knowledge of tsunami mechanics, and past disasters have led to establishment of a Seismic Sea Wave Warning System (SSWWS) operated by the U. S. Coast and Geodetic Survey. As research continues man will move progressively toward a better understanding of, and protection from, this dangerous phenomenon.

II. SEISMOLOGICAL PRINCIPLES

Tsunamis, or tidal waves as they are sometimes incorrectly called by lay people, are generated from oceanic earthquakes and volcanic eruptions. First, in order to have an understanding of the importance of seismological events in tsunami generation, some basic concepts of seismology will be presented.

The earth is believed to consist of an outer crust varying in thickness from 2-3 miles under oceans to 25 miles beneath continents. Under the crust lies a rock mantle descending to about 1800 miles, and below the mantle is the fluid outer core with an apparently solid inner core at a depth of approximately 3,200 miles. Stresses generated in the crust and mantle interface are stored in the form of strain, i.e., physical deformation of rock structure. Under normal conditions, stress is removed through plastic deformation of the rock. However when stresses accumulate too rapidly to be removed by plastic flow, some structural compensation will usually occur. Large blocks of material are slowly

forced into highly strained positions along faults and held in place by a supporting structure of stronger materials. These zones of weakness continue to shift; but when more stress causes supporting rocks to rupture, sides of the fault move horizontally and vertically with respect to each other and create motions within the earth called "earthquakes". Horizontal movement is termed "strike-slip", while vertical movement is "dip-slip". Examples of both are shown in Figures 1 and 2.

The earth's most active earthquake region is the circum-Pacific seismic belt, which lies in the major geologic faults along coasts of the continents surrounding the Pacific Ocean and along deep ocean trenches of the Pacific island arcs. This region is appropriately called the "Ring of Fire". Other active regions include the mid-Atlantic Ridge, the area from southeastern and southern Asia into southern Europe, and the Indian Ocean up through the eastern Mediterranean to southern Asia. During the period August 1965 to the end of 1966 approximately 600,000 temblors were recorded throughout the world, with 60,000 strong enough to be felt, and 400 resulting in damage.

Four basic waves are produced by earthquakes. There is the primary or "P" wave, the secondary or "S" wave, the Love wave, and Rayleigh wave. The latter two are surface waves of much greater wave length and period than "P" and "S" waves. Primary waves are longitudinal like a sound wave and propagate through both liquids and solid. They are usually the first signal of an earthquake. Speed of "P" waves varies from approximately 15,000 miles per hour in the earth's crust to more than 30,000 miles per hour through the core. As a primary wave progresses through the earth, particles are pushed together and displaced away. Objects imbedded in the ground experience a series of sharp pushes and pulls parallel to the wave path.

Secondary or "S" waves are transverse like radio waves or ocean swell. They travel half the speed of "P" waves and displace particles at right angles to the direction of wave travel. The vertical component of this motion is damped by gravity, but side-to-side shaking in the horizontal can be quite destructive.

The difference between "P" and "S" wave arrival times over a network of seismological stations allows determination of an earthquake's location. The point in the earth of earthquake origin is called the "focus". The epicenter is the point on the earth's surface directly above the focus. The distance between the epicenter and focus is an earthquake's focal depth.

Intensity is a measure of an earthquake's severity at a specific location. The Mercalli Scale measures intensity subjectively through experienced observers employing a scale division of 12 classes ranging from I, felt under especially favorable conditions, to XII, total damage. This method of measuring earthquake severity is analogous in

meteorology to estimating wind speeds employing the Beaufort Scale. Rating earthquakes or wind in this subjective manner has the disadvantage of being a relative measure.

The objective method now employed to measure earthquake is the Richter Scale. It rates earthquakes in absolute terms, referring to a logarithmic not arithmetic scale. An earthquake of magnitude 8 would represent seismograph amplitudes ten times larger than those of magnitude 7, or 100 times larger than a magnitude 6 tremor. Most people think of this scale as ranging from 0 to 10. However, because it's an absolute scale, no highest or lowest value exists. Seismographs have recorded tremors ranging from 8.9 to -3 on the Richter Scale. The destructive 1964 Alaska earthquake was recorded at various stations as magnitude 8.4, 8.5, and 8.6.

Energy comparisons are also possible within the Richter Scale. For example an earthquake with a magnitude 5.0 has 1/1000 the energy of one with magnitude 7.0. For comparison purposes the energy of a magnitude 7 earthquake is approximately equal to 1 million tons of TNT.

III. THE TSUNAMI

A tsunami is a series of traveling ocean waves of extremely long length and period. Over the deepest portions of the ocean, their wave length may be over 100 miles, their amplitude a few feet, and their speed near 600 miles per hour. They are seldom felt or seen by observers on ships but the kinetic energy represented by a tsunami is large. Tsunami waves extend through the depth of the ocean literally feeling the bottom as they progress. A tsunami wave represents a movement of the entire vertical section of the ocean through which it passes. As the wave approaches the rising topography of a coastline, friction becomes an active force causing its speed to diminish and its height to increase. Some of the disastrous effects of historical tsunamis are summarized below.

Year	Location of Tsunami	Deaths	Damage
1883	Krakatoa, East Indies	36,000	not available
1896	Japan	27,000	not available
1933	Japan	1,000	not available
1946	Hilo, Hawaii	163	25 million
1960	Hilo, Hawaii	61	22 million
1960	Chile	1,000	not available
1960	Japan	229	not available
1964	Oregon, California, and Alaska	100	not available

Because of its potential for future human death and property destruction, the tsunami cannot be ignored.

IV. CHARACTERISTICS OF TSUNAMIS

Tsunami wave lengths vary anywhere from 30 to 300-400 miles with wave periods of several minutes to an hour. As a tsunami runs onto the beach, a gentle rise in water level or a devastating wave can result. Tsunami waves propagate radially from their source. An analogous situation occurs when a pebble is dropped into a calm pool of water. However, it must be emphasized that a tsunami wave extends throughout the depth of the ocean, unlike the aforementioned example in which the radiating waves are near-surface phenomena.

The typical height of a tsunami in open water is only a few feet. Since the wave length of a tsunami is much greater than the depth of water through which it is traveling, it is called a "shallow-water wave". Its speed through water is approximately given by the equation $S = \sqrt{gh}$ where S is tsunami speed, g is acceleration of gravity (32 feet per sec²), and h is depth of water through which it is traveling. This physical relationship allows prediction of arrival time if ocean depth and time of initial tsunami generating shock are known. As an example, the speed of a tsunami in water 18,000 feet deep is approximately 450 knots; in 900 feet it is 100 knots, and in 60 feet it is 25 knots.

Because the tsunami is a series of waves, it is difficult to know which wave will be the highest. Frequently the first wave is not the highest, although the highest one will usually come early in the series. Figures 3 and 4 from (1) give some representative wave heights recorded from tsunamis and show a specific tsunami's wave height variability at different locations. Note the significant rise and fall in water level between waves. This allows many curious people to venture out to previously unseen beach areas, later to be trapped and drowned by the next wave. These examples show the variability of wave period, making timing of the next wave difficult.

V. TSUNAMI GENESIS

The general belief among scientists is that tsunamis originate from a vertical displacement of water. The process by which this displacement is accomplished is still uncertain; however, some possible explanations are vertical displacement of the ocean floor occurring with earthquakes, submarine avalanches, long-period earthquake waves, and resonance of trench water (see Figure 4).

The most popular theory is vertical displacement of water by underwater earthquakes. A study by Leet (2) showed that during the period 1861 to about 1947 some 15,000 earthquakes were recorded near coastal areas with only 124 tsunamis being observed. A later catalog showed 1,098 South America west coast temblors recorded with 19 observed tsunamis. Statistics such as these illustrate the fact that all earthquakes are not accompanied by a tsunami. This fact alone makes an understanding of tsunamigenesis difficult.

As previously mentioned, earthquake movements are of two types, strike-slip (horizontal motion) and dip-slip (vertical motion). Vertical motions are quite favorable for tsunami generation. The reason might best be shown through the following example: vertical (up and down) movements of a dish beneath water will create much larger volume displacements of water than horizontal (sliding) movements. This is comparable to water displacements caused by rock displacements beneath the ocean during an earthquake. Thus the type of earthquake motion becomes a very important factor in tsunamigenesis.

Submarine avalanches are a second possible cause of tsunamis. The slide must be of sufficient magnitude so as to displace a large volume of water. However this cause is believed to occur less frequently than earth movements. Long-period earthquake waves causing resonant oscillations of water or deformation of the ocean floor are other suggested causes which occur at a lesser frequency so as to have minimal importance in tsunami generation. These long-period waves from within the earth subsequently develop water displacements extending to the sea surface.

Other important factors affecting tsunami generation and magnitude are water depth, earthquake magnitude, depth of the earthquake, and efficiency of energy transfer. Tsunami magnitude measures the waves severity by energy comparison. Although there exists a relationship between tsunami magnitude and earthquakes, the nature of this relationship is not well defined. Studies have shown that earthquakes of magnitude 6.5 or greater are usually necessary before tsunami generation is likely. Dip-slip earthquakes are tsunamigenic, while strike-slip are not. Iida (3) has shown that earthquakes associated with strike-slip faulting are almost never accompanied by tsunamis even though the magnitude is nearly 7.

Large tsunamis require deeper water than smaller tsunamis. The scatter diagram in Figure 5 from (1) shows this relationship quite well. Studies have shown that most tsunamis are associated with earthquakes between focal depths of 0-40 kilometers, with only a few tsunamis associated with focal depths between 40-80 kilometers, and none with focal depths greater than 80 kilometers.

The efficiency of energy transfer from the earth's crust to the ocean water is not well understood. However studies by seismologists have indicated that the ratio between tsunami energy and earthquake energy

can vary from 1/10 to 1/100. Understanding the exact relationship of each factor to tsunami generation is the goal geophysicists are striving toward.

VI. RUNUP

As a tsunami wave approaches shore, a number of changes in the wave's shape take place. These changes are associated with dissipation of energy as the wave enters shallower water; speed of the wave decreases and height increases. The rise in wave steepness can occur quite rapidly with the wave reaching a limiting ridge-like crest. As it progresses into shallower water, turbulent water is spilled from the crest, and thereafter the wave will continuously dissipate energy as it advances. It is this runup wave that makes the tsunami a destructive phenomenon. Runup is defined as the maximum elevation reached by the wave above the initial water level. Some historic runups are indicated below.

<u>Year</u>	<u>Location</u>	<u>Runup Height</u>
1883	Mera, Java	135 feet
1896	Kamaishi, Japan	100 feet
1946	Hilo, Hawaii	26 feet
1960	Hilo, Hawaii	35 feet
1964	Kodiak Island, Alaska	60 feet

The variability of runup at different locations associated with a specific tsunami can be extreme. Figures 7 and 8 from (4) show examples of variability for four recent tsunamis which have affected the islands of Oahu and Hawaii in the Hawaiian chain. Note in Figure 7 that the 1960 tsunami caused a 35-foot runup at Hilo while at Papai-kou some 5 miles away the runup was only 9 feet. Similar variations occurred for other towns on Oahu and Hawaii.

Runup variability makes prediction of expected wave heights and taking of protective measures difficult. It is caused by a number of factors such as change in coastal slope, direction of wave propagation to the coastline, coastal shape, and underwater terrain features.

The slope of the ocean floor affects wave heights significantly. For example a slope of 1:50 produces a tsunami wave approximately 7 times higher than a 1:500 slope. The direction taken by waves can be altered by varying water depths. As a wave advances over changing underwater topography, it will become refracted. Figure 9 is a wave refraction chart from (1) showing the movement of the 1960 Chilean tsunami across

the Pacific. The movement of the tsunami is always perpendicular to the wave front. Note how the wave progresses quite symmetrically across the ocean until it encounters the more changeable ocean floor of the western Pacific. Of most importance is the refraction which occurred around the Hawaiian Islands. Figure 10 from (4) shows this refraction in more detail. Note how the wave with an initial direction of movement from 132° was turned and approached portions of Oahu's northwest coast nearly headon. Figure 11, also from (1) shows an even more detailed drawing of wave refraction around the island of Hawaii associated with the 1946 tsunami. Again note how the wave front changes direction as it passes over the varying ocean topography around the islands. These examples illustrate the fact that even though a shoreline may not be in the direct path of an advancing tsunami, topographical changes in ocean depth can cause a direct strike.

A tsunami wave can be either focused (crowding of energy into a smaller area) or defocused (spreading out) depending on the trend of the bottom contours. An example of focusing waves is shown for Hilo in Figure 11. The wave front was focused into the harbor. This explains in part the excessive runup indicated in Figure 7 at Hilo as compared to other nearby towns.

Large abrupt discontinuities in ocean depth can lead to reflection of energy back to the sea. These energy interactions between waves can form complicated energy dispersion patterns, which made runup predictions difficult and at times impossible.

Resonance is a controlling factor of runup. Waves entering a harbor bay at a period equal to the "frequency of the harbor" will generate an oscillation in it. This relationship is a function of the potential ratio of tsunami period to the period of the bay. The greater the buildup of the oscillation and the greater the number of waves, the greater is the peak response. Thus it becomes important to know what the tsunami period is.

Shape of the coastline is another important factor. A triangular-shaped bay will usually have a higher tsunami wave at its head than at its mouth. It is not uncommon to have significant runup differences over very short distances because of this.

These are some of the more important factors affecting tsunami runup. Evaluation of all in a short time is impossible. Present prediction techniques are performed mostly by hand, employing available studies and forecast schemes. These, along with the Seismic Sea Wave Warning System, form the first line of defense against the tsunami. Reports by Adams (4) and Cox (5) are excellent summaries of prediction techniques.

In the future, computerized techniques evolving from research and improved instrumentation will lead to better understanding and improved predictability. However until more of the interrelationships are understood, the best protective measure is evacuation from potentially affected areas.

VII. SEISMIC SEA-WAVE WARNING SYSTEM (SSWWS)

Tsunamis have been the scourge of the Pacific since man's settlement of the coastal areas. Warnings and protection from their danger were nonexistent until the late 1940s. It was after the disastrous Hawaiian tsunami of April 1946 that a plan was devised to warn the public of possible tsunami inundation. This warning facility was named the Seismic Sea Wave Warning System. It was put into operation in 1948 with headquarters at the U. S. Coast and Geodetic Survey's magnetic and seismological observatory in Honolulu, Hawaii. At first the facility was designed for protection of the Hawaiian Islands only but later was expanded to encompass the whole Pacific area. The 1948 network started with 4 seismic stations and 9 tide gages. Presently there are 20 seismic and 40 tide stations.

The warning system employs a worldwide network of seismological stations to detect and locate earthquakes, a network of tide gages to record passing tsunami waves, and an expanding communications system to speed transmission of information and warnings to users in 11 countries bordering the Pacific. Appendix A lists the seismological and tide stations presently in use by the Coast and Geodetic Survey along with planned additions.

Seismograph stations are the first line of detection for the Seismic Sea Wave Warning System. These are operated domestically by the Coast and Geodetic Survey and private institutions, and overseas by private institutions and governments of cooperating Pacific nations. The focal point of this network is the Honolulu Observatory, which maintains a continuous around-the-clock watch for earthquake activity. As soon as an earthquake of sufficient magnitude is recorded, the SSWWS responds immediately. Participating seismological stations report local arrival times for the "P" and "S" waves. From this information the earthquake epicenter is determined. A tsunami watch is issued if the earthquake is of sufficient magnitude and the epicenter is located under or near the ocean. This "watch" informs SSWWS participants of the occurrence and location of an earthquake of sufficient magnitude such that the possibility of a tsunami exists.

Because tsunamis follow known physical laws when moving through water, accurate arrival time estimates can be calculated. Through operational application of the laws, charts such as the one shown in Figure 12 from (1) are employed to forecast wave arrival times at various locations within the SSWWS. Similar charts have been prepared for all stations in the SSWWS.

After confirmation of a significant earthquake and issuance of a tsunami watch, the SSWWS goes to its second line of detection. This is the network of tide stations located throughout the Pacific. At these stations continuous gage measurements of the tide cycle are recorded. Passage of a tsunami wave will appear on the tidal record as a distinctive abnormality. (Examples of these records are shown in Figure 3.) Where tidal variations are small, seismic sea wave

detectors have been installed which record only passing waves having tsunami characteristics.

When a major oceanic earthquake has been recorded, observers at all tide stations are requested to closely monitor their tidal records and immediately report any "abnormal" activity. If a positive indication of a tsunami is recorded, this information is relayed to the Honolulu Observatory. This first indication will usually come from tide stations nearest the earthquake epicenter. With a positive confirmation, Honolulu Observatory issues a tsunami warning including estimated arrival times, alerting SSWWS members of the approach of a potentially destructive seismic sea wave. Following the advice of the Honolulu warning, local warnings, evacuation, and other emergency procedures are then undertaken by designated agents of the SSWWS. Local agents attempt to prevent loss of life and reduce property damage during the emergency. Tsunami Safety Rules from an ESSA pamphlet (6) are listed below. Follow these rules if you are involved in a tsunami emergency.

- "1. All earthquakes do not cause tsunamis, but many do. When you hear that an earthquake has occurred, stand by for a tsunami emergency.
- "2. An earthquake in your area is a natural tsunami warning. Do not stay in low-lying coastal areas after a local earthquake.
- "3. A tsunami is not a single wave, but a series of waves. Stay out of danger areas until an 'all-clear' is issued by competent authority.
- "4. Approaching tsunamis are sometimes heralded by a noticeable rise or fall of coastal water. This is nature's tsunami warning and should be heeded.
- "5. A small tsunami at one beach can be a giant a few miles away. Don't let the modest size of one make you lose respect for all.
- "6. The Pacific Tsunami Warning Center does not issue false alarms. When a warning is issued, a tsunami exists. The tsunami of May 1960 killed 61 in Hilo, Hawaii, who thought it was 'just another false alarm'.
- "7. All tsunamis--like hurricanes--are potentially dangerous, even though they may not damage every coastline they strike.
- "8. Never go down to the beach to watch for a tsunami. When you can see the wave you are too close to escape it.

"9. Sooner or later, tsunamis visit every coastline in the Pacific. Warnings apply to you if you live in any Pacific coastal area.

"10. During a tsunami emergency, your local Civil Defense, police, and other emergency organizations will try to save your life. Give them your fullest cooperation.

"Unless otherwise determined by competent scientists, potential danger areas are those less than 50 feet above sea level and within one mile of the coast for tsunamis of distant origin; or less than 100 feet above sea level and within one mile of the coast for tsunamis of local origin.

"Stay tuned to your radio or television stations during a tsunami emergency--bulletins issued through Civil Defense and ESSA offices can help you save your life!"

For the reader's additional information, listings of the SSWWS organization and communication structure are given in (7) and (8).

A tsunami warning is taken down after the waves have crossed the whole Pacific. The 1964 Alaska earthquake afforded an excellent opportunity of following a tsunami across the Pacific. The following was its course:

March 27, 1964	0344 GMT* - a very strong earthquake occurred near Seward, Alaska.
	0555 GMT - Kodiak Island, Alaska, experienced a 10-12 foot water rise.
	0700 GMT - tsunami reached Tofino, British Columbia.
	0739 GMT - first wave hit Crescent City, California.
	0900 GMT - tsunami reached the Hawaiian Islands nearly 6 hours after its time of origination.
	0920 GMT - a 12-foot wave smashed Crescent City, California, causing loss of life and widespread damage. This wave was probably the fourth in the series.

*Greenwich Mean Time

- 1020 GMT* - tsunami reached Hokkaido, Japan.
- 1100 GMT - Honolulu Observatory issued an all clear for Hawaii.
- 1355 GMT - tsunami arrived at Kwajalein Island in the western Pacific over ten hours after time of origination.
- 1910 GMT - tsunami reached La Punta, Peru, twelve hours and fourteen minutes after its birth.

All too often the passage of a tsunami leaves a trail of death and destruction behind. However protective measures taken before the passage of the wave have saved countless lives and reduced property losses.

VIII. THE FUTURE

What does the future hold for the Seismic Sea Wave Warning System? Tsunami research should continue at an accelerated pace. Employment of modern computers that can evaluate and perform mathematical computations on observational data will be on the increase. More time will be spent on tsunami-modeling studies near coastal areas and around ocean islands. Scientists in tectonics, geology, seismology, and oceanography along with engineers in instrumentation, communications, coastal and ocean engineering will pursue studies of tsunami problems. Exchanges of new ideas and findings between nations of the Pacific should continue.

The latest example of such an exchange occurred in October 1969, when scientists and engineers from all over the world met in Honolulu, Hawaii, for the International Tsunami Symposium. Attendees came from Russia, Japan, Canada, Australia, West Germany, and the United States. Theoretical and operationally oriented papers covering many of the topics and concepts discussed in this Technical Memorandum were presented. Many other ideas were exchanged through informal discussions.

Two other goals are new and more efficient instrumentation and increases in the seismic and tide gage network. Advanced underwater instruments made to record a tsunami passage in midocean are under development and testing. Operational use of these will likely occur in the near future. Information obtained from such instrumentation will enable scientists to study the tsunami in its undisturbed state. All present tide gage measurements are obtained near land areas where complicated energy changes occur. The closest undisturbed recordings have come from small islands and atolls in the Pacific.

*Greenwich Mean Time

New advanced electronic recording tide gages and automated tide stations are being implemented where possible. These will permit establishment of a more sophisticated and detailed network. Such additional data are needed for research and will become more readily available soon. A goal of 30 seismic stations and 120 tide gages has been set, and this should satisfy most future operational needs.

Development of warning systems for protection against locally generated tsunamis will continue. One such system has already been installed for Alaska.

Employment of the geostationary satellite as the principal communications link between seismic and tide stations and the SSWWS will likely be a reality in the 1970s.

These are but a few of the future plans and goals. No doubt there will be others along with new breakthroughs in understanding the physical laws governing tsunami generation, motion, and runup. One fact is certain, the scourge of the Pacific has past its peak as an unexpected cause of death to men who inhabit its domain.

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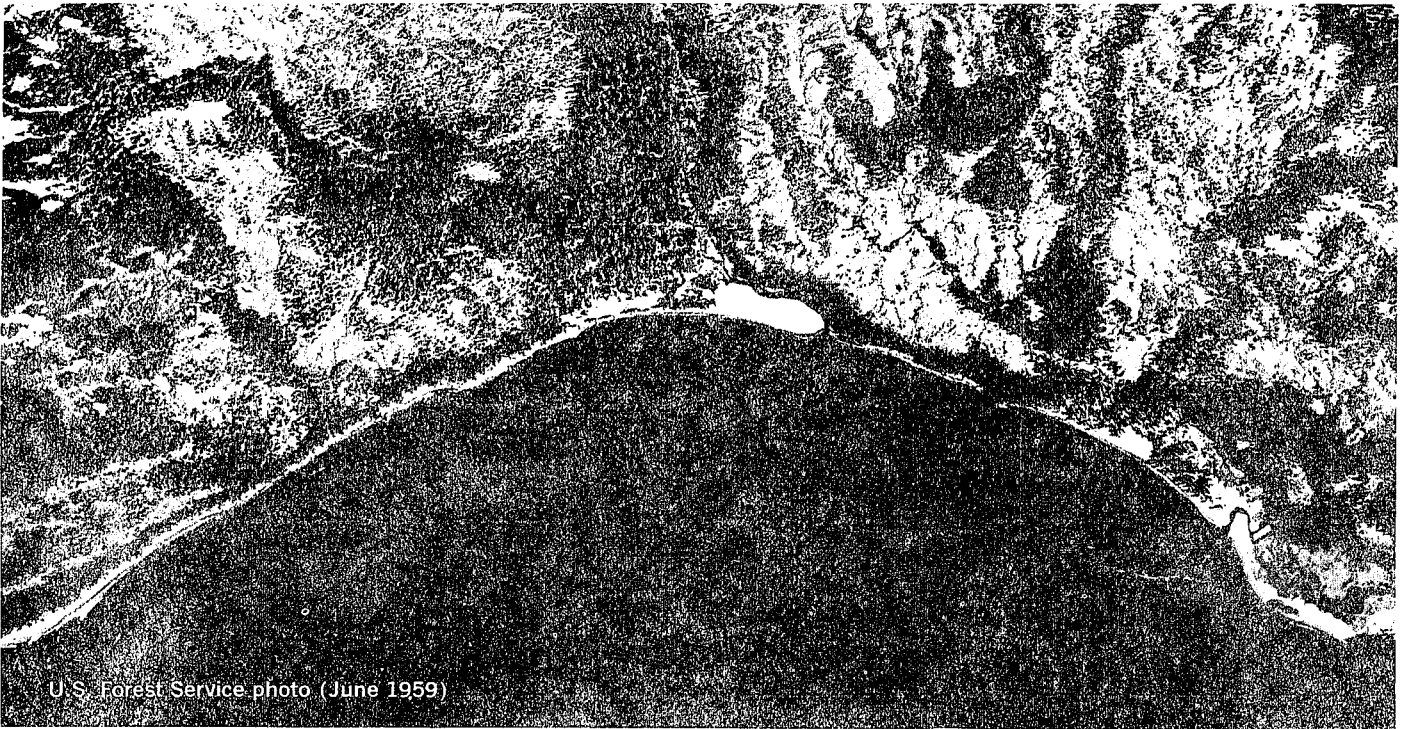
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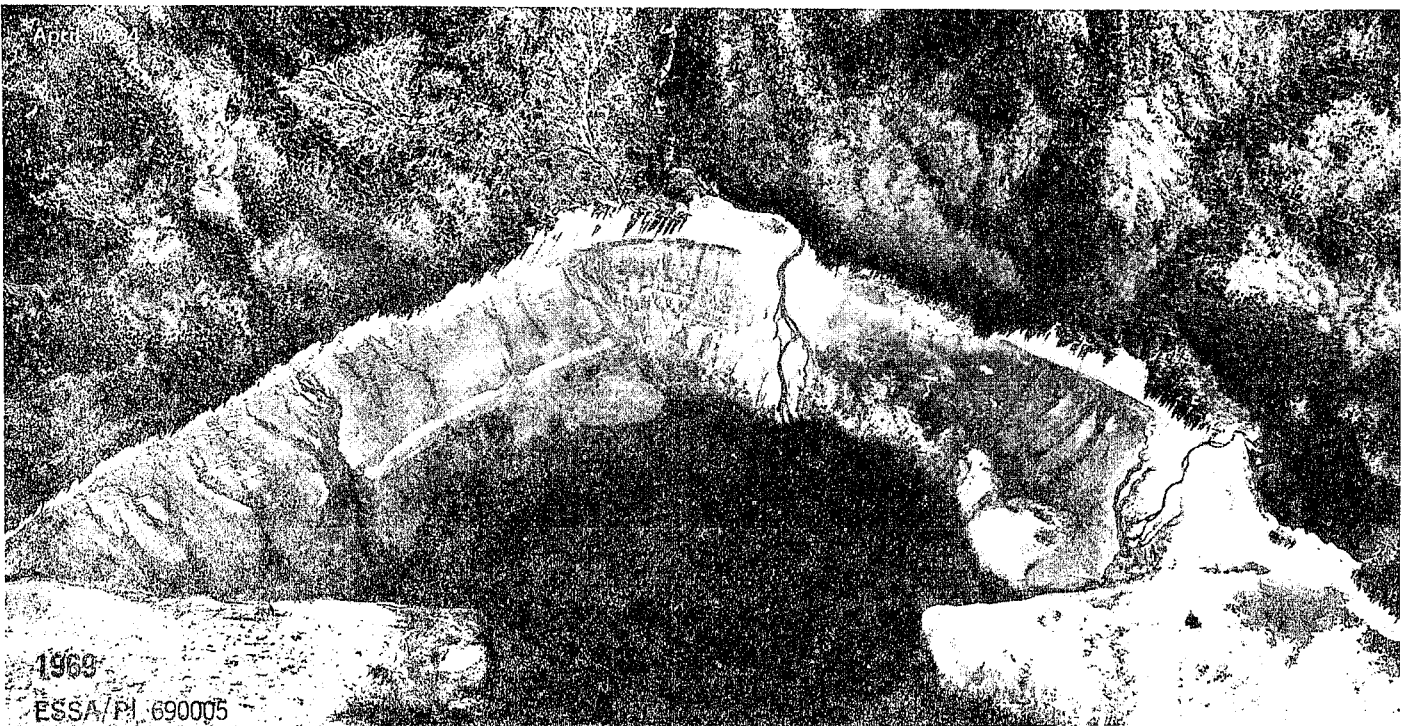
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8. U. S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey, "Communication Plan for Tsunami Warning System". Sixth Edition, Rockville, Maryland, May 1969.

FIGURE 1. DIP-SLIP EARTHQUAKE MOVEMENT

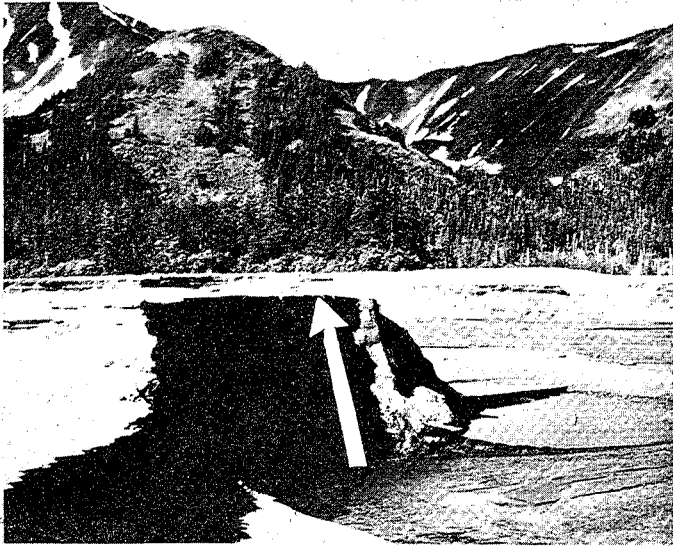


Montague Island, Alaska, before 1964 earthquake.

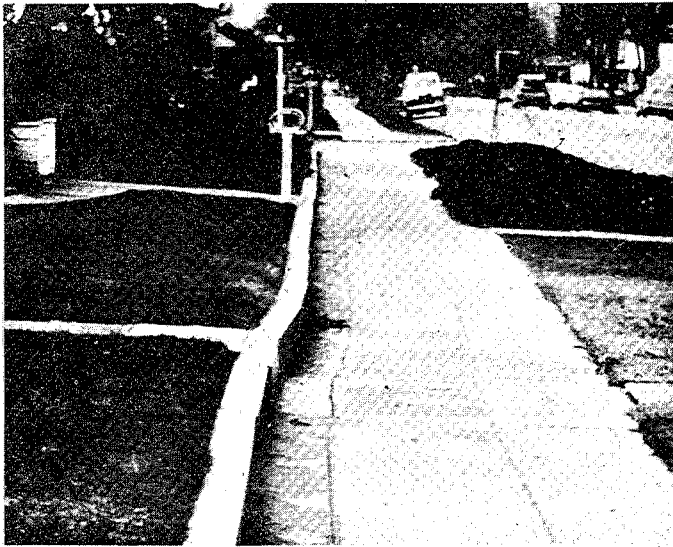


Montague Island, Alaska, after earthquake showing approximately 35 feet of vertical motion along the Hanning Bay fault.

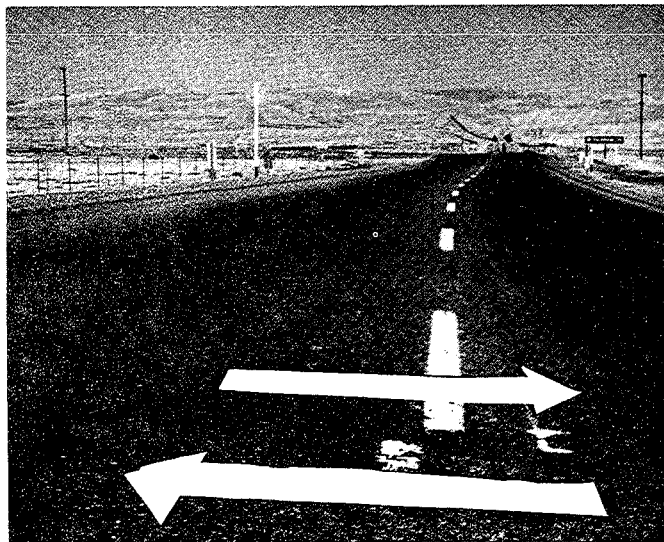
FIGURE 2



Dip-Slip Movement

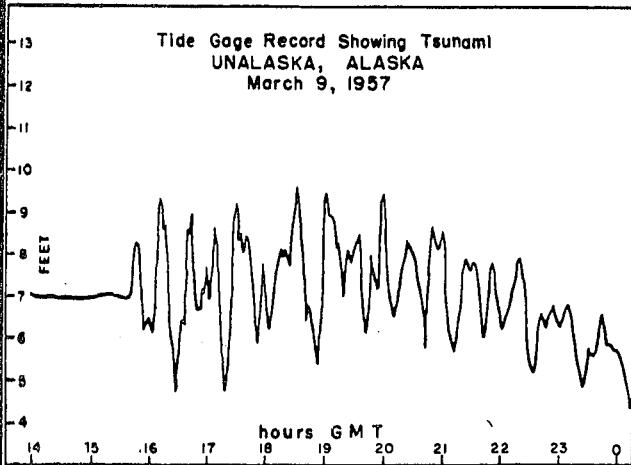
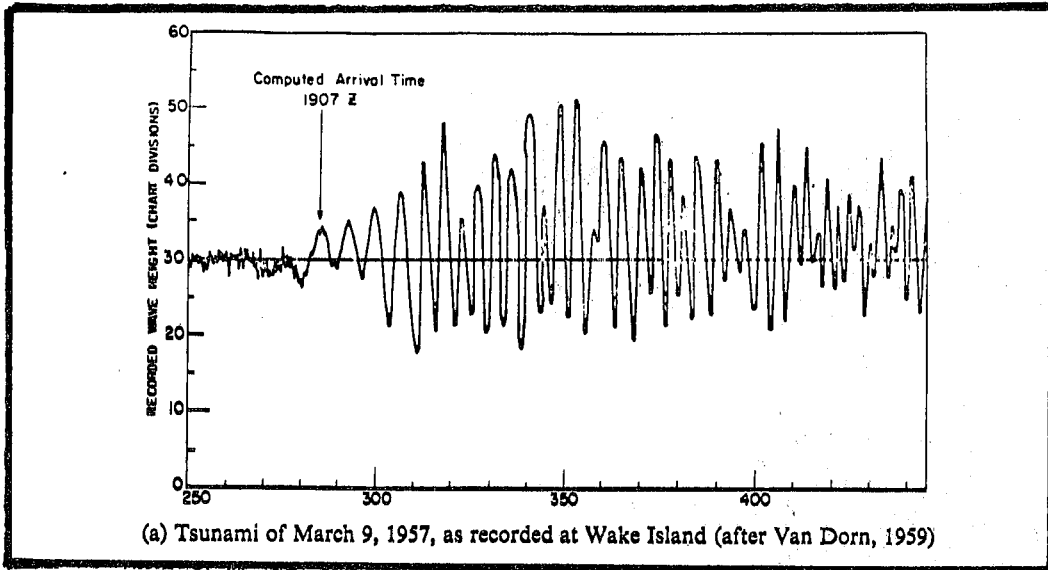


Strike-Slip (horizontal) Movement

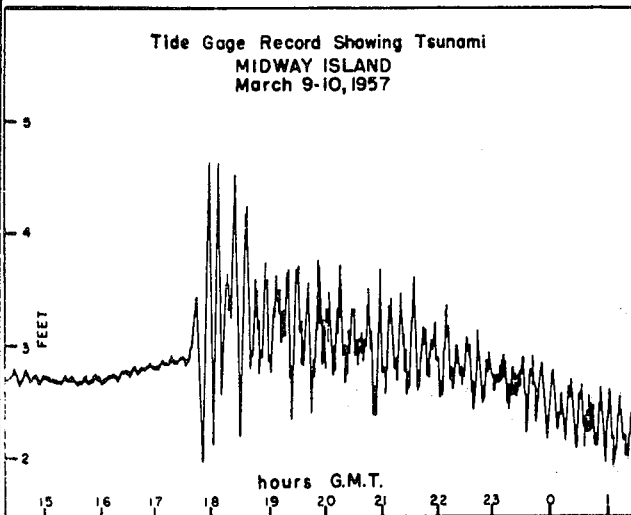


Strike-Slip (horizontal) Movement

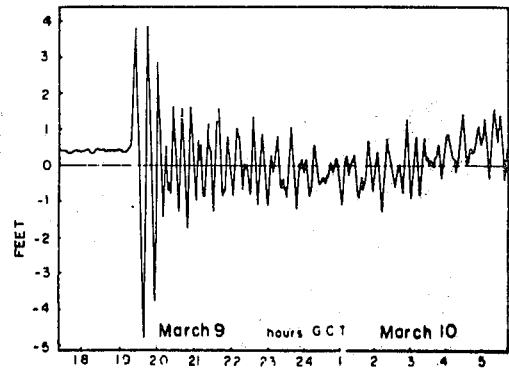
FIGURE 3. EXAMPLES OF TIDE GAGE RECORDS.



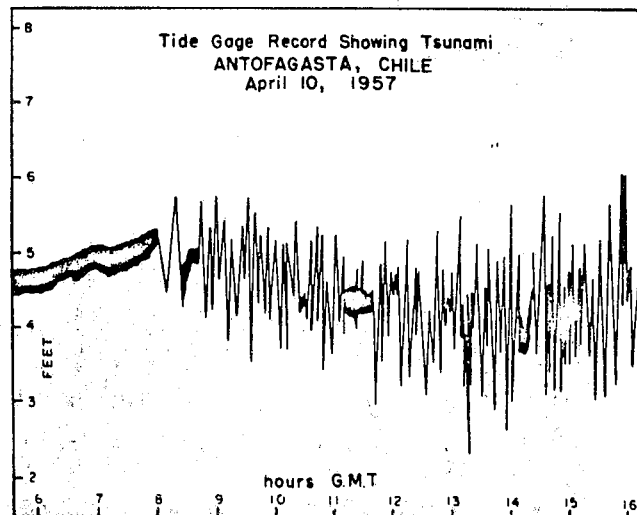
b) Period 1st to 2nd crest; 27 minutes; 3rd wave highest (after Salsman, 1959)



c) Period 1st to 2nd crest; 12 minutes; 1st wave highest (after Salsman, 1959)

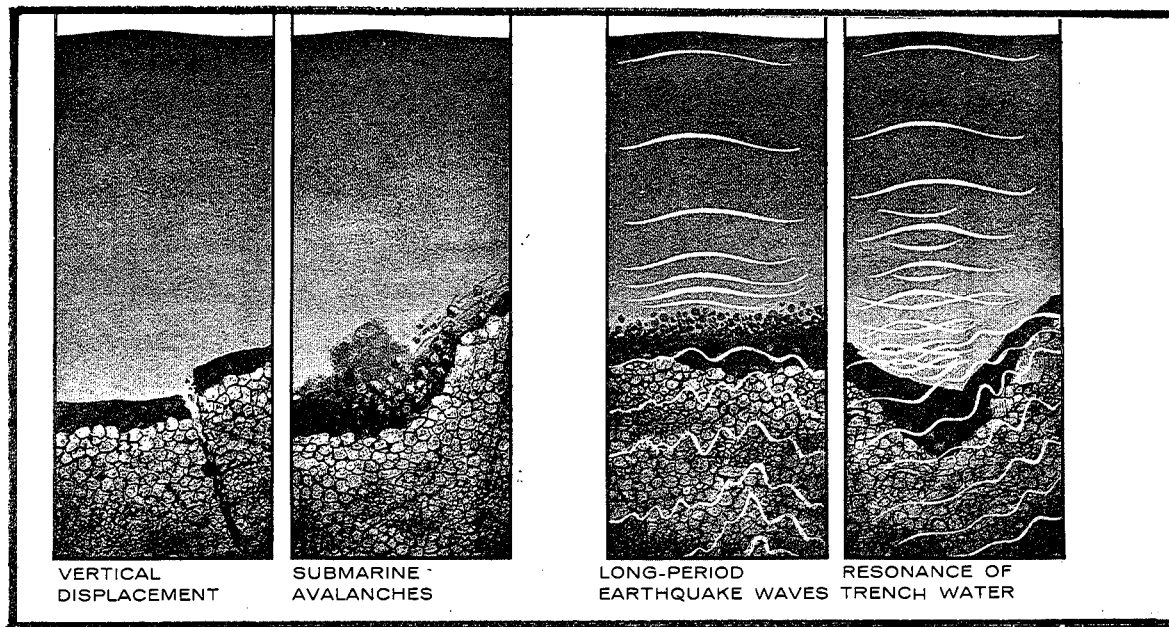


(d) Record of the tsunami of March 9, 1957, from the Hilo tide gage. Time is 10 hours ahead of Hawaiian time. Period 1st to 2nd crest; 19 minutes. 1st wave highest (Courtesy, U.S.C. & G.S.)



(e) Period 1st to 2nd crest; 14 minutes; 7th wave highest (after Salsman, 1959)

FIGURE 4. MECHANICS OF TSUNAMI GENERATION.



SOME INITIAL PERIODS AND MAXIMUM HEIGHTS
OF TSUNAMI ORIGINATING NEAR KAMCHATKA ON
NOVEMBER 4, 1952, AS OBTAINED FROM TIDE GAUGE RECORDS
(after Zerbe, 1953)

Tide station	Initial wave period first to second crest (min)	Initial rise (ft)	Maximum rise (or fall) (ft)
Adak, Alaska	48	1.4	6.9
Tolfino, B. C.; Canada	28	0.6	2.0
Crescent City, Calif.	25	1.7	6.8
Avila, Calif.	20	1.4	9.5
Los Angeles Harbor, Calif.	55	0.4	3.6
La Paz, Mexico	38	0.2	1.6
Salina Cruz, Mexico	35	0.3	4.0
Apra Harbor, Guam	53	0.5	0.9 (fall)
Wake I.	12	1.2	1.7
Midway I.	8	1.9	6.6
Hilo, Hawaii	20	4.0	7.9 (fall)
Johnson I.	29	1.2	1.4 (fall)
Yap I.	55	0.2	0.4 (fall)
Canton I.	13	0.3	0.7
Pago Pago, Samoa	18	0.9	6.0 (fall)
La Libertad, Ecuador	33	1.5	6.2 (fall)
Antofugasta, Chile	17	1.3	4.7 (fall)
Caldera, Chile	20	2.0	9.3

FIGURE 5. A TSUNAMI'S HEIGHT AND PERIOD RECORD AT VARIOUS LOCATIONS.

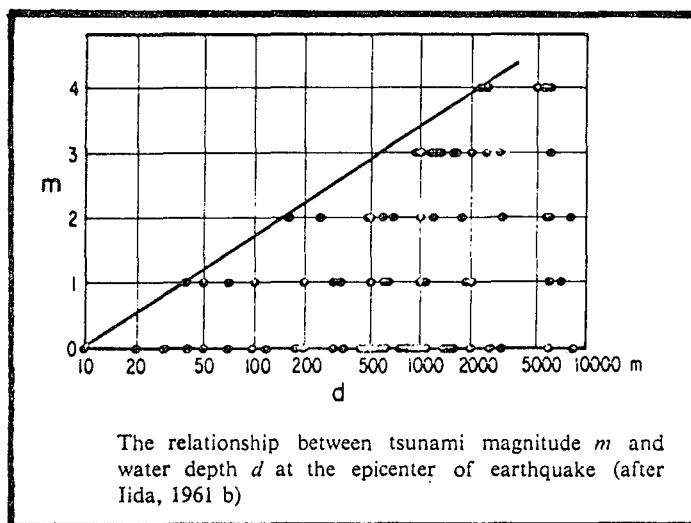
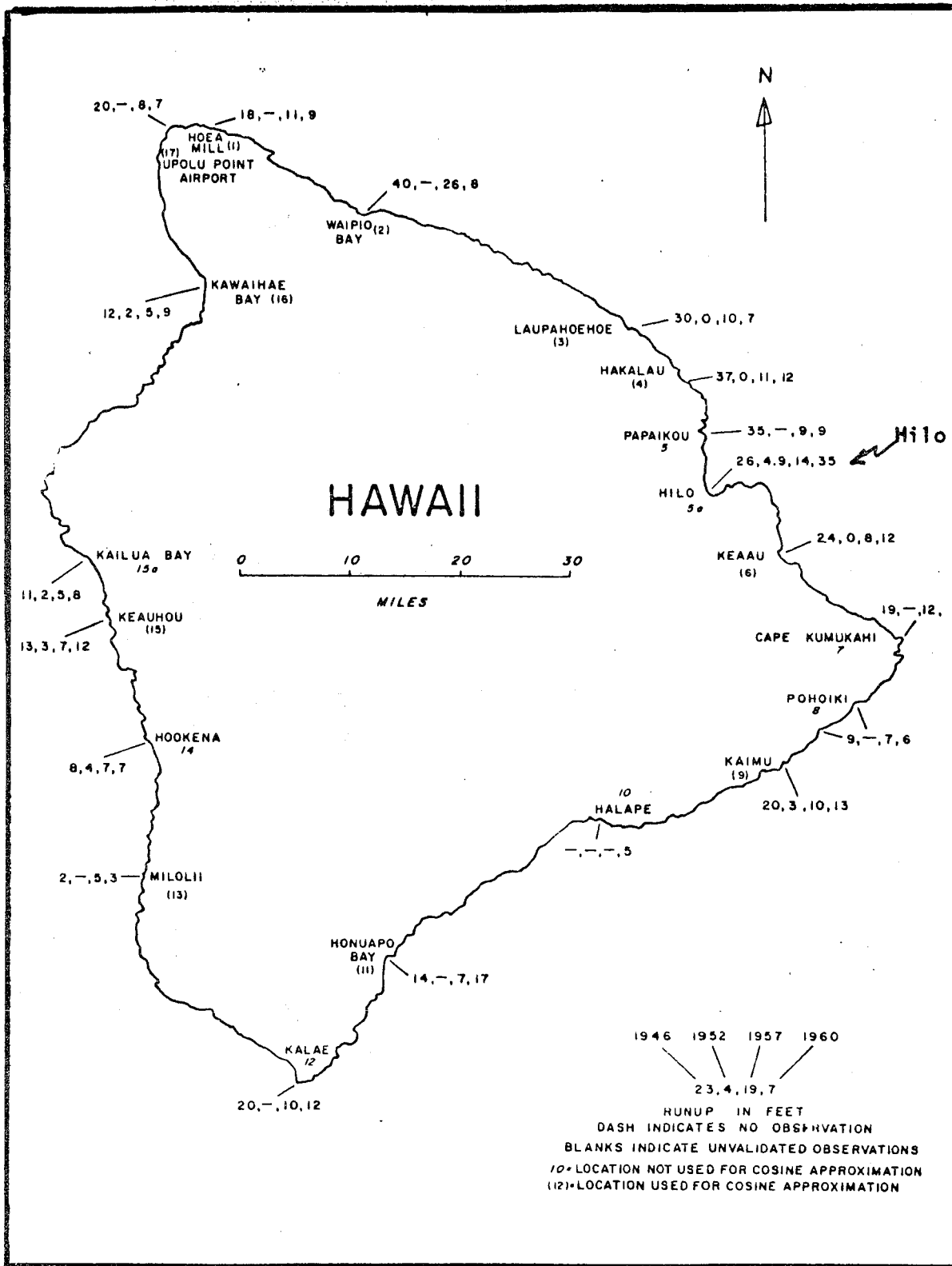


FIGURE 6. RELATIONSHIP OF WATER DEPTH TO TSUNAMI SEVERITY.

FIGURE 7. PAST RUNUP DATA ON HAWAII.



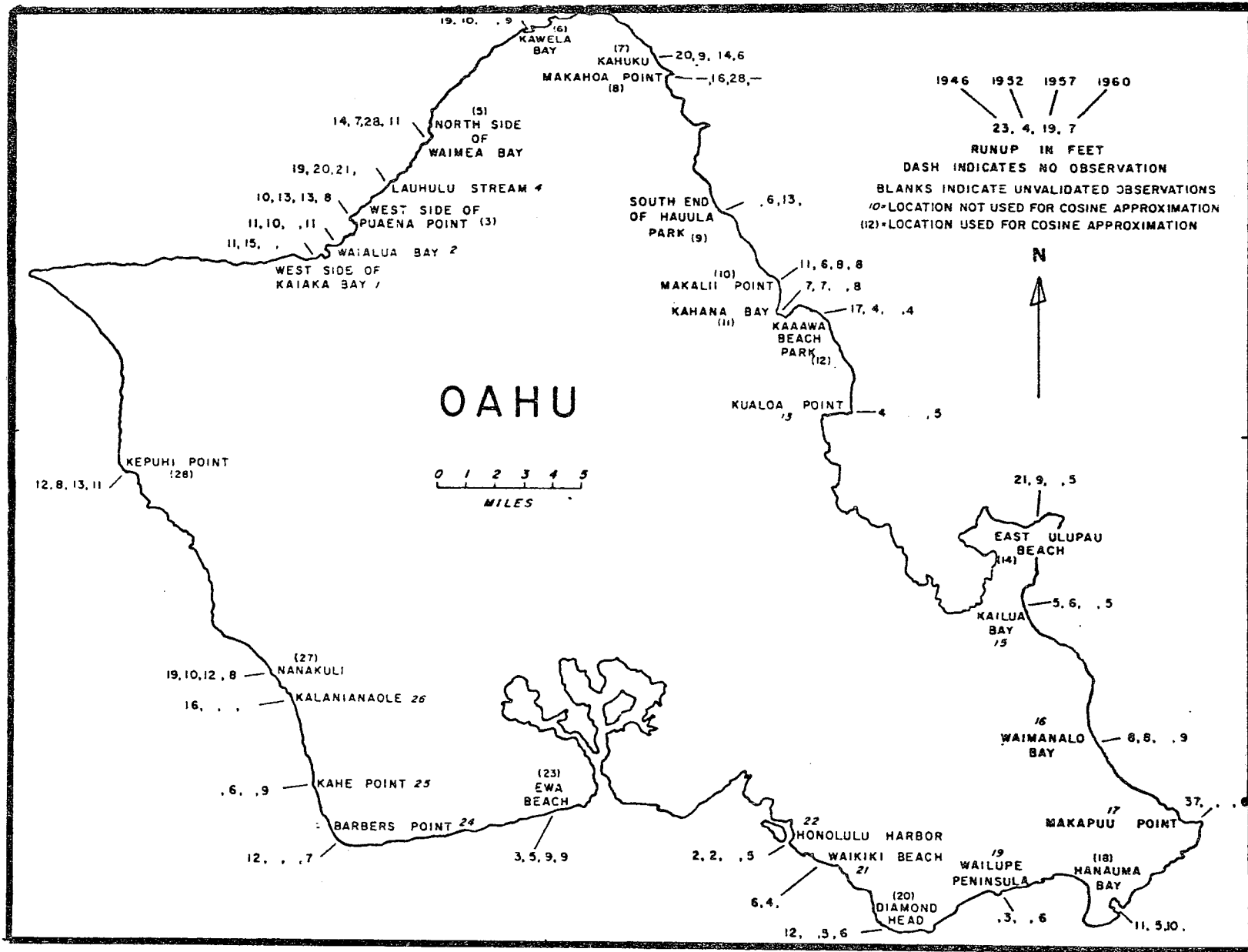


FIGURE 8 . PAST RUNUP DATA ON OAHU.

FIGURE 9. WAVE REFRACTION CHART FOR THE CHILEAN TSUNAMI OF MAY 23, 1960 (AFTER WADATI, HIRONO, AND HISAMOTO, 1963).

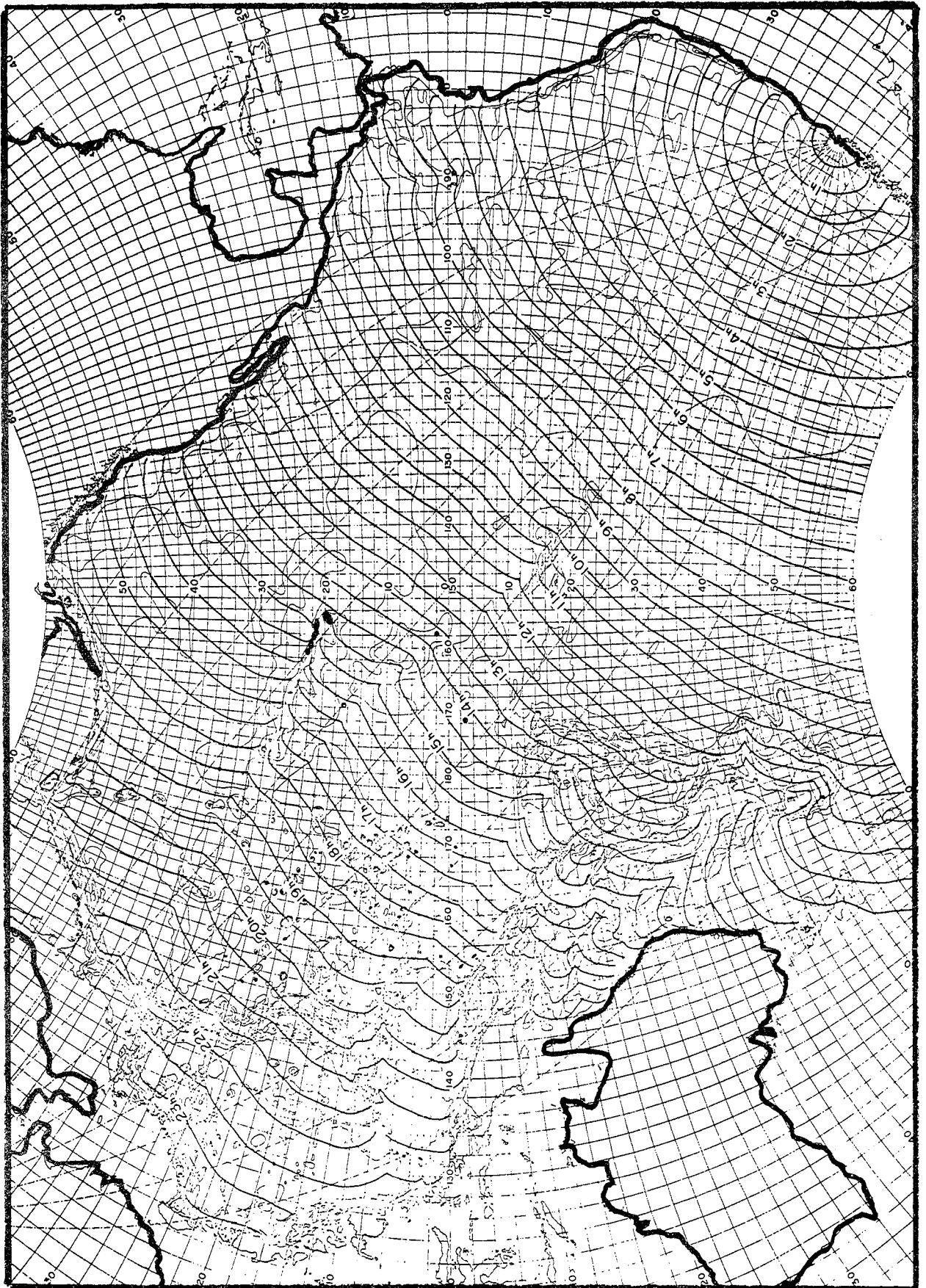
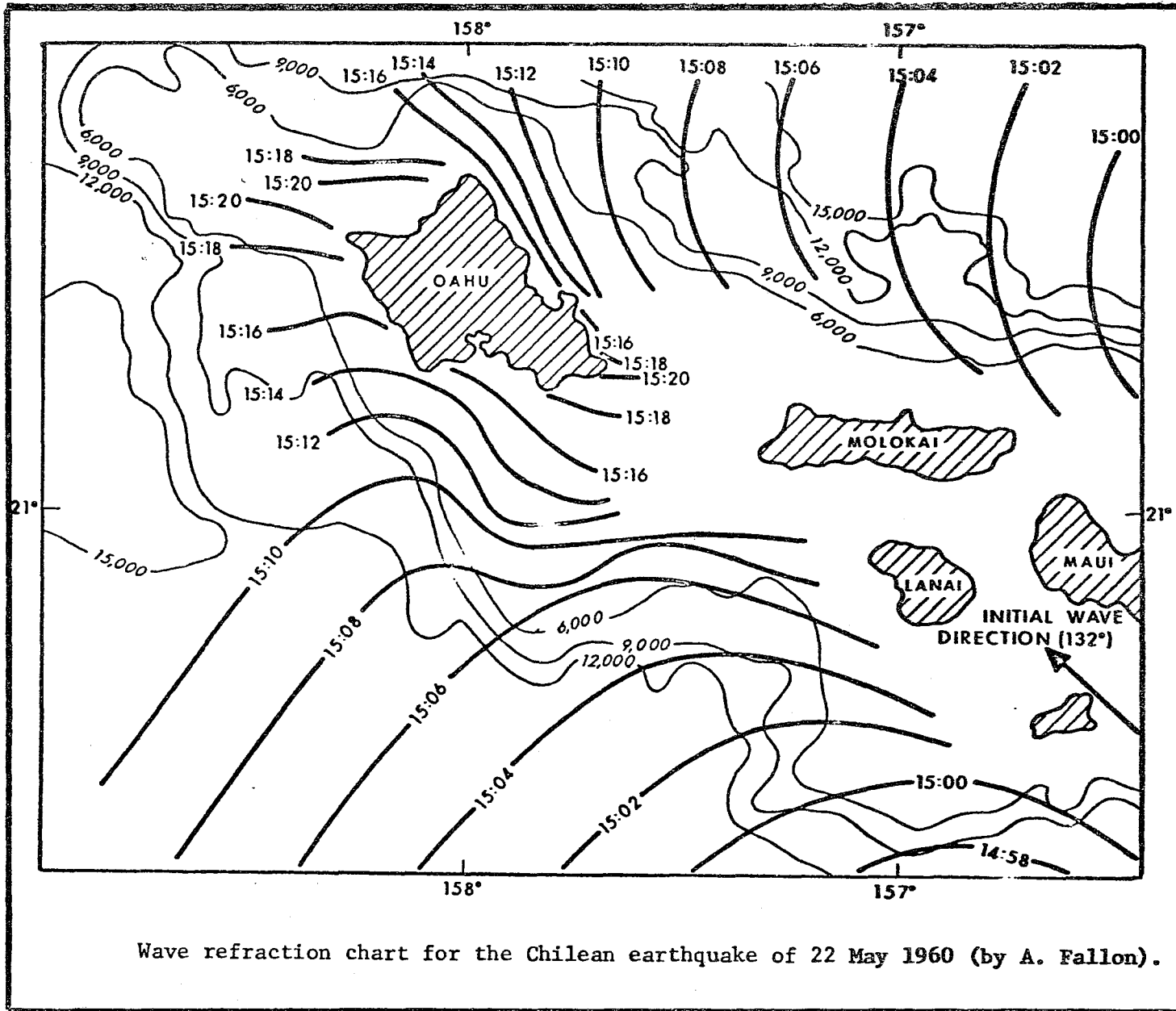
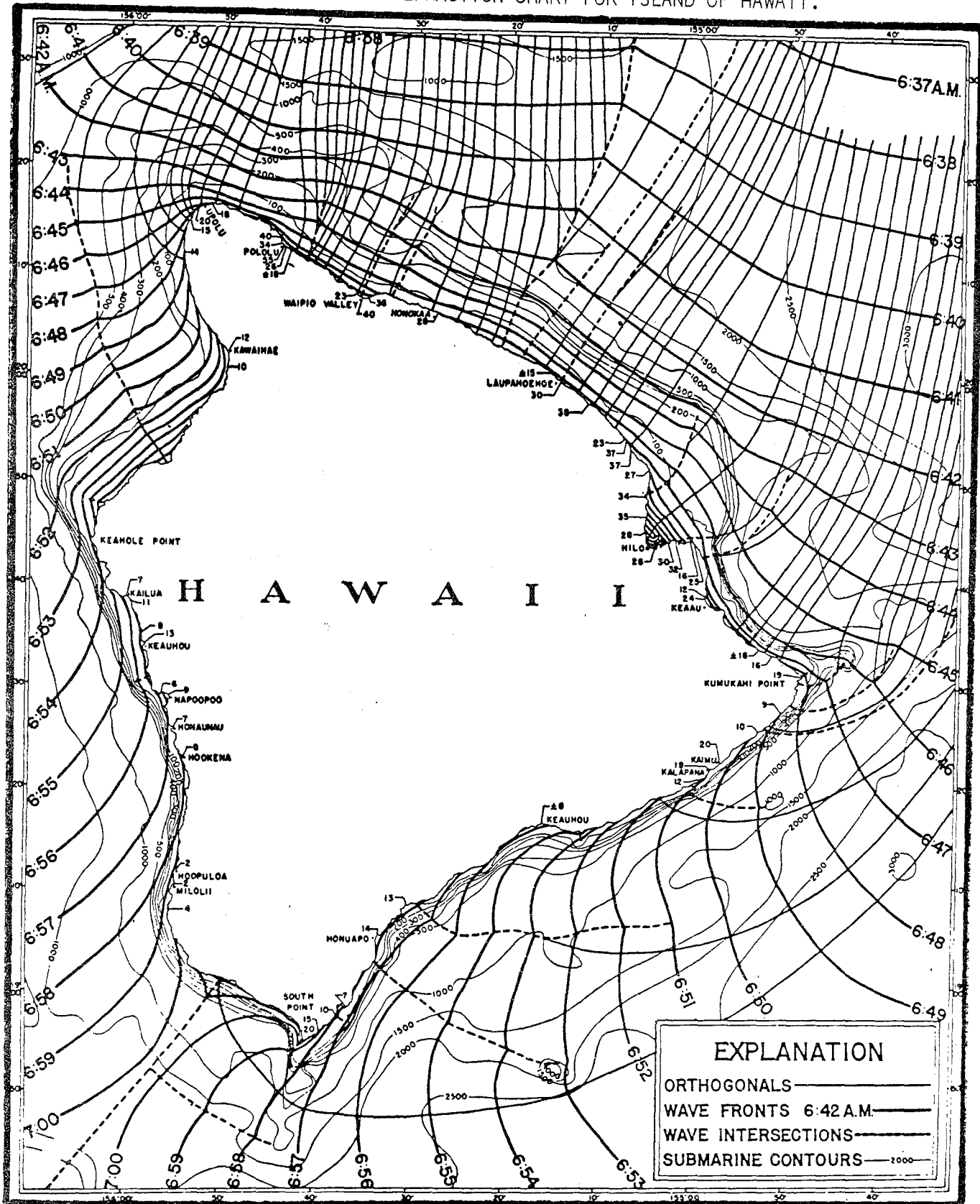


FIGURE 10. DETAILED WAVE REFRACTION CHART FOR HAWAIIAN ISLANDS.



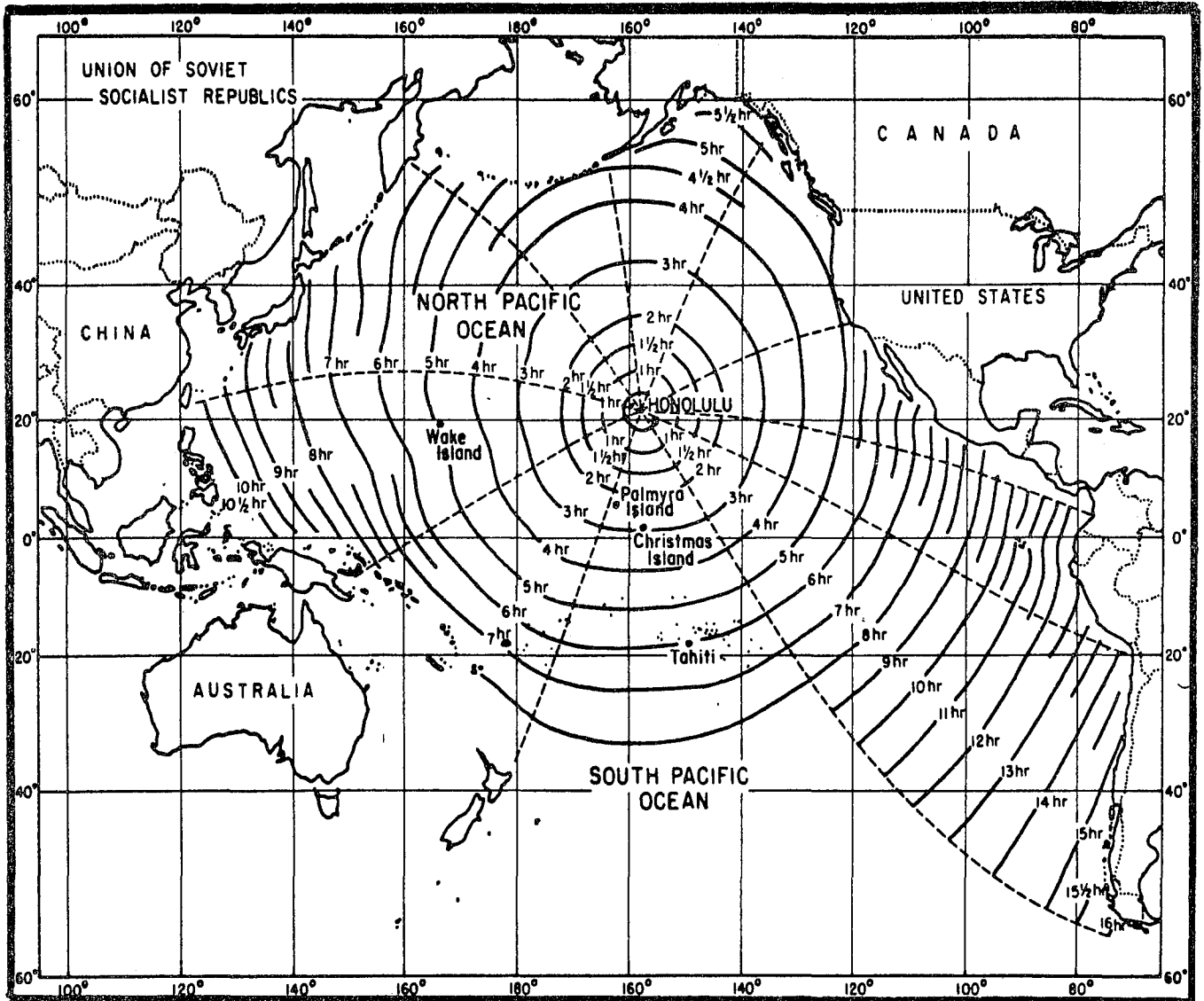
Wave refraction chart for the Chilean earthquake of 22 May 1960 (by A. Fallon).

FIGURE 11. DETAILED WAVE REFRACTION CHART FOR ISLAND OF HAWAII.



Map of the island of Hawaii, showing heights (in feet above lower low water) reached by the water during the tsunami, wave fronts, orthogonals, and submarine contours (in fathoms). Times refer to computed time of arrival of first wave (from Shepard, MacDonald and Cox, 1950)

FIGURE 12. TRAVEL TIMES OF TSUNAMIS TO HONOLULU, HAWAII (U.S. COAST AND GEODETIC SURVEY).



ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

Tsunami Warning System

I. Existing Network

A. Seismograph Stations:

1. Guam, Mariana Island
2. Honolulu, Hawaii
3. Tucson, Arizona
4. Newport, Washington
5. Adak, Alaska
6. College, Alaska
7. Palmer, Alaska
8. Sitka, Alaska
9. Hong Kong, B.C.C.
10. Tokyo, Japan
11. Manila, Philippines
12. Apia, Samoa
13. Tahiti
14. Santiago, Chile
15. Huancayo, Peru
16. Pasadena, California
17. Berkeley, California
18. Victoria, Canada
19. La Plata, Argentina
20. Noumea, New Caledonia

B. Tide Stations:

1. Legaspi, Philippines
2. Shimizu, Japan
3. Hachinohe, Japan
4. Marcus Island
5. Guam, Mariana Island
6. Moen Island
7. Kwajalein
8. Wake Island
9. Attu, Alaska
10. Adak, Alaska
11. Unalaska, Alaska
12. Kodiak, Alaska
13. Sitka, Alaska
14. Midway Island
15. Johnston Island

16. Shemya, Alaska
17. Apia, Samoa
18. Pago Pago
19. Suva
20. Tahiti
21. Hilo, Hawaii
22. Hawiliwili, Hawaii
23. Easter Island
24. Puerto Montt, Chile
25. Puerto Williams, Chile
26. Punta Arenas, Chile
27. Talcahuano, Chile
28. Valparaiso, Chile
29. Antofagasta, Chile
30. Arica, Chile
31. La Punta, Peru
32. Balboa
33. La Jolla, California
34. San Pedro, California
35. Crescent City, California
36. Tofino, Washington
37. Cold Bay, Alaska
38. Seward, Alaska
39. Acajutla, El Salvador
40. Noumea, New Caledonia

II. Additions to the Network

(FY 1969)

A. Seismograph Stations:

1. Suva, Fiji
2. Tacubaya, Mexico
3. Wellington, N.Z.
4. Marcus Island
5. Port Moresby, Papua
6. Antofagasta, Chile

B. Tide Stations:

1. Galapagos Islands
2. Manzanillo, Mexico
3. Neah Bay, Wash.

4. Salina Cruz, Mexico
5. Talara, Peru
6. Marsden Point, N.Z.
7. Newport, Oregon
8. Prince Rupert, B.C.
9. Darao, Philippines
10. Okinawa
11. Gambier Island

III. Modernization

(FY 1969)

A. Seismograph Stations:

1. Apia, Samoa
2. Manila, Philippines
3. Honolulu, Hawaii
4. Guam, Mariana Island
5. Hong Kong, B.C.C.
6. Victoria, Canada
7. Huancayo, Peru
8. Tucson, Arizona
9. Sitka, Alaska
10. Adak, Alaska
11. Palmer, Alaska
12. La Plata, Argentina

B. Tide Stations:

1. Tahiti
2. Apia, Samoa
3. Valparaiso, Chile
4. La Punta, Peru
5. Easter Island
6. Suva
7. Balboa, C.Z.
8. Crescent City, California
9. Wake Island
10. Johnston Island
11. San Pedro, California
12. Antofagasta, Chile
13. Lebu, Chile
14. Arica, Chile
15. Puerto Montt, Chile

Western Region Technical Memoranda: (Continued)

- No. 27 Objective Minimum Temperature Forecasting for Helena, Montana. D. E. Olsen. February 1968. (PB-177 827)
- No. 28** Weather Extremes. R. J. Schmidli. April 1968. (PB-178 928)
- No. 29 Small-Scale Analysis and Prediction. Philip Williams, Jr. May 1968. (PB-178 425)
- No. 30 Numerical Weather Prediction and Synoptic Meteorology. Capt. Thomas D. Murphy, U.S.A.F. May 1968. (AD-673 365)
- No. 31 Precipitation Detection Probabilities by Salt Lake ARTC Radars. Robert K. Belesky. July 1968. (PB-179 084)
- No. 32 Probability Forecasting in the Portland Fire-Weather District. Harold S. Ayer. July 1968. (PB-179 289)
- No. 33 Objective Forecasting. Philip Williams, Jr. August 1968. (AD-680 425)
- No. 34 The WSR-57 Radar Program at Missoula, Montana. R. Granger. October 1968. (PB-180 292)
- No. 35 Joint ESSA/FAA ARTC Radar Weather Surveillance Program. Herbert P. Benner and DeVon B. Smith. December 1968. (AD-681 857)
- No. 36 Temperature Trends in Sacramento--Another Heat Island. Anthony D. Lentini. February 1969. (PB-183 055)
- No. 37 Disposal of Logging Residues Without Damage to Air Quality. Owen P. Cramer. March 1969. (PB-183 057)
- No. 38 Climate of Phoenix, Arizona. R. J. Schmidli, P. C. Kangieser, and R. S. Ingram. April 1969. (PB-184 295)
- No. 39 Upper-Air Lows Over Northwestern United States. A. L. Jacobson. April 1969. (PB-184 296)
- No. 40 The Man-Machine Mix in Applied Weather Forecasting in the 1970s. L. W. Snellman. August 1969. (PB-185 068)
- No. 41 High Resolution Radiosonde Observations. W. W. Johnson. August 1969. (PB-185 673)
- No. 42 Analysis of the Southern California Santa Ana of January 15 - 17, 1966. Barry B. Aronovitch. August 1969. (PB-185 670)
- No. 43 Forecasting Maximum Temperatures at Helena, Montana. David E. Olsen. October 1969.
- No. 44 Estimated Return Periods for Short-Duration Precipitation in Arizona. Paul C. Kangieser. October 1969. (PB-187 763)
- No. 45/1 Precipitation Probabilities in the Western Region Associated with Winter 500-mb Map Types. Richard P. Augulis. December 1969. (PB-188 248)
- No. 45/2 Precipitation Probabilities in the Western Region Associated with Spring 500-mb Map Types. Richard P. Augulis. January 1970. (PB-189 434)
- No. 45/3 Precipitation Probabilities in the Western Region Associated with Summer 500-mb Map Types. Richard P. Augulis. January 1970. (PB-189 414)
- No. 45/4 Precipitation Probabilities in the Western Region Associated with Fall 500-mb Map Types. Richard P. Augulis. January 1970. (PB-189 435)
- No. 46 Applications of the Net Radiometer to Short-Range Fog and Stratus Forecasting at Eugene, Oregon. L. Yee and E. Bates. December 1969.
- No. 47 Statistical Analysis as a Flood Routing Tool. Robert J. C. Burnash. December 1969. (PB-188 744)

**Revised