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MAXIMUM TSUNAMI AMPLITUDES AND ASSOCIATED CURRENTS ON THE COAST OF BRITISH COLUMBIA

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ABSTRACT

Maximum tsunami water levels and currents along the British Columbia outer coast have been computed for waves originating from Alaska, Chile, the Aleutian Islands (Shumagin Gap), and Kamchatka. Three computer models have been developed to generate and propagate a tsunami from each of these source regions in the Pacific Ocean to the continental shelf off Canada's west coast, and into twenty separate inlet systems. The model predictions have been verified against water level measurements made at tide gauges after the March 28, 1964 Alaska earthquake. Simulated seabed motions giving rise to the Alaskan and Chilean tsunamis have been based on surveys of vertical displacements made after the great earthquakes of 1964 (Alaska) and 1960 (Chile). Hypothetical bottom motions have been used for the Shumagin Gap and Kamchatka simulations. These simulations represent the largest tsunamigenic events to be expected from these areas.

Maximum wave and current amplitudes have been tabulated for each simulated tsunami at 185 key locations along the British Columbia coast. On the north coast of British Columbia, the Alaska tsunami generated the largest amplitudes. In all other regions of the west coast, the largest amplitudes were generated by the Shumagin Gap simulation. Wave amplitudes in excess of 9 m were predicted at several locations along the coast and current speeds of 3 to 4 m/s were produced. The most vulnerable regions are the outer coast of Vancouver Island, the west coast of Graham Island, and the central coast of the mainland. Some areas, such as the north central coast, are sheltered enough to limit expected maximum water levels to less than 3 m.

INTRODUCTION

The west coast of Canada is vulnerable to the effects of seismic sea waves, or tsunamis, generated at numerous locations along the active subduction zones of the Pacific Rim. These events are infrequent and often cause little or no damage. Occasionally, however, a great earthquake generates a large tsunami that may cause extensive loss of life and property damage. This was demonstrated on March 28, 1964 when a magnitude 8.4 earthquake in Prince William Sound, Alaska, generated the most damaging tsunami to date on Canada's west coast. Fortunately, no loss of life occurred in British Columbia but property damage in Port Alberni was estimated to be several million dollars (Spaeth and Berkman, 1967).

Forecasting future earthquakes is not possible at present and hence, the time of arrival of the next large tsunami is unknown. It is certain, however, that these events will continue to occur and that the risk to lives and property is very real and should not be ignored. To implement effective planning of land use and disaster relief, it is necessary to have an estimate of the largest waves that can be expected to arrive along the British Columbia coastline. Through the use of digital computers it is now possible to simulate tsunami generation and propagation by numerically solving the appropriate mathematical equations. This approach allows complete flexibility in specifying tsunami source regions and generation mechanisms, as well as treating the complex topography and bathymetry of the coastal waterways.

This paper summarizes the results of a study that has determined representative tsunami wave heights and current velocities along the British Columbia coastline that are likely to result from great earthquakes around the Pacific Rim. The methods used to accomplish this rely on advanced numerical modelling techniques for simulating tsunami generation and propagation using a digital computer. The numerical models solve complex mathematical equations over a large portion of the Pacific Ocean, the continental shelf off Canada's west coast, and the major inlet systems of British Columbia. This is the first time that numerical modelling methods have been applied to this region on such an extensive scale in order to estimate tsunami wave heights. Previously, estimates have been based solely on experience and intuition, or on statistical methods applied to historical tsunami records (e.g., Marshal, Macklin Monahan, 1986). This study provides a major improvement in accuracy of estimated tsunami waves over a large portion of British Columbia's coastline.

The focus in the present study has been to develop new tools for estimating tsunami wave heights over the entire coastline of British Columbia. The objectives of this study are to:

- derive a set of numerical models for tsunami generation and propagation from their point of origin to the heads of inlets along the British Columbia coast;
- examine the sensitivity to tsunami water levels in inlets to different source locations (directional effect on water levels), and to source strength by varying the magnitude of bottom motions;
- identify the source region that is most likely to produce the largest tsunamis along the British Columbia coast from epicentres located in Alaska, Chile, the Aleutian Islands (Shumagin Gap), and Kamchatka;
- determine the maximum expected water levels at selected locations along the British Columbia coast for earthquakes at the above sources and identify critical inlets where tsunamis are magnified by topography;
- identify areas in the modelled inlets where large current speeds will result from the passage of a tsunami wave; and

- provide recommendations on improved estimates of most probable maximum tsunami levels.

Output from the numerical models consists of wave heights and current velocities at discrete locations and times. The time interval between values is typically a few minutes and the spatial separation between output points ranges from 2 to 5 km along the coast. This information has been used to prepare maps and tables showing the largest wave heights and currents from each source area at many locations along the British Columbia coastline. These locations were selected primarily on the basis of local human activity, including townsites, Indian villages, log booming grounds, recreational areas, and industrial development.

We note that the effects of dry land flooding have not been included owing to the large amount of additional topographic data that is required and the special demands created for high-resolution, local-area models in many locations. This does not pose serious problems in most areas. However, near the heads of inlets (where there is often an extensive area of flatlands associated with a river mouth) modelled wave heights may be appreciably overestimated. The four source areas shown in Fig. 1 have been identified as likely sites for generation of tsunamis that could threaten Canada's coastline. This is based on the occurrence of previous tsunamigenic earthquakes and on estimates of the likelihood of future great earthquakes in each area.

METHODOLOGY

Tsunamis arriving at British Columbia's outer coast propagate into all exposed inlet systems. Twenty of the more exposed systems (Table 1, Figs. 2 and 3) have been identified and incorporated into this study. Each has a corresponding numerical model that uses time-varying water elevations at one or more connections to the continental shelf to calculate the water surface response and currents within the system. Construction of each model required detailed extraction of bathymetry and dimensional data (cross-sectional and surface areas) and calibration.

Seismic activity in the Pacific Ocean is confined primarily to zones adjacent to the continental margins where subduction of the oceanic plates under the continental land masses episodically releases bursts of energy in the form of an earthquake. Other areas, such as the Hawaiian Islands, are also sites of large earthquakes but these do not pose a threat of producing a destructive tsunami in British Columbia waters.

If an earthquake results in vertical (dip-slip) motion of the oceanic crust, then it is tsunamigenic, that is, it will result in the deformation of the water surface and subsequent propagation of the disturbance outward from the source as a seismic sea wave (tsunami). Tsunamis from even moderately small earthquakes may result in significant damage within a short distance of the source. If the earthquake is sufficiently large (with a Richter scale magnitude greater than 7.5 to 8.0), however, then a large tsunami may be generated and damage will result at great distances from the source. This latter situation is most relevant to the west coast of Canada.

Three distinct numerical models were used to simulate tsunami generation and propagation to the inlets of British Columbia. A deep ocean model (DOM) with 0.5° resolution (Fig. 1) has been used to simulate bottom motions that give rise to tsunamis and to propagate the resulting waves to the continental shelf (Fig. 4) off Canada's west coast. There, a 5-km resolution model (C2D) covering the shelf propagates the waves to the entrances of the inlets. Finally, 2-km resolution models (FJORD1D) determine water levels and current velocites in the inlets. The shelf and inlet models were run simultaneously as a coupled system. Wave

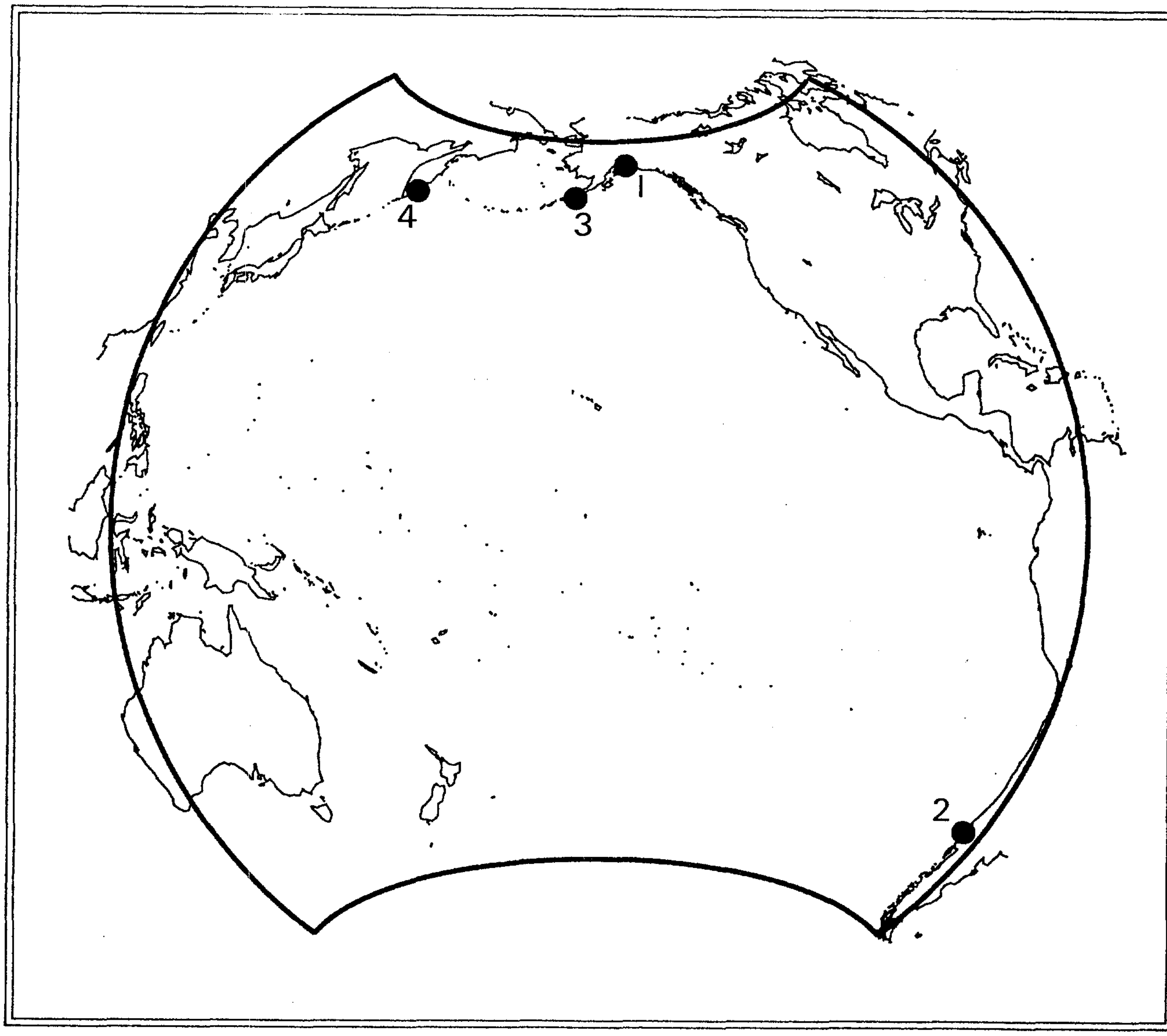


Fig. 1 Epicentres of earthquakes used in tsunami simulations. The bold line is the boundary of the deep ocean model (DOM). (1: Alaska, 2: Chile, 3: Shumagin Gap, 4: Kamchatka)

amplitudes on the edge of the shelf were specified from a preceding run of the deep ocean model. The theoretical aspects of this study have been reported in Dunbar et al. (1989).

After confirming the correctness of all model components using historical tsunami data, the three models were run for a set of simulated tsunamigenic earthquakes. These included simulations for measured bottom displacements at the source regions of the 1960 Chilean and 1964 Alaskan tsunamigenic earthquakes, and hypothetical earthquakes at the Shumagin Gap and Kamchatka Peninsula sites. In addition, the Alaskan simulation was repeated for a case where bottom motions were amplified by 25%. The simulations provided the wave amplitudes and currents to be discussed later.

Table 1 British Columbia Inlet Systems Included in Tsunami Simulations

System	Areas Included	System	Areas Included
A	Portland Canal Observatory Inlet-Hastings Arm Alice Arm Khutzeymateen Inlet Work Channel	J	Smith Inlet
		K	Mereworth Sound Belize Inlet Nugent Sound Seymour Inlet
B	Prince Rupert Inlet	L	Holberg–Rupert Inlet Quatsino Sound–Neroutsos Inlet Forward Inlet
C	Rennell Sound		
D	Tasu Sound	M	Klaskino Inlet
E	Douglas Channel Kildala Arm Gardner Canal Sheep Passage–Mussel Inlet	N	Quoukinsh Inlet
		O	Nuchalitz Inlet
F	Spiller Channel Roscoe Inlet Cousins Inlet Cascade Inlet Dean Channel Kwatna Inlet South Bentinck Arm	P	Port Eliza Espinosa Inlet Tahsis Inlet Cook Channel–Tlupana Inlet Zuciarte Channel–Muchalat Inlet
G	Laredo Inlet	Q	Sydney Inlet Shelter Inlet Herbert Inlet
H	Surf Inlet	R	Pipestem Inlet
I	Rivers Inlet Moses Inlet	S	Effingham Inlet
		T	Alberni Inlet

SIMULATION OF THE 1964 ALASKAN TSUNAMI

The March 28, 1964 Alaskan earthquake presents an excellent opportunity to verify the integrated DOM–C2D–FJORD1D model system using a well documented tsunamigenic event. The most critical component of the simulation (final bottom displacements in the generation zone) are known as well for this earthquake as for any other. Plafker (1969) has constructed contours of final bottom displacements based on surveys of the coastline before and after

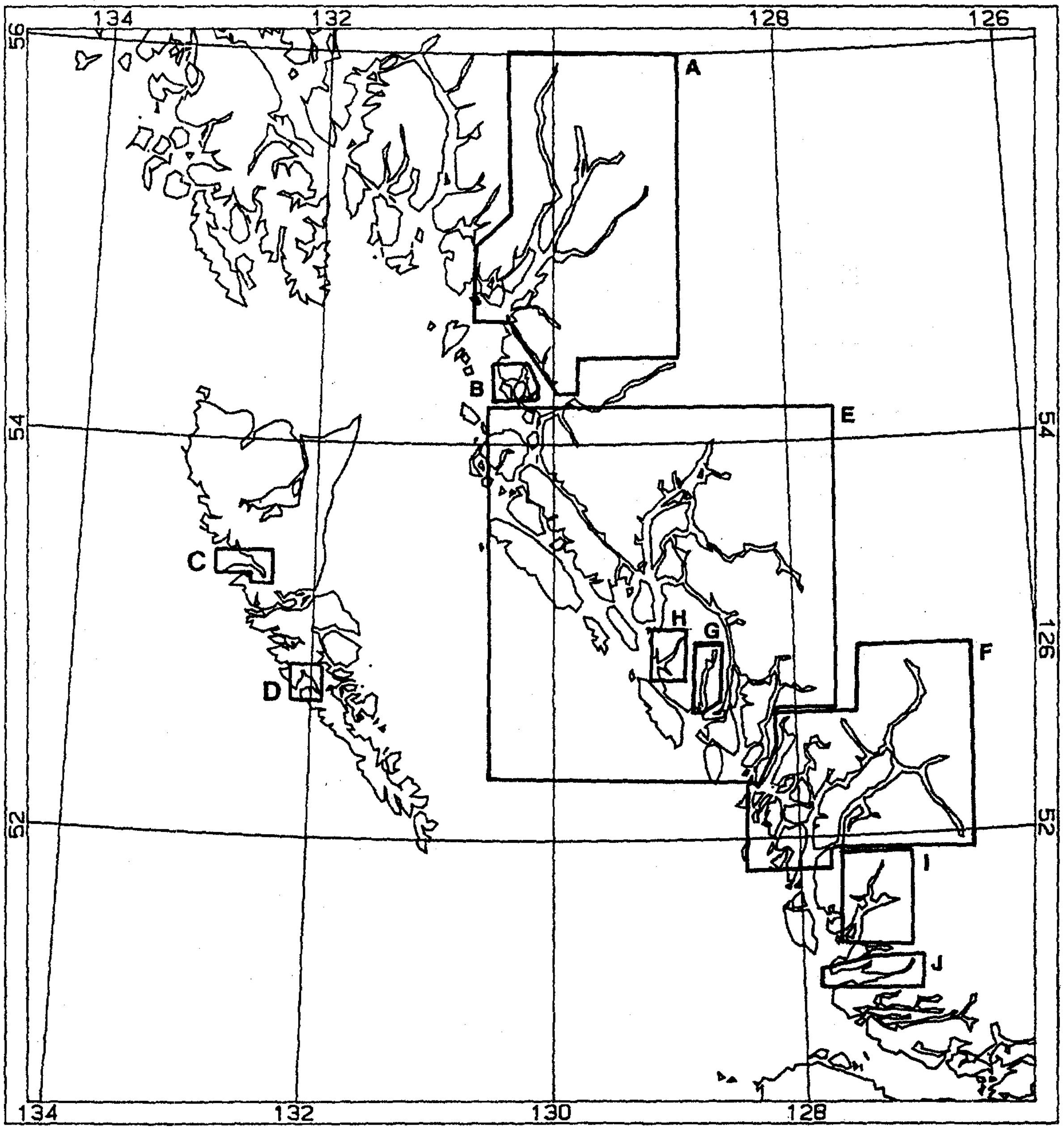


Fig. 2 Inlet systems for the north coast of British Columbia.

the earthquake. These were digitized and used to generate displacement values at DOM grid locations in the generation zone (Fig. 5).

Table 2 lists the tide gauge stations and corresponding models used in the comparison. Figure 6 presents the modelled elevations together with the observed tsunami wave as extracted from tide gauge records. The time of arrival of the initial model wave has been adjusted to synchronize it with the observed wave. The size of this adjustment is indicated on each panel. These time differences average about 6% of the total travel time for the initial wave and are likely due, for the most part, to differences in the locations of the tide gauge and model output points, and to small errors in specifying arrival times.

In all cases, the initial measured wave had a positive elevation which varied in amplitude

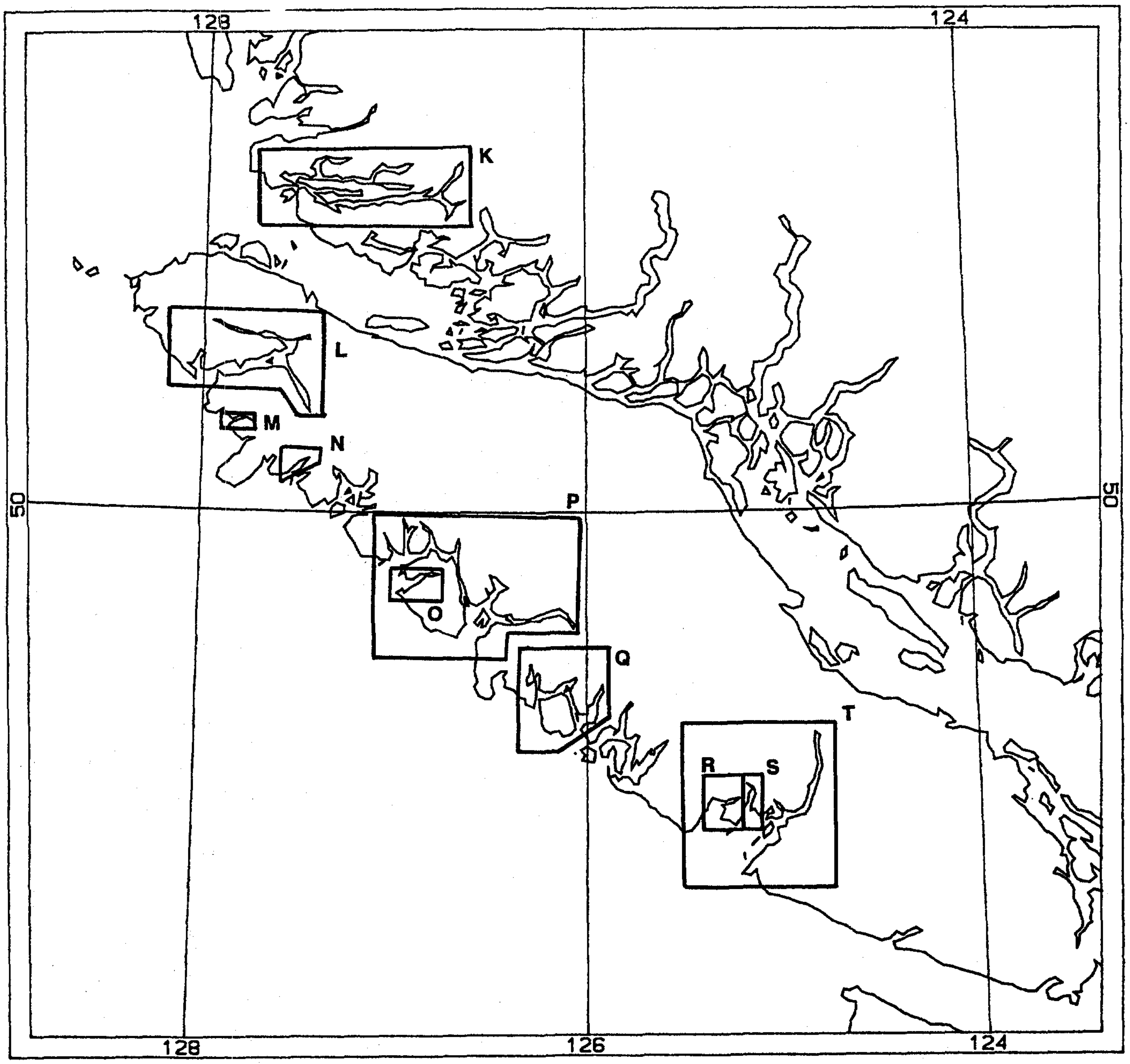


Fig. 3 Inlet systems for the south coast of British Columbia.

from 5 to 10 cm at Sweeper Cove and Unalaska, from 1.0 to 1.5 m at the other gauge locations, and approximately 3 m at Port Alberni. At each location the numerical model reproduced the elevations well. In many locations (Sitka, Ketchikan, Yakutat, Prince Rupert, Alert Bay, Tofino, Tasu Sound, and Bella Bella) the model also provided a good estimate of the shape and timing of the following trough. From these results we conclude that the numerical models provide a reliable simulation for the magnitude and shape of the leading wave form.

The degree to which second and subsequent wave forms predicted by the model reproduced the measurements varies depending upon location. Good results were obtained at Prince Rupert and Yakutat; reasonable agreement was found at Tofino. At the other gauge sites (e.g., Tasu Sound) the numerical model results contain moderate amplitude waves at frequencies

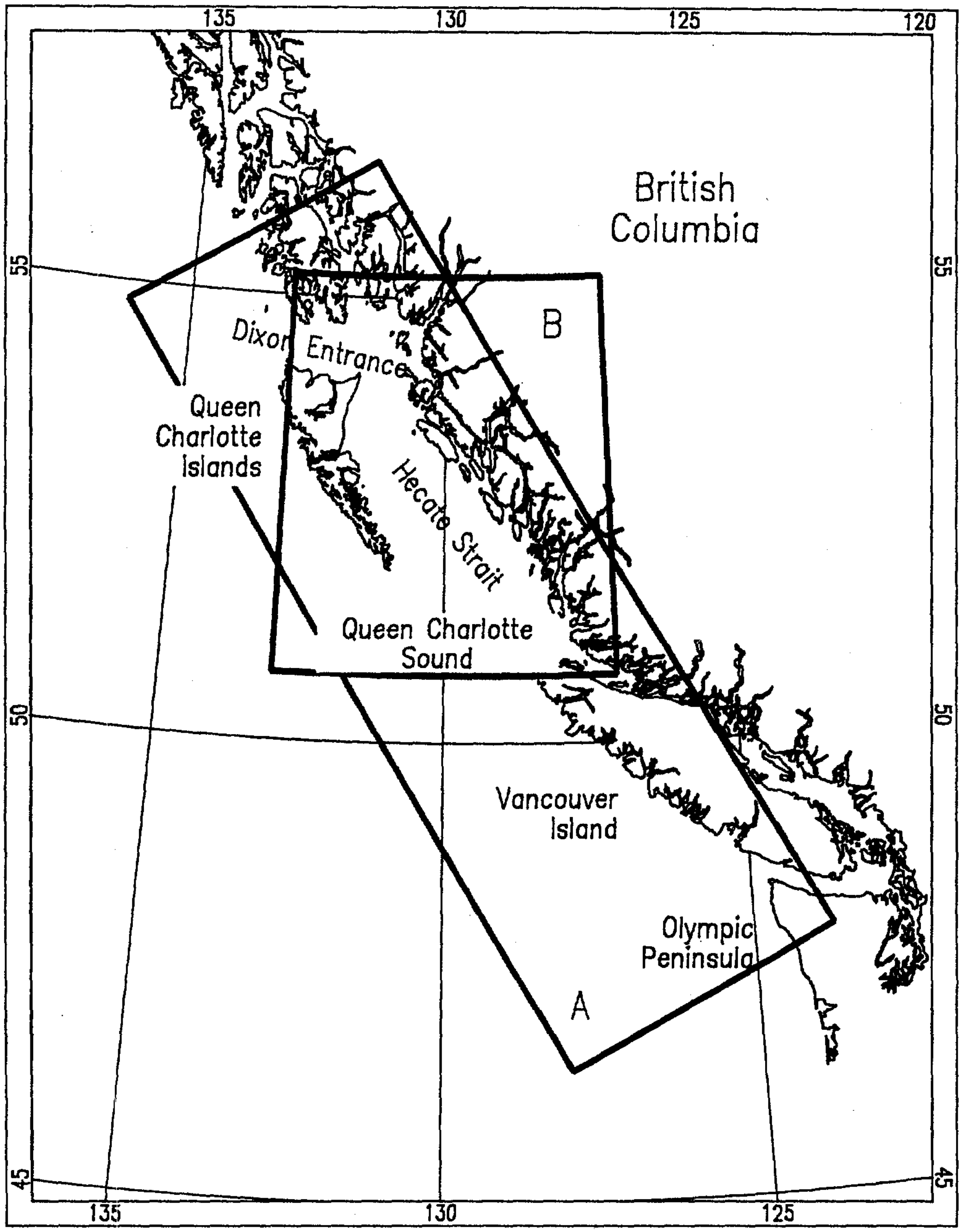


Fig. 4 Shelf model grid outline (A) and outline of region used for field plots of northern British Columbia (B).

higher than the incoming tsunami. These are interpreted as reflections within the model produced by the boundary conditions along the coast and at the heads of the inlets. These reflections occur in nature (they are in the measured waves at Tofino and Ocean Falls, for example) but are difficult to reproduce precisely in the model at the resolution and boundary treatment adopted here. If, however, we examine the envelopes of positive and negative amplitudes (crest heights and trough depths around mean water level) the worst conditions are predicted to within an accuracy of approximately 50%, and often much better. Thus, we conclude that the model is capable of identifying source regions leading to worst conditions along the coast, of identifying the critical inlet areas in terms of inundation levels, and of

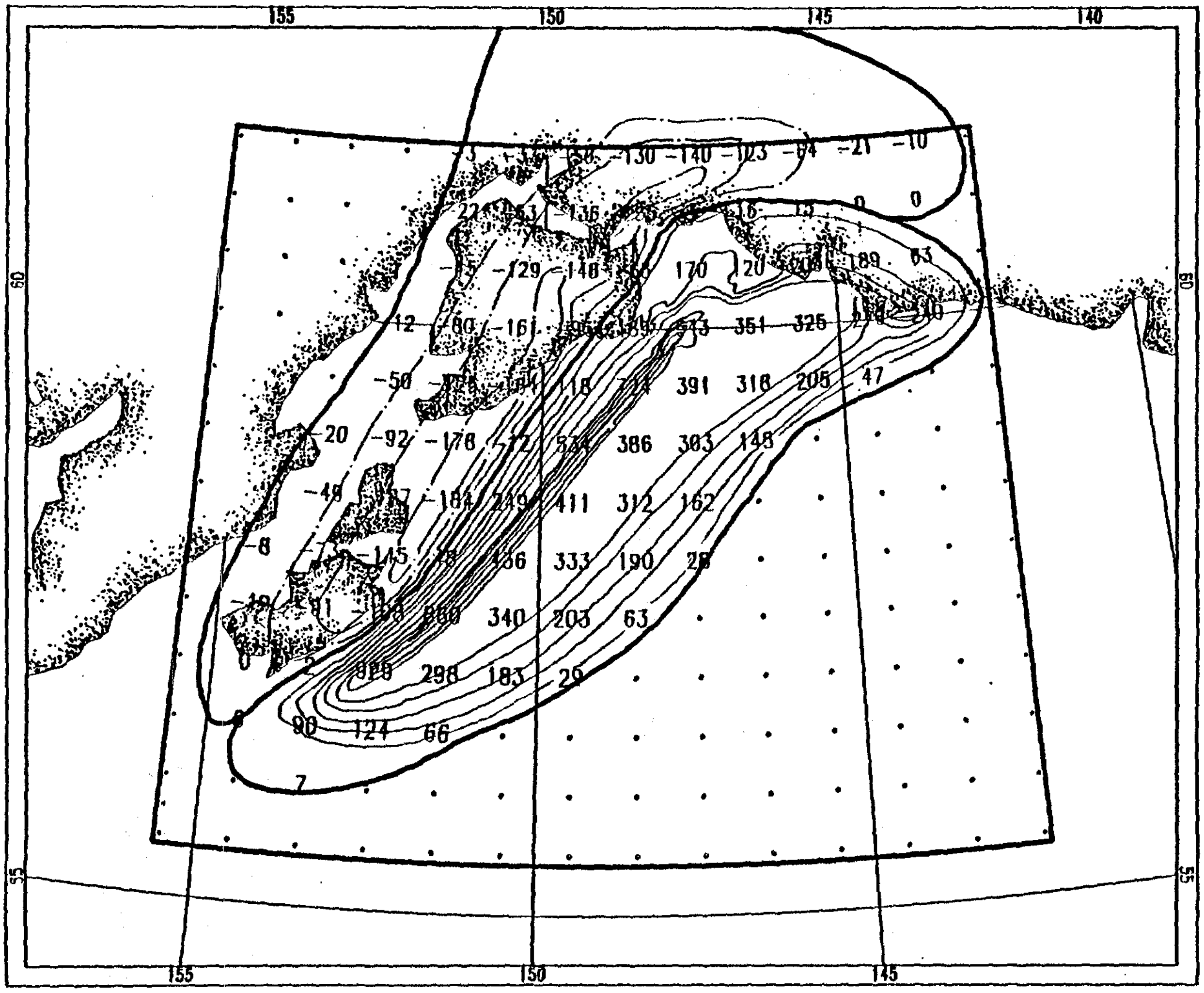


Fig. 5 Tsunami generation region for the 1964 earthquake. Contours and numbers represent final bottom displacements (in cm). Dashed lines indicate downthrust; solid lines represent upthrust; and the bold line corresponds to no vertical movement. Contours were digitized from Plafker (1969).

providing guidance on expected maximum tsunami water levels and currents. (An overall accuracy of the order of 50% for the model offers a substantial improvement in confidence over conventional statistical methods based on extrapolating measured tsunami levels, or levels derived from earthquake magnitude (e.g., Comer, 1980). In the statistical approaches uncertainty is introduced through the very small number of available observations, or through the error of converting between magnitude and tsunami wave amplitude, and through modifying the extreme values at one location into the site of interest at a second location.)

The simulation at Port Alberni shows that the first wave is modelled well but thereafter, the predicted wave lags the measured wave. The modelled third wave has the largest amplitude (6 m); observations (Wigen and White, 1964) suggest that the third wave was, in fact, the highest at about 4.2 m above the tidal water level. However, the modelled wave lags observations by about one half a wave period (1 1/4 h). Wigen and White (1964) recognize that the Port Alberni observations are quite imprecise since the gauge at the townsite had broken and these high water values are a synthesis made up from data collected up the Somass River

Table 2 Tide Gauge Records for the 1964 Alaskan Tsunami Used to Calibrate and Verify the Numerical Models

Number	Location	Longitude (deg)	Longitude (min)	Latitude (deg)	Latitude (min)	Model
1	Sweeper Cove	176	39	51	51	DOM
2	Unalaska, Alaska	166	32	53	53	DOM
3	Yakutat, Alaska	139	44	59	33	DOM
4	Sitka, Alaska	135	20	57	03	DOM
5	Ketchikan, Alaska	131	39	55	21	Shelf
6	Prince Rupert	130	20	54	19	Fjord
7	Tasu Sound	132	01	52	45	Shelf
8	Bella Bella	128	08	52	10	Fjord
9	Ocean Falls	127	41	52	51	Fjord
10	Alert Bay	126	56	50	35	Shelf
11	Tofino	125	55	49	09	Shelf
12	Port Alberni	124	49	49	14	Fjord

at the head of Alberni Inlet and from eye witness accounts at the town.

The differences in height and timing between the modelled and observed data reflect the fact that Alberni Inlet is nearly resonant with the initial wave (100- to 110-minute period), and the treatment of the reflecting boundary conditions at Port Alberni. Modelled water levels at the head of the Inlet could be improved by incorporating a high-resolution model of the flood-dry area in the Somass River valley that allows the tsunami to dissipate some energy by inundating the surrounding land.

FUTURE TSUNAMI SIMULATIONS

Simulations were performed for tsunamis generated at four seismically active regions (Fig. 1). Specific locations for each earthquake were selected based on the occurrence of previous great earthquakes or, in the case of the Shumagin Gap, on the hypothesis that a strong earthquake is likely to occur within a few decades. The locations of each earthquake epicentre shown in Fig. 1 are provided in Table 3. The simulation results are presented as follows. Maximum water levels and currents are tabulated for 185 key locations in British Columbia. These results show which areas are sensitive to tsunamis, and the effects of wave directionality on maximum wave levels at these locations.

Prince Rupert Sound in Alaska is the site of the great earthquake of March 28, 1964 that devastated large parts of Alaska and generated a series of tsunamis that caused damage throughout the Pacific Rim. The mechanism of this earthquake has been studied extensively and it provides the best data on ocean floor displacements. These were determined by Plafker (1969) and form the basis of this simulation. Figure 5 shows contours of final bottom displacements together with values interpolated from these onto the DOM grid (0.5° resolution). Two simulations, denoted by numbers 1a and 1b in Table 3, were performed for this generation zone. The first used the bottom displacements as interpolated from measurements.

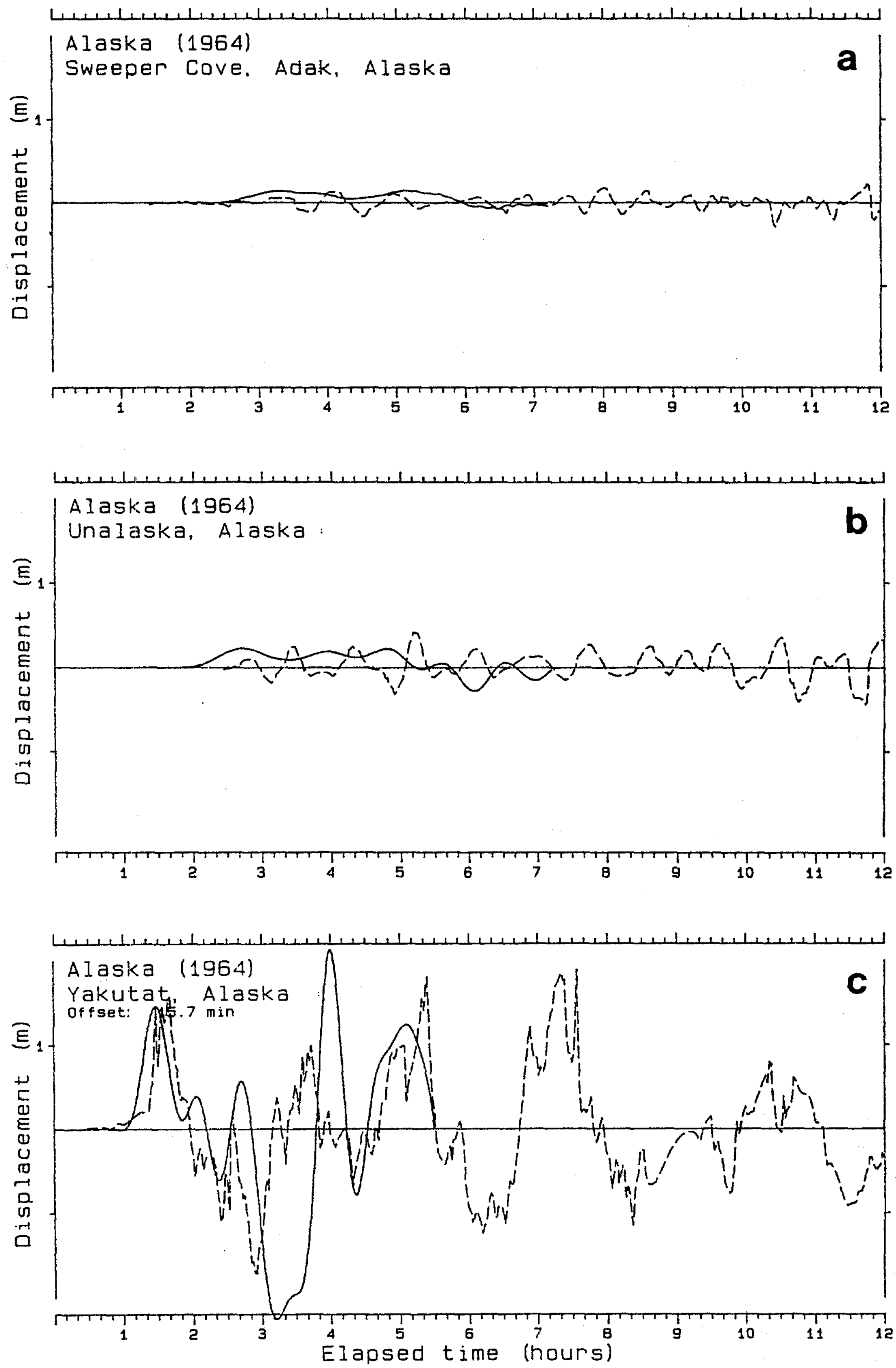


Fig. 6 Observed (dashed) and modelled (solid) tsunami wave heights. Station locations and model source are given in Table 2.

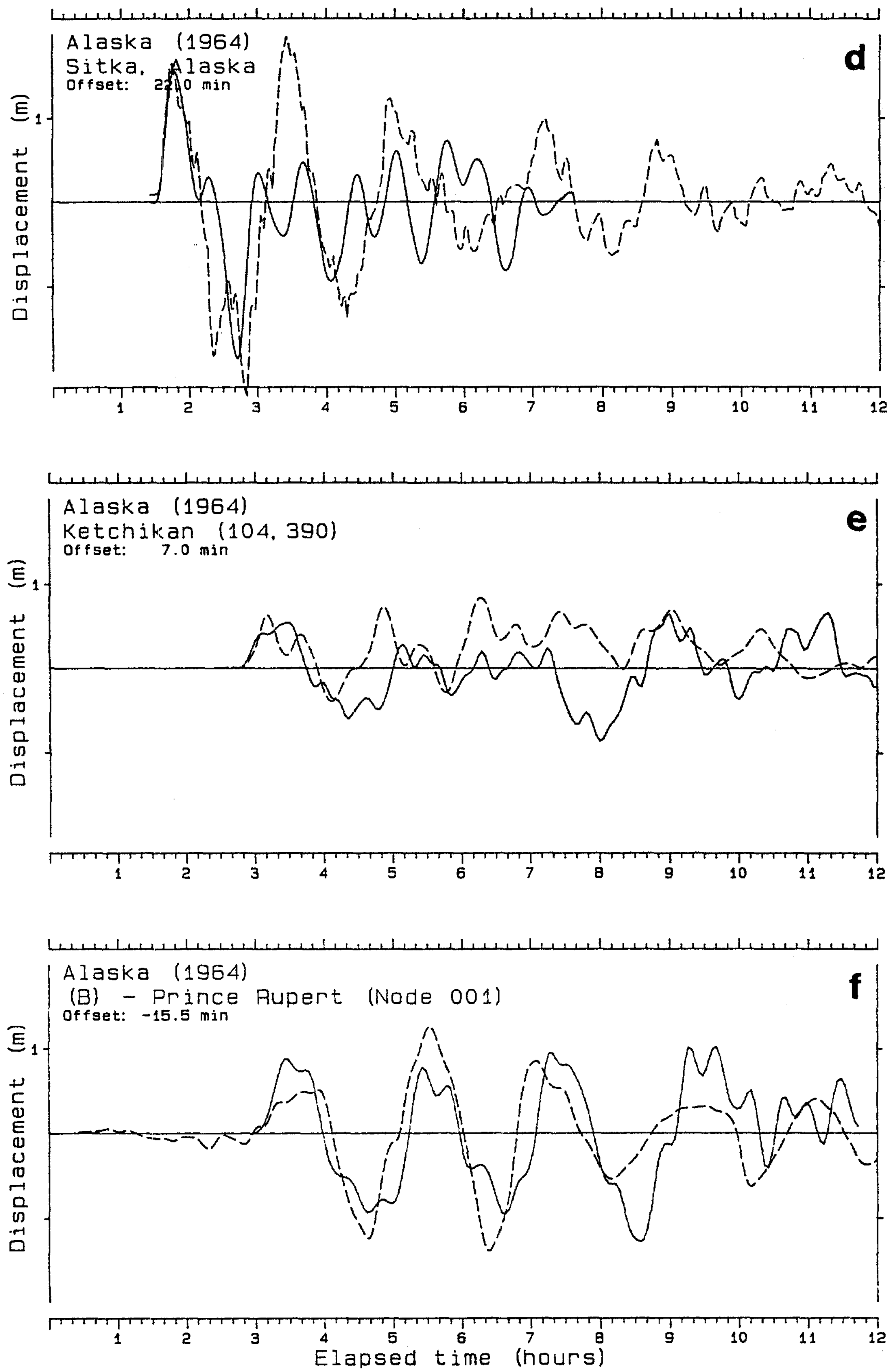
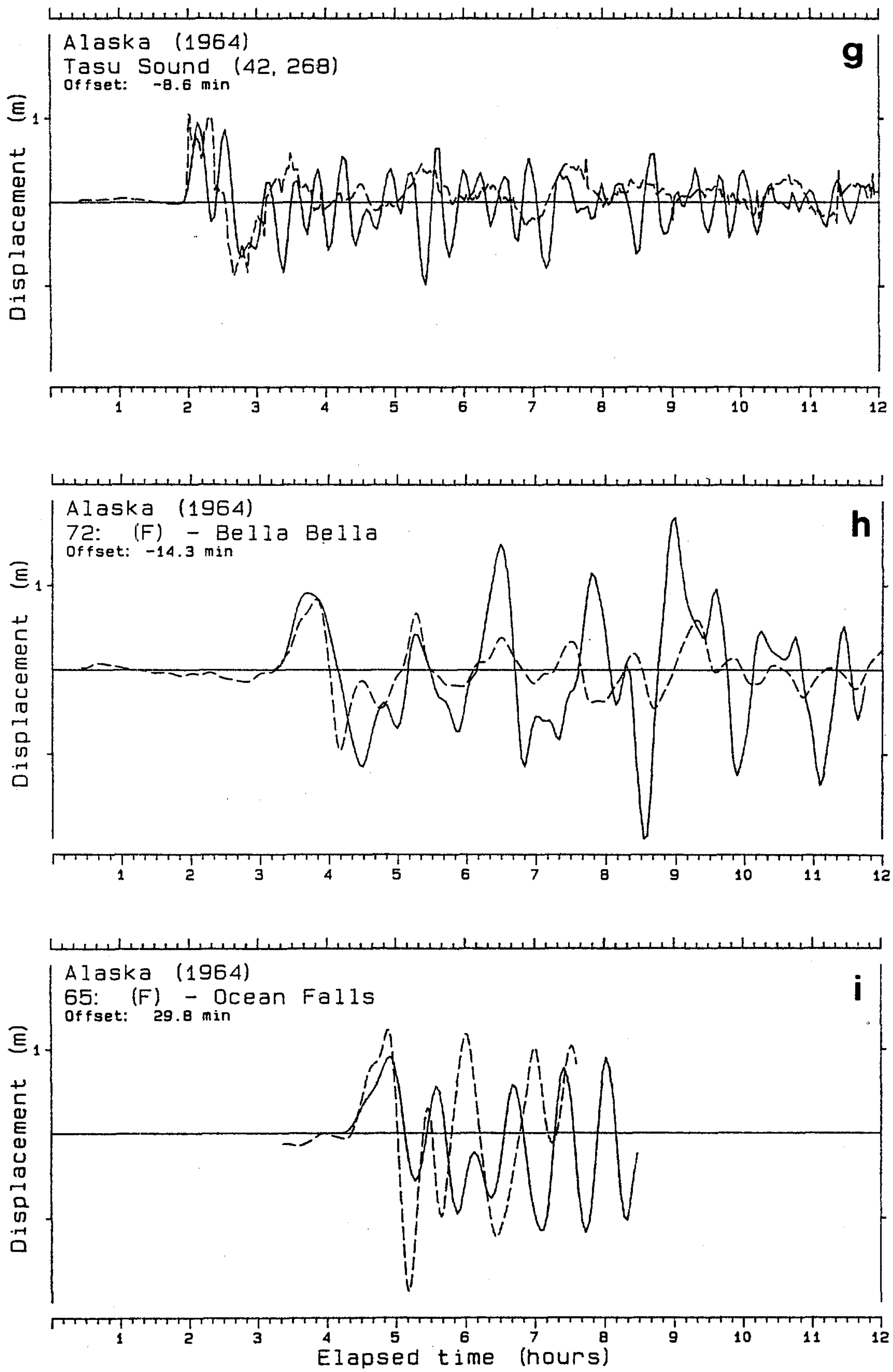


Fig. 6 Continued.



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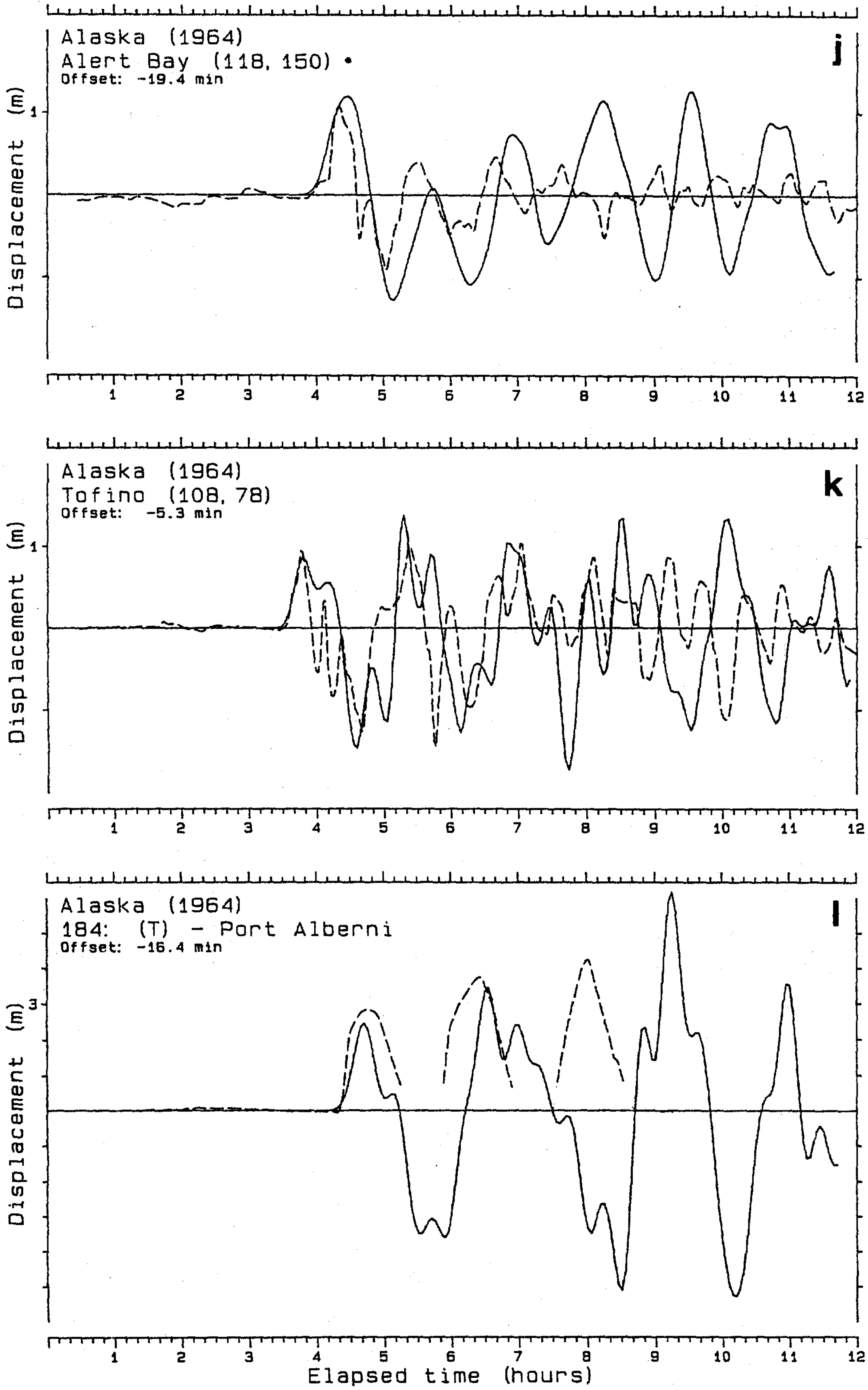

Fig. 6 Concluded.

Table 3 Locations of Earthquake Epicentres Used for Tsunami Simulations

Source Number	Region	Data Source of Ellipse Foci	Epicentre		Area (km^2)	Volume (km^3)
			Latitude	Longitude		
1a	Alaska	Plafker (1969)	61° 02.4′N	147° 43.8′W	266,400	446
1b	Alaska	(same as 1a increased by 25%)	61° 02.4′N	147° 43.8′W	266,400	558
2	Chile	Plafker and Savage (1970)	39° 00.0′S	74° 30.0′W	106,400	139
3	Shumagin Gap	156.0° 53.5°N 163.5°W 51.5°N	54° 00.0′N	162° 00.0′W	141,700	634
4	Kamchatka	196.0°W 55.0°N 203.0°W 50.0°N	54° 48.0′N	200° 24.0′W	98,740	434

The second set of displacements, 25% greater than the measurements, was used to simulate an extremely large tsunamigenic earthquake and to examine the effect of a known increase in amplitude of bottom motions on the resulting tsunami.

The bottom displacements used for the simulation of the 1960 Chilean earthquake tsunami were derived from Plafker and Savage (1970). This event was selected as a representative large earthquake originating from this area. Figure 7 shows the contours of bottom displacement taken from Plafker and Savage together with values interpolated onto grid points and used in the generation phase of the simulation.

In a detailed discussion of the seismic potential of the Shumagin Gap, Davies et al. (1981) identified an area near 52°N, 160°W that has not had a major rupture since at least 1900. Adjacent areas are also at possible risk of rupturing should a major earthquake occur in this seismic gap. Figure 8 shows the area that has been used to simulate a major tsunamigenic earthquake in this part of the Aleutian chain. The bottom displacements correspond to a hypothetical maximum upthrust of 10 m. The total volume of water displaced by the final seabed surface is the greatest of all five simulations.

The generation zone (Fig. 9) was positioned off the east coast of Kamchatka where, in 1952, a magnitude 8.3 earthquake generated a large tsunami. This site was selected as a representative location for a large tsunamigenic earthquake originating from the northwest Pacific.

The displacement fields for the Shumagin Gap and Kamchatka were specified as regions having an elliptical plan view, with the orientation of the major axis of each ellipse selected to align approximately with the local fault zone. Displacements along lines parallel to the minor axis (i.e., perpendicular to the fault) follow a prescribed form which was based on the displacement field for the 1964 Alaska earthquake (Plafker, 1969).

At 185 locations along the coast of British Columbia (Table 4), vulnerable to inundation by tsunamis, simulated water levels and currents have been calculated. These locations have

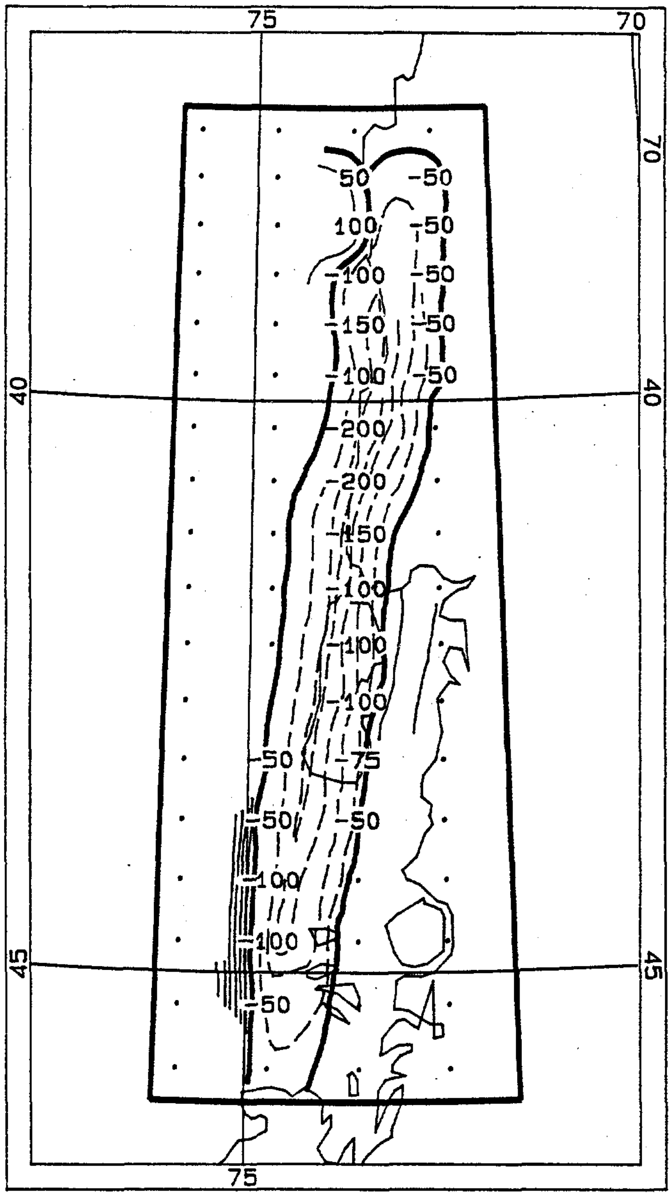

Fig. 7 Tsunami generation region for the 1960 Chilean earthquake. Contours and numbers represent final bottom displacements (in cm). Dashed lines indicate downthrust; solid lines represent upthrust; and the bold line corresponds to no vertical movement. Contours were digitized from Plafker and Savage (1970).

been compiled by consulting hydrographic charts and the British Columbia atlas. The selection criterion was the presence of, or potential for, human activity at each site. Townsites, Indian Reserves, log booming grounds, mill sites, wharves, and parkland are some of the centres of such activity that have been included in the list.

MAXIMUM TSUNAMI WATER LEVELS AND CURRENTS

At each of the 185 key locations, the calculated maximum tsunami wave amplitude and current speed for each simulated source have been listed. These represent maximum (positive) water level and current speed values extracted from the entire length of each simulation,

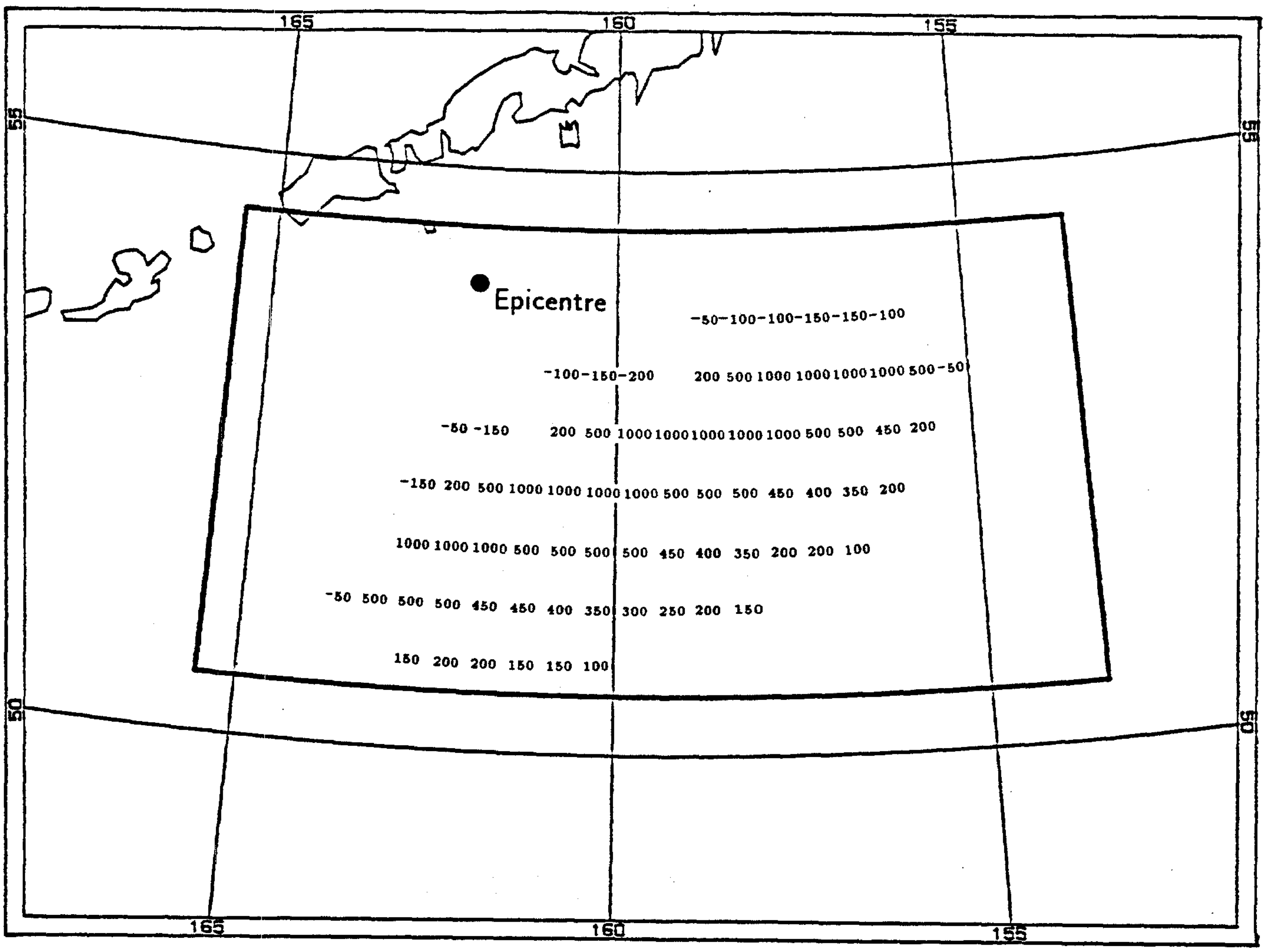

Fig. 8 Tsunami generation region for a hypothetical earthquake in the Shumagin Gap area of the Aleutian Islands. Values correspond to final bottom displacements (cm).

containing four to five waveforms. Results for all five tsunami simulations are presented in Tables 5 to 11 together with accompanying diagrams that show the locations of each station (Figs. 10 to 16).

It is interesting that the Alaska tsunami produces maximum water levels in system A. The Shumagin Gap tsunami is lower which contrasts with all other systems (except B) where it generally provides the highest water levels. The reason for this difference lies in the shape of the waveforms in relation to the orientation and size of Dixon Entrance. The simulation results suggest that the extreme northern coast appears to be more vulnerable to tsunamis originating from northerly source regions in the Gulf of Alaska than to those with epicentres at more southerly latitudes.

A comparison of wave amplitudes and station locations reveals that the largest waves occur at, or near, the heads of the inlets. This is a general result for the reflecting boundaries imposed on the numerical solutions for each channel and is expected for actual tsunamis. In system A the model results near the inlet entrance (e.g., stations 1, 15, and 36) are about 1 m; at the inlet head (e.g., stations 27, 30, and 35) wave amplitudes range between 2.8 and 3.3 m.

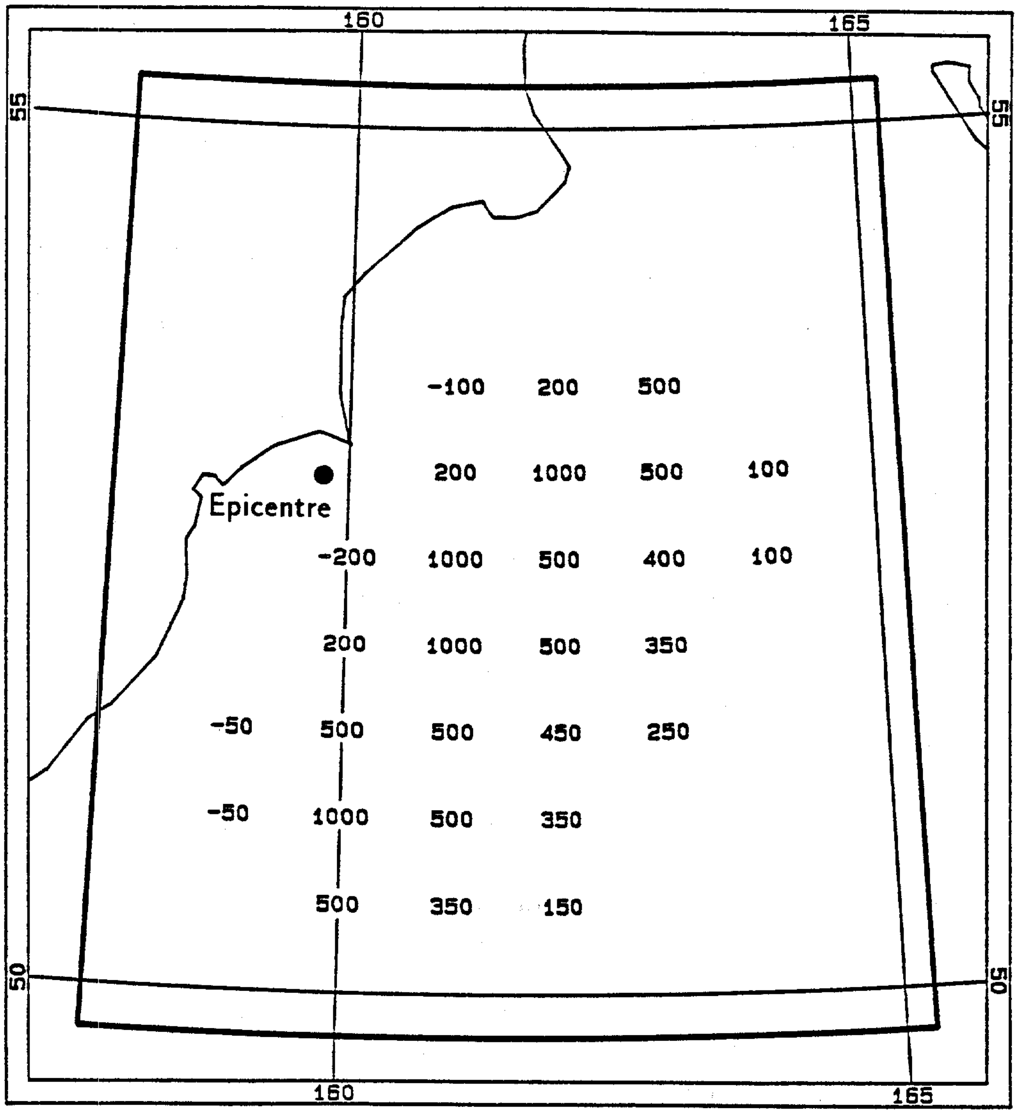

Fig. 9 Tsunami generation region for a hypothetical earthquake off the coast of Kamchatka. Location is modelled after the 1952 earthquake. Numbers correspond to final bottom displacements (cm).

We note that the actual amplitude values right at the inlet heads are sensitive to the reflecting boundary condition and the 2-km grid resolution used in the fjord model. As a rule, they will be overpredicted because the influence of overland flooding on wave dissipation has been neglected. The accuracy of tsunami water level predictions within 5 to 10 km of the heads of each inlet could be improved through use of local area high-resolution models that incorporate flooding and drying, or some other form of relaxation on the total reflective condition.

The largest results of all simulations were predicted for system C (Rennell Sound) located on the west coast of the Queen Charlotte Islands (Graham Island). Exceptionally large values for both wave height and current speed were found for station 46 at the head of the sound which prompted a closer look at the results for this system. It was determined that the large

Table 4 Selected Locations from the Fjord Model

Number	Fjord System*	Description
1	A	Indian Reserve
2	A	Indian Reserve
3	A	Indian Reserve at Grave Bay–Ensheshese River
4	A	Indian Reserve near Reservation Point
5	A	Indian Reserve at head of Quottoon Inlet
6	A	Indian Reserve/Pile
7	A	Indian Reserves
8	A	Indian Reserve
9	A	Indian Reserve at Union Inlet
10	A	Indian Reserve at Steamer Passage
11	A	Indian Reserve at Kumeon Bay
12**	A	Booming Grounds
13	A	Booming Grounds
14**	A	Booming Grounds
15	A	Indian Reserve
16	A	Indian Reserve
17	A	Gwent Cove
18	A	Arrandale/Indian Reserve at Bay Point
19	A	Kincolith
20	A	Indian Reserve
21	A	Indian Reserve
22	A	Indian Reserve at Salmon Cove
23	A	Indian Reserve at Stagoo Creek
24	A	Indian Reserve
25	A	Indian Reserve at Perry Bay
26**	A	Kitsault
27**	A	Alice Arm/Indian Reserve
28	A	Anyox
29	A	Indian Reserve
30	A	Indian Reserve at head of Hastings Arm
31	A	Indian Reserve at Whiskey Bay
32	A	Indian Reserve
33	A	Indian Reserve at George River
34	A	Hyder, Alaska
35**	A	Stewart
36**	A	Port Simpson
37	A	Indian Reserve near Reservation Point
38	A	Indian Reserve at Spakels Point
39	A	Indian Reserve
40	B	Indian Reserve at Venn Passage
41	B	Oldfield
42	B	Port Edward

Table 4 Continued

Number	Fjord System*	Description
43	B	Seal Cove
44**	B	Prince Rupert/Salt Lake Prov. Park/Damsite
45	B	Seal Cove
46**	C	Last point in Rennell Sound
47	D	Floats
48	D	Magneson Point–Westrob Mines/Causeway /Ramp/Mooring/etc.
49**	D	Morring Chain at Hunger Harbour
50	E	Port Blackney
51	E	Klemtu
52	E	Butedale
53	E	Hartley Bay/Indian Reserve/Public Wharves
54	E	Kitkiata Inlet/Indian Reserve/Log Dump
55	E	Kemano Bay/Steamer Landing
56	E	Kitlope Anchorage
57	E	Kildala Arm
58**	E	Kitimat
59	E	Port Essington
60	E	Kitkatla
61	E	Oona River
62	F	North Pulpwoods Ltd./Logging Camp/etc. on South Bentinck Arm
63**	F	Bella Coola
64	F	Kimsquit (abandoned)
65	F	Ocean Falls
66	F	Indian Reserve at Clatse Creek
67	F	Indian Reserve
68	F	Shearwater
69	F	Indian Reserves
70	F	Indian Reserve
71	F	Indian Reserve at Kyarti
72**	F	Bella Bella/New Bella Bella
73	F	Cabin/Ruins near head of Spiller Inlet
74	F	Namu
75**	G	Head of Laredo Inlet
76**	H	Head of Surf Inlet leading to Belmont Surf Inlet Mine
77**	I	Duncanby Landing
78	I	Wadhams/P.O./ Union Oil Co.
79	I	Dawson Landing/Oil Tanks
80	I	Brunswick Cannery at Sandell Bay
81	I	Shell Oil Tanks at Scandinavia Bay

Table 4 Continued

Number	Fjord System*	Description
82**	I	Rivers Inlet Cannery at the head of Rivers Inlet
83	I	Head of Hardy Inlet
84	I	Head of Moses Inlet
85	I	Good Hope
86	J	Imperial Oil Co. store at Boswell
87**	J	Nalos Landing
88	J	Last point in Branch 7–Ahclakerho Channel
89	J	Wyclese Indian Reserve
90	K	Village Cove
91	K	Village Cove
92	K	Chief Nollis Bay
93**	K	Holmes Point
94	K	Eclipse Narrows
95	K	Holmes Point
96	K	Eclipse Narrows
97	L	Indian Reserve
98	L	Indian Reserve
99	L	"A" Frame/Log Dump/Wharf at Mahatta River
100	L	Customs Office
101**	L	Jeune Landing/Wharf/Piles/"A" Frame
102	L	Rumble Beach/Yacht Club/Booming Ground
103**	L	Port Alice
104	L	Indian Reserve/Booming Ground
105	L	Indian Reserve
106	L	Indian Reserve
107	L	Indian Reserve
108**	L	Island Copper Mines at Rupert Inlet
109	L	Coal Harbour
110	L	Barge/Ramp/Float
111	L	Indian Reserve
112	L	Holberg/"A" Frame
113	L	Indian Reserve
114**	L	Winter Harbour
115	L	Indian Reserve/Booming Ground
116	L	Government Wharf/Float/etc. at Bergh Inlet
117**	M	Klaskino Anchorage
118	M	Head of Klaskino Inlet
119	N	Indian Reserve at head of Ououkinsh Inlet
120**	N	Indian Reserve at Byers Çove
121**	O	Port Langford
122	O	Indian Reserve at narrows between here and next point
123	O	Indian Reserve at narrows between here and last point

Table 4 Continued

Number	Fjord System*	Description
124**	O	Indian Reserve at head of Nuchatlitz Inlet
125	O	Indian Reserve
126	P	Nootka/Piles
127	P	Indian Reserve/Log Dump at Mooyah Bay
128	P	Log Dump
129**	P	Gold River/Tahsis Pulp Mill
130	P	Indian Reserve/Log Dump at Matchlee Bay
131	P	Indian Reserve
132	P	Indian Reserve
133	P	Indian Reserve
134	P	Indian Reserves
135	P	Indian Reserve/Log Dump
136	P	Plumper Harbour/Log Dump
137	P	Indian Reserve
138	P	Indian Reserve/Booming Ground
139	P	Float/Pier/Booming Ground at Blowhole Bay
140	P	Boat House/Building/"A" Frame/Booming Ground
141**	P	Tahsis/Barge/Mooring/Indian Reserve/Float /Public Wharves/Booming Ground
142	P	Indian Reserve/Float
143	P	Indian Reserve at head of Port Eliza
144	P	Indian Reserve/Road/Float at Little Espinosa Inlet
145	P	Indian Reserve
146	P	Booming Ground/Float
147	P	Indian Reserve at Graveyard Bay
148	P	Ehatisaht (abandoned)/Indian Reserve
149	P	Indian Reserve
150	P	Float
151	P	Zeballos/Public Wharves/Indian Reserve/Float /Seaplane Float
152	P	Yuquot/Public Wharves
153	P	Indian Reserve at Catala Island
154	P	Indian Reserve
155	P	Hecate (abandoned)/Esperanza/Ways Float /Imperial Oil/Public Wharves
156**	Q	Indian Reserve
157	Q	Indian Reserve at head of Sydney Inlet
158**	Q	Stewardson Inlet
159	Q	Indian Reserve at head of Shelter Inlet
160	Q	Indian Reserve at head of Herbert Inlet at Moyeha Bay/Moyeha River
161**	Q	Indian Reserve

Table 4 Concluded

Number	Fjord System*	Description
162	Q	Indian Reserve at Megin River
163	Q	Ahousat/Public Wharves/Chevron
164	R	Indian Reserve at Toquart River
165**	R	Head of Pipestem Inlet
166	S	Indian Reserve at Coeur d'Alene Inlet
167**	S	Booms at head of Effingham Inlet
168	S	Indian Reserve
169	T	Indian Reserve
170	T	Indian Reserve
171	T	Indian Reserve
172**	T	Indian Reserves at Rainy Bay and Ecole in Rainy Bay
173	T	Fishpen/Public Wharves at San Mateo Bay
174**	T	Green Cove/Piles/Booms
175	T	Kildonan/Piles/Booms
176	T	Booms/Indian Reserve at Snug Basin
177	T	Indian Reserve at Nahmint River
178**	T	Public Wharves
179**	T	Sproat Narrows/Piles/Fishpen/Booms
180	T	Fishpens at Underwood Cove
181	T	China Creek Provincial Park
182	T	Floats/Indian Reserve at Stamp Narrows
183	T	Fog Signal/Indian Reserve at Iso River/Polly Point
184**	T	Port Alberni
185	T	Indian Reserve

* from Table 1.

** Sites for which tsunami elevation time-series have been plotted.

values were due to the shape of Rennell Sound which resembles a funnel. The cross-sectional area of the inlet decreases rapidly toward the head resulting in magnification of both currents and wave amplitudes as the wave propagates up the inlet. In the present numerical scheme, the grid spacing of the inlet model (2 km) does not adequately resolve such rapid changes in geometry. For this reason, the simulation results for station 46 have been discarded. A special high-resolution module would be required to yield satisfactory predictions at this location.

Tables 12 and 13 summarize the extreme events to be found in Tables 5 through 11. Maximum water levels in excess of 3 m and current speeds greater than 2 m/s have been extracted and presented together with a location name.

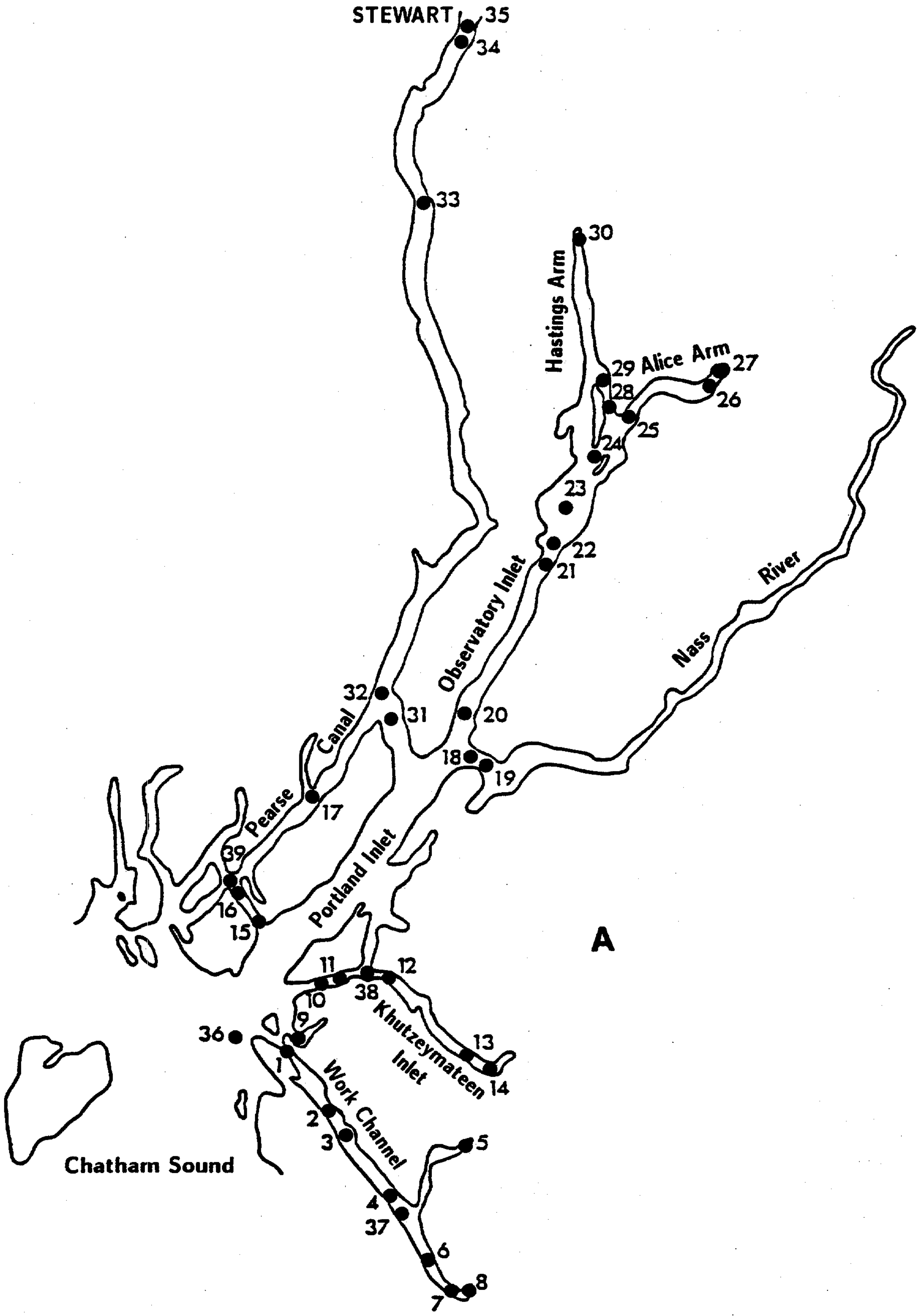

Fig. 10 Map showing water level and current locations listed in Table 5.

Table 5 Maximum Tsunami Water Levels and Currents for System A

Location Number	Inlet System	Source Region*					Source Region*				
		1a	1b	2	3	4	1a	1b	2	3	4
		Water Level† (m)					Current Speed‡ (m/s)				
1	A	0.6	0.7	0.0	0.6	0.2	1.15	1.32	0.02	1.13	0.41
2	A	0.7	0.9	0.0	0.8	0.3	0.13	0.15	0.00	0.12	0.05
3	A	0.8	0.9	0.0	0.8	0.3	0.12	0.13	0.00	0.11	0.04
4	A	0.8	1.0	0.0	0.8	0.3	0.09	0.10	0.00	0.08	0.03
5	A	1.1	1.3	0.0	0.9	0.4	0.04	0.04	0.00	0.04	0.01
6	A	0.8	1.0	0.0	0.9	0.3	0.08	0.10	0.00	0.09	0.03
7	A	0.9	1.0	0.0	0.9	0.3	0.05	0.06	0.00	0.06	0.02
8	A	0.9	1.1	0.0	0.9	0.3	0.04	0.04	0.00	0.04	0.01
9	A	1.6	1.8	0.0	1.6	0.3	0.59	0.69	0.01	0.64	0.11
10	A	1.7	1.9	0.0	1.7	0.4	1.11	1.27	0.02	0.83	0.20
11	A	1.9	2.1	0.0	1.9	0.4	1.08	1.25	0.01	0.84	0.19
12**	A	2.3	2.6	0.0	2.1	0.5	0.14	1.36	0.02	1.13	0.26
13	A	3.0	3.5	0.0	2.6	0.6	0.18	0.20	0.00	0.20	0.04
14**	A	3.0	3.5	0.0	3.0	0.7	0.10	0.11	0.00	0.12	0.03
15	A	1.2	1.3	0.0	1.1	0.3	0.22	0.26	0.00	1.29	0.07
16	A	1.3	1.5	0.0	1.5	0.5	0.50	0.57	0.01	0.44	0.08
17	A	1.6	1.9	0.0	1.0	0.2	0.30	0.36	0.00	0.32	1.08
18	A	1.4	1.7	0.0	0.9	0.2	0.12	0.15	0.00	0.14	0.04
19	A	1.4	1.7	0.0	0.9	0.2	0.39	0.49	0.01	0.42	0.10
20	A	1.3	1.6	0.0	0.9	0.2	1.87	2.30	0.02	1.69	0.37
21	A	1.9	2.4	0.0	1.7	0.3	0.50	0.62	0.01	0.47	0.10
22	A	2.0	2.5	0.0	1.8	0.3	0.51	0.63	0.01	0.48	0.11
23	A	2.1	2.7	0.0	1.9	0.3	0.17	0.21	0.00	0.16	0.04
24	A	2.3	2.9	0.0	2.1	0.4	0.49	0.60	0.01	0.46	0.11
25	A	1.6	2.0	0.0	1.4	0.3	1.01	1.15	0.03	0.96	0.36
26**	A	1.8	2.2	0.0	1.5	0.4	0.08	0.09	0.00	0.08	0.02
27**	A	1.8	2.2	0.0	1.5	0.4	0.05	0.06	0.00	0.05	0.02
28	A	2.5	3.1	0.0	2.2	0.4	0.23	0.28	0.00	0.20	0.04
29	A	2.7	3.3	0.0	2.2	0.4	0.33	0.41	0.01	0.33	0.07
30	A	2.8	3.4	0.0	2.4	0.5	0.07	0.09	0.00	0.09	0.02
31	A	1.5	1.8	0.0	1.0	0.2	0.42	0.52	0.01	0.44	0.08
32	A	1.6	1.9	0.0	1.1	0.2	0.44	0.54	0.01	0.36	0.08
33	A	2.8	3.4	0.0	1.9	0.3	0.30	0.35	0.00	0.26	0.06
34	A	3.2	4.0	0.0	2.2	0.4	0.17	0.22	0.00	0.19	0.03
35**	A	3.3	4.1	0.0	2.3	0.4	0.23	0.29	0.00	0.25	0.04
36**	A	0.9	1.1	0.0	0.8	0.2	—	—	—	—	—
37	A	0.8	1.0	0.0	0.8	0.3	—	—	—	—	—

Table 5 Concluded

Location Number	Inlet System	Source Region*					Source Region*				
		1a	1b	2	3	4	1a	1b	2	3	4
		Water Level† (m)					Current Speed‡ (m/s)				
38	A	2.1	2.3	0.0	2.0	0.4	—	—	—	—	—
39	A	1.6	1.8	0.0	1.3	0.3	—	—	—	—	—

* from Table 3.
** signifies the existence of a corresponding time-series plot.
† Water levels refer to mean water level. The effects of tide must be added to the tsunami levels shown here.
‡ Current speeds represent the rate of water flow averaged over the cross-sectional area of the fjord.

Table 6 Maximum Tsunami Water Levels and Currents for Systems B, C, and D

Location Number	Inlet System	Source Region*					Source Region*				
		1a	1b	2	3	4	1a	1b	2	3	4
		Water Level† (m)					Current Speed‡ (m/s)				
40	B	0.7	0.8	0.0	0.7	0.2	0.31	0.35	0.03	0.39	0.12
41	B	1.8	2.2	0.0	1.7	0.3	1.29	1.52	0.04	1.25	0.26
42	B	1.5	1.7	0.0	1.2	0.3	0.94	1.10	0.07	1.40	0.29
43	B	0.7	0.8	0.0	0.6	0.2	0.14	0.16	0.02	0.11	0.05
44**	B	1.9	2.3	0.0	1.7	0.3	0.53	0.61	0.02	0.77	0.12
45	B	2.3	2.7	0.0	1.8	0.3	—	—	—	—	—
46	C***	—	—	—	—	—	—	—	—	—	—
47	D	1.8	1.9	0.1	2.0	0.7	0.28	0.31	0.03	0.39	0.11
48	D	1.9	2.0	0.1	2.0	0.7	0.12	0.13	0.01	0.24	0.07
49**	D	2.1	2.2	0.2	2.4	0.7	0.24	0.29	0.03	0.54	0.16

* from Table 3.
** signifies the existence of a corresponding time-series plot.
*** Results for site 46 at the head of Rennell Sound are not available because of limited resolution in the numerical model.
† Water levels refer to mean water level. The effects of tide must be added to the tsunami levels shown here.
‡ Current speeds represent the rate of water flow averaged over the cross-sectional area of the fjord.

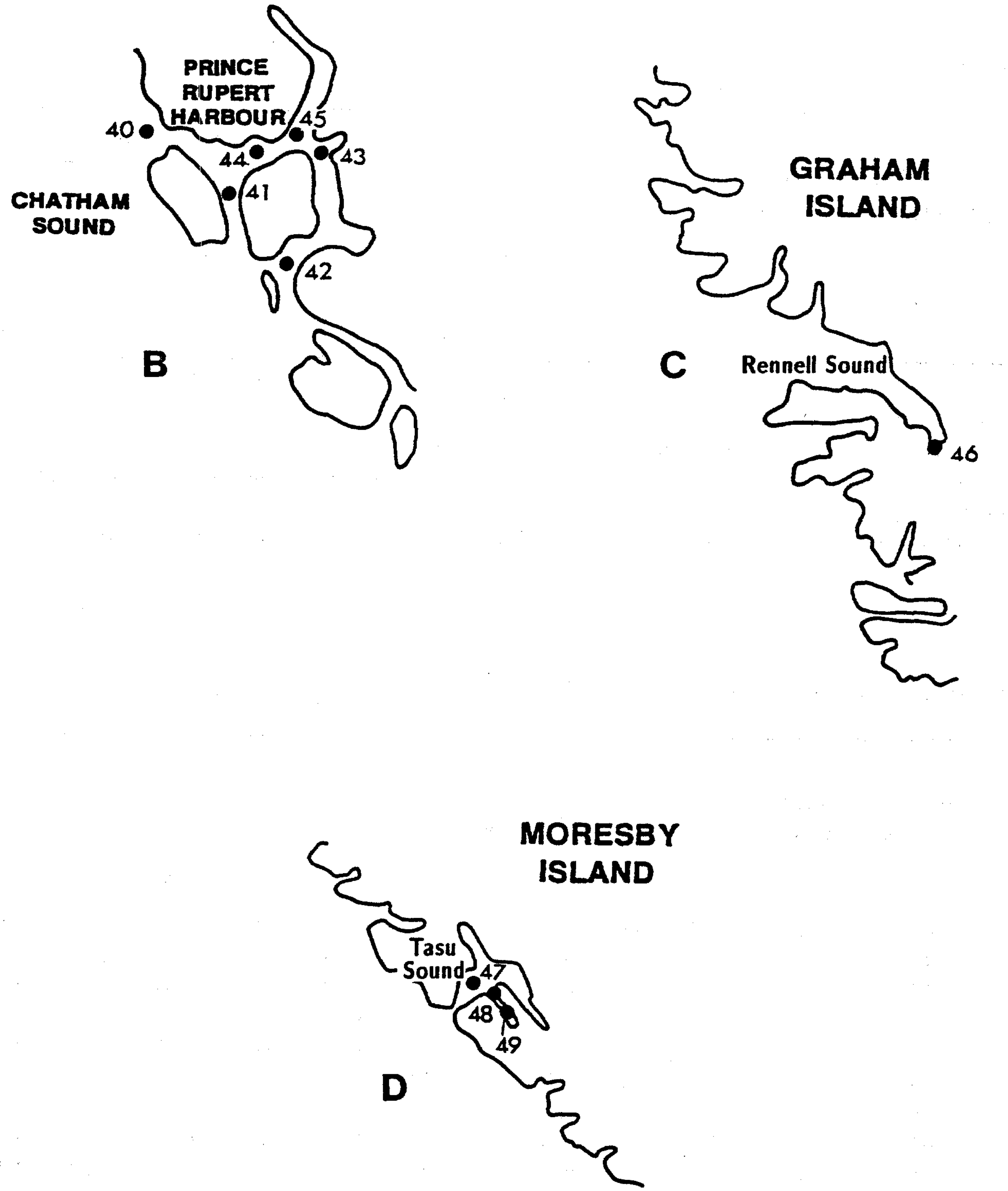

Fig. 11 Map showing water level and current locations listed in Table 6.

CONCLUSIONS

The vulnerability of Canada's west coast to tsunamis generated in seismically active regions of the Pacific Rim provided the impetus for this study of tsunami hazard in British Columbia. Three different computer models have been developed that calculate tsunami wave elevations and currents in the region of generation, along the propagation path across the Pacific Ocean basin, over the continental shelf, and into the complex inlet networks of British Columbia's coastline.

Table 7 Maximum Tsunami Water Levels and Currents for System E

Location Number	Inlet System	Source Region* Water Level† (m) 1a	1b	2	3	4	Source Region* Current Speed‡ (m/s) 1a	1b	2	3	4
50	E	1.4	1.7	0.3	3.5	0.8	0.70	0.84	0.05	0.81	0.36
51	E	2.4	2.9	0.4	4.3	1.3	0.73	0.86	0.17	1.22	0.42
52	E	2.5	3.1	0.1	3.3	0.7	0.47	0.57	0.03	0.62	0.11
53	E	1.1	1.3	0.1	1.0	0.2	0.05	0.06	0.00	0.08	0.03
54	E	1.1	1.4	0.1	1.5	0.5	0.30	0.36	0.01	0.46	0.10
55	E	1.2	1.5	0.1	1.4	0.4	0.12	0.15	0.01	0.18	0.06
56	E	1.8	2.2	0.2	2.3	0.7	0.04	0.05	0.00	0.05	0.03
57	E	1.2	1.5	0.2	2.5	0.8	0.04	0.04	0.01	0.05	0.03
58**	E	1.2	1.4	0.1	1.9	0.4	0.02	0.03	0.00	0.03	0.02
59	E	1.1	1.2	0.1	1.0	0.4	0.25	0.27	0.04	0.28	0.17
60	E	1.3	1.6	0.1	1.3	0.4	—	—	—	—	—
61	E	1.7	1.9	0.0	1.6	0.3	—	—	—	—	—

* from Table 3.

** signifies the existence of a corresponding time-series plot.

† Water levels refer to mean water level. The effects of tide must be added to the tsunami levels shown here.

‡ Current speeds represent the rate of water flow averaged over the cross-sectional area of the fjord.

Past tsunamis have arrived at the British Columbia coast from several different source regions. Four of these have been investigated in this study in order to evaluate the potential for damage from a future tsunami. These source regions have been selected on the basis of previous large tsunamis (e.g., the Alaska 1964 earthquake and the Chile 1960 event), or the potential for producing large tsunamis (e.g., the Shumagin Gap). The damage potential from a tsunami is directly related to the amplitude of the largest wave (or waves) and, in some instances, to the magnitude of the associated current. Thus, at 185 key locations along the coast of British Columbia, maximum modelled wave amplitude and current speed have been tabulated for each tsunami source. These results have led to the following conclusions:

1.) Generation and propagation of the initial tsunami wave crest to the heads of British Columbia's inlets can be modelled successfully (Dunbar et al., 1989).

2.) Based on the simulation of the 1964 Alaska tsunami, the following estimates of model

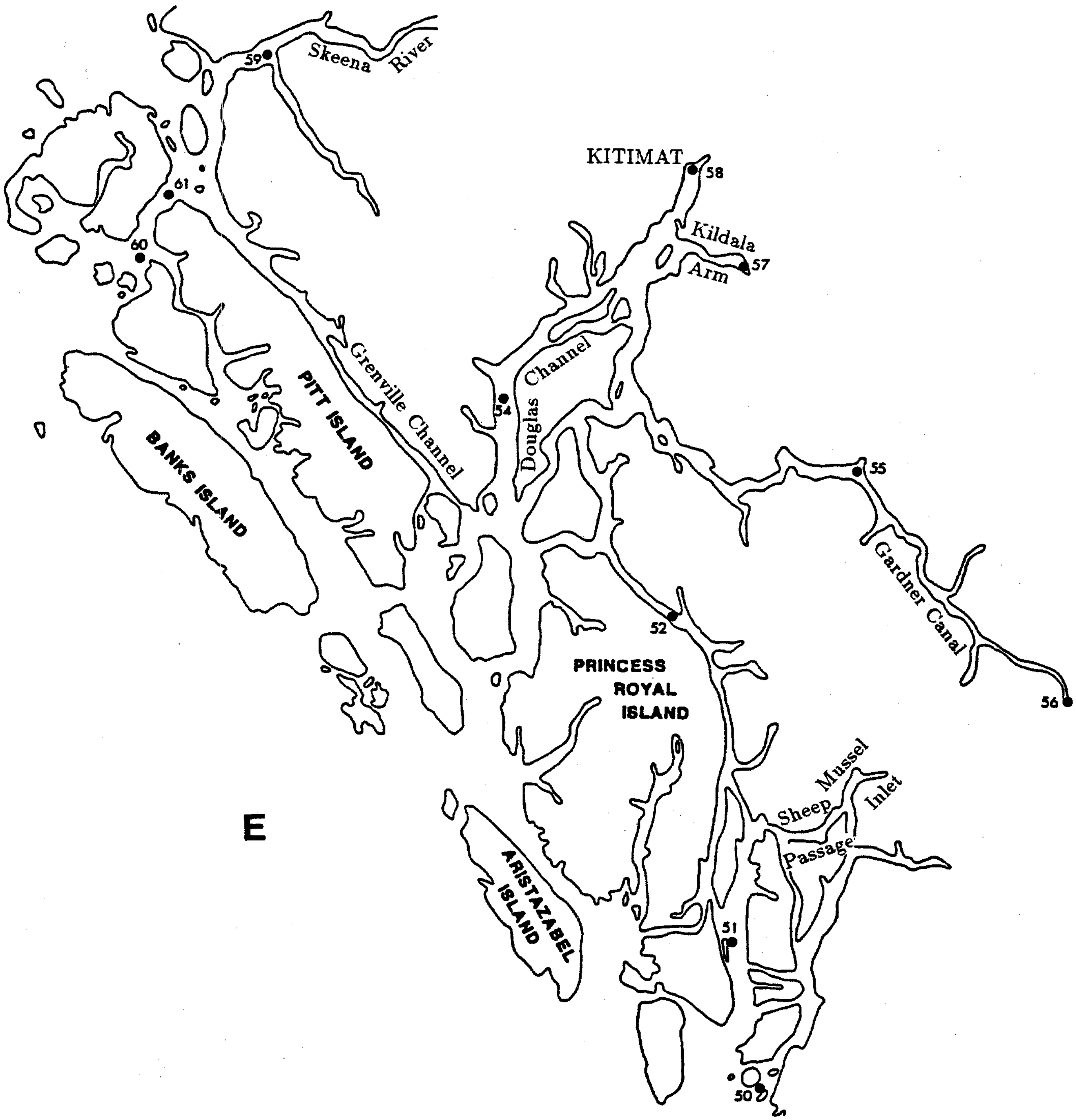

Fig. 12 Map showing water level and current locations listed in Table 7.

accuracy have been made. Wave arrival times are considered accurate to within 2%. Initial wave amplitude is accurate to within 20 cm and is often much better (assuming the seabed displacement field is known exactly). Subsequent wave amplitudes are accurate to within 15%.

3.) Tsunami wave heights are strongly influenced by source location and magnitude. Modelled earthquakes in the Shumagin Gap region of the Aleutian Islands and in the area of the 1964 Alaska earthquake produced the largest waves and strongest currents. These two areas were the closest sources, as well as the largest events modelled.

4.) Maximum modelled water levels vary significantly from one region to another along the coast. The following list summarizes the results for six geographic zones indicating critical areas that are subject to high water levels. In most cases (exceptions noted), these estimates are based on the occcurence of a very large tsunamigenic earthquake in the Shumagin Gap region of the Aleutian Islands.

   - North Coast, Chatham Sound: (largest waves from the Alaska source location) generally from 3 to 4 m in Observatory Inlet; 4 m at Stewart; 3.5 m at other inlet heads.
   - West coast of Graham Island: extreme water levels exceeding 8 to 10 m at the head of Rennell Sound. The shape of this inlet amplifies the wave energy.
   - North Central Coast, Caamano Sound to Milbanke Sound: 3.5 to 4.5 m in Princess Royal Channel; up to 7 m at the head of Spiller Channel; amplitudes ranging between 4 and 6 m at Ocean Falls and Laredo Inlet.
   - South Central Coast, off Fitz Hugh Sound and Smith Sound: up to 9 m at the heads of Smith Inlet and Moses Inlet.
   - Northwest coast of Vancouver Island, Quatsino Sound: 5.5 to 7 m in Quatsino Sound; up to 9 m in Neroutsos Inlet; 8.5 m in Quatsino Narrows.
   - Central coast of Vancouver Island, Checloset Bay to Nootka Sound: extreme water levels of 10 m or more at the head of Quoukinsh Inlet; up to 10 m at heads of Machalat and Tlupana Inlets; up to 7 or 8 m in Espinosa Inlet; 4.5 t0 5 m at Port Eliza.
   - South coast of Vancouver Island, Clayoquot Sound to Barkley Sound: 3 to 4 m in Sydney Inlet; up to 8 m at the head of Alberni Inlet, 7 to 8 m in Pipestem Inlet, and 4 to 4.5 m in Effingham Inlet.

5.) Chile, the farthest source point, produced the smallest waves, and is not considered a probable source of tsunamis greater than 1.5 m amplitude in the coastal inlets.

6.) Scaling the bottom displacement values results in a corresponding, approximately linear scaling of wave heights, i.e., for a particular source area, a 20% increase in the amplitude of water displaced by the earthquake results in a 20% increase in maximum water levels.

7.) The highest crest in a series of tsunami waves is often not the first to arrive. Consequently, the behaviour of a series of waves inside the inlets must be predicted, which demands, in turn, a realistic treatment of boundary conditions, most especially the reflection condition at the landward end. More accurate modelling of extreme water levels near inlet heads that exhibit significant adsorption of wave energy, or flooding of dry ground will require fine resolution, one- or two-dimensional submodels covering the area near the head of the inlet.

8.) The principal limitation to estimating tsunami wave heights more accurately for particular sources is the uncertainty associated with specifying the final bottom displacements that will result for an earthquake occurring at that source.

Table 8 Maximum Tsunami Water Levels and Currents for System F, G, and H

Location Number	Inlet System	Source Region*					Source Region*				
		1a	1b	2	3	4	1a	1b	2	3	4
		Water Level† (m)					Current Speed‡ (m/s)				
62	F	2.0	2.3	0.1	3.0	0.4	0.19	0.22	0.01	0.17	0.07
63**	F	1.5	1.8	0.2	2.2	0.6	0.03	0.03	0.01	0.05	0.01
64	F	1.2	1.5	0.2	2.0	0.3	0.48	0.58	0.07	0.79	0.25
65**	F	2.7	3.3	0.3	4.2	3.1	0.27	0.33	0.03	0.28	0.27
66	F	1.7	2.1	0.1	1.9	0.6	0.84	1.02	0.04	0.67	0.26
67	F	2.0	2.4	0.2	1.1	0.8	1.10	1.34	0.06	1.15	0.30
68	F	1.6	2.0	0.2	2.4	0.7	0.78	0.97	0.07	0.67	0.35
69	F	2.0	2.5	0.2	2.8	0.9	0.74	0.92	0.07	0.82	0.43
70	F	1.6	1.9	0.1	1.9	0.4	0.46	0.55	0.02	0.26	0.15
71	F	1.8	2.1	0.1	2.0	0.6	0.83	1.00	0.05	0.78	0.37
72**	F	1.8	2.2	0.1	2.8	0.7	0.97	1.18	0.12	1.24	0.58
73	F	5.9	7.2	0.3	4.0	3.4	0.54	0.66	0.04	0.35	0.36
74	F	1.0	1.3	0.1	1.2	0.5	—	—	—	—	—
75**	G	3.7	4.4	0.4	5.6	1.5	0.16	0.20	0.03	0.47	0.13
76**	H	2.2	2.5	0.3	3.3	1.5	0.14	0.17	0.02	0.24	0.14

* from Table 3.

** signifies the existence of a corresponding time-series plot.

† Water levels refer to mean water level. The effects of tide must be added to the tsunami levels shown here.

‡ Current speeds represent the rate of water flow averaged over the cross-sectional area of the fjord.

Improvements can also be made to the numerical models and their application in the inlets, designed to increase the accuracy of the results. Such improvements are focused on the continental shelf and the inlet systems. The deep ocean model performance appears satisfactory as formulated.

The foregoing considerations lead to the following:

1.) Research to improve understanding of earthquake ground motion is recommended. The objectives of such research include parameterization of the types of motion that are possible in each potential earthquake area, and the probability of occurrence of the parameter values. Given the likelihood that destructive tsunamis will originate around the northern Pacific Rim, attention should initially be directed at source points there.

2.) This study has considered distant earthquakes. However, it has been hypothesized that a local earthquake in the Fuca plate subduction zone could also generate a severe tsunami. This type of event could be modelled using the techniques developed here. Simulation of locally-generated tsunamis, originating at locations with a high likelihood of seismic activity, is recommended. Such simulations would provide greater confidence in the maximum wave amplitudes developed in this study.

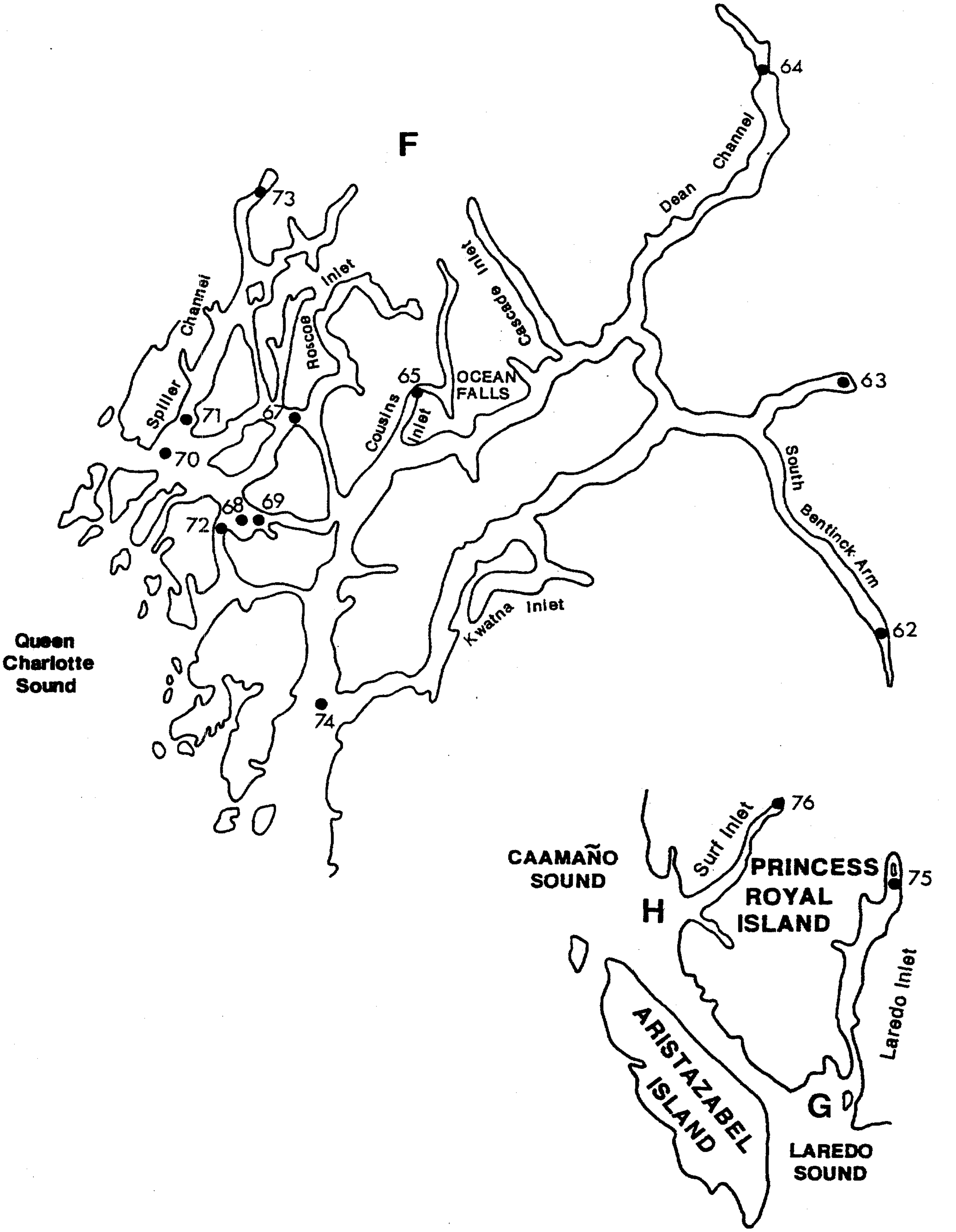

Fig. 13 Map showing water level and current locations listed in Table 8.

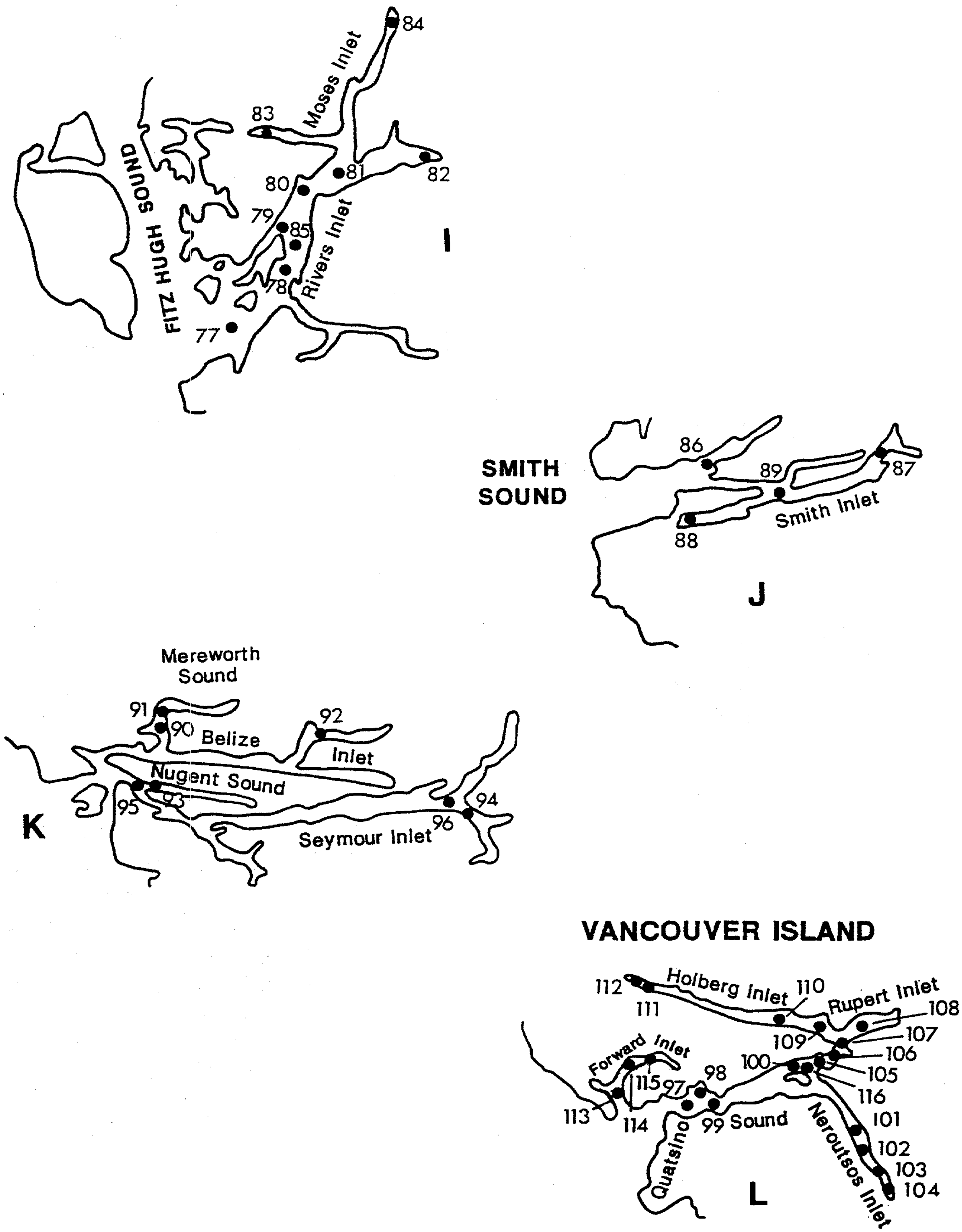

Fig. 14 Map showing water level and current locations listed in Table 9.

Table 9 Maximum Tsunami Water Levels and Currents for System I, J, K, and L

Location Number	Inlet System	Source Region* Water Level† (m) 1a	1b	2	3	4	Source Region* Current Speed‡ (m/s) 1a	1b	2	3	4
77**	I	1.9	2.2	0.1	3.1	1.3	0.75	0.89	0.03	0.83	0.21
78	I	1.8	2.1	0.1	2.7	1.2	0.63	0.73	0.03	0.80	0.19
79**	I	2.3	2.8	0.1	2.8	1.5	1.16	1.43	0.10	1.73	0.52
80	I	2.2	2.7	0.1	2.4	1.2	0.57	0.69	0.03	0.83	0.17
81	I	2.5	3.0	0.1	3.3	1.1	0.60	0.72	0.04	0.85	0.18
82**	I	3.1	3.6	0.2	5.0	1.5	0.08	0.09	0.01	0.11	0.04
83	I	4.7	5.6	0.2	5.3	1.6	0.16	0.18	0.01	0.15	0.05
84	I	5.9	7.2	0.3	9.2	5.1	0.13	0.15	0.01	0.19	0.16
85	I	1.8	2.2	0.1	2.3	1.2	—	—	—	—	—
86	J	3.4	4.1	0.4	4.6	3.5	0.89	1.09	0.16	1.16	0.90
87**	J	7.6	9.3	0.4	8.4	2.2	1.31	1.64	0.25	1.66	0.81
88	J	1.2	1.4	0.2	1.2	0.4	0.03	0.03	0.01	0.04	0.01
89	J	4.9	6.0	0.4	5.0	1.3	—	—	—	—	—
90	K	0.1	0.1	0.0	0.1	0.0	0.07	0.09	0.01	0.13	0.08
91	K	0.1	0.1	0.0	0.1	0.0	0.06	0.07	0.01	0.09	0.08
92	K	0.1	0.1	0.0	0.1	0.0	0.01	0.01	0.00	0.01	0.01
93**	K	0.3	0.3	0.0	0.5	0.2	0.39	0.45	0.04	0.56	0.20
94	K	0.0	0.1	0.0	0.0	0.0	0.01	0.01	0.00	0.01	0.01
95	K	0.3	0.3	0.0	0.6	0.3	—	—	—	—	—
96	K	0.1	0.1	0.0	0.1	0.1	—	—	—	—	—
97	L	1.7	2.1	0.5	7.2	2.4	1.09	1.37	0.14	1.79	1.39
98	L	1.9	2.1	0.5	7.2	2.4	1.18	1.48	0.11	1.66	1.51
99	L	2.2	2.5	0.5	6.1	2.5	1.16	1.40	0.11	2.35	1.40
100	L	2.7	3.5	0.4	6.7	4.0	0.94	1.11	0.19	2.46	0.89
101**	L	3.0	3.7	0.4	5.4	3.6	0.67	0.84	0.10	1.68	1.24
102	L	3.1	3.9	0.3	5.5	4.2	1.03	1.25	0.18	2.65	1.83
103**	L	3.9	4.7	0.5	9.1	7.2	2.77	3.13	0.57	5.76	4.30
104***	L	—	—	—	—	—	—	—	—	—	—
105	L	3.5	3.9	0.5	8.5	4.2	1.26	1.42	0.30	2.50	1.55
106	L	3.8	4.3	0.7	7.9	4.8	1.41	1.65	0.22	2.84	1.16
107	L	3.3	3.7	0.7	8.1	4.4	2.60	2.92	0.42	4.71	3.00
108**	L	0.7	0.9	0.1	1.2	0.8	0.18	0.21	0.04	0.26	0.17
109	L	0.3	0.4	0.0	0.8	0.4	0.29	0.33	0.02	0.23	0.33
110	L	0.7	0.8	0.1	1.0	0.9	0.26	0.30	0.03	0.25	0.28
111	L	1.2	1.4	0.1	1.3	1.1	0.06	0.07	0.01	0.14	0.06
112	L	2.1	2.3	0.2	3.4	2.3	1.22	1.35	0.18	2.27	1.25

Table 9 Concluded

Location Number	Inlet System	Source Region* 1a	1b	2	3	4	Source Region* 1a	1b	2	3	4
		Water Level† (m)					Current Speed‡ (m/s)				
113	L	2.5	2.7	0.3	6.1	2.8	2.04	2.29	0.29	3.72	2.02
114**	L	5.3	6.1	0.8	9.6	6.1	9.47	12.76	0.90	21.42	9.65
115***	L	—	—	—	—	—	—	—	—	—	—
116	L	2.7	3.2	0.4	7.0	3.7	—	—	—	—	—

* from Table 3.
** signifies the existence of a corresponding time-series plot.
† Water levels refer to mean water level. The effects of tide must be added to the tsunami levels shown here.
‡ Current speeds represent the rate of water flow averaged over the cross-sectional area of the fjord.

3.) Improvements in model accuracy should focus, as a first priority, on the treatment of flooding/drying areas within the inlet systems. In most of the inlets examined in this study, local-area high-resolution models are required, typically at the inlet head, to refine the water level criteria.

4.) As a second step, water level accuracy in certain systems, which are close to resonance, would be improved by higher resolution of the entrance to the inlet and improved coupling between the shelf and fjord model. A case in point is Barkley Sound, a complicated area composed of many small islands and deep channels with multiple connections to Alberni Inlet. This system is only partially resolved in the present model.

5.) Further evaluation of tsunami water levels should also consider the influence of tides. Tidal forcing applied along the shelf model boundary can be coupled with tsunami levels from the deep ocean model to give a combined simulation over the shelf and up into the fjords. Simulations can be phased to combine tidal high water with the tsunami crest elevations, providing an estimate of maximum probable combined water level in a dynamically coupled calculation. This type of modelling should be done in conjunction with improved treatment of flooding in the inlets.

ACKNOWLEDGMENTS

We wish to thank R.M. Rutka for typesetting the text.

Table 10 Maximum Tsunami Water Levels and Currents for System M, N, O, and P

Location Number	Inlet System	Source Region* Water Level† (m) 1a	1b	2	3	4	Source Region* Current Speed‡ (m/s) 1a	1b	2	3	4
117**	M	3.0	3.7	0.4	5.5	2.3	2.08	2.40	0.45	2.99	2.32
118	M	4.2	5.0	0.7	5.7	3.7	0.37	0.43	0.09	0.97	0.50
119	N	8.6	10.1	1.2	13.0	4.6	0.80	0.98	0.13	2.29	1.04
120**	N	1.3	1.6	0.3	3.9	1.7	—	—	—	—	—
121**	O	2.1	2.6	0.3	3.3	1.2	0.76	0.91	0.17	1.93	0.98
122	O	3.3	3.8	0.6	4.4	1.7	0.56	0.62	0.12	1.22	0.40
123	O	0.2	0.2	0.0	0.2	0.1	0.02	0.03	0.01	0.04	0.02
124**	O	0.2	0.2	0.0	0.2	0.1	0.00	0.00	0.00	0.01	0.00
125	O	1.9	2.4	0.3	2.9	1.1	—	—	—	—	—
126	P	1.7	2.1	0.2	2.9	2.3	0.74	0.91	0.06	1.76	1.06
127	P	2.4	3.0	0.2	4.5	1.8	1.33	1.64	0.13	2.66	0.47
128	P	5.9	7.3	0.4	10.6	1.6	0.33	0.40	0.04	0.86	0.18
129**	P	6.1	7.5	0.4	10.8	1.7	0.13	0.16	0.02	0.36	0.09
130	P	6.5	8.0	0.4	11.1	2.2	0.22	0.26	0.03	0.68	0.24
131	P	1.9	2.3	0.2	3.0	1.8	1.25	1.53	0.11	2.59	0.80
132	P	1.6	2.0	0.2	4.2	1.8	0.71	0.88	0.06	1.69	0.81
133	P	2.2	2.7	0.2	8.4	3.3	1.14	1.40	0.08	3.53	1.54
134	P	3.5	4.1	0.3	10.3	6.0	0.51	0.63	0.03	1.65	0.87
135	P	3.7	4.3	0.3	11.1	6.4	0.42	0.53	0.03	1.89	0.77
136	P	2.1	2.6	0.2	4.7	2.8	0.51	0.60	0.07	1.85	0.86
137	P	1.8	2.2	0.1	3.5	2.1	1.31	1.62	0.24	2.30	0.64
138	P	1.8	2.1	0.3	2.3	1.2	0.75	0.88	0.11	1.42	0.54
139	P	1.9	2.2	0.3	2.7	1.3	0.31	0.36	0.04	0.75	0.25
140	P	1.9	2.3	0.3	2.9	1.2	0.10	0.12	0.02	0.31	0.12
141**	P	2.0	2.3	0.3	3.1	1.3	0.06	0.08	0.02	0.21	0.08
142	P	1.6	1.9	0.1	3.6	0.9	1.25	1.48	0.20	1.87	1.19
143	P	2.9	3.3	0.5	4.7	2.8	0.49	0.55	0.10	1.18	0.60
144	P	3.8	4.6	0.3	5.2	1.8	0.52	0.63	0.06	1.21	0.38
145	P	4.5	5.4	0.4	6.8	2.2	0.45	0.54	0.05	1.11	0.34
146	P	4.7	5.6	0.4	7.6	2.3	0.36	0.43	0.04	0.91	0.27
147	P	2.2	2.7	0.1	3.4	1.0	0.66	0.82	0.09	1.15	0.61
148	P	2.1	2.7	0.1	3.5	1.0	0.73	0.89	0.10	1.30	0.68
149	P	2.7	3.4	0.3	4.4	2.2	0.48	0.56	0.05	0.97	0.43
150	P	3.4	4.2	0.4	5.3	2.6	0.59	0.68	0.07	1.21	0.53
151	P	3.9	4.8	0.4	6.1	2.9	0.25	0.30	0.03	0.51	0.23
152	P	1.6	1.9	0.2	3.6	2.0	—	—	—	—	—
153	P	1.2	1.6	0.1	3.1	0.9	—	—	—	—	—

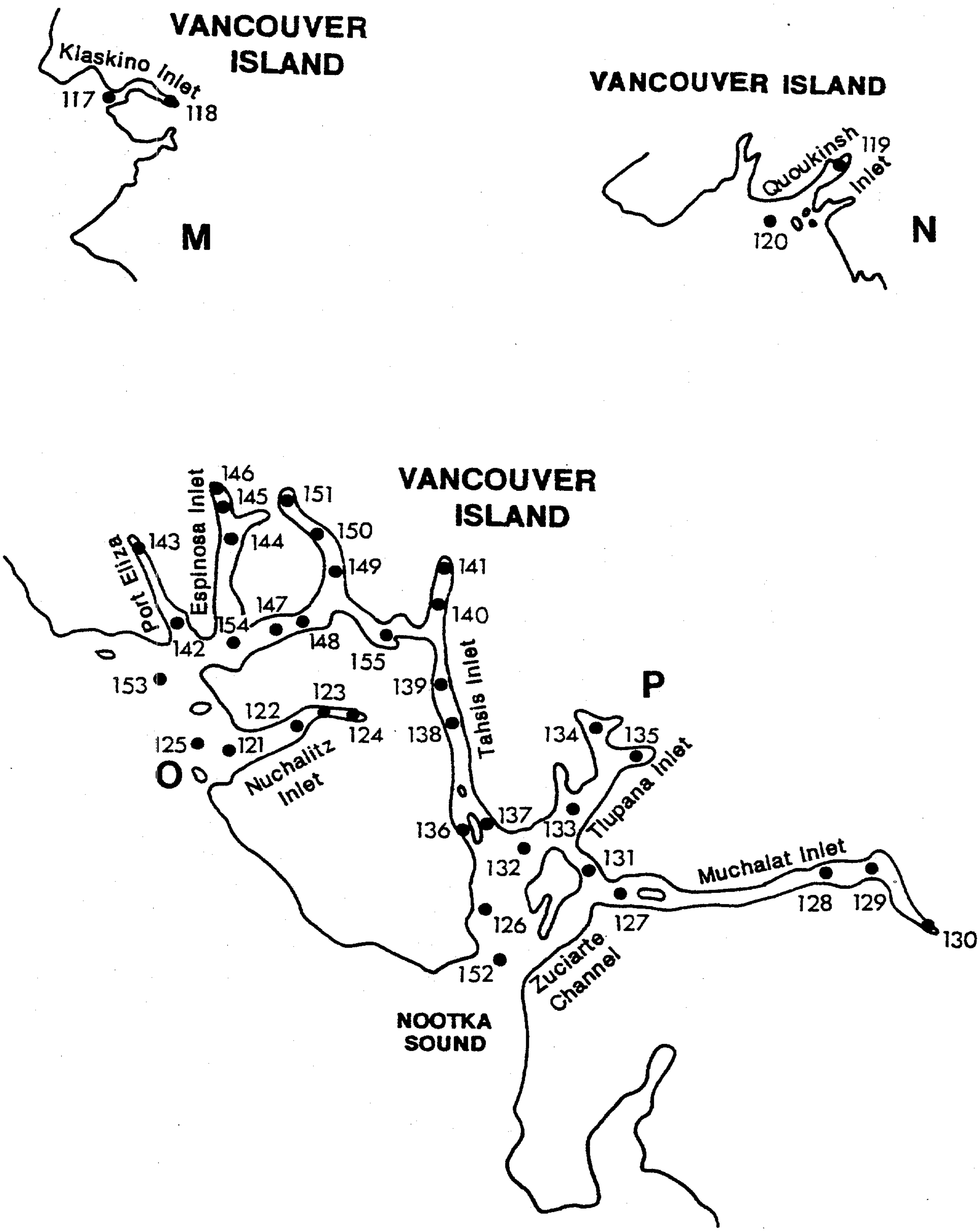

Fig. 15 Map showing water level and current locations listed in Table 10.

Table 10 Concluded

Location Number	Inlet System	Source Region* 1a	1b	2	3	4	Source Region* 1a	1b	2	3	4
		Water Level† (m)					Current Speed‡ (m/s)				
154	P	2.2	2.7	0.2	3.2	1.3	—	—	—	—	—
155	P	2.4	3.0	0.3	5.5	2.7	—	—	—	—	—

* from Table 3.

** signifies the existence of a corresponding time-series plot.

† Water levels refer to mean water level. The effects of tide must be added to the tsunami levels shown here.

‡ Current speeds represent the rate of water flow averaged over the cross-sectional area of the fjord.

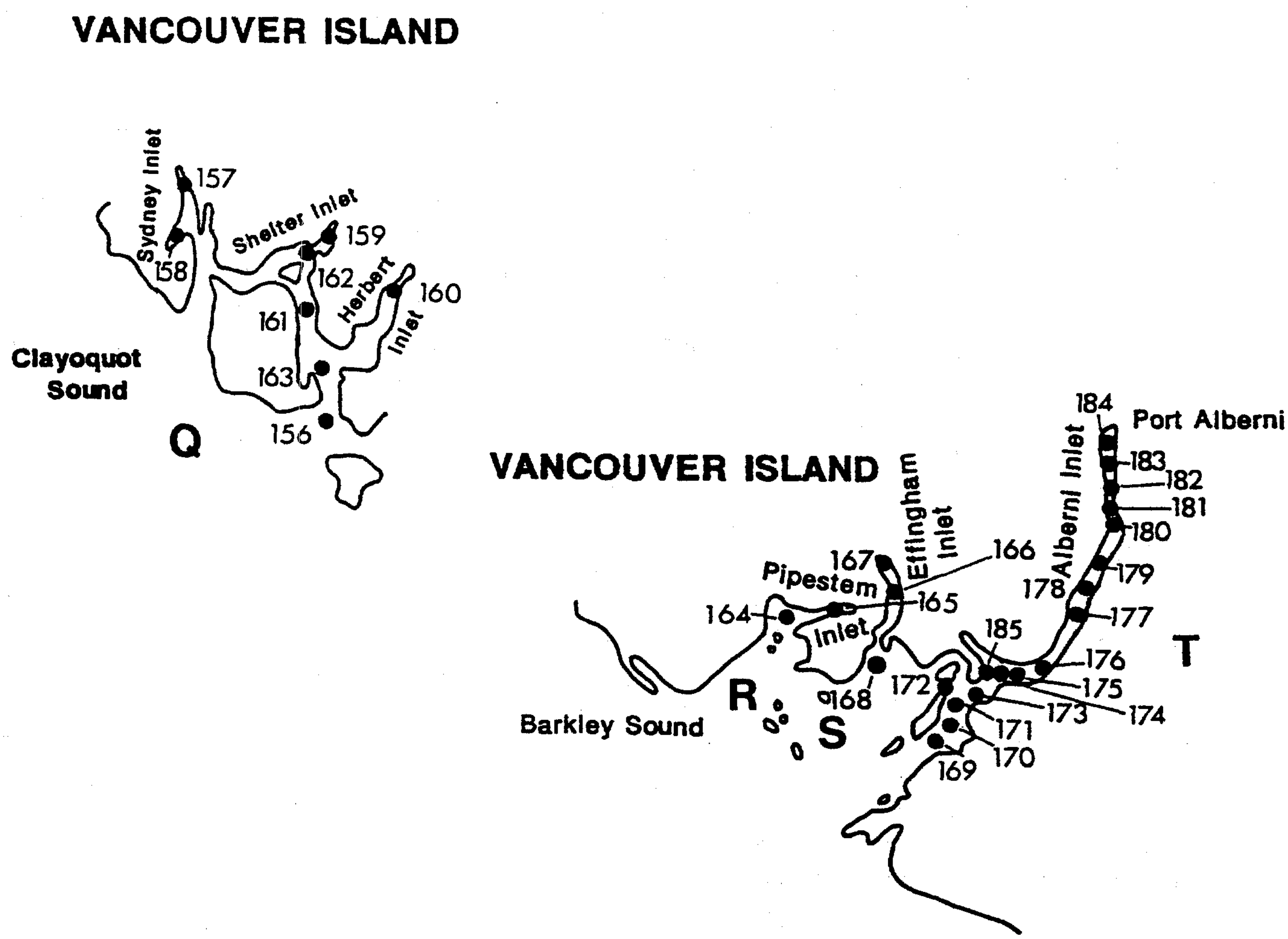

Fig. 16 Map showing water level and current locations listed in Table 11.

Table 11 Maximum Tsunami Water Levels and Currents for Systems Q, R, S, and T

Location Number	Inlet System	Source Region*					Source Region*				
		1a	1b	2	3	4	1a	1b	2	3	4
		Water Level† (m)					Current Speed‡ (m/s)				
156**	Q	0.8	0.9	0.1	1.4	0.6	0.65	0.74	0.09	1.31	0.73
157	Q	1.8	2.3	0.3	3.8	1.4	0.10	0.12	0.03	0.41	0.12
158**	Q	1.7	2.2	0.3	3.1	1.2	0.07	0.08	0.02	0.21	0.08
159	Q	1.1	1.4	0.1	2.8	1.0	0.05	0.06	0.01	0.18	0.05
160	Q	0.8	0.9	0.1	1.5	0.6	0.03	0.04	0.00	0.07	0.02
161**	Q	0.7	0.8	0.1	0.9	0.4	0.29	0.33	0.05	0.35	0.16
162	Q	1.0	1.4	0.1	2.5	0.9	—	—	-	—	—
163	Q	0.8	0.9	0.1	1.1	0.3	0.00	0.00	0.00	0.00	0.00
164	R	2.2	2.7	0.4	7.6	2.9	0.46	0.55	0.11	3.70	1.25
165**	R	3.0	3.6	0.4	5.2	2.3	0.18	0.22	0.06	0.95	0.43
166	S	2.3	3.1	0.3	4.5	1.2	0.22	0.25	0.02	0.33	0.17
167**	S	2.6	3.3	0.3	4.1	1.5	0.13	0.14	0.02	0.25	0.14
168	S	2.0	2.5	0.2	3.1	0.9	—	—	—	—	—
169	T	2.7	3.0	0.2	2.4	1.4	0.74	0.89	0.07	0.93	0.29
170	T	2.7	3.1	0.3	2.5	1.4	0.80	0.94	0.08	1.02	0.30
171	T	2.7	3.1	0.3	2.6	1.3	1.14	1.33	0.12	1.48	0.46
172**	T	2.3	2.6	0.2	3.3	1.0	1.53	1.73	0.13	2.16	1.04
173	T	2.8	3.2	0.3	2.9	1.0	0.99	1.19	0.12	1.46	0.65
174**	T	3.4	4.2	0.4	3.7	1.1	0.72	0.93	0.16	1.43	0.93
175	T	3.8	4.7	0.5	4.1	1.4	0.52	0.67	0.12	1.06	0.69
176	T	4.1	5.1	0.6	4.6	1.8	0.29	0.38	0.07	0.63	0.40
177	T	3.3	4.1	0.3	3.9	2.2	0.40	0.48	0.05	0.58	0.20
178**	T	3.5	4.3	0.3	3.9	2.2	0.80	0.95	0.11	1.51	0.57
179**	T	4.1	5.1	0.4	3.5	1.4	1.15	1.28	0.12	2.47	0.98
180	T	4.2	5.4	0.4	3.8	1.1	0.65	0.79	0.06	1.48	0.61
181	T	4.2	5.3	0.4	3.8	1.2	0.74	0.89	0.08	1.56	0.64
182	T	5.3	6.3	0.5	6.8	2.5	1.65	2.01	0.22	3.46	1.34
183	T	5.7	6.8	0.5	7.5	3.0	1.11	1.35	0.15	2.39	0.86
184**	T	6.2	7.4	0.6	8.3	3.6	0.93	1.17	0.12	2.14	0.67
185	T	3.0	3.4	0.3	3.0	1.1	—	—	—	—	—

* from Table 3.

** signifies the existence of a corresponding time-series plot.

† Water levels refer to mean water level. The effects of tide must be added to the tsunami levels shown here.

‡ Current speeds represent the rate of water flow averaged over the cross-sectional area of the fjord.

Table 12 Summary of Extreme Tsunami Amplitudes

Location	Maximum Tsunami Height	Source Area
North Coast	3.5 m near the head of Khutzeymateen Inlet	Alaska
	3 to 3.5 m throughout Hastings Arm (north end of Observatory Inlet)	Alaska
	3.5 to 4 m near Stewart	Alaska
North Central Coast	3.5 to 4.5 m west of Princess Royal Island	Shumagin
	4.2 m in Cousins Inlet	Shumagin
	7.2 m at the head of Spiller Channel	Alaska
	5.6 m at the head of Laredo Sound	Shumagin
	3.3 m at the head of Surf Inlet	Shumagin
South Central Coast	3.3 to 9.2 m at the heads of Rivers and Moses Inlets	Shumagin
	6 to 9.3 m in Smith Inlet (increasing toward the head)	Alaska
Northwest coast of Vancouver Island	5.5 to 7.2 m in Quatsino Sound	Shumagin
	up to 9 m in Neroutsos Inlet	Shumagin
	8 to 8.5 m in Quatsino Narrows	Shumagin
	3.4 m at the head of Holberg Inlet	Shumagin
	6 to 7 m in Forward Inlet	Shumagin
	5 to 6 m in Klaskino Inlet	Shumagin
	$>$ 10 m at the head of Quoukinsh Inlet	Shumagin
Central coast of Vancouver Island	3.5 to 4.5 m in Nuchalitz Inlet	Shumagin
	4.5 to $>$ 10 m in Muchalat and Tlupana	Shumagin
	Inlets (increasing toward the heads)	Shumagin
	3.5 to 4.5 m at south end of Tahsis Inlet	Shumagin
	3 m at the head of Tahsis Inlet	Shumagin
	3.6 to 7.6 m in Port Eliza and Espinosa Inlets	Shumagin
	3.5 m in Nootka Sound	Shumagin
South coast of Vancouver Island	3 to 4 m in Sydney Inlet	Shumagin
	4 to 8 m in Pipestem and Effingham Inlets	Shumagin
	3 to 8 m in Alberni Inlet (increasing toward the head)	Shumagin

Table 13 Summary of Extreme Tsunami Wave Current Speeds

Location	Maximum Tsunami Current	Source Area
North Coast	2.3 m/s at entrance to Observatory Inlet	Alaska
North Central Coast	currents less than 2 m/s	n/a
South Central Coast	currents less than 2 m/s	n/a
Northwest coast of Vancouver Island	2.5 to 4.7 m/s in Quatsino Narrows	Shumagin
	2.5 to > 5 m/s near Port Alice on Neroutsos Inlet	Shumagin
	3 m/s at entrance to Forward Inlet	Shumagin
	3 m/s at entrance to Klaskino Inlet	Shumagin
	2 m/s in Quoukinsh Inlet	Shumagin
Central coast of Vancouver Island	2.7 m/s at entrance to Muchalat Inlet	Shumagin
	2.5 to 3.5 m/s near entrance to Tlupana Inlet	Shumagin
	2.3 m/s at south end of Tahsis Inlet	Shumagin
South coast of Vancouver Island	3.7 m/s at entrance to Pipestem Inlet	Shumagin
	2 to 3.5 m/s in Alberni Inlet	Shumagin

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THE LARGEST HISTORICAL TSUNAMIS IN THE NORTHERN ADRIATIC SEA: A CRITICAL REVIEW

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ABSTRACT

Italy is one of the Mediterranean regions most exposed to tsunamis of both seismic and volcanic origin. The paper reviews critically the three events that, according to the recent literature, are reputed to be the most severe that have ever occurred in the Northern Adriatic Sea, namely the cases of the 30 April 793, of March 1106 and of the 26 March 1511. In the light of our investigations, mostly based on a careful cross-examination of copious original sources, no one of the above events may be considered a disastrous tsunami. In the first case, we deal with a dubious tsunami, that possibly occurred in the Gulf of Trieste due to a Slovenian earthquake and that was associated by somebody to a false event, here shown to be a duplication of the 801 Spoleto earthquake in Central Italy. The second case is a clear example of misinterpretation and of progressive corruption over the years of the informative content of the original sources: our conclusion is that no tsunami did occur. As regards the third event, neither remarkable nor extensive damage seems to be reported in the available Italian sources, though some yugoslavian documents remain to be carefully inspected. Our research shows unmistakably the need for a revision and an integration of the previous studies on the Italian tsunamis, also in order to provide a firm basis to the estimates of tsunami risk.

INTRODUCTION

Italy is known to be one of the regions in the Mediterranean Sea that is most exposed to the attack of tsunamis of both seismic and volcanic origin. A recent compilation by Caputo and Faita (1984, hereafter CF catalog), that is the first scientific attempt at producing an exhaustive catalog of the tsunamis observed on the Italian coasts, counts 154 events covering a time span of about 20 centuries. The total is remarkable as may be realized from the comparison with the numerous tsunami catalogs available for Greece: for example, the latest published compilations by Papadopoulos and Chalkis (1984) and by Papazachos et al.(1986) list respectively 85 events in a period of 35 centuries and 59 events in one of 25 centuries.

Before the publication of the CF catalog, the only investigation that could be found in the modern literature regarding Italy was a list of the Mediterranean tsunamis assembled by Ambraseys (1964) and reproposed by Karnik (1971) that included almost exclusively the last-century events, and therefore did not allow to be deduced any reliable picture of tsunami potential around Italy. The CF catalog may certainly be viewed as a significant step towards a better assessment of tsunami hazard. The Sicilian and Calabrian coasts appear without doubt as the most dangerous of the whole Italy, which is in fair agreement with the tectonic setting of the area, characterized by a notably high seismicity as well as by a remarkable volcanic activity (three of the greatest European volcanoes, that is Etna, Vulcano and Stromboli are located here). A second cluster of events is apparent in the Gulf of Naples where the volcanic areas of Campi Flegrei and Vesuvio are quite effective in producing tsunamis.

On the Eastern Italian coasts the tsunami activity cannot considered at all negligible. Indeed about one fourth (23 out of 88) of the events with certain seismic origin pertain to the Adriatic, where three different tsunami generation areas may be easily distinguished: despite the discrepancy that will be clarified in the concluding section, in a broad sense they fit in with the seismogenic sources involving the Adriatic that have been determined in recent accurate investigations on Italian seismicity (see Mulargia et al.,1987a and 1987b). Following a South-North direction, the first region embraces the Gargano promontory (Puglia), with a considerable occurrence rate of intermediate size shocks; the second extends from Ancona to Rimini in the Central Adriatic and is characterized by a comparatively higher occurrence rate of intermediate size earthquakes; the last area faces the northern end of the sea (the Gulf of Trieste, also known as the Gulf of Venice) and may be considered the strongest seismogenic region of the Eastern Italy.

If we restrict our attention to the most severe events, a good proportion of them seems to have occurred in the Northern Adriatic. According to the evaluation of Caputo and Faita (1982), who adopted the Ambraseys intensity scale for tsunami rating (see Karnik, 1971), 3 out of the 12 events that are classified at the topmost levels of the scale (i.e. judged to be either very strong = intensity V or disastrous = intensity VI) occurred in the northern part of the Adriatic Sea in the year 792 (or 793), in 1106 and in 1511. In this work we carry out a revision of the three events with the primary goal of providing a firm and reliable basis for the assessment of the tsunami potential of the area. Figure 1 illustrates the main geographical places that will be referred to in the paper. The study has been carried out by collecting and interpreting as many original

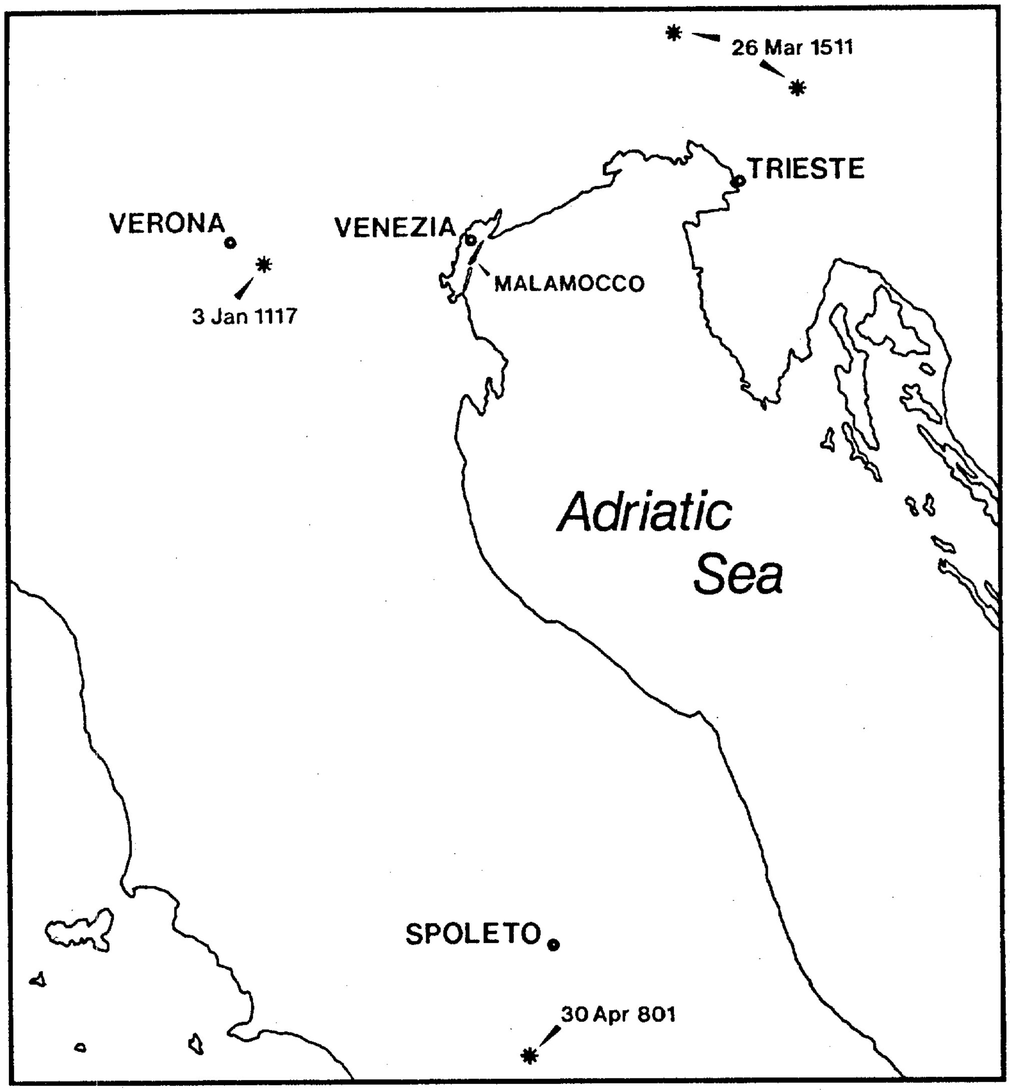

FIGURE 1 Geographic map of the Northern Adriatic Sea including the places referred to in the paper. The epicenters of the relevant earthquakes, taken from the Progetto-Finalizzato-Geodinamica seismic catalog (Postpischl, 1985) are also shown.

sources and documents as possible, according to the most rigorous requirements of the historical research. The main findings may be summarized as follows: the 792 (or 793) event is a dubious-tsunami case, the 1106 event is a clear case of misinterpretation (no tsunami did occur), the 1511 event has been overestimated.

The discrepancy with the Caputo and Faita evaluation is clear and may be explained simply by observing that the CF catalog is, as a matter of fact, an uncritical collection of past compilations, mainly performed by scholars and scientists in the last two centuries and does not face the problem of the adequate analysis of the original sources. The modern historical research has anyway shown very patently that relying on intermediate passages often leads to erroneous conclusions, since manipulation and distortion of the original information is likely to occur, as has been many times confirmed even in the course of the research carried out in assembling the catalogs of the historical earthquakes. One of the main consequences of our work is the indication that the Italian tsunami CF catalog needs revision: the work of Caputo and Faita has the unquestionable merit of being the first modern tsunami catalog for Italy, but it may be extended in time, completed with the inclusion of new events and, most important of all, enhanced by the accurate analysis of the major events, which is the aspect with the greatest impact on the studies on tsunami hazard.

REVISION OF THE 793 EVENT

In order of time the first event we take into account is located at the end of the 8th century. It is estimated at Ambraseys intensity V-VI, i.e. very strong-disastrous (Caputo and Faita,1982); in the CF catalog it is suggested that it is associated to an earthquake with its epicenter close to Verona and is supported by 5 references: 3 of them are by Italian authors and mention that an earthquake occurred in 793 without tsunami, the other 2 mention a tsunami of seismic origin in 792, without however giving any information on the generating earthquake. One of the references (Baratta, 1901) dates the earthquake 30 April 793, locating it in the area of Verona. The analysis of the original sources and of the historiographic tradition shows that no earthquake at all occurred in 792 or 793 in Italy and that the 793 Verona shock must be regarded as a typical case of the false duplication of a single event: the 30 April 801 Spoleto earthquake (see Figure 1) described unanimously by a number of early medieval sources (see e.g. Annales Heinhardi edited by Pertz, 1828 and Liber Pontificalis edited by Duchesne, 1955). The event had a great resonance in the medieval world, far superior to its actual size, since it was associated to the presence in Spoleto on 30 April 801 of the Emperor Charlemagne, who together with the Pope was reputed the highest authority in the world. The first reference to the 793 Verona earthquake is much later, being included in a monograph written by a scholar (Dalla Corte, 1596), who concentrated on the history of Verona from antiquity up to his time. However, none of the medieval chronicles regarding Verona, that contain precious information on all the facts relevant to the life of the civic community, make any mention of an earthquake in that year. Therefore Dalla Corte's work results as unreliable. His error is mainly due to a well documented transaction between Charlemagne and the Verona clergy and citizens concluded in 798, where the Emperor signed a commitment of partially supporting the reconstruction of the defensive walls encircling the city. Dalla Corte took the document arbitrarily as a clear evidence of downfall caused by a previous disaster and found that an earthquake that had occurred some time earlier could fit perfectly into his scheme. However, the ruin of the town walls finds an easier explanation in the progressive decline of Verona, also involving other prominent public constructions such as the Arena and the Roman Theater (see Saraina, 1649).

The above analysis shows that the 793 Verona earthquake is a false event. What about the tsunami? The idea of relating it to the 801 Spoleto shock is quite weak, since its epicenter was located too far from the Adriatic coasts to generate a tsunami (see Figure 1). One further possibility seems to be that of the association with a shock, ignored in the CF catalog, that is reported to have occurred in February 792 with epicentral intensity VIII (MKS) in a recent version of the Slovenian seismic catalog (see Ribarič, 1982). No contemporary medieval sources, however, make mention of this earthquake, for which the first references may be found only 900 years later in the 17th century (Valvasor, 1689). Therefore legitimate doubts arise over the occurrence of the shock. Nonetheless, even if we accepted that the earthquake did occur, both its estimated size and epicentral position would not support the generation of a strong tsunami. In consequence we may state that the 30 April 793 tsunami included in the CF catalog should be changed to an extremely dubious, certainly not strong, February 792 tsunami.

REVISION OF THE 1106 TSUNAMI

The second event we consider here is dated 1106 and is given the maximum possible Ambraseys intensity, i.e. VI, (Caputo and Faita, 1982), since it was thought to determine the catastrophic devastation of the town of Malamocco, placed on the homonymous isle separating the Lagoon of Venice from the open Adriatic Sea (see Figure 1). In the CF catalog 5 references are given in support of the event; among them the most detailed is Baratta's (1901). Our analysis of the contemporary sources, however, leads to the conclusion that no tsunamigenic earthquake took place in 1106 in the Venice lagoon. The 12th century Venetian sources (when Venice was still called Rivoalto) report that at the beginning of the century most of the coasts surrounding the lagoon were being transformed into marshy and unhealthy areas, since the shoreline was progressively receding, that the local economy was therefore rapidly declining and that a large proportion of the population was being forced to migrate into safer places (see e.g. Venetiarum Historia ... edited by Cessi and Bennato, 1964; see also Cessi, 1965) . The town of Malamocco was certainly the most affected in the lagoon: indeed, here more than in other places, the gradual shoreline recession caused damage, leading repeatedly to the inundation of the urban center (weather storms, exceptional tides) (see Sigonio, 1591); moreover, a fire, that occurred in 1106, caused the almost total destruction of the buildings, mostly made of wood, and led the people to abandon the town (Annales Venetici Breves in Simonsfeld's edition, 1883). Most moved to Chioggia in the southern lagoon, where also the bishop's residence was authorized to move in 1110 by the patriarch of Aquileia (see e.g. Novagero, 17th century and Historia Ecclesiastica in Muratori's edition, 1727). The migration took place slowly over the course of some years and the new town of Malamocco was founded on the same old site only about 1120.

In the above reconstruction of the events, scrupulously based on the original contemporary sources, there is no space for a tsunami in the Lagoon of Venice. It is, however, interesting to understand the reasons that in the following centuries gave origin to a strong tradition supporting the idea of a severe tsunami in the area. Though the roots of an erroneous historical version are generally difficult to trace back, after a thorough analysis of the pertinent historical literature we recognized that there are essentially four pieces of information that were mixed up in the story:

a) an earthquake, that is reported to have occurred in 1106 or in 1107 somewhere in Europe by some middle-age sources (see e.g. the Annales Marbacenses edited by Wilmans, 1871 or the work of Honorius Augustodunensis also edited by Wilmans, 1852);

b) the aforementioned inundations, that afflicted the coastal areas in the lagoon several times;

c) the aforementioned transfer of the episcopal seat in 1110, a fact of remarkable interest for the contemporary historiography, mainly in the hands of the ecclesiastical scholars;

d) the strong earthquake (MCS I=X-XI) with its epicenter close to Verona (see Figure 1), that in 1117 caused devastation and heavy damage in a very large area.

The last two items were erroneously associated in the north-european medieval tradition, where the Verona earthquake is described as having caused the transfer of a whole town (see the abbatial Annales of Melrose and of Coggeshale respectively edited by Pauli, 1885 and by Liebermann and Pauli, 1885). An evident mistake (maybe a simple transcription error) is then the back-dating of the Verona earthquake to the year 1107 appearing in the 15th-century work of Jacobus Malvecius (see Muratori's edition, 1729), a mistake that comes to the CF tsunami catalog through the seismic catalog compiled by Mallet (1852-1854). A crucial milestone for the onset of the wrong tradition is the work of Andrea Dandolo, a famous 14th-century historian, who erroneuously adapted the above item a) and speaks of an earthquake as having occurred in 1106 in the Lagoon of Venice, including it among the memorable events of the decade 1000-1110, in addition to the fire, the inundations and the episcopal seat transfer (see the 1938 edition of Dandolo's Chronica). Dandolo's version was the basis of most of the following historical studies on Venice and its surrounding area such as Dolfin's (15th century) and Sanudo's (16th century; see the 1884 edition) and was given much credit also by Sigonio (1591), who for the first time postulated a causative relationship between the 1106 earthquake and the inundations: this may be considered the precise point where the idea of a tsunami is introduced in the description of our story. In the following centuries the tradition progressively turned into the occurrence of a catastrophic tsunami (Baratta, 1901),

even though it never failed to be accompanied by substantial doubts and objections (Galliciolli, 1795; Zanon, 1937).
According to the foregoing analysis, we then suggest that the 1106 tsunami should be deleted from the CF catalog.

REVISION OF THE 26 MARCH 1511 TSUNAMI

The last event we put under examination is the 26 March 1511 tsunami affecting Venice as well as Trieste and the Istrian coasts. The CF catalog provides 7 references for the event, that is attributed Ambraseys intensity V-VI, very strong-disastrous (Caputo and Faita, 1982). Our analysis makes clear that the tsunami has been overestimated as regards its destructive strength on the Lagoon of Venice. Regarding the effects on the Istrian coasts, the study is not yet completed and no definite judgement may be made. The event is to be correlated to an earthquake or to a couple of close-in-time earthquakes (see Ribarič, 1979; see also Figure 1) that occurred in Friuli (and Istria) with an epicenter about 80 km from the sea and epicentral intensity I=IX-X (MCS). Although the shock was (shocks were) felt in a very extended region comprising North-East Italy, Istria, Austria and other Central European provinces, the source area is not likely to have involved the coastal regions and can have generated at most a weak tsunami in the Northern Adriatic.

One contemporary source mentions that at the time of the earthquake the water level went through abnormal agitation in Venice: the water withdrew so much that the bottom of the less deep channels could be seen (Sanudo, 16th century, 1884). The agitation is also reported in later non-Venetian sources (see Buoni, 1571), pointing out, however, that the water level rose up to the first-floor windows of the houses. Other contemporary sources (see Zaccaria and Priuli in Galliciolli, 1795), remark and describe the unusual water agitation in detail, but they date it 29 March, three days after the earthquake, ascribing it to mere meteorological perturbations. Whatever the truth, however, it is clear that the waves did not cause any victims or destruction in Venice. Moreover, even a recent historical review based on the analysis of contemporary documentation in the Trieste area failed to find any evidence of a tsunami there (Gentile et al., 1984). Therefore, the tsunami, on the occurrence of which many legitimate doubts still remain, should be given at least a lower Ambraseys intensity.

CONCLUSIONS

The main conclusion of our work is simple to summarize: we have examined the three tsunami cases that, according to Caputo and Faita (1982), catastrophically affected the coasts of the Northern Adriatic Sea and we have shown that none of them was a severe event. Our finding profoundly modifies the previous evaluation of the tsunami risk in that area and gives us a picture certainly more consistent with the seismicity: indeed the seismogenic regions surrounding the Northern Adriatic appear to have a negligible extension on the submarine crust (Mulargia et al., 1987a) and cannot be expected to generate large local tsunamis. The last consideration is that the present study shows the need to extend the critical review also to the other Italian events, so far reputed to be major tsunami cases, for a better general understanding and for a better assessment of the historical truth.

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MEMORIUM

(Sergei Sergeevich Voit (1920-1987)

by S.L. Soloviev, V.D. Larichev, B.I. Sebekin and V.V. Zmur

Professor S.S. Voit*, a well-known Soviet scientist in the field of hydrodynamics, the problem of tsunami included, died on 22nd November 1987.

S.S. Voit was born in Moscow on 12th October 1920. Upon graduating from secondary school in 1938, he entered the Mechanico-Mathematic Faculty of the Moscow University, from whence in August 1941 he was called up for military service. In 1942-1943 he was fighting at the Veronezh, Kalinin, Bryansk and Central fronts. Soon after the famous Kursk battle he was taken as prisoner, but a yer later escaped. For two months he was fighting as a member of a guerilla force and later, in 1944-1945, was a battery commander in combat army units on the territory of Hungary, Austria and Czechoslovakia.

Upon returning in 1946 to the Moscow University, S.S. Voit graduated in 1948 and started on his post-graduate studies at the University's Institute of Mechanics. In 1951 he completed his post-graduate course and supported a candidate's thesis.

In 1951-1963, S.S. Voit was working at the Marine Hydrophysical Institute, USSR Academy of Sciences, then in Moscow. In 1961-1963 he was Deputy Director of the Institute.

In 1963 he joined the Moscow Physico-Technical Institute, where he later organized the Chair of Ocean Thermohydrodynamics. In 1964 S.S. Voit supported his doctor's thesis and was granted professorship at the Institute. From 1965 he simultaneously started working at the Institute of Oceanology, USSR Academy of Sciences.

The author of more than a hundred scientific papers, combining in his work a far-reaching practical tendency of research and a profound mathematical culture, S.S. Voit was a representative of the classical school of Russian hydromechanics, continuing the traditions of S.A. Chaplygin, M.E. Kochin, and L.N. Sretenskiy. S.S. Voit's theoretical investigations on different problems of marine hydrodynamics are universally known. He has made a fundamental contribution to the formulation and solution of the problem of the effect of the Coriolis force on the dynamics of ocean waves, S.S. Voit was one of the first to have investigated much more complicated transient wave processes in the oceans. In this field he offered a far-reaching analysis of diverse and practically important phenomena, such as the effect of seafloor topography on sea waves, the exitation of waves due to travelling atmospheric perturbations, generation of internal waves, propagation of tsunami waves, run-up of transient waves onto the shelf, reflection and diffraction of waves, etc. S.S. Voit was the first to have discovered and studied the specific edge waves generated by the Earth's rotation, later termed double Kelvin waves. The results of these investigations are found to be directly related to the materials of oceanographic observations.

A subtle and profound theoretician, S.S. Voit showed great interest for observations in the ocean and took part in numerous sea expeditions.

On the 14th cruise of the research vessel "Mikhail Lomonosov" S.S. Voit elaborated and supervised a large-scale program of hydrological observations which made it possible to determine the main hydrophysical characteristics of the Lomonosov current. For these investigations S.S. Voit and his colleagues were granted in 1970 the State Award of the USSR.

S.S. Voit did a great deal on the problem of tsunami. Jointly with his collaborators he formulated and studied the problem of the excitation of tsunami waves by horizontal mass forces at the source, thereby providing an explanation for the usually observed well-defined directivity of tsunami radiation, was searching for general analytical solutions to the problems of tsunami excitation by different processes, was studying microseisms produces by propagating strong tsunami waves, etc.

S.S. Voit's work was well-known in other countries and he had numerous friends outside the USSR: in the FRG, Canada, USA, Australia, etc. S.S. Voit was many times invited to other countries to take part in conferences and for lecturing, carried on a vast scientific-organizational work, being a member of a number of international scientific committees. In 1979 he was elected Vice-President of the Commission on Tsunami, International Union of Geodesy and Geophysics.

Prof. S.S. Voit combined scientific research work with extensive teaching activities. The chair set up and headed by him at the Moscow Physico-Technical Institute trained during its existence more than 200 highly-qualified oceanographers who are successfully contributing today to the various fields of ocean research, principally at the institutes of the USSR Academy of Sciences and the USSR's Hydrometeoservice, many of them under S.S. Voit's direct leadership being granted degrees of candidates and doctors of science.

A genuine Russian intellectual, Sergei Sergeevich Voit won universal respect by his kindness, responsiveness, honesty and integrity. Contact with him, a man of lofty civic virtues, an outstanding scientist and wonderful pedagogue, will not be forgotten by his colleagues, friends and collaborators.

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Note: Abbreviations and Russian spelling of journals.

AMM - Applied Mathematics and Mechanics (Prikladnaya Matematika i Mekhanika), Moscow.
AMS - Achievements of mathematical sciences (Uspekhi Matematicheskikh Nauk), Moscow.
CMHI - Contributions of the Marine Hydrophysical Institute (Trudy Morskogo Gidrofisicheskogo Instituta), Moscow-Sevastopol'.
Oc - Oceanology (Okeanologiya), Moscow.
PhAO - Proceedings of the Academy of Sciences of the USSR. Physics of the Atmosphere and of the Ocean series (Izvestiya Akademii Nauk SSSR, Seriya Fiziki Atmosfery i Okeana) Moscow.
RAS - Reports of the Academy of Sciences of the USSR (Doklady Akademii Nauk SSSR), Moscow.

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