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PHYSICAL AND BIOLOGICAL EFFECTS

CANNIKIN

OCTOBER 1973

UNITED STATES ATOMIC ENERGY COMMISSION
NEVADA OPERATIONS OFFICE
Las Vegas, Nevada

NOTICE

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NVO-123
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CHAPTER 1

INTRODUCTION AND HISTORY

1.1 INTRODUCTION

The Cannikin event of November 6, 1971, was a nuclear test of less than five megatons (Mt) yield,* and was detonated at a depth of 5875 feet (1790 meters) on Amchitka Island, Alaska, in the western part of the Aleutian chain. The primary purpose of the event was to proof-test the Spartan warhead for use in the Safeguard ABM system. The physical and biological effects of the test therefore, although important, were of secondary concern.

The results of two previous underground nuclear detonations on Amchitka Island and five large underground detonations at the Nevada Test Site (NTS) were used to form the basis for predictions of the effects of the Cannikin event. Allowances were made for the obvious differences in the seismic and biological settings of NTS and the Aleutian Islands in preparing the predictions.

Shots detonated at Amchitka and NTS were as follows:

Event	Detonation Date	Depth Feet	(Meters)	Yield
	AMCHITKA			
Long Shot	November 29, 1965	2300	(700)	80 Kt
Milrow	October 2, 1969	4000	(1220)	∿1 Mt
	NTS			
Greeley	December 20, 1966	3985	(1215)	825 Kt
Boxcar	April 26, 1968	3800	(1160)	1.2 Mt
Benham	December 19, 1968	4600	(1400)	1.1 Mt
Jorum	September 16, 1969	3800	(1160)	< 1 Mt
Handley	March 26, 1970	3960	(1207)	> 1 Mt

1.2 HISTORY

Amchitka, part of the Rat Island Group of the Aleutian Islands, at Latitude 51.5^{o}N and Longitude 179^{o}E, is located 1340 miles (2160 kilometers) west-southwest of Anchorage and 2500 miles (4000 kilometers) west-northwest of Seattle (see Figures 1 and 2). The Aleutian Island chain is of volcanic origin and the region is seismically very active. Amchitka itself has no volcanoes and has had none since Tertiary times (Carr, et al., 1971, p. 701). Like other Aleutian Islands, Amchitka has a rugged coastline, subject to very active erosion

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*The exact yield is classified, but it is not necessary for the purposes of this report.

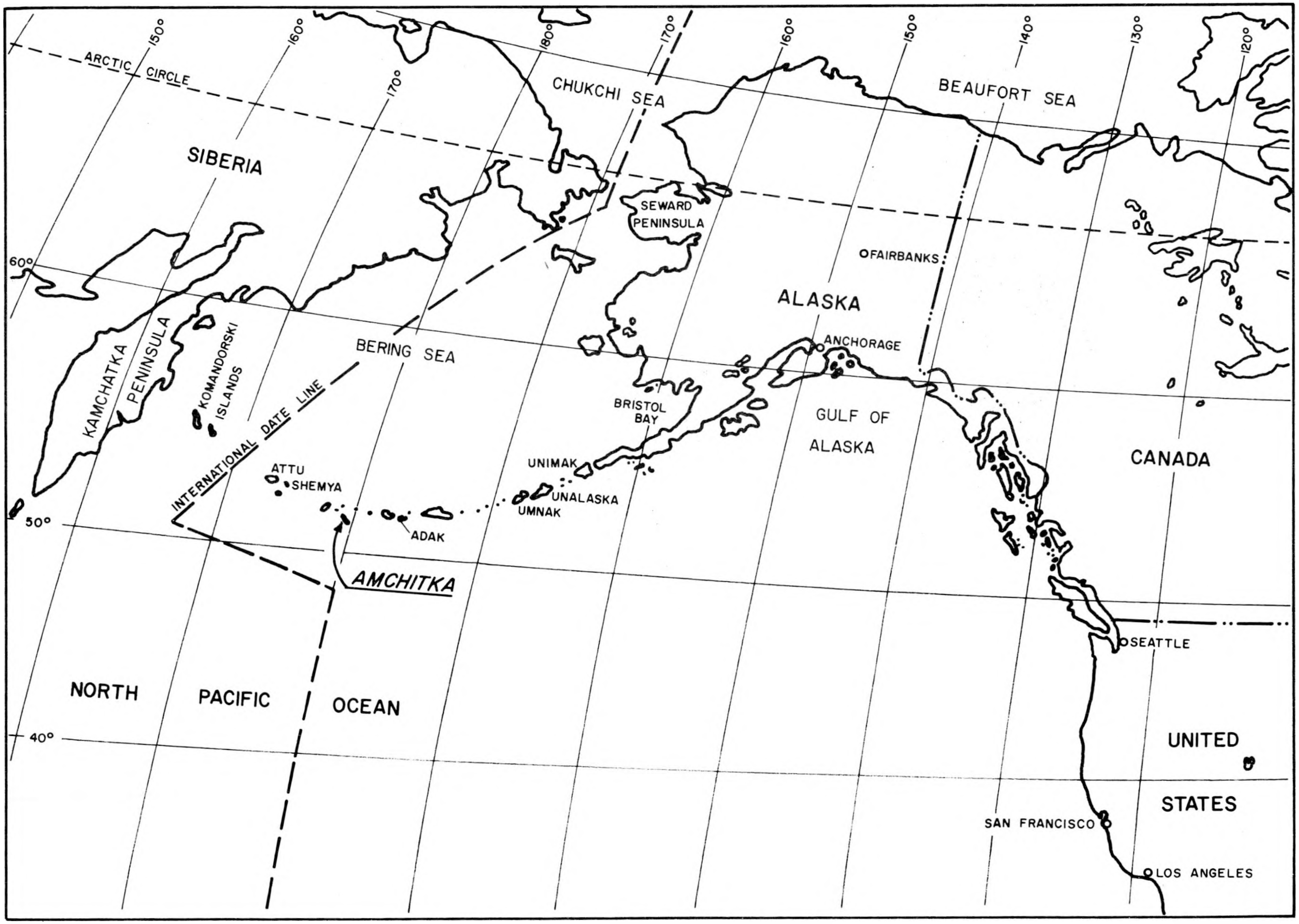

FIGURE 1. The area of interest.

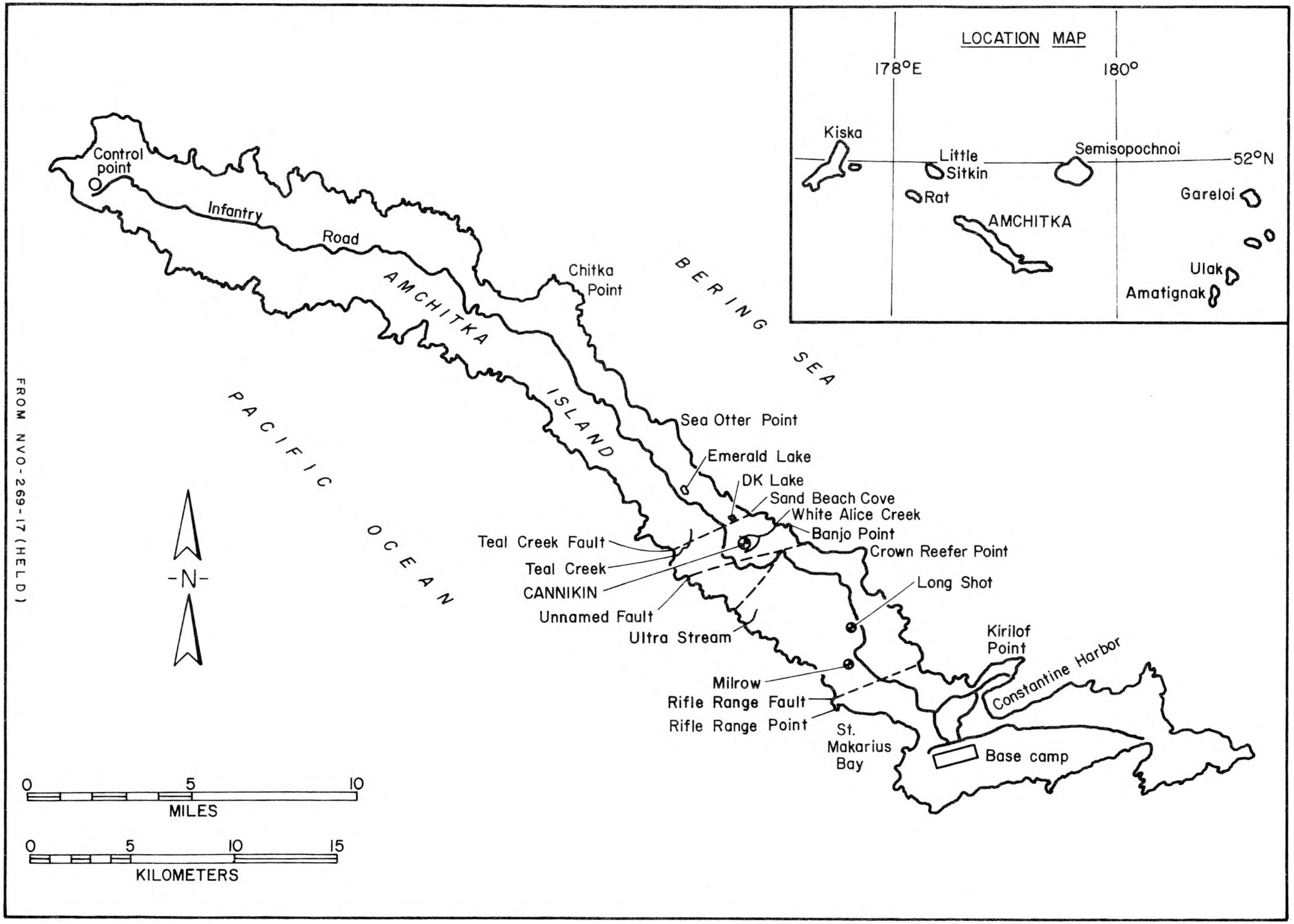

FIGURE 2. Map of Amchitka Island.

by frost action and by the stormy waters of the region. The Aleutians are foggy, rainy, and windswept much of the time; the climate is temperate with a record high of +65°F and a low of +13°F (Armstrong, 1971). Sea ice is practically never seen and there is no permafrost. Amchitka is covered by grass and moss and dotted with many ponds and lakes in its lower elevations, but is nearly bare on exposed portions of the mountainous west end. Large numbers of birds are seen in the rocky cliffs at some seasons of the year, and the surrounding ocean waters are rich in marine life.

The Island was first inhabited more than 2500 years ago (Desautels et al., 1970), by paleo-Aleuts from the east (Laughlin, 1967) and there are numerous coastline middens that date from their occupation. It was visited and taken over by Russians following Bering's discovery of the Aleutians in 1741, and probably had a resident population of several hundred at that time. Lütke lists only 42 residents in 1825, and Veniaminov no longer lists Amchitka as inhabited in 1834 (and, in fact, reports only 1484 Aleuts anywhere) (Hrdlicka, 1945). Jones (1971) reports that the last permanent settlement on Amchitka was abandoned in 1849. Since 1849, Amchitka has had no permanent population, only occasional visitors such as Aleuts after sea game or trapping foxes (there is a gravestone of an Atka woman there yet, dated 1930).

The Russians, and after 1867, the Americans, exploited the area for sea otter furs, to the near extinction of this animal, hunting finally being stopped by international treaty in 1911. Blue fox farming was introduced in 1921. These foxes are said to have wiped out breeding populations of the Aleutian Canada Goose (Kenyon, 1961) and were themselves eliminated only with difficulty in the 1950s (Berns, 1960).

In June 1942, the Japanese bombed Dutch Harbor, and landed troops on Attu and Kiska, evacuating the 39 Attu Aleuts to Hokkaido (Garfield, 1969). In the ensuing U.S. military buildup, Amchitka became the western outpost, a fighter and bomber base for use against the Japanese-held islands. Over 10,000 troops were on the Island at one time, the last of whom did not leave until 1951. Most of the presently existing roads, airstrips, and harbor facilities on the Island are rebuilt World War II installations.

Amchitka was considered for nuclear cratering tests in 1951, but was rejected because of inadequate soil cover as well as the expense of operating such a remote site. Those proposed tests were scaled down and became the Jangle underground and Jangle surface series at NTS in November 1951.

Amchitka was the site of the Long Shot nuclear detonation of 1965. This shot was fired as part of the Department of Defense's (DOD's) program on detection of nuclear tests to determine travel times and location accuracies of natural and man-made seismic sources near island arcs and oceanic trenches. The Long Shot technical program was primarily carried out by distant observations, but it also included on-Island measurements of ground shock and water pressures and some biological observations (Day and Murrell, 1967; Seymour and Nakatani, 1967).

In 1966, it appeared that the DOD would soon ask the Atomic Energy Commission (AEC) to design nuclear explosives of yields larger than could be safely tested at NTS; the limitation there being ground motion and its effect on high-rise buildings in Las Vegas. The AEC's Nevada Operations Office (NV), assisted by its contractors and the weapons laboratories, began to look for supplemental test sites. The basic criteria were that the sites have geological properties suitable for the proposed tests and for containment of resulting radioactivity, that the sites be sufficiently remote to give reasonable assurance of safety, and (later) that the sites be U.S. territory. After screening, three sites remained that were considered possibly satisfactory; these were (1) northwest of the Brooks Range in Alaska, near Cape Beaufort; (2) central Nevada, north of the existing NTS; and (3) Amchitka Island.

At Cape Beaufort, it appeared that the principal problem would be ecological; for instance, important caribou calving grounds were nearby. In addition, it would be extremely costly to operate in an area that would have to be supplied largely by air. Therefore, little was done there other than reconnaissance.

Of the two remaining sites, each had its own problems. The Central Nevada Test Area, as it is now called, is about equidistant from Las Vegas, Reno, and Salt Lake City. Its limitation on use was the ground motion effects on high-rise buildings in those cities and on less vulnerable buildings in closer towns and ranches. Amchitka needed careful review along biological and seismic lines, but it also had the great advantage of remoteness from human populations, all-season ports, and repairable facilities and roads left from World War II.

The decision was made to explore the Central Nevada area and Amchitka simultaneously, and exploratory drilling started in Nevada in 1966 and on Amchitka in May 1967. At Amchitka, biological studies were started in mid-1967 and seismic studies in mid-1969. Geological studies had started before Long Shot. Calibration shots were planned for both sites. The Faultless event at the Central Nevada site was detonated on January 19, 1968. The Milrow event, detonated on October 2, 1969, was a calibration shot at Amchitka.

The intent of a "calibration shot" is to produce a data base for extrapolation and prediction of what a larger shot will do: Milrow was to produce additional information on whether it would be safe to fire Cannikin. Areas of concern associated with the use of this island as a test site were effects on wildlife and ecology, the seismic response of a region of high natural seismicity, and the possibility of a damaging tsunami such as had been generated by earthquakes in the eastern part of the Aleutian chain. In addition, the National Environmental Policy Act (NEPA) of 1969 (PL 91-190) became law on January 1, 1970, and became effective on April 30, 1970, when the Council of Environmental Quality issued preliminary guidelines on the preparation of Environmental Impact Statements as required in Section 102 of that act. Results from background biological, geological, hydrological, and seismic studies and from the Milrow shot were used in the preparation of Environmental Statements for Cannikin (AEC, 1970, 1971a).

Milrow produced no surprises. The measured ground shock fit into Nevada patterns. Fault displacement and induced seismicity were distinctly less than in Nevada. Although there was no apparent radioactive leakage after Milrow, low levels of tritium had appeared in nearby ponds some months after detonation of Long Shot (Fenske, 1970). This, too, however, fit the Nevada experience, which indicates that large shots contain radioactivity better than the small shots. Biologically, the effects were drainage of two lakes, numerous tears and cracks in nearby tundra, and partial kill of stickleback in two lakes. There were no discernible effects on other fish, sea otter, or other fauna (Kirkwood, 1970). Also, there were no tsunami waves detected at all (Kirkwood, 1970; Merritt, 1970; Olsen et al., 1972).

Extrapolation of Milrow effects to the Cannikin yield was made; ground shock by well-known scaling rules, containment by careful design and due care, and biological effects according to the predicted increased radius of ground shock. No problem with radioactivity was envisaged.

The estimate of seismic and tsunami risk was less satisfactory because of the possibility of threshold effects. There were few aftershocks after Milrow, and all were shallow focus events. None were associated with the major thrust fault known to underlie the Aleutians. Therefore, there was no real likelihood that Cannikin aftershocks would generate a response either.

The February 3, 1965, Rat Island earthquake was the largest well-documented earthquake on record near Amchitka (von Hake and Cloud, 1966). It had no serious consequences to any point of habitation either from ground shock or water waves. In addition, there is historical evidence and geophysical reasons why an earthquake in this region would not generate a damaging tsunami. This assurance did not satisfy the whole public, and the matter was taken as far as the Supreme Court on the issue of compliance with the NEPA. A plea for an injunction was heard and was rejected by a narrow margin by the Court on the morning that Cannikin was detonated.

Documentation of the environmental aspects of the Cannikin shot was secondary to the measurement of the yield and technical performance of the warhead. Cannikin was not a calibration shot for some future larger test, although had it not been successful, another test might have become necessary. Nevertheless, it was important to make as detailed an examination of its effects as had been made on Milrow to assure that the public had indeed been safeguarded; to better understand the phenomenology of underground explosions; to provide a foundation for responses to inquiries from official investigating bodies, for defending legal actions, for dealing with political pressures, or for responding to any claims for damage that may occur; and, although the decision to have such a program had already been made, to meet the prediction requirements of the NEPA.

The principal matters of concern for the Cannikin technical program were containment of radioactivity, effects on the local ecology, and the possibility of triggering a large earthquake and generating a damaging tsunami. Results of the program to consider these questions are given in the succeeding chapters.

CHAPTER 2

SURFACE PHENOMENA

2.1 SHOT TIME EFFECTS

At the time Cannikin was fired, the people nearest the detonation point were the 241 people at the Control Point at the northwest end of Amchitka, 23 miles away. In addition, there were project and Navy ships, and a plane circling surface ground zero (SGZ) ready to take pictures. The nearest nonproject people were the crew of a fishing vessel out of Seattle that had taken refuge from the previous day's storm in a cove on the east side of Semisopochnoi Island 35 miles to the northeast. Those at the Control Point felt a long, gentle ground roll that lasted half a minute and that was later found to have had a peak acceleration of .09 g. Closed circuit TV monitors of the SGZ area showed dust, water, and debris thrown into the air.

Aerial photography conditions were minimal due to general cloudiness. Figure 3 was taken from a plane four nautical miles (4.5 statute miles or 7.4 km)* to the northeast of SGZ by EG&G, Inc., photographers. The phenomena visible are those seen earlier on Long Shot and Milrow; a quick-spreading dark ring on the ocean as the shock wave reaches the surface, followed by all ponds and much of the surrounding sea turning white and frothy as seen in this photograph. Streams show as white lines where their banks squeezed the water out and up. Some spouts or geysers are also to be seen in these pictures, but not as many as were seen at Milrow. Other pictures show a number of spouts in the ocean at the right edge of this view, approximately on the seaward extension of Teal Creek Fault (see map, Figure 2).

Pictures taken from unmanned surface stations by Pan American show some of these phenomena more clearly. For instance, cameras at a station 1.3 km (0.8 mi.) northwest of SGZ recorded what happened at DK Lake, an extensive study lake in the biology program (see map, Figure 30), and a lake in which a pressure record was taken (Figure 4). Another camera overlooking Square Bay 6.5 km (4 mi.) east-southeast showed the middle part of a small sea stack breaking out making two sea stacks.

Even before foot and vehicle traffic was allowed in the vicinity of the SGZ, overflights by helicopter were made. Figures 5 and 6 compare what those on such flights saw at SGZ with what was to be seen two days before the shot. Most of the buildings that Figure 5 shows present two days before the shot had been removed preshot, but what had been left was strewn about. A notable exception was the cable reel building, which looks unscathed in Figure 6, though later

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*Data herein are given as reported, then converted to metric or English units, as appropriate.

FIGURE 3. Surface ground zero and the region east of it at 2.4 sec. Plane was at 24,000 ft. on an azimuth of 55°, (EG&G photo, 70 mm format, 150 mm lens, 20 frames per sec.)

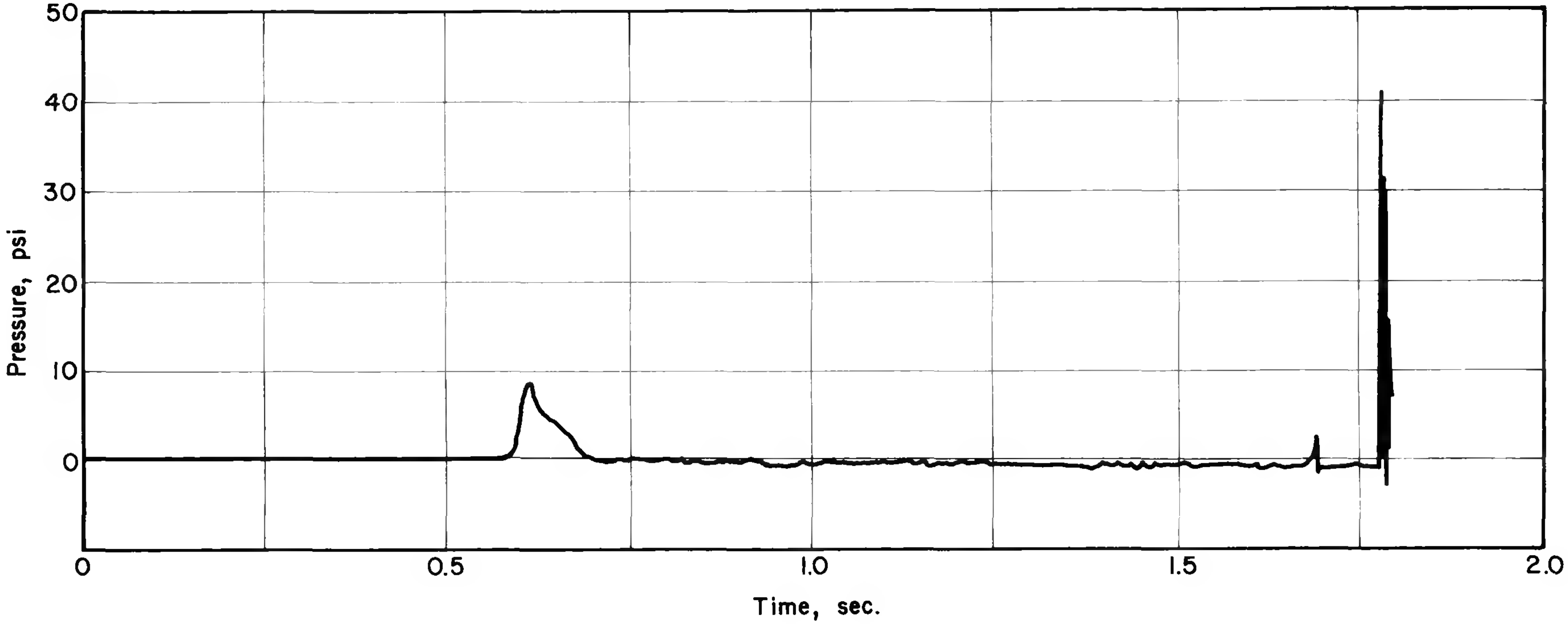

FIGURE 4. Pressure measured in Lake DK. (Merritt, 1972 b)

FIGURE 5. Surface ground zero and recording trailer park on Nov. 4 (D–2) (BMI photo 2A38)

FIGURE 6. Surface ground zero and recording trailer park on Nov. 7 (D+1) (BMI photo 2B17)

inspection indicated that all roof trusses had been bent. The trailers in the distance were those in which measurements of weapon performance were made; they were well shock mounted and survived. Ground motion at SGZ had a peak acceleration of 36 g, and a peak transient displacement of 25 feet (7.7 m); the trailers experienced a peak acceleration of 21 g (Perret, 1972; Jackson, 1973).

2.2 SURFACE DISRUPTION

Figure 6 also shows some cracks in the tundra, notably two just below the SGZ area, and the path followed by water released when the dikes broke around two mud pits to the left of the SGZ area. To the right, the north fork of White Alice Creek appears to be accumulating water in a newly formed lake.

More striking than this was the magnitude of disruption along the Bering Sea coast to the north. There were numerous rockfalls in a 2 km (1.2 mi.) stretch between Teal Creek Fault and Banjo Point. The bedrock of these cliffs was breccia of the Banjo Point formation, and this had been a singularly rocky region even for Amchitka. The rockfall area coincides with an interval of obvious uplift of the marine intertidal bench. Virtually all the sea stacks and cliffs in this area were damaged, the greatest damage being on promontories along the Bering coast. Turf slips and slides were more characteristic west of Teal Creek Fault and east of Banjo Point, where the outcrops are composed of the softer Chitka Point formation (Carr and Quinlivan, 1967; Morris and Snyder, 1972).

Two views of this disruption are shown in Figures 7 and 8. Figure 7 was taken across Sand Beach Cove, where Teal Creek Fault meets the sea and where the Banjo Point formation in the background gives way to the Chitka Point formation. In the immediate foreground of the picture is a turf slide that had avalanched out onto the sand, resembling snow or mud slides in form. This particular slide came down from a minor drainage indentation in the formerly grass-covered slope, and it is probable that the additional lubrication of that water made this slide larger than other nearby ones. In the middle foreground is the remains of a sand boil, which when first reached on foot four days after the shot was about 6 m (20 ft.) in diameter at the lip and about 1.2 m (4 ft.) high. The aerial motion pictures taken at shot time show a water spout higher than the adjacent sea cliffs, which are about 45 m (150 ft.) high, and it is believed that the boil is the remaining visible evidence of that spout. By late February 1972, tidal action had erased all signs of the sand boil and was eroding the face of the slide shown in Figure 7. Figure 8 is another picture taken in the middle of the area of worst damage. In this picture, the uplift of the marine intertidal bench is quite evident.

Beyond the region of worst damage, turf slides dominate, decreasing in number and magnitude as the distance from SGZ increases. The Pacific shore is a more precipitous one; damage there consisted of

FIGURE 7. View eastward across Sand Beach Cove, showing rock falls, turf slides, and a sand boil. (Photo: Merrell, NMFS, 20B2)

FIGURE 8. Cliff falls and uplifted tidal bench in the middle of the uplift area. (Photo: Merrell, NMFS, 20B1)

intermittent falls of the turf that normally grows down over the edges of the sea cliffs. The consequences of these changes to the Island biota will be discussed in Chapter 6.

The amount and extent of these rockfalls and turf slides were more than predicted. There had been predicted a "volume of displaced material . . . for the Bering coast . . . on the order of 2900 cubic yards (2200 m^3), when all the potential individual rockfalls and turf slides are combined; a similar estimate for the Pacific coast totals approximately 4100 cubic yards (3100 m^3)," (Kirkwood and Fuller, 1971, p. 7). Postshot comparable estimates are 25,000 m^3 (32,700 yds.^{3}) and 2,000 m^3 (2,616 yds.^{3}), for the Bering and Pacific coasts, respectively (Everett, Ohio State University, as quoted in Kirkwood and Fuller, 1972, p. 53-4). The measured ground motion at Sand Beach Cove was 10 g vertically and 4 g horizontally (Perret, 1972).

There had been some concern before Cannikin over an archaeological site about where the Unnamed Fault intersects the Pacific coast (Figure 2). This site consisted of a long string of occupation zones already being eroded away by natural forces, as a continuous trickle of midden materials onto the beach below testified. To recover some of the values that might be lost, archaeologists from the University of Alaska excavated some 92 m^2 (990 ft.^{2}) of the site, uncovering among other things a complete house site, the first such complete site in the western Aleutians (Cook, et al., 1972). However, the shock-induced loss was less than feared; an area of 45 m^2 (484 ft.^{2}) was lost by cliff fallout of 820 m^2 (8215 ft.^{2}) of site in the portion of the site at risk (Merritt, 1972a). In addition, there was cracking in the face of some other sites. Figure 9 shows such a crack in the site nearest SGZ, a site 2.7 km (8800 ft.) east on the Bering coast.

Some cracks, faults and other permanent displacements of the land surface near SGZ were caused by the shot-time ground motion; these were greatly increased by collapse of the explosion cavity 38 hours after the shot and consequent subsidence of the ground surface. Fortunately, good photographic documentation by the Battelle Memorial Institute (BMI) and by EG&G, Inc., is available of this area before the shot, after the shot but before collapse, and after collapse. Geologists were able to make detailed surveys on foot after collapse, and between that and interpretation of the photographic records have produced the crack and fault map of Figure 10. In this figure, the light lines refer to those effects present before collapse, and the heavy lines to the additional effects caused by collapse.

Before collapse, the principal cracks were movements on Teal Creek Fault, 1.1 km (0.7 mi.) northwest of SGZ, on the Unnamed Fault 760 m (2500 ft.) south of SGZ, and two northwest-trending fractures less than 200 m (660 ft.) northeast of SGZ (the latter two are in the foreground of Figure 6). After collapse, many more cracks and faults appeared, mostly down dropped towards SGZ. The largest of these breaks was along the north fork of White Alice Creek, showing 2.9 m

FIGURE 9. Crack in the grass-covered slope at archaeological site 67. (Author's photo)

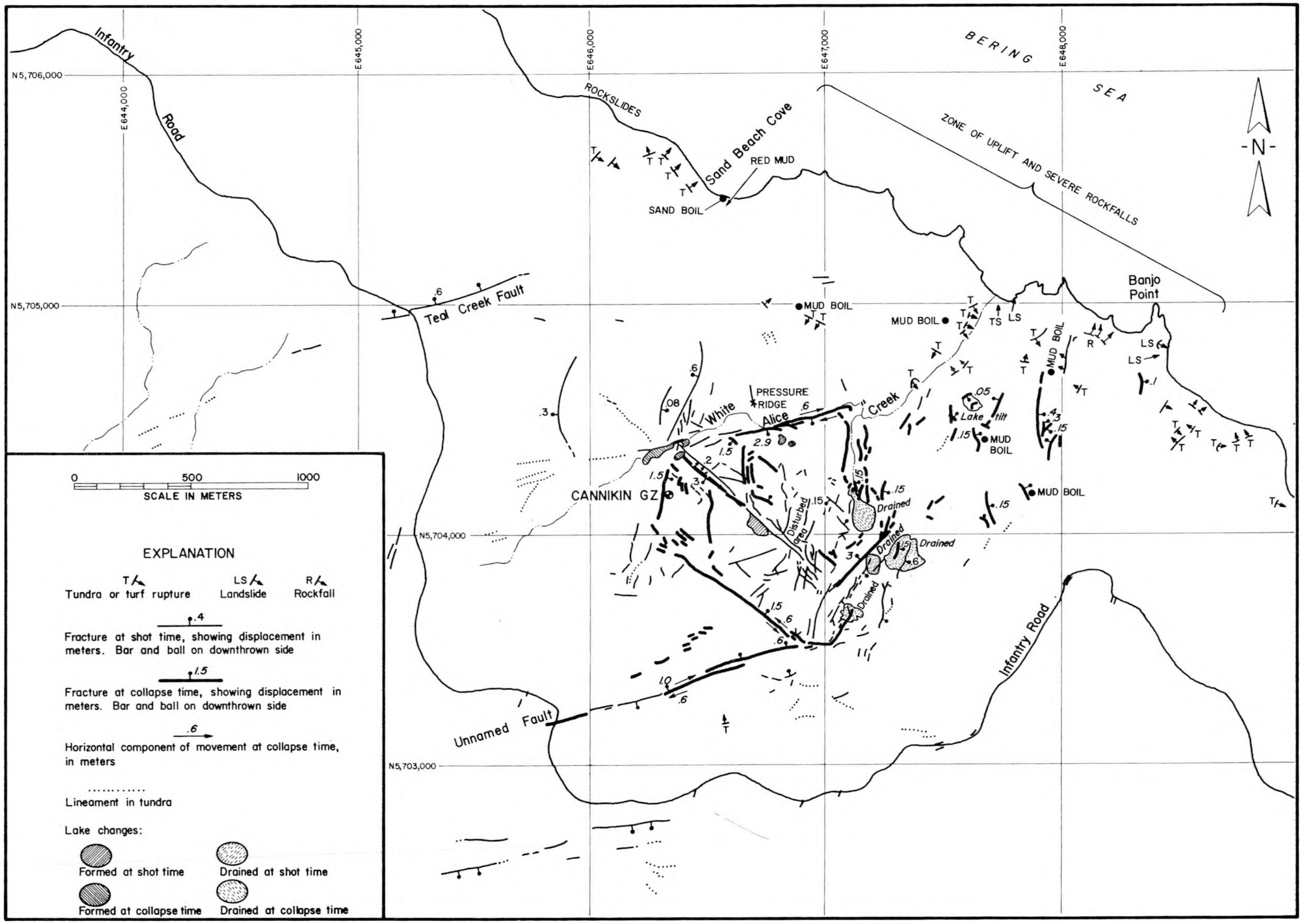

FIGURE 10. Cracks and fault movements near surface ground zero (USGS 474-148)

(9.5 ft.) vertical displacement at one point and 0.6 m (2 ft.) of lateral movement. This White Alice fracture would itself have dammed the creek even if the general subsidence had not lowered the stream bed above that point and effectively dammed it. Subsidence also greatly increased the length of fracturing on the Unnamed Fault south of SGZ. Generally speaking, these fractures follow the trace of pre-shot lineaments and creeks. They extend laterally to shorter distances than experienced in Nevada. The thick turf in some places is several feet thick which undoubtedly obscured other smaller cracks and movements.

A group of postcollapse fractures, generally trending north to northeast a kilometer east of SGZ, cut through a number of ponds with turf bottoms, and water in them drained out. New lakes were formed. To the north of SGZ (to the right in Figure 6), the north fork of White Alice Creek was dammed by ground movement and by movement of a spoil pile, forming a small lake before collapse and a bigger one afterwards. The general subsidence about SGZ left the White Alice Creek drainage area without an outlet to the sea, but the small lakes shown to the east of SGZ in Figure 10 remained about the same size for nearly a year. During that time, it is presumed that rain falling in the drainage area went underground. In October and November, 1972, this basin filled, forming a new lake called Cannikin Lake. This new lake is 40 acres in area and 8 m (25 ft.) deep, and is now one of the dominant features of the Island (Figure 22).

Out under the sea, diver-biologists from the National Marine Fisheries Service (NMFS) have seen rock spalled from the steep sides of underwater cliffs and pinnacles. These underwater breaks are particularly evident because they show clean surfaces lacking the otherwise ubiquitous cover of algae and benthonic invertebrates. Blocks as large as 3 m (10 ft.) in diameter have been displaced several meters from their original positions (Barr, NMFS, priv. comm.). The continuity of these features with on-shore features has not yet been determined.

2.3 UPLIFT AND SUBSIDENCE MEASUREMENTS

Level line surveys were made by Holmes & Narver, Inc., surveyors along several lines as shown in Figure 11. Three lines were run lengthwise to the Island, one along Infantry Road up the center of the Island and one along each of the coasts. Profiles of the net upward or downward movements along these lines are shown in Figure 12, projected onto the dashed lines in Figure 11 in order not to distort distances. The top profile shows uplift along the Bering coast of as much as a meter (3.3 ft.): this uplift is very evident to the eye, particularly with the broken off stipes of kelp floating in the surge channels and white, dead coralline algae on the newly exposed sides of the blocks that used to constitute the intertidal bench. The greatest uplift is at the west end of the damaged area, at the Teal Creek Fault. Surveys indicate that the movement radially outward was just as large, i.e., one meter. The uplift decreases eastward with a

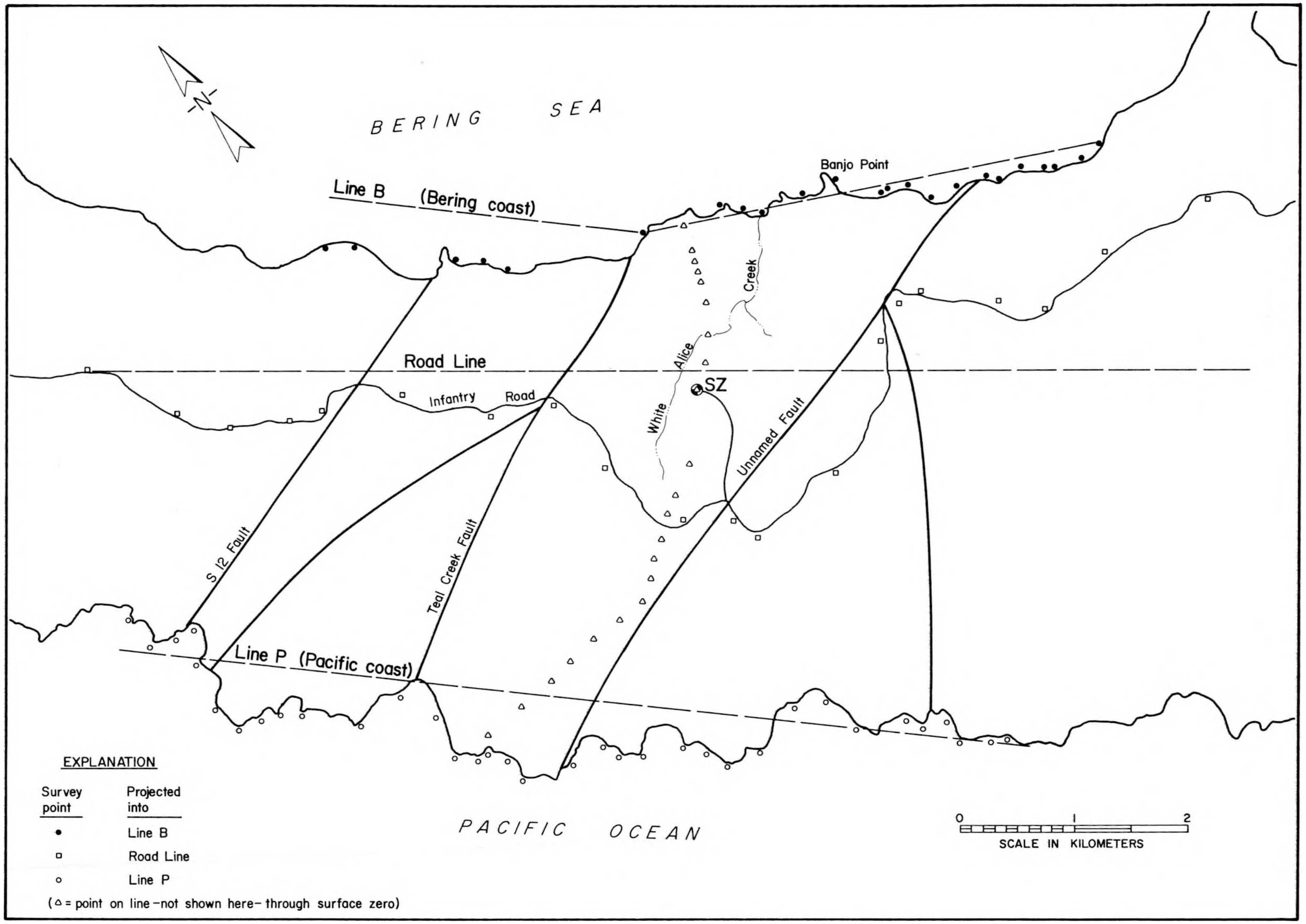

FIGURE 11. Locations of level-line surveys. (H&N)

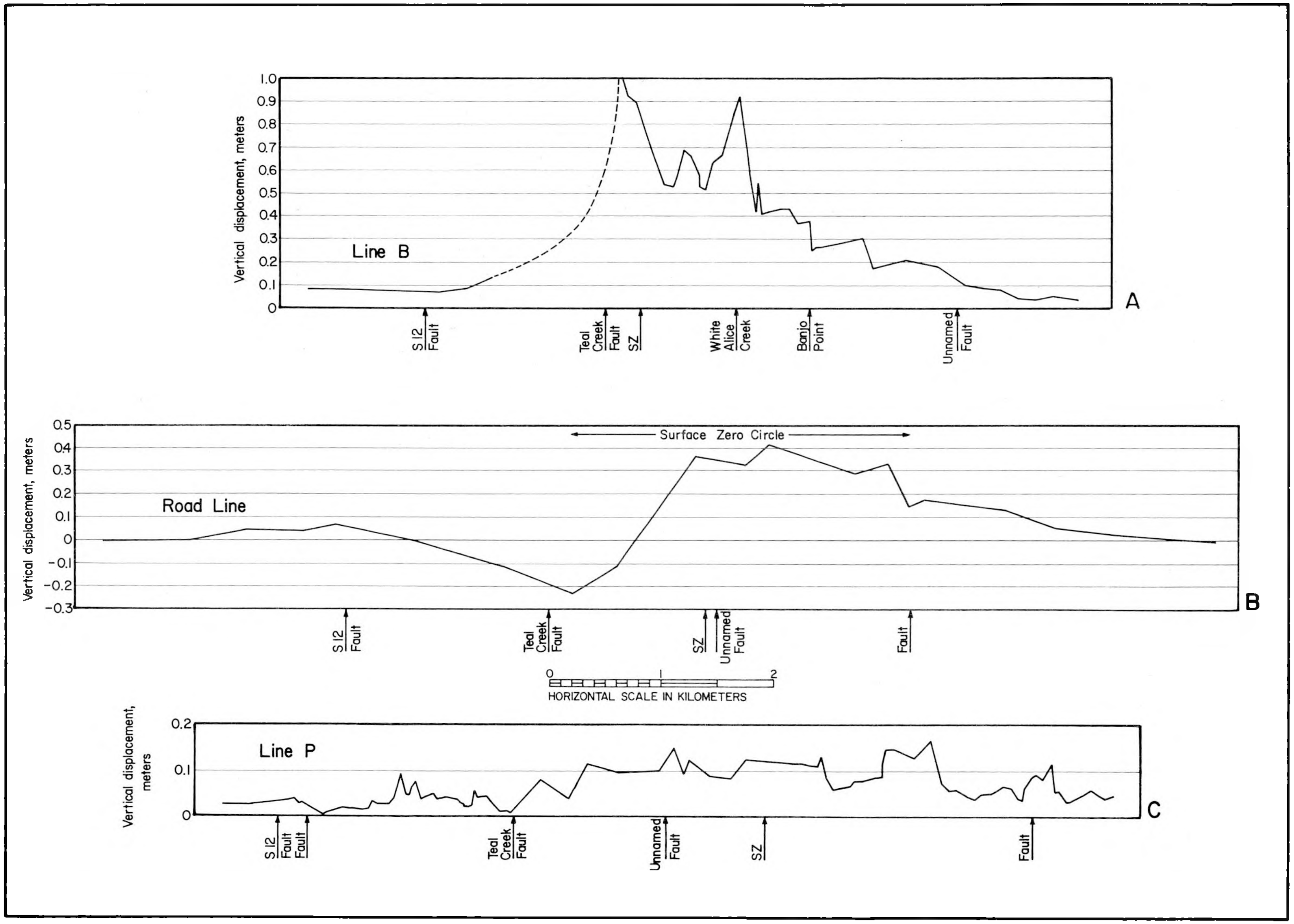

FIGURE 12. Vertical displacements resulting from Cannikin. (H&N)

secondary maximum just east of the outlet of White Alice Creek, as if the block had been hinged somewhere east of Banjo Point. Figure 12a does not show what happened just beyond the west end of the uplift--all preshot survey markers for a distance of 1.5 km (4920 ft.) were buried under turf slides, but the visual impression is that the uplift drops quickly to very little, hence, the dashed line shown. The profile of elevation changes down the center of the Island (Figure 12b) is deceptive in that the road makes a wide sweep around SGZ, nowhere approaching it closer than 1.1 km (3600 ft.). These uplifts, though closer to SGZ than those on the Bering coast, are smaller. On the Pacific coast, uplifts were so small that the scale in Figure 12c had to be twice that of Figure 12a and b to show them at all. There the maximum uplift was 17 cm (6.5 in.).

Two cross-Island lines were also surveyed. Elevation changes on the cross-Island line 1.5 km (4920 ft.) west of SGZ were small (maximum 6.1 cm or 2.4 in.) and are not included here. Only one point on the line through SGZ itself shows the expected large negative net displacement that one expects from cavity subsidence, and there the net subsidence is 5 m (16 ft.) from its preshot elevation. Almost all other measurements along this survey line are positive.

The U.S. Geological Survey (USGS) is in the process of analyzing these uplifts and subsidences. A postcollapse contour map of the area near SGZ and another of elevation changes are reproduced as Figures 13 and 14 (Morris, 1973). The maximum subsidence is 400 m (1300 ft.) east-southeast of SGZ, and is about 40 feet (12 m) below its preshot elevation. A secondary low of -20 feet (6 m) occurs on the entrance road 600 m (2000 ft.) south of SGZ. The subsidence is far from symmetric, as might perhaps be expected from the inhomogeneous nature of the underlying rock, not nearly as regular as the Milrow subsidence. Maximum permanent uplifts were in the order of 5 m (16 ft.), 850 m (2800 ft.) to the northeast, and 1200 m (3900 ft.) to the south of SGZ. Cannikin Lake is at 114 feet (35 m) elevation.

2.4 SUMMARY

Cliff damage and uplift were considerably larger than expected in a 2 km (1.2 mi.) stretch of Bering coast. The damage consisted of rockfalls and turf slides. Permanent uplift and radial outward movement were as much as one meter.

The uplift and subsidence area near SGZ was very irregular. The greatest subsidence was southeast of SGZ. Around it, the subsidence and associated faulting have left an enclosed basin that has filled to create a new lake, Cannikin Lake.

Cracks and faultlike displacements are common out to 1.3 km (4250 ft.) from SGZ, but overall were shorter than is seen in Nevada. Some of these were direct shot-related features; more were associated with collapse. The largest displacement seen was 2.9 m (9.5 ft.) on a collapse-caused fault north of SGZ.

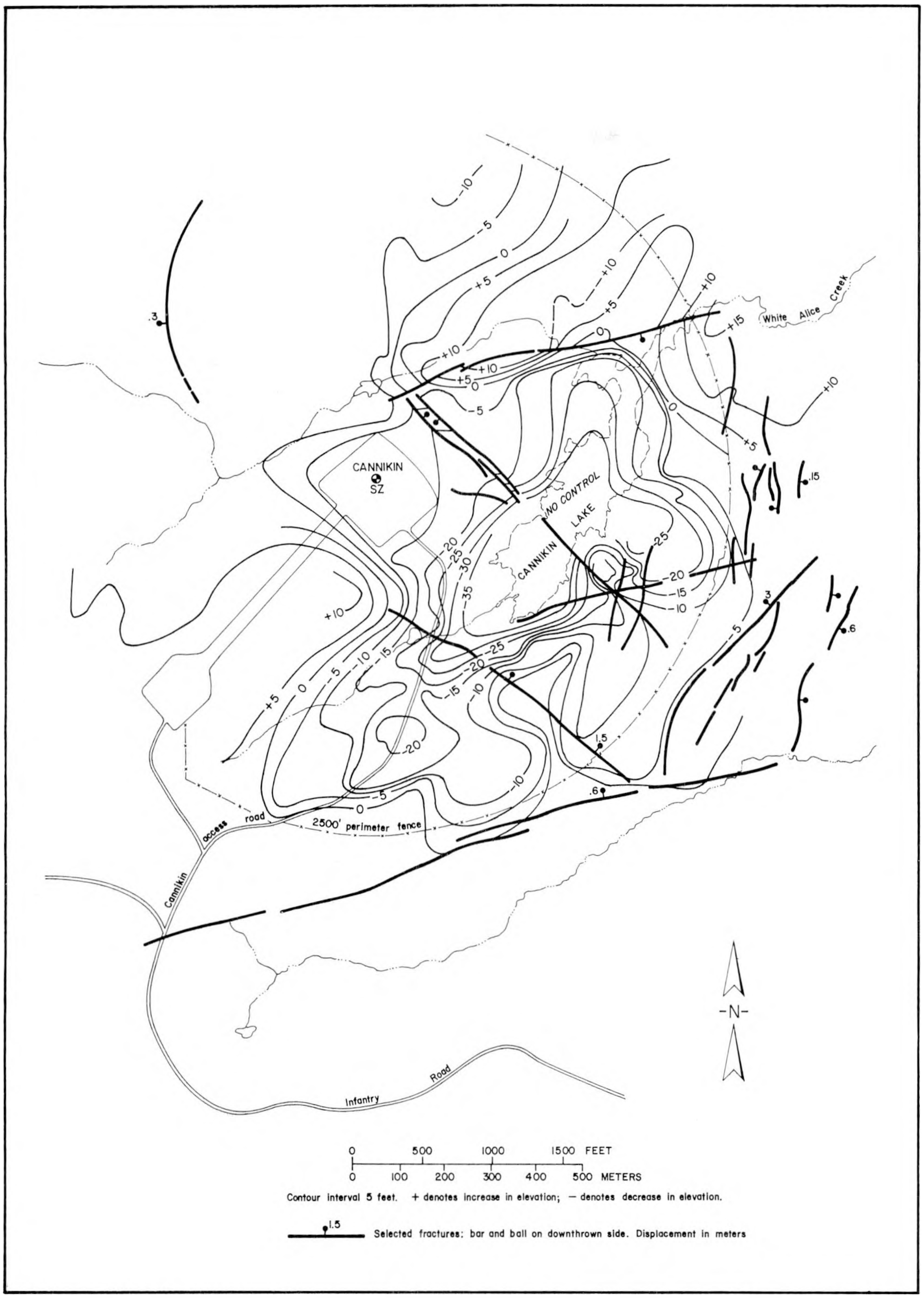

FIGURE 13. Post-collapse contour map of area near surface ground zero

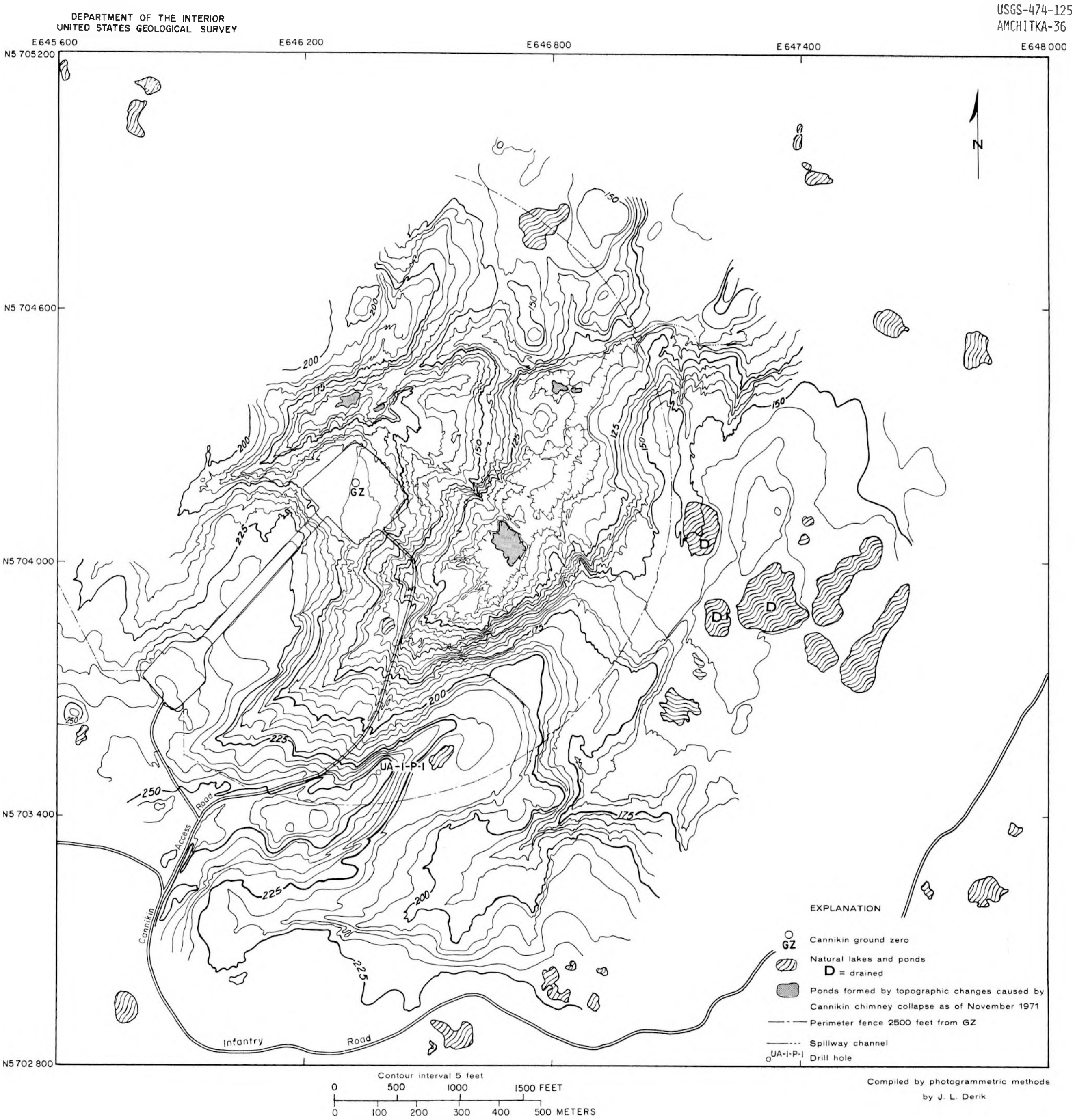

FIGURE 14. Map of contours of elevation changes.

Visible shot-time phenomena resembled those of the Milrow and Long Shot events. Spouts and spray were more extensive at sea, but there were fewer spouts on land than observed during Milrow.

CHAPTER 3

GROUND SHOCK AND WATER PRESSURES

When an underground nuclear shot is fired, the first obvious effect is the ground shock and its disturbance of the surface. It was this ground shock, the accompanying increased water pressures, and soil and rock disturbances that were the immediate cause of almost all other surface effects observed on Cannikin.

Ground shock has been a matter of study since the first underground nuclear detonation in 1957. Since then, data have been recorded under many circumstances and in many materials, including measurements of shots in alluvium, tuff, salt, dolomite, and in granite and other dense igneous rocks. Analyses of such measurements have been extensively reported in the scientific literature; see, for instance, Adams et al. (1961), Sauer et al. (1964), or Murphy and Lahoud (1969). These studies show, as expected, that the amplitude of ground motion decreases with distance and that at a given distance, the larger the explosion, the greater the motion. Detonations in dense nonporous rocks produce larger motions than detonations in light porous rock such as alluvium. The material underlying the recording station affects the incoming motion: e.g., a layer of alluvium amplifies motions, making them larger than what they would be on bare rock. Close to the source, peaks follow scaling rules derived from dimensional analysis, the so-called cube root scaling; farther out where more and more complex geological structure becomes involved, motions are scaled by more empirical methods.

Ground shock was measured on both previous nuclear shots fired at Amchitka and the results were consistent with experience elsewhere with shots in hard rock (Day and Murrell, 1967; Environmental Research Corp. (ERC), 1970; Orphal, 1971; Perret and Breding, 1972).

Water shock, as experienced in Cannikin, has not received much attention. The problem is intrinsically different from that posed by shocks generated by explosions in water, as described by Cole (1948) and many investigators since. Shocks from explosions in rock are of longer duration and have slower rise times than those in water. The problem is also different from that posed by underwater pressures resulting from surface and air bursts, since such pressures are mediated by airblast. Experience thus consists only of measurements made by the two earlier nuclear explosions at Amchitka (Day and Murrell, 1967; Merritt, 1970, 1973).

The Long Shot measurements were made by the Corps of Engineers Waterways Experiment Station and consisted of acceleration and velocity measurements in vertical holes near surface ground zero and on the land surface. Measurements of overpressure and velocity were made at the sea floor at two places in the Bering Sea (Day and Murrell, 1967).

Milrow ground motions were measured by two agencies. Sandia Laboratories (SL) measured acceleration and velocity in vertical holes near surface ground zero and on the land surface to 32,000 feet (10 km) from SGZ (Perret and Breding, 1972). The U.S. Coast and Geodetic Survey (at the time of Cannikin, the Earth Sciences Laboratories of the National Oceanographic and Atmospheric Administration, NOAA/ESL) made measurements at seven additional points on Amchitka as well as on Shemya and Adak (ERC, 1970; Orphal, 1971).

Milrow water pressures were measured by the AC Electronics Defense Research Laboratories (now General Motors' Delco Electronics) and SL, working together, at five stations in the Bering Sea and in the Pacific. There were no measurements of pressure in on-shore, freshwater ponds and streams (Merritt, 1973).

Cannikin ground motion measurements were made by three agencies. SL made measurements of acceleration and velocities in bore holes near SGZ and on the surface to 18,000 feet (5.5 km), using active gages* (Perret, 1972). In addition, SL installed passive accelerometers* at a number of places where biological observations were to be made (Merritt, 1972, 1973). The Lawrence Livermore Laboratory (LLL), weapons laboratory for Cannikin, installed accelerometers and velocity gages at their recording trailer park and at a microwave repeating station (Jackson, 1973; priv. comm.). The NOAA/ESL made measurements at eight additional places on Amchitka, and on five other islands as far away as Shemya and Adak (West and Christie, 1971; Orphal and Smookler, 1972).

Cannikin water pressure measurements were all in surface water on land, and consisted of five channels of active gages and 18 passive gages in ponds and streams as far as 5 km (3 mi.) from SGZ. It had also been intended to install passive pressure gages on marine fish-holding pens in the Bering Sea, but heavy seas on the day before Cannikin prevented such pens from being installed and those gages were not used. Since it had been decided a year earlier not to use Milrow-type canisters on Cannikin, no deep-water measurements at all were made (Merritt, 1972b, 1973).

The locations of ground and water instrumentation used in Cannikin are shown in Figure 15. In general, three components of acceleration and velocity were measured, and transient displacements were determined by integration. Representative of these measurements, Figures 16 and 17 show the peak vertical accelerations and velocities vs distance. Each figure also shows the best fit to these data (defined as the least-squares fit of logarithms of peak motion to the logarithms of slant range from the detonation point).

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*Active gages are gages and recording systems that yield the whole time history of the phenomenon being measured. These call for hardwire or radiotelemetry of signals to a central recording station.

Passive gages are self-recording instruments that indicate only the peak value of the phenomenon being measured.

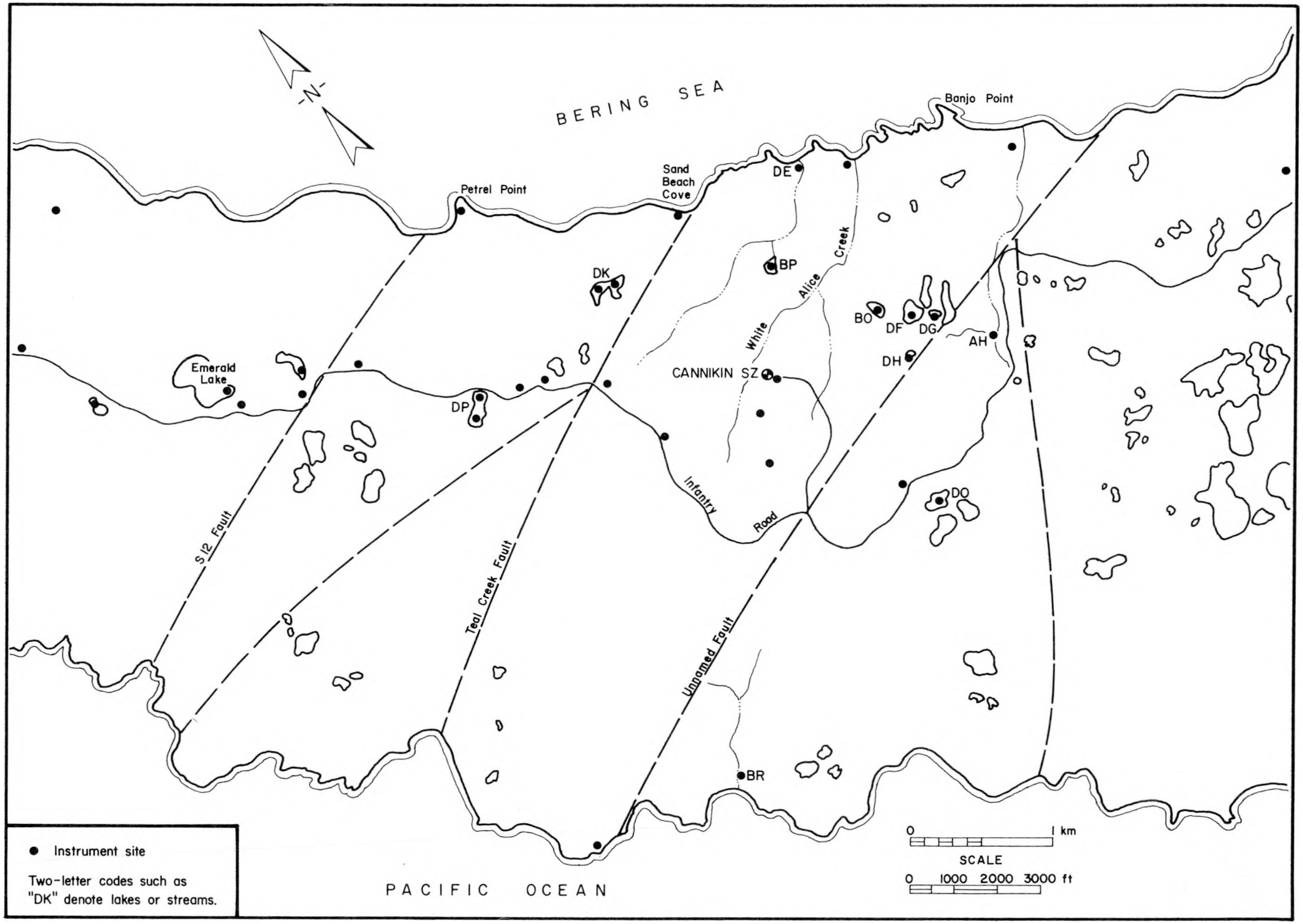

FIGURE 15. Location of ground motion and water pressure instruments.

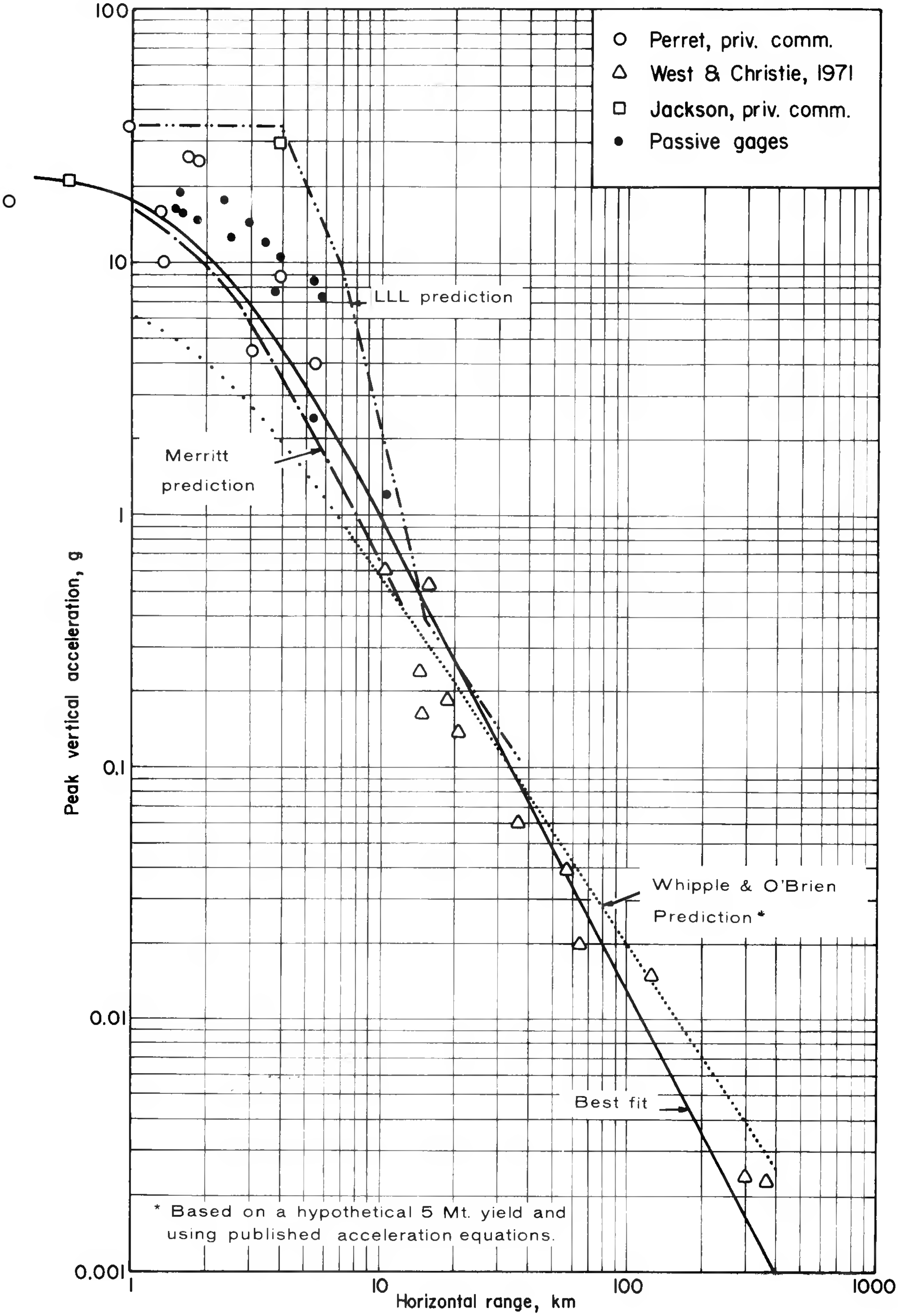

FIGURE 16. Peak vertical accelerations versus distance, with various preshot predictions.

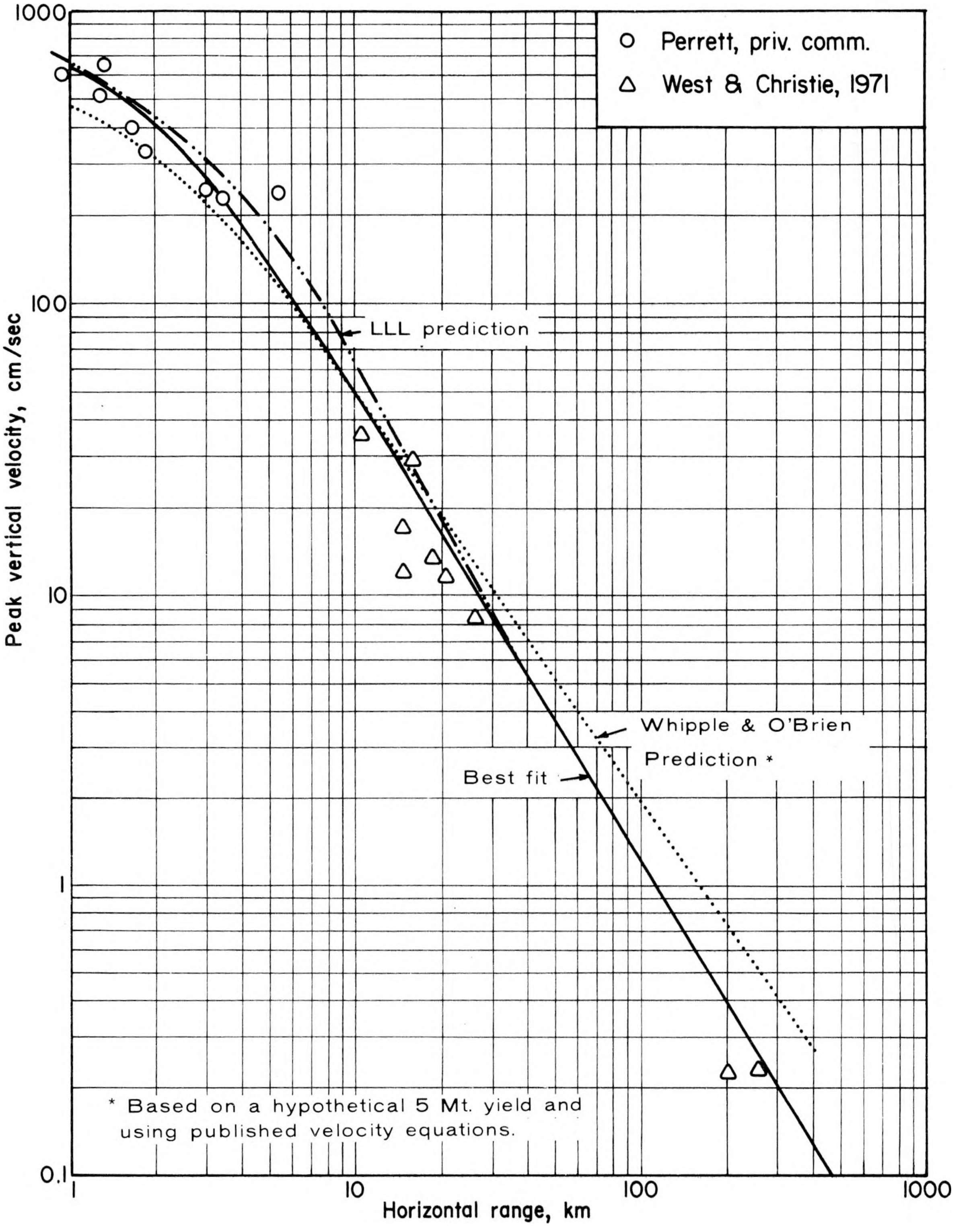

FIGURE 17. Peak vertical velocities versus distance, with various preshot predictions.

Several predictions are on record and are shown on the two figures. In Figure 16, the highest of these is a prediction by Jackson of LLL (priv. comm.), intended to be a maximum prediction for safety and shock mounting of unmanned trailers near SGZ and, as the figure shows, the prediction was satisfactory from that standpoint. Also shown is an ERC curve (from Whipple and O'Brien, 1970), and a curve made available to participants in the bio-program (Merritt, priv. comm.), both intended to be median predictions. Merritt's curve was a cube-root scaled extrapolation of Milrow data, and tends to be low.

In Figure 17, the solid line is the best fit to peak vertical velocities. Both the data and the preshot predictions surround it with much less scatter than the scatter in Figure 16--another indication of the well-known fact that close-in accelerations are hard to predict because of the spall phenomenon. Merritt's Milrow extrapolation is, to the scale of this figure, coincident with the resulting best fit curve.

In Figures 16 and 17, the ERC prediction curves are of particular interest because they are curves deriving solely from NTS experience. The data measured on Cannikin at distances beyond 10 km (6.2 mi.), the intended range of validity of these predictions, agree with the predictions to within the scatter of the original NTS data (σ_g = 2.88, 2.50, respectively; see Whipple and O'Brien, 1970, p. 3-25), though with some tendency to be low. Because the geology of Amchitka is similar to the geology of the Pahute Mesa area of NTS in those respects that influence ground shock (Orphal and Smookler, 1972), this agreement and the earlier agreement of Milrow data (Orphal, 1971), tend to confirm the applicability of the NTS prediction equations for peak motion to explosive yields considerably higher than those that have been fired at NTS.

At NTS and elsewhere near populated areas, pseudo-relative velocity spectra (PSRV)* are used to estimate the response of structures to ground motion. PSRV spectra on Cannikin tend to be lower than the corresponding Milrow spectra (extrapolated to 5 Mt) in the approximate period range 0.5 to 2.5 seconds, but are otherwise very similar. This is attributed to yield-dependent scaling exponents, as predicted by Mueller and Murphy (1971).

Surface spall (the splitting away of surface layers under the influence of tensile reflections from the surface) usually occurs from large underground explosions. It was observed on Long Shot, on Milrow, and again on Cannikin. The evidence for such spall is a wave form showing a period of free fall, terminated by one or more acceleration pulses as the spall gap closes. These second pulses are erratic and difficult to predict, giving rise to scatter such as in Figure 16. The depth of spall is dependent on the strength of the wave reaching the surface and its rate of decrease after the peak passes. The radial extent is limited by the fact that an

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*The PSRV spectrum represents the peak response to ground motion of a series of single-degree-of-freedom systems (mass-spring systems) with slight, usually 5 percent, damping. It approximates the Fourier amplitude spectrum.

acceleration of greater than 1 g is necessary to produce the spall separation. Spall does not extend as far to sea as on land, because the reflection of the wave from the surface is broken up by any moderately deep layer of water (Merritt, 1973). By way of comparison, Table 1 shows spall depths and radial extents on land on the three nuclear shots fired at Amchitka.

TABLE 1--MEASURED SPALL DEPTHS AND RADIAL EXTENTS

Event	Yield	Depth of Burst	Spall Depth	Spall Radius	Radius to 1 g
Long Shot	80 kt	700 m (2300 ft.)	30-150 m (98-492 ft.)	1.2 km (.75 mi.)	Not determined
Milrow	∿1 Mt	1220 m (4000 ft.)	90-150 m (295-492 ft.)	5 km (3.1 mi.)	5.5 km (3.42 mi.)
Cannikin	<5 Mt	1790 m (5875 ft.)	150 m (492 ft.)	5.5 km (3.42 mi.)	9 km (5.6 mi.)

Milrow measurements in water 40 to 200 feet deep (12 to 60 m) had indicated that a dominant perturbing factor on overpressures was repeated reflections or reverberations in the water. In Cannikin's shallow water, this factor was even more influential. Records from the five active pressure gages gave wave shapes much like acceleration records, except that slap-down gave a rapidly oscillating signal instead of the usual one or two spikes. An example is shown in Figure 4.

For very shallow water, Banister has suggested (priv. comm.) that if one can neglect reverberations and assume the water moves as a unit, pressure should be related to acceleration by the mass per unit area:

$$\Delta P = \rho d a,$$

where ΔP is overpressure, ρ is the density of water, d the depth at point of measurement, and a acceleration. This expression and the more complex one describing reverberations were applied to certain simplified but representative situations. It was found that for sharp wave fronts (ones in which the acceleration rises to its peak in less than the reverberation time), the more exact answer oscillated around the pressure inferred from the expression above, whereas for slowly rising wave fronts, the two equations yield about the same results. This accounts for the simple first pulse and the oscillatory second pulse in Figure 4.

In shallow water, a pressure gage should act like an accelerometer, provided one knows what the overshoot factors are. If a complete pressure history is available, as for the five Cannikin active pressure gages, these factors are obvious, but in any case they must be between one and two. Figure 18 shows how accelerations inferred from pressure readings compare with the best fit line of Figure 16. Because all these measurements were taken within the spall region, all the passive gage measurements must represent slap-down pulses. The scatter is somewhat but not

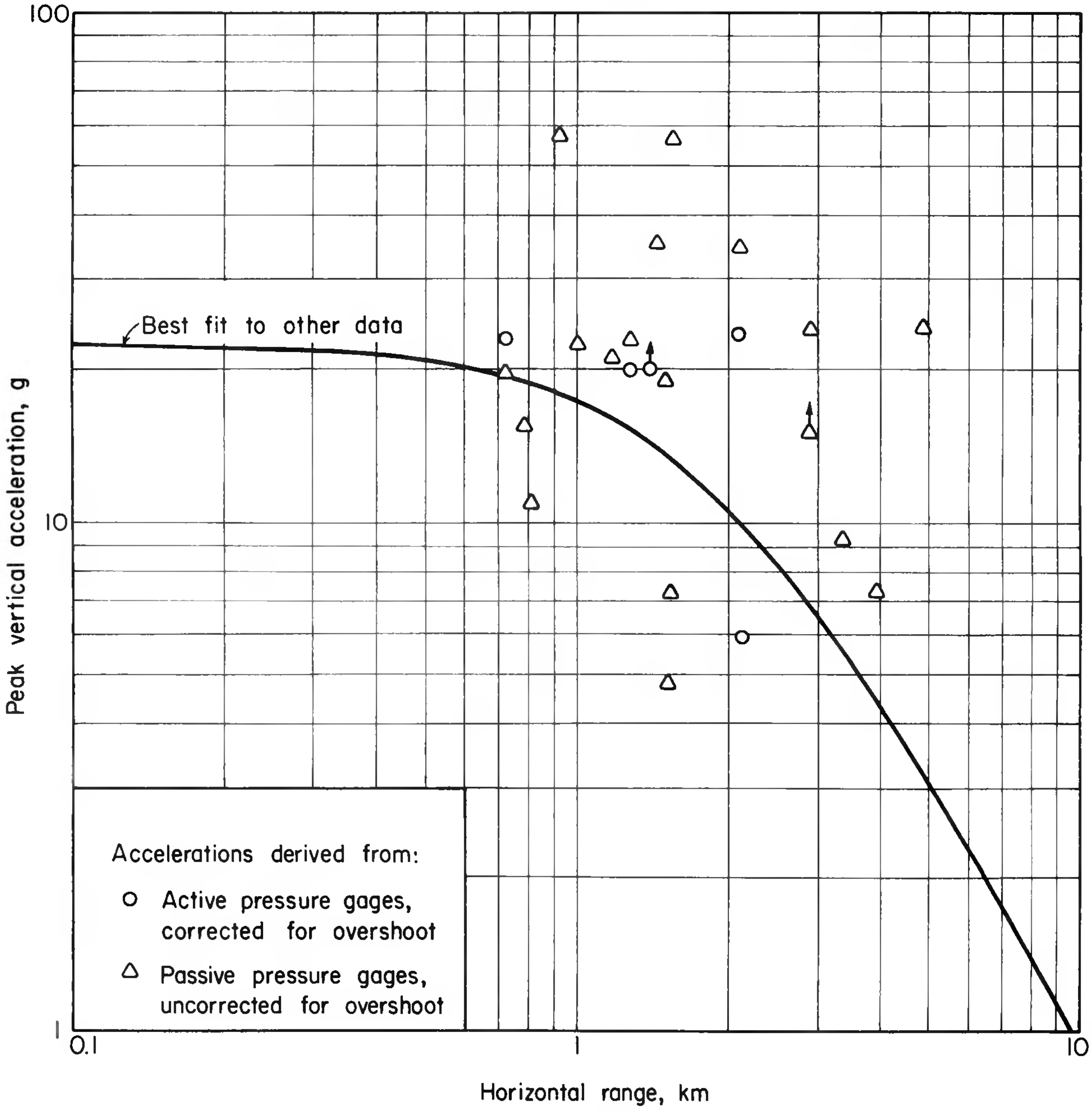

FIGURE 18. Peak vertical accelerations derived from pressure gages, compared to accelerations measured directly.

a great deal larger than the scatter seen in direct measurements of acceleration shown in Figure 16. Several attempts have been made to account for the scatter in the pressure measurements, but none were successful, and the scatter remains a factor that can only be treated statistically (Merritt, 1973).

Although it was not possible to install pressure gages in the sea off Amchitka, pressures there are still of interest. They have been reconstructed, using the theory verified on Milrow and applied to the Cannikin measured ground motion. Figure 19 is a contour map of estimated sea bottom overpressures and gives the outer limit of water spall. Above the ocean floor, overpressures were less, decreasing linearly to zero at the surface.

According to this figure, the region of water spall was less extensive relative to the pressure contours than it was for Milrow, a consequence of a longer rise time. On the other hand, another effect took place on Cannikin that was almost absent on Milrow. If water is deep enough close to SGZ, there can be a depth below which bulk cavitation takes place (Wentzell et al., 1969; Merritt, 1973). For Milrow, these conditions were fulfilled only in a narrow submarine canyon in the Pacific; for Cannikin, there was a considerable area over which this took place. This area is also shown in Figure 19.

In summarizing, two conclusions derived from the Milrow experience are worth repeating because Cannikin results confirm them:

Ground shock at Amchitka follows the same general pattern as ground shock elsewhere, including NTS. This also means that the Cannikin data are useful in confirming that existing prediction methods can be scaled to higher yields than heretofore, especially to higher yields than have been possible in Nevada.

Measured underwater overpressures are as much affected by the depth of water and depth of measurement as by distance from the shot. It was not possible to repeat the Milrow deep-water measurements, but shallow-water measurements fit into the pattern indicated by Milrow. Shallow water pressures are closely akin to the acceleration of the underlying ground.

The scatter in acceleration and water pressure measurements remains uncomfortably large, and largely unexplained, except that it is associated with the well-known unpredictability of slap-down accelerations. This appears to be an inherent fact of nature, dependent on essentially immeasurable properties of the subsurface material.

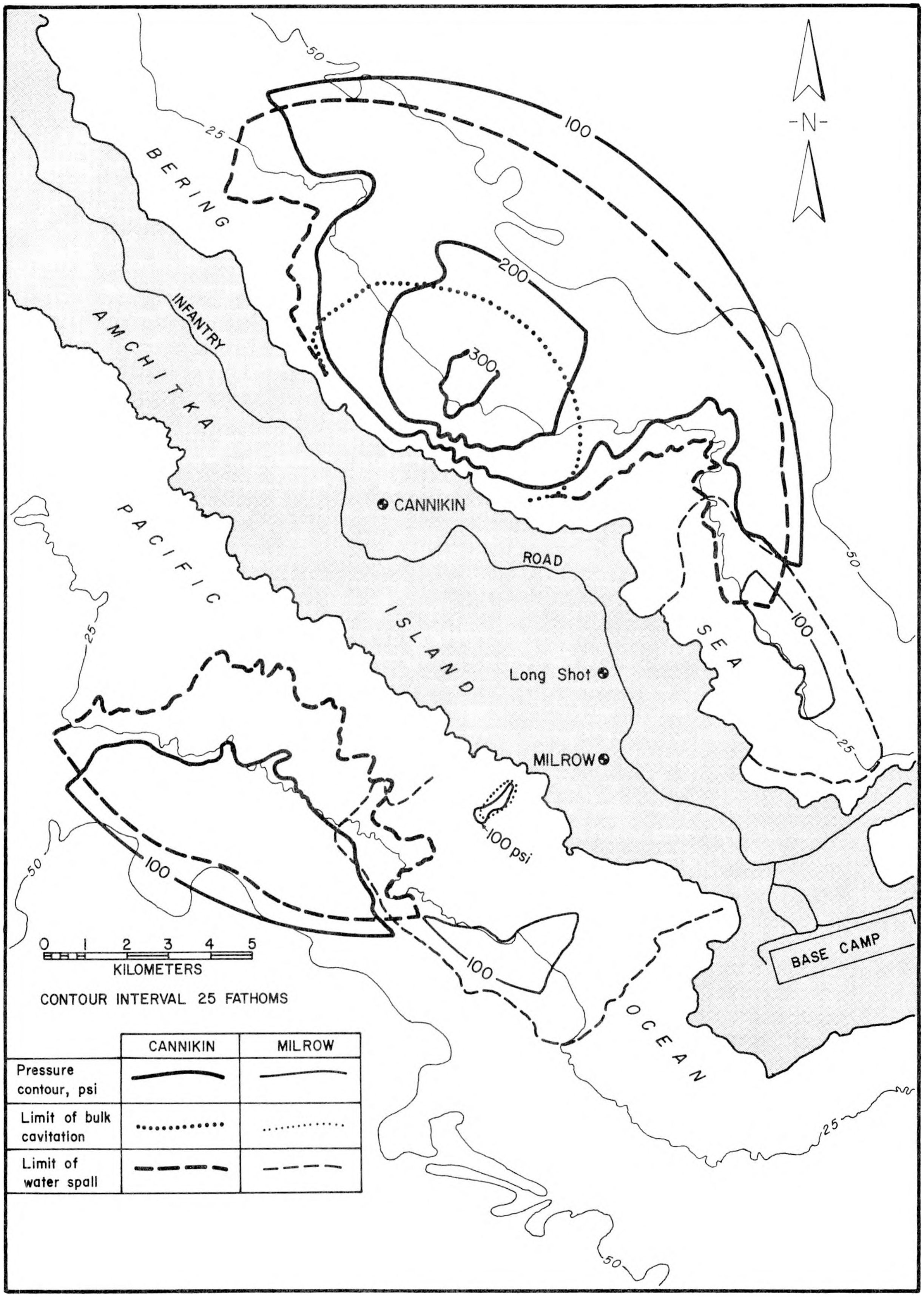

FIGURE 19. Contours of underwater pressures and cavitation region. (Merritt, 1972 b)

CHAPTER 4

HYDROLOGIC EFFECTS

4.1 GENERAL

One of the great preshot concerns about Cannikin was about possible release of radioactivity into the biosphere via the groundwater system. Hydrologic studies of groundwater and surface water flow before and after Cannikin concerned this possibility; related studies were directed at the groundwater pressure response to the Cannikin explosion.

4.2 HYDROLOGIC SETTING

Amchitka is a long, narrow island, lower than most others in the Aleutians; the maximum elevation near the Cannikin site is about 300 feet (90 m) above mean sea level. These lower areas are generally covered with peat of varying thickness underlain by clayey soil whose hydrologic significance is that it is nearly impenetrable to rainwater. Therefore, almost all of the 83 cm (33 in.) annual rainfall goes to the sea by surface runoff. The underlying rocks are volcanic breccias and basalts, they are saturated nearly to the surface, and their effective porosity is contained mostly in fractures.

Our understanding of the subsurface water flow is based on hydrologic measurements in a number of test holes near the Cannikin SGZ, as well as elsewhere on Amchitka. These measurements indicate a slightly decreasing hydraulic potential with depth, increasing salinity (though tenfold less than at the Milrow site) and other dissolved solids, and increasing temperature (Ballance, 1970, 1972; Ballance and Dinwiddie, 1972; Beetem et al., 1971a and b; Sass and Moses, 1969). These data imply that whatever rainwater penetrates the surficial peat and underlying poorly permeable clay flows downward at the center of the Island, then outward and finally upward, emerging under the nearby sea. The process is a long, slow one. One carbon-14 analysis has been made of water from a depth of 3150 feet (960 m). Its date was 11,000 years; corrected for the fact that to get underground the water had had to go through carbon-bearing plant remains and then flow through rock bearing traces of carbonate, its age is almost surely less, but it is still old, old water. Ages in the thousands of years can also be inferred from rock transmissivities and gradients of hydraulic potential (Ballance, 1970). Thus, radioactivity borne in the water was expected to be a long time appearing at the surface, barring a near-immediate seepage of tritium to the surface as at Long Shot or by mixing within the collapse chimney. The former possibility we will defer to Chapter 5; the latter we will take up now.

4.3 CHIMNEY INFILL

Following Cannikin, LLL drilled back into the working point volume to obtain radiochemical samples diagnostic of the nuclear detonation itself, which activity was largely trapped in the walls of the underground cavity formed by Cannikin. (No drillback activities had been attempted on Long Shot or Milrow.) Following collapse, the cavity volume was distributed partly as interstices in the chimney rubble, and partly as subsidence volume. This drillback has also permitted hydrologic measurements not possible on the two previous nuclear explosions at Amchitka: measuring rate of infill and sampling from depth. All work accomplished down this hole was done through a 4-inch (10 cm) drill pipe that was left in the hole for the hydrologic program as a protection against cave-in as well as a means of disposal of a possibly contaminated tool.

Water level measurements from the drillback hole are plotted in Figure 20. At the completion of radiochemical sampling in late February 1972, the drill pipe was perforated near the bottom, providing the hydraulic connection with the chimney. In early July, water in the drillback hole stopped rising. New perforations made from July 21 to July 26 caused a surge upwards making it clear that the lack of rise had been due to clogging of the original perforations.

The processes to be considered in accounting for the way the Cannikin chimney has filled are interception of surface flow and drainage out of the surrounding rock. From late May to early June, the chimney filled at a rate of about 9 m/day (30 ft./day). Neglecting seasonal variations, rainfall of a meter per year on a watershed of 2 km^2 (0.77 $mi.^2$) into a chimney of equal capacity per depth and total interstitial volume equal to a spherical cavity of radius 130 m (427 ft.), would fill the chimney at a rate of a little over a meter per day. (The same estimate results from assuming that all the decrease in flow of White Alice Creek flows into the chimney.) Any part of the original cavity volume that ends up as subsidence volume instead of interstitial volume increases this rate, but the net result of this order-of-magnitude estimate is the conclusion that other factors must also have contributed to the infill in addition to the infiltration of rainfall and the interception of the flow in White Alice Creek.

To account for the chimney infill by drainage from the surrounding rock (dewatering) above, one would have to postulate that the interstitial porosity in the chimney is greater at the bottom than at the top of the chimney, since the infill was slower between November and February than later. This is an unreasonable assumption, contrary to experience elsewhere. Thus, dewatering cannot be the sole source of infill water either. We conclude that both sources contributed to the infill.

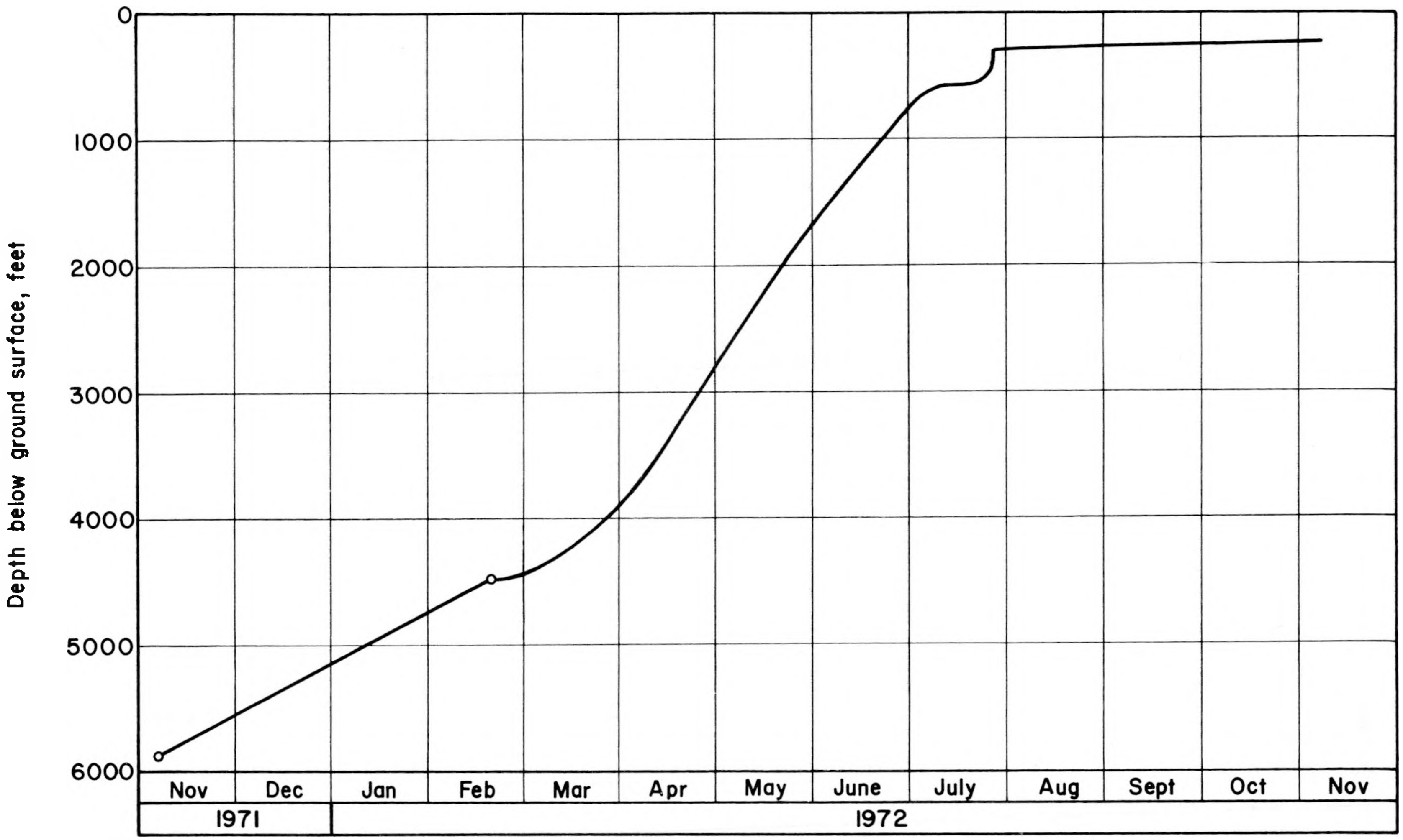

FIGURE 20. Water levels in drill-back hole versus time.

It has been suggested that the slower rate of infill before March 1972 was while dewatering from the lower part of the section was the only contributor to the rise of water in the chimney. Water from higher levels and water intercepted at the surface was slow in filtering down through the chimney rubble. Then as flow from above finally reached the rising water surface, the rate of rise increased.

In February and July 1972, prior to reperforating, gamma activity logs were run in the drill pipe. The results of the two logs are closely similar. Activity rises above background at a vertical depth of 1400 m (4700 ft.) and is irregularly above background below that. In July, a temperature log was run. Although temperatures had not reached equilibrium after an accidental flushing with water in April, being below the preshot temperatures reported by Sass and Moses (1969), the log does indicate a sharp change in gradient at a vertical depth of 1640 m (5250 ft.), see Figure 21. These data indicate that in eight months, there was essentially no mixing upward in the chimney due to thermal instability, but some mixing of radioactivity upward at early time by some other process.

Water in the drill pipe is presumably at hydrostatic equilibrium with water at the bottom of the chimney, that being where the perforations are. Water higher in the pipe entered earlier, and thus, a longitudinal profile exists of radiation intensity levels at various times in the lower part of the chimney since the pipe was last flushed. This fact was used to get the activity history. In April 1972, tritium levels were 1-3 x 10^6 pCi/ℓ, dropping two orders of magnitude by July. The first levels are close to what one would expect in the undiluted source; the latter imply dilution. The water contained no alpha activity, but it did have some beta emitters other than tritium, unidentified because there was insufficient sample for analysis (Claassen, USGS, priv. comm.).

In early November, a new hole (HTH-3) was drilled to the top of the water rising in the chimney. Analyses of water from this hole showed no radioactivity above background, neither alpha emitters nor tritium or other beta emitters.

4.4 SURFACE CHANGES

Cannikin Lake started to form at the end of September 1972; its configuration on November 5 is shown in Figure 22. At that time, it had not risen high enough to find an outlet to sea, but since the end of November 1972, it has spilled over the lip of the subsidence sink into White Alice Creek, and thus into the sea. The mouth of the creek is in the upper right in Figure 22. Cannikin Lake is approximately 40 acres in area, and 25 feet (8 m) deep. Its water, too, is free from detectable radioactivity.

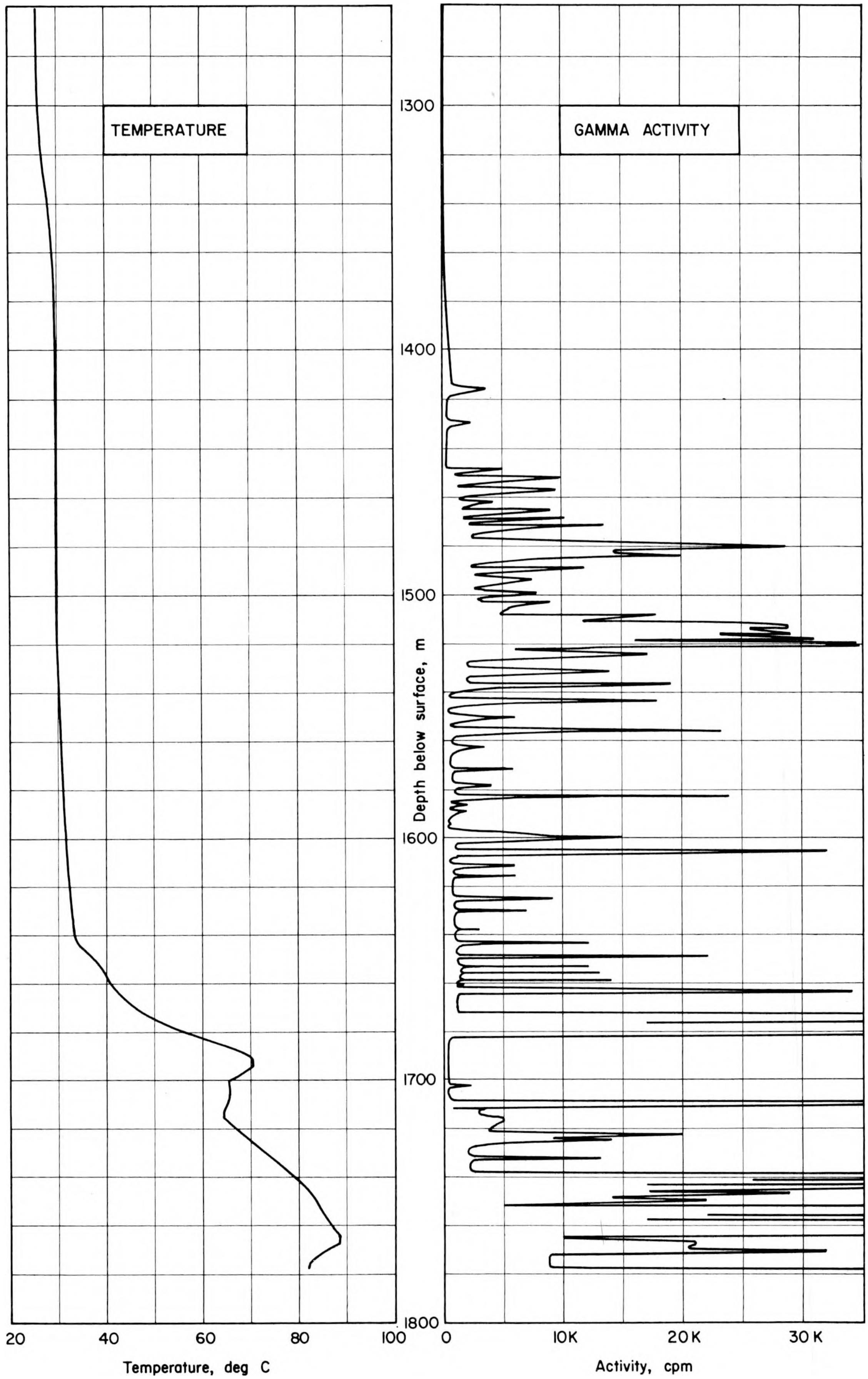

FIGURE 21. Temperature and gamma logs in drill-back hole.

FIGURE 22. Cannikin Lake, November 1972. (Photo: Mercier, BMI)

The flow of five streams and one spring were monitored before and after Cannikin, ranging out to 14 km (9 mi.), Constantine Spring, near Base Camp) (Gonzales and Wollitz, 1972a and b).

Rainfall during the preshot storm had caused all streams to be high, but by the previous midnight, all had returned to base flow. All streams but one, the second closest, experienced some perturbations of flow. The most drastic effects were, naturally, in White Alice Creek. There, compaction and vertical displacement sent a 15-minute flood downstream, leaving streambed material and fish stranded as much as two meters above the streambed. After this receded, discharge fell to less than a quarter of the preshot flow until collapse occurred at 38 hours after the detonation. At that time, flow ceased altogether for two weeks, and then was only a bare trickle. We believe that the missing water was intercepted by the subsidence sink and flowed into the chimney. Since Cannikin Lake filled, flow in White Alice Creek has been about 80 percent of preshot volume.

In no other stream was there a permanent disturbance of flow. The only other effect worth noting was at Falls Creek, 7.1 km (4.4 mi.) west; the walls of a mud storage pit failed, releasing part of the contents downstream.

4.5 GROUNDWATER PRESSURE MEASUREMENTS

Fluctuations in the groundwater fluid pressure were documented by USGS in various wells ranging in distance from 1.2 to 14 km (0.75 to 8.7 mi.) from SGZ. Of the five successful measurements, four were in closed holes and one in an open hole (Gonzalez and Wollitz, 1972a and b).

The initial signals recorded in these holes are reflections of the ground shock signals described in Chapter 2. To illustrate this point, Figure 23 shows that measurements of the peak positive pressure vs slant range from the explosion, and the USGS predictions agree with the pressures inferred from measured vertical surface velocities, by the usual relation:

$$\Delta P = \rho c u/2$$

where ρ is density of the surrounding rock, c is its compressional velocity and u is measured surface velocity, and half is the usual ratio between subsurface and surface velocities (rock properties from Lee, 1968). In other respects, too, these fluid pressure signals resembled ground motion signals. For instance, at the closest point (hole HTH-1, 2.1 km (6900 ft.) slant range), both initial and slap-down pulses are to be seen, and at the right times--the signal plotted in Figure 23 is the slap-down signal. At the Officers' Club hole, 13 km (8 mi.) distant, two later signals can be seen that Willis et al. (1972, p. 46-7) say may be later-arriving seismic signals.

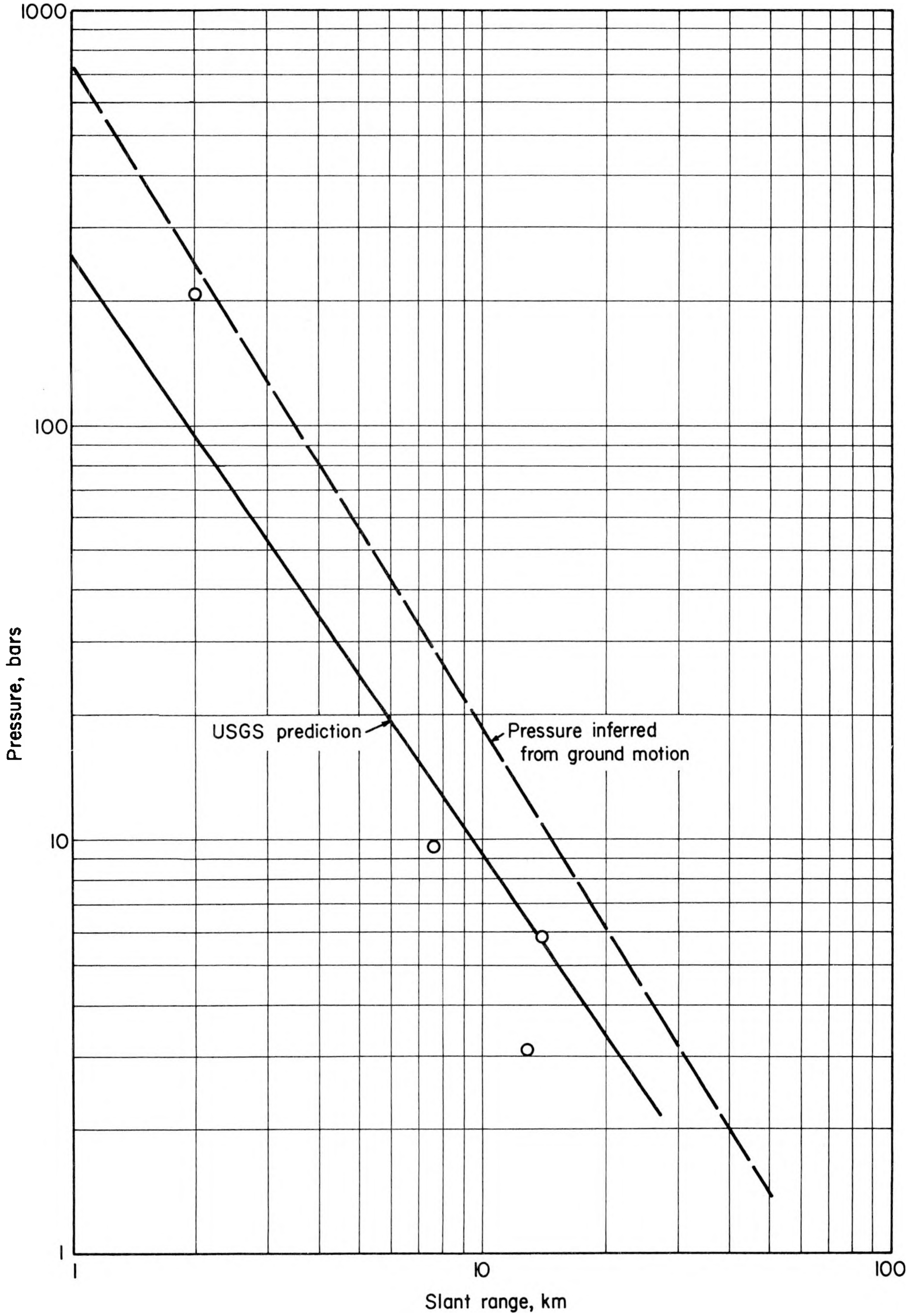

FIGURE 23. Pressures measured in closed drill holes, compared to predictions and to ground motion.

All four closed holes recorded the seismic aftershocks discussed below in Chapter 7. All also recorded the collapse at 38 hours.

The one open hole was near the Long Shot site, 6.7 km (4.2 mi.) distant. After an initial transient increase, water level there declined steadily until collapse of the chimney. Thereafter, water level declined faster for a few hours, reaching a net depression of level of 2.1 m (6.9 ft.), then began rising.

Long-term pressure changes in these five holes show little overall pattern other than being strongly negative close in and slightly positive farther out. In particular, water levels in them do not help define the putative draw-down by the collapse chimney.

4.6 SUMMARY

A postshot hole, drilled for radiochemical samples, has permitted a detailed study of chimney infill and concentrations of radioactivity in water near the detonation point.

The chimney took about a year to fill with water. Infill was probably a result both of surface water interception and inflow from the surrounding rocks.

Samples of water taken from the bottom of the chimney contained tritium and a trace of some other unidentified beta emitter. Samples of water taken from the top of the chimney and from Cannikin Lake were free of radioactivity.

As of late September 1972, a new lake, Cannikin Lake, started to form within the subsidence sink. Now full and overflowing, it is about 25 feet (8 m) deep and is one of the dominant features of the landscape.

Transient stream flow changes generally consisted of an initial outsurge followed by a period of reduced flow. White Alice Creek, which formerly drained the Cannikin area, was reduced to almost no flow while the missing flow was going into the collapse chimney.

Fluid pressure signals were observed in five holes. Initial signals were closely related to ground shock signals.

CHAPTER 5

RADIOACTIVITY

5.1 PREVIOUS EXPERIENCE

The concern over possible escape of radioactivity from Cannikin resulted, in part, from leaks of tests at the NTS. There had been 238 announced United States nuclear shots since the Limited Test Ban Treaty of 1963 up to the time of Cannikin. These included five Plowshare cratering shots. Of the other 233, 17 leaked radioactivity detectable offsite. Thirteen of these were tunnel experiments and/or experiments involving open lines of sight partway through the stemming (the material used to refill the emplacement hole or tunnel). Only four fully buried shots have leaked. All four were in alluvium, were less than 2000 feet deep, and had small yields (Vermillion 1973).

The Baneberry test leak, on December 18, 1970, was of particular concern during the Cannikin discussion because it had been heavily publicized. The primary cause of the leakage was an unexpected and unrecognized abnormally high water content in the medium surrounding the detonation point. The significance of the water was not appreciated before the shot was fired (AEC, 1971b).

In contrast, no large-yield United States detonation has leaked detectable radioactivity, and there had been 13 of these* before Cannikin, all fully stemmed, and all but one (Pipkin) fired under the water table.

Long Shot does not appear on the list of 18 shots whose release of radioactivity was detectable offsite. However, it did have a minor seep of activity observable above background near its SGZ. This was first evident as traces of radioiodine in samples taken in late November and December, a month after the shot, in a pond 100 m (330 ft.) north-northwest of SGZ (Pond LP in Figure 24). Radiokrypton was also found in soil gas and could be stripped from water draining the pad area. The initial breakthrough was thus within the first month. The amount of seepage was insufficient to be detectable above background anywhere but the immediate SGZ area.

The main activity front reached the surface between then and the next September, and was then observable as tritiated water in ponds as far away as 150 m (500 ft.) from SGZ. Today, tritium above background is to be found only in mud pits on the north edge of the SGZ pad, 60 m (200 ft.) away, and in a ditch draining those pits. The levels in these two places are plotted in Figure 25. The highest level ever observed is 5130 tritium units (TU) (16.9 pCi/mℓ), which is 1/60 the Radiation Concentration Guide for drinking water continuously used by the general public (1000 pCi/mℓ). The fact that tritium levels have

*Intermediate or low-megaton shots: Bilby, Corduroy, Halfbeak, Greeley, Commodore, Faultless, Boxcar, Benham, Jorum, Milrow, Pipkin, Handley, Carpetbag. (Springer and Kinnaman, 1971)

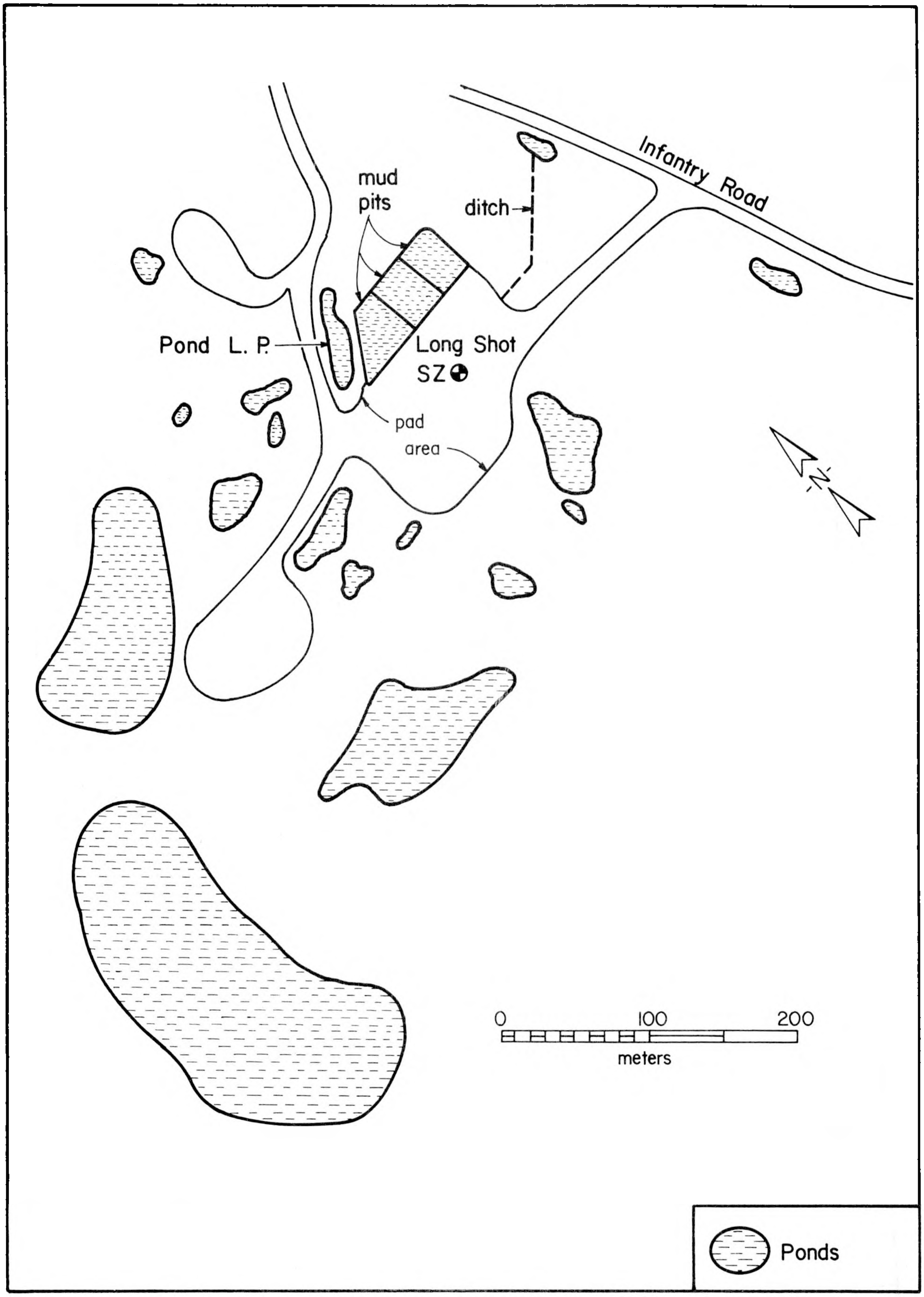

FIGURE 24. Ponds and streams near Long Shot surface ground zero (Held, 1972)

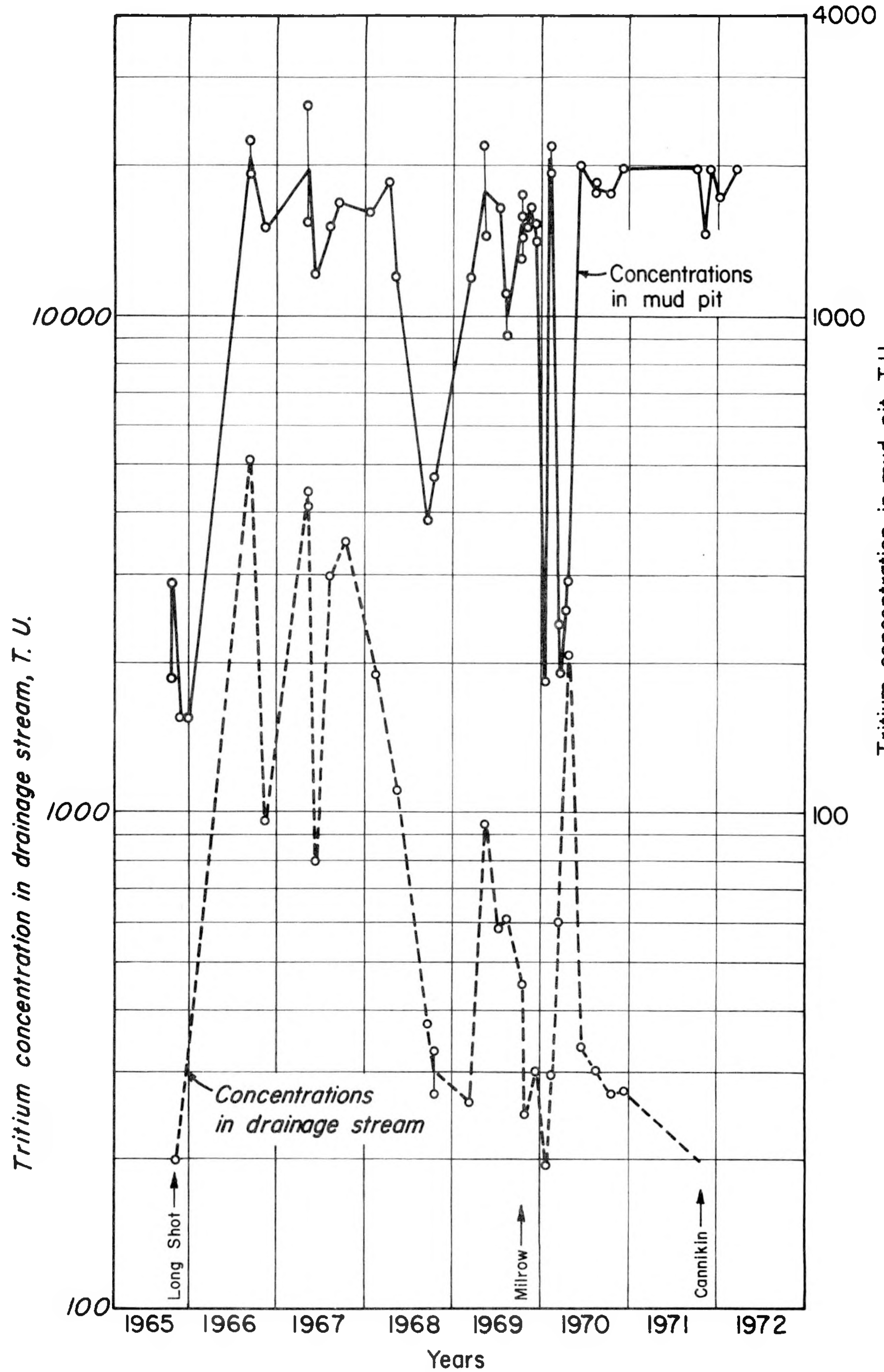

FIGURE 25. Tritium concentrations in ponds and streams near Long Shot. (Data from: Castagnola, 1969 a, b; Essington et al, 1970, 1971; Essington, 1971; Beetem et al, 1971; Schroder and Ballance, 1972 a, b.)

remained at about 2000 TU in the mud pits, in spite of seven years of rainfall and outflow, indicates that this pond is still being fed fresh tritium from somewhere.

In late 1971, a number of shallow holes was drilled in the Long Shot surface zero area to determine the underground distribution of radioactivity. These indicated an increase in tritium content of water with depth down to a zone between 200 and 300 feet deep, then a decrease below that. They also indicated a decrease with distance away from the placement hole. Strontium and cesium were not observed. These observations indicate that gaseous activity, mostly tritium and krypton, moved at an early time to the top of the chimney (which at Long Shot did not reach the surface). As the chimney filled with water, these gases were pushed ahead upwards, passing through uncompacted material in the upper portion of the stemming, out into the spall zone, where they went into solution. Thence, they continue to diffuse to the surface ponds where they are still being detected (Fenske, 1970; Korver, Teledyne Isotopes Westwood, priv. comm.).

On Milrow and Cannikin, there were two essential differences from Long Shot that have meant that no tritiated water has been observed there. First, both chimneys reached the surface, so that any tritium or krypton that may have come to the top of the rising water in the chimney has dissipated at undetectably low levels.* Second, the emplacement holes contained impermeable plugs of epoxy cement preventing the stemming from becoming an escape route.

It remains true as of the end of 1973 that no radioactivity above background of any sort has been observed at Milrow.

5.2 CANNIKIN MEASUREMENTS

Cannikin shot-time monitoring consisted of nine air samplers and 18 gamma detectors on a ring of 2500 feet (760 m) radius about SGZ, as well as instruments at SGZ. The gamma detectors were connected by hardwire telemetry to the Control Point at the northwest end of Amchitka, so that there would be no delay in knowing if a release of radioactivity from Cannikin had occurred. Nothing above background was detected by these instruments.

Background environmental radioactivity on Amchitka has been found by several independent investigators to be similar qualitatively and quantitatively to that found in arctic regions elsewhere in North America and Scandinavia. Koranda et al. (1969), for instance, report that "the fallout radionuclide ^{137}Cs dominates the radioactivity found in biological and soil samples collected on Amchitka Island, with low but measurable concentrations of ^{155}Eu, ^{144}Ce, ^{125}Sb, and ^{54}Mn. Central Alaskan vegetation has similar concentrations of ^{137}Cs and coastal Alaskan vegetation has slightly higher concentrations." (The highest levels were found in lichen of the

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*Intermittently, bubbles of gas have come up the Cannikin drillback hole that have contained ^{85}Kr, HTO, HT, and ^{14}C. By the end of 1972, there had been about 4000 m^3 (14,000 ft.^{3}) of such gases containing a total of 1 1/4 curies of activity (Doles, 1972). This hole is now sealed.

genus Cladonia, about 24 pCi/g dry weight.) Similarly, Held (1971) says that "the concentrations of the radionuclides found were small and within the range of values reported for similar samples from other parts of the northern hemisphere. ^{55}Iron was the predominant fallout radionuclide in fish." Tritium background levels were determined by Castagnola (1969a) to be 140 ± 46 TU in surface ponds and 75 ± 31 TU in the sea. These levels, too, are like those in other islands at this latitude. Background levels vary, of course, with rain, season, and other factors, a spring peak being especially evident as it is everywhere in the north.

5.3 BIOLOGICAL INDICATOR ORGANISMS

The University of Washington's Laboratory of Radiation Ecology (LRE) undertook a program of finding indicator organisms and monitoring radiation levels in various elements of the biosphere. Indicator organisms are those which are used to determine the presence of certain radionuclides in the biosphere. They should be available throughout the year, sufficiently plentiful that the act of sampling itself does not deplete them, and at the proper place in the food chain to concentrate activities early enough to be usefully detectable. LRE chose finally to monitor the seaweed Fucus, the freshwater moss Fontinalis, a higher plant Ranunculus (buttercup), and plankton and other fine particulate matter in the sea. All nuclides found were either naturally occurring (especially ^{40}K) or from worldwide fallout, except for the aforementioned tritium near Long Shot SGZ. Post-Cannikin concentrations were either lower than immediate pre-Cannikin values or approximately the same. LRE concluded that "there was no release of radioactivity as a result of the Cannikin test" (Held, 1972).

It was noted in Chapter 4 that a hole was drilled back into the Cannikin chimney and core samples for radiochemical analysis were taken. It necessarily follows that some radioactivity was brought to the surface. All core samples brought up have been shipped to Livermore, California. All tools were washed down and the wash water reinjected into the chimney. The drilling tools themselves have been left in the drillback hole. Careful monitoring by the Eberline Instrument Corporation has found no detectable residual surface activity as a result of this operation.

5.4 SUMMARY

Tritiated water continues to be found in ponds at Long Shot SGZ. The results from shallow holes drilled nearby plus the surface radiation history now permit us to attribute this to gaseous radionuclides pushed to the surface by water rising in the chimney.

No radioactivity has been detected by shot-time air sampling and gamma detectors or in pre- and postshot biological sampling above the normal background. Cannikin did not leak detectably.

Drillback into the Cannikin chimney did not result in residual surface radioactivity, although small amounts of radioactive gases were detected.

Background levels of radioactivity are like those found elsewhere in the north, both quantitatively and qualitatively.

CHAPTER 6

BIOLOGICAL EFFECTS

6.1 HISTORY

Amchitka has had a long history of human disturbance. The impact of the aboriginal Aleuts now seems small, but we suspect that their pressure on the sea otter population permitted a much larger sea urchin and mollusk population than now exists, indirectly benefiting the Aleuts by giving them a food resource available to the whole population and not just able-bodied men (Desautels et al., 1970, p. 336; Laughlin, 1972).

The discovery of the Aleutians and the Komandorskis by the Russians in the 1740s was followed by a period of extensive fur hunting that led to a tenfold decrease in the Aleut population, the extinction of the northern sea cow in the Komandorskis, and the near extinction of the fur seal and the sea otter everywhere. By the time an international protective treaty was signed in 1911, Amchitka had one of the few remaining populations of sea otters. In 1913 in Executive Order 1733, President Taft reserved the Aleutian Islands "as a preserve and breeding ground for native birds, for the propagation of reindeer and fur bearing animals, and for the encouragement and development of the fisheries," but with the condition that "the establishment of this reservation shall not interfere with the use of the islands for lighthouse, military, or naval purposes . . . ."

In conformance with this directive and as an aid to native subsistence, in 1921, blue foxes were introduced into most of the Aleutian Islands where they did not already exist, including Amchitka. Deleterious effects were observed very soon, particularly a drastic reduction of numbers of the Lesser or Aleutian Canadian Goose (Branta canadensis leucopareia) (Murie, O. J., 1959, p. 67). Permits were slowly phased out; the permit for Amchitka held by the Atka Village community was terminated in 1947 (Jones, 1960).

From 1943 through 1951, Amchitka was occupied by U.S. military forces. It is believed that the Norway rat was introduced during this period (Murie, O. J., 1959, p. 325), although they had long been present on some neighboring islands.* Many miles of roads, much debris, and several thousand now rotting small buildings remain on Amchitka from the military occupation.

From 1951 through 1960, a fox and rat eradication program was carried out, using strychnine and 1080. Foxes were eradicated, but the rat

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*Rat Island, just west of Amchitka, was named that by Lütke in 1827 (Orth, 1967), rats having escaped ashore there after shipwreck (Pallas, 1782, quoted in Masterson and Brower, 1948, p. 75, 92).

population was not permanently affected. Feral dogs and cats were also eradicated or disappeared from natural causes (Berns, 1960; Jones, 1960). In 1962, a program of controlled harvesting of sea otters was initiated by the Alaska Department of Fish and Game. In 1965, Long Shot was fired, and in 1967, construction activities and bioenvironmental studies in preparation for additional nuclear testing were started. Since the latter date, there has been continuous occupation of Amchitka by a population that has varied up to a high of nearly 800 people. Continuous AEC occupation of the Island ended in September 1973.

As part of the Long Shot program, a small bioenvironmental program was carried on by the University of Washington. It concluded that " . . . there was no damage to any population of organisms living on or near Amchitka Island as a consequence of the Long Shot nuclear detonation. The only dead or injured animals observed were two cod and three diving birds . . . " in Cyril Cove about 6500 feet (2 km) to the east-northeast of the Long Shot SGZ (Seymour and Nakatani, 1967). Other observable effects on living things were: tundra was cracked near SGZ, mud flowed out over vegetation, and tundra mounds were split to distances of several thousand feet (McKeown, USGS, priv. comm., 1967, Shacklette et al., n. d.). The basis for these conclusions was censuses of various kinds of wildlife; a search for dead or injured organisms immediately after the Long Shot detonation; live-box experiments with freshwater fish, marine fish, fish eggs, and crabs; and a postshot botanical survey of the area near surface ground zero.

The AEC program has supported radiobiological studies since 1943 in the days of the Manhattan project. Recent ambitious studies include work at the site of the proposed Chariot nuclear excavation experiment in northwestern Alaska (Wilimovsky and Wolfe, 1966) and study of the effects of radiation on a tropical rain forest in Puerto Rico (Odum, H. T., 1970). In 1966, the BMI Columbus Laboratories was managing a program of ecological studies in Panama for the AEC and the Atlantic-Pacific Interoceanic Canal Commission relative to the feasibility of constructing a new canal. They were asked to organize and manage studies at Amchitka as well. This program has continued to the present, albeit somewhat changed with time, and its results are the basis of this chapter.

The Amchitka bioenvironmental program is designed to predict, document, and evaluate the effects of AEC activities on the biota and the environment; to recommend measures for minimizing adverse effects; and to predict the radiological hazards to man that might result from food chains should there be an inadvertent release of radioactivity. The basic structure of the ecology has been investigated along the traditional lines of reconnaissance, collection and sampling, community studies, and interpretation. Effects were determined by observations before and after each shot, and in some cases by deliberate exposure of relevant organisms in holding pens and liveboxes. Where possible and appropriate, the measurements are quantitative, as in the chemistry and productivity of lakes. A part of the effort is to develop mathematical models to predict the prompt and long-term consequences of destruction of food supplies, or loss of part of a population, or introduction of radionuclides into the ocean.

The bioenvironmental program relies heavily on scientists from various universities and government laboratories.

6.2 SETTING

The landscape of Amchitka is barren but spectacular, an archetype of a maritime tundra regime. The physical environment is characterized by a narrow temperature range, seldom more than $10^{\circ}F$ per day, with nightly freeze and daily thaw in the winter; seemingly ever present winds, often of considerable velocity but without prevailing direction; an annual precipitation of 83 cm (33 in.) with rain every month of the year, although there is more from July to January; heavy fog and cloudiness, particularly in the summer growing season (Armstrong, 1971); low solar energy input, less than 60 kilocalories/cm^2/year, as compared with over 200 at NTS (Amundson, U. Tenn., priv. comm.); and igneous bedrock with retarded physical and chemical weathering in areas where peat accumulations over clayey soil serve as a protective mantle. There is no permafrost. The distribution of plants is largely controlled by drainage and wind erosion. In the mountain and plateau country of the western third of the Island, vegetation can be thick in stream bottoms, but becomes alpinelike and sparse in areas exposed to the wind. The eastern third of the Island is characterized by numerous shallow lakes and ponds with little or no drainage connections, and is everywhere covered by vegetation. This gives way in the higher central region, including the Cannikin site, to areas of more integrated drainage and greater wind erosion, with fewer lakes and with patches of bare gravel on ridges caused by diurnal freeze-thaw and high winds. The topography is gently rolling, slopes being covered with a crowberry-lichen-grass complex, and poorly drained lowlands typically with sedge and lichen.

The short, foggy summer and certain other factors result in little sexual reproduction in the higher plants; most plant reproduction is by vegetative means. A lack of terrestrial herbivores* and slow decomposition have resulted in large accumulations of standing dead material and a buildup of peat that is often several meters thick.

Natural revegetation is faster than in the Arctic, but depends strongly on drainage and is limited by a lack of nutrients. Berms around quonset huts from the 1940s are nicely covered with grass; but numerous pits dug for gun emplacements or lookout points remain full of water and show little sign of recovery.

*Other than rats and some birds.

The barrenness of the land is reflected in the fauna. There are only two land-dwelling mammals on the Island, rats and man. Fauna of lakes and streams live to a large extent on a detritus economy, the highest trophic level of residents being the Dolly Varden, stickleback, and sculpin. The only other fish found inland are a few silver, pink, and sockeye salmon which spawn in the early fall (Neuhold and Helm, 1968).

One hundred and three species of birds have been identified, some of them only very occasionally. Most species are water birds (Williamson et al., 1972). Birds of special interest are the Bald Eagle, endangered in the southern 48 states but common in Alaska, and the Peregrine Falcon, also endangered elsewhere. No Aleutian Canada Geese breed on the Island. This species is known to breed only on Buldir Island and has been exterminated from Amchitka and other Aleutian Islands, presumably by predation by introduced foxes. The Department of the Interior has considered Amchitka among several other islands as suitable for reestablishment of these geese and tried unsuccessfully to do so in the spring of 1971.

The sea about Amchitka is much richer than the land. The waters of the North Pacific Ocean and the Bering Sea adjacent to Amchitka are heavily fished at certain seasons of the year. The five species of Pacific salmon that migrate through the area are among the most important commercially. Chums and odd-year-run pinks that pass near Amchitka tend to go to Asia; sockeye and even-year-run pinks go to Alaskan streams; kings are uncommon, returning to the Alaskan mainland to spawn; the native streams for coho are not given. Salmon that spawn on Amchitka itself only number in the hundreds. Japanese are the only fishermen that take salmon on the high seas, but fishermen from all nations take salmon from their own inshore fisheries as the salmon return to their home streams for spawning. Near Amchitka, Russians and Japanese have taken ocean perch and other bottom fish in midyear in recent years. In isolated spots on Bowers Bank and near the islands, there are king crab, and a few American crabbing vessels now operate out of Adak during the season. The ship mentioned in Chapter 2 that took refuge at shot time behind Semisopochnoi was a crabber. Japanese and Russians have been harvesting whales in the western Aleutians until mid-fall. Fur seals pass through the Aleutian passes to and from their breeding grounds in the Pribilofs, with peaks in June and November. By terms of the 1911 treaty, they are not taken on the high seas. (Abrams et al., 1968)

Amchitka and other islands in the Aleutians are home to sea otters, sea lions, and harbor seals. The sea otters have made a comeback from near extinction 60 years ago and are at or near carrying capacity in the western Aleutians (Kenyon, 1969). As a result and in line with customary game management practices, the state of Alaska has been harvesting sea otters at Amchitka since 1962. More recently, with the logistic help of the AEC, the state has been transplanting sea otters back into depopulated portions of its former range. Over a thousand sea otters have been removed from the Amchitka population by these two means since 1967.

Immediately surrounding Amchitka, the rich algal flora (including extensive kelp beds) is a very significant component of the environment, providing food and shelter to a wide variety of invertebrates and habitat for sea otters and for fish such as rock greenlings and Irish lords.

6.3 MILROW

The biological effects of Milrow were small, especially as compared with the effects of site preparation and other operational activities. Because there was no release of radioactivity, all effects were due to ground and water shock and terrain changes. A few dead fish were seen near the shore, but not recovered, and there was no detectable change in fish stocks offshore. There was no discernible effect on any sea mammal population, even among 15 sea otters penned on the shore within 4500 feet (1410 m) of SGZ at shot time. There was a small uplift on a tidal bench on the Pacific coast about an acre in area, and shifts in the algal and invertebrate communities inhabiting it are still (mid 1973) taking place. About 10,000 m^3 (353,000 $ft.^3$) of rock and peat materials fell along the two coasts, but no eagle or peregrine nest sites were destroyed, and there were no detectable effects on bird populations. Subsidence about surface ground zero half drained two lakes that had not, however, borne fish. Somewhat further away, numerous stickleback were killed in two lakes, but no Dolly Varden. The stickleback in these lakes have since returned to near preshot densities. There were numerous tundra cracks and several tundra ruptures akin to the tundra mound cracked by Long Shot.

6.4 NONSHOT-RELATED EFFECTS

By contrast, the very presence of several hundred men on the Island preparing for this task has had its effect. The old military road network had to be renovated, and in the mountainous sections, entirely rebuilt. A new camp has been built, with associated water, sewage, and power systems. Old gravel pits have been extended and new ones opened. New roads have been built to the Milrow SGZ, to the Pacific beach at the site of a sea otter pen, and to a winch station for underwater cable on the Bering side. Cables have been laid, more often than not away from existing roadways. There have been several leaks of drilling mud into streams, killing the flora and fauna of those streams at least for a time, although recovery from the older spills such as in the stream draining the Milrow site itself is now nearly complete. Recreational fishing and walking the beaches has had a lesser impact. Overall, about 1012 acres of land have been disturbed in one way or another (AEC/NV, 1972). Some of this, of course, is redisturbance of land originally used by the military. Except near the Milrow and Cannikin surface ground zeros, these effects are much more obvious and aesthetically displeasing than direct shot effects.

6.5 EFFECTS ON THE SEA OTTER

The question of Cannikin effects on sea otter has been particularly sensitive because they have recovered from near extinction, and are lovely animals that seem to enjoy life and arouse interest and affection in most people who see them. Preshot predictions were that " . . . as many as 20 to 240 sea otters may suffer eardrum rupture, which could eventually lead to their death. Sea otter mortality of this magnitude should have negligible effects on the Amchitka sea otter population." (Kirkwood and Fuller, 1971, p. 26.) The basis for this prediction was an estimate of 100 psi overpressure necessary to cause eardrum rupture, as many as 1600 animals in the relevant areas on the two coasts, and as many as 15 percent diving at any one time (ibid., p. 18-19). As we shall see, this estimate was low as regards absolute numbers, though not as regards long-range impact.

A key question is how many of these animals there are about Amchitka. Wildlife counts are notoriously difficult and uncertain; they depend upon the season, seeing conditions, and the observer and the method he uses. Lensink (1962, p. 61) had estimated 4000 to 7000 in 1956 in the eastern half alone, Kenyon's 1969 monograph on the sea otter estimates the whole Island population at 2078 in 1959 and 1525 in 1965 (p. 150). Lensink's observations were made with binocular and telescope from the shoreline; his actual count was 2568 and he assumed he had seen half of the animals. Kenyon's observations were made from a DC-3 aircraft; his actual counts were 1560 and 1144; he assumed he had seen three-quarters of the animals.

Whole Island counts made since Kenyon's counts have been from a helicopter, with various observers at various times. (See Estes and Smith, 1973, for a resume.) Those in 1969 used a semiphotogrammetric technique (Stephan, 1971; Stephan and Mercier, 1972). These data are shown in Figure 26, without any estimated correction for the portion of the whole number seen. The scatter speaks for itself with respect to the difficulty and uncertainty of the counts.

In June 1971, the method of counting with a telescope from headlands was reinstituted by University of Arizona biologists, with the improvement over Lensink of using a helicopter to get quickly from point to point. Numbers thus seen were impressively higher than helicopter counts; repeated passes by both methods over the same areas on the same day indicate that shore-based counts consistently are a factor of two higher than helicopter counts. Thus, the total sea otter population about Amchitka appears to be about 7000 (Estes and Smith, 1973).

On Milrow there had been no observable effect on the sea otter population. The Cannikin effort was conducted by the University of Arizona's Cooperative Wildlife Research Unit. The preparatory work concentrated on behavioral studies. At shot time, the effort turned to local counts, intensive searches along the beaches for dead or dying animals, and autopsies of those found. (An attempt to use the EG&G airplane to

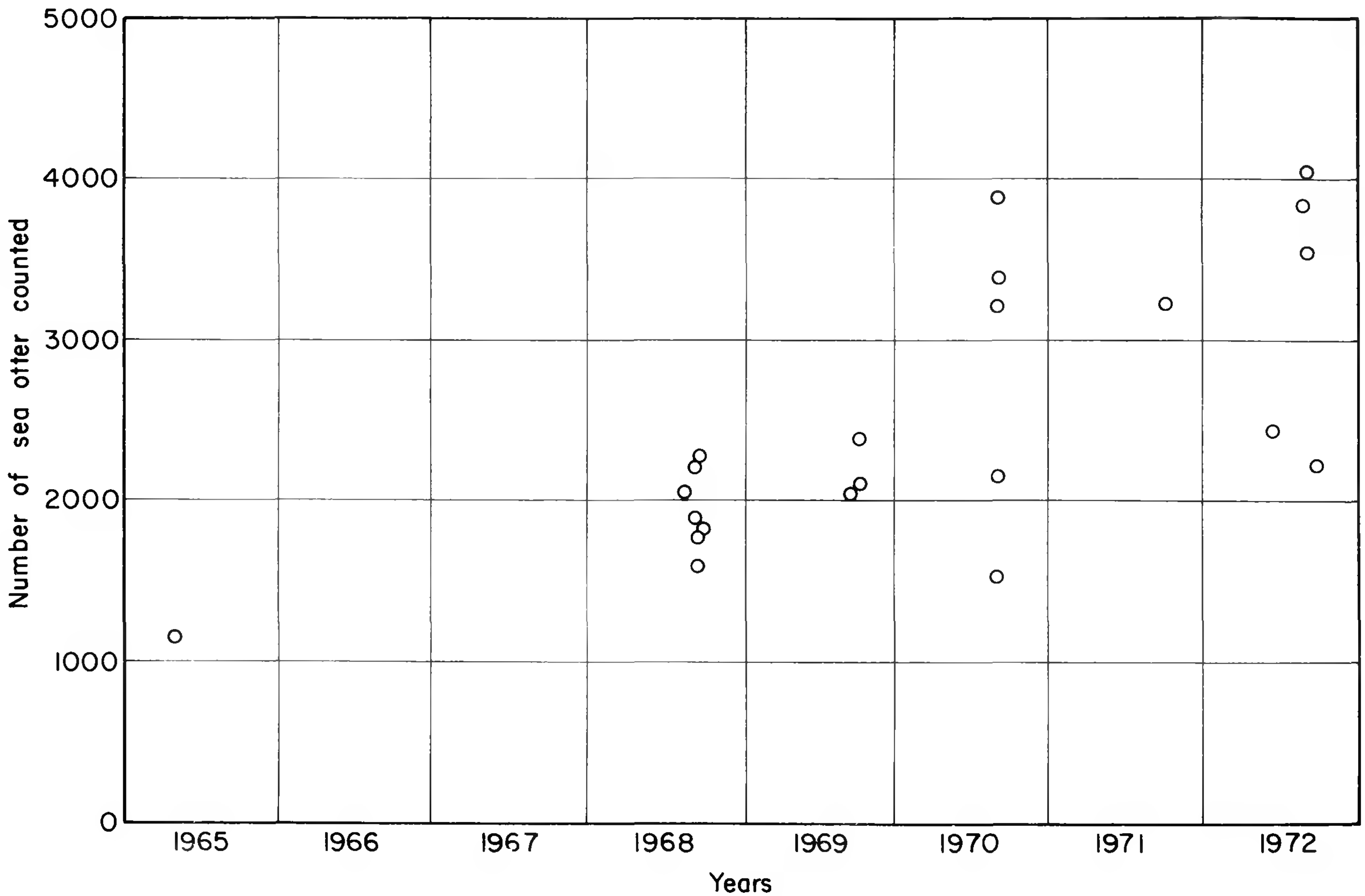

FIGURE 26. Sea otter counts around the whole of Amchitka.

photograph the number of sea otters hauled out on the beach at shot time failed because of poor weather. An aerial reconnaissance by helicopter within three hours after the shot also yielded no results.) Contrary to the Milrow experience, 23 dead, dying, or injured sea otters were found in the beach searches, as well as 4 seals, 16 birds, and several hundred fish. Data on the 23 sea otters are given in Table 2; places where they were found are shown in Figure 27.

Ten of 12 animals autopsied suffered massive pressure effects: severely hemorrhagic lungs, sometimes ruptured, hemorrhage along the vertebral column and within the spinal canal, and subdural hemorrhage on the brain. In some instances, there was fracture inward of the bones of the eye socket. The internal parts of the ears suffered varying degrees of damage. The abdominal viscera were little affected. Three of the ten had other injuries as well: in one, subcutaneous edema and ventral hemmorhage; in a second, a fractured skull; and in a third, external injury to the thorax and a fractured zygoma. The remaining two were found under fallen rocks. One had a crushed skull. The other had been caught in the hindquarters, with resulting rupture of abdominal viscera and severe hemorrhage in the muscles of the rear legs (Rausch, 1973).

These observations say clearly that a prediction based on delayed mortality from eardrum damage missed a dominant effect. Four of the ten animals autopsied that had suffered pressure-related injuries had intact eardrums. On the other hand, all 10 had massive lung hemorrhages, worse than had been observed on any but 2 of the 12 animals subjected to pressure tank tests before Milrow (Wright, 1971), and most appeared to have died immediately. Only two animals that might have been marginally injured were found. All this suggests that mortality was high in limited areas, and most other animals escaped unhurt. (The listing in Table 2 of two abandoned pups indicates a class of late deaths not foreseen preshot.) A possible cause of this all-or-none injury is explosive decompression associated with the bulk cavitation mentioned in Chapter 3, the only real inconsistency with this hypothesis being the orbital fractures seen in some animals (Rausch, 1973).

There is no rational basis to tell what fraction of the total these 23 constituted, except that clearly they were not all. The fact that more dead sea otters were found on the Pacific than on the nearer Bering coast indicates that wind and currents must have carried other carcasses away from where they could be found. It has also been suggested that waterlogging of floating animals, or the inherent lack of buoyancy of submerged animals may have hidden some carcasses, and, indeed, one such animal was recovered in a trawl on November 22.

In the impasse, we must turn on census methods, imperfect though they be. The region of Bering coast marked A in Figure 27 has been the site of a number of censuses, both shore and helicopter based. These census numbers, unadjusted for fraction seen, are plotted in Figure 28. The apparent decrease in numbers between June 1971 and late

TABLE 2--SUMMARY OF OBSERVATIONS ON 23 SEA OTTERS AFFECTED BY CANNIKIN

Date Retrieved or Seen	Location Pacific	Location Bering	Condition	Sex: Weight, kg	Comments
D-Day		x	Injured[a]	Female: 19.0[b]	Pressure-related injuries
D+1	x		Dead[a]	Female: 21.8	Pressure-related injuries Evidence of external trauma
D+2	x		Dead[a]	Female: 11.3	Pressure-related injuries
D+2	x		Dead[a]	Female: 19.0	Pressure-related injuries
D+2	x		Dead[a]	Male: 17.2	Pressure-related injuries
D+2	x		Dead[a]	Male: 20.4	Pressure-related injuries
D+2	x		Dead[a]	Female: 18.1	Fracture of skull
D+3	x		Dead[a]	Female: 20.8[b]	Killed by rockfall
D+3	x		Dead[a]	Female: 18.6	Killed by rockfall
D+3	x		Dead[a]	Female: 20.4[b]	Pressure-related injuries Evidence of external trauma
D+3	x		Dead[a]	Female: 17.2	Pressure-related injuries
D+3	x		Dead[a]	Female: 22.2[b]	Pressure-related injuries
D+3	x		Dead	- -	Carcass deteriorated; autopsy not feasible
D+4	x		Dead	- -	Caught on offshore rocks
D+4	x		Injured	- -	Crippled; not recovered
D+4	x		Abandoned	- -	Pup; not recovered
D+4	x		Injured	- -	Crippled; not recovered
D+4		x	Abandoned	- -	Pup; recovered but released
D+16		x	Dead	- -	Killed by pressure pulse in water; recovered by bottom trawl 2.5 km offshore
D+20		x	Dead	- -	Skeleton only; skull showed evidence of pressure pulse damage
D+20		x	Dead	- -	Skeleton only; skull showed evidence of pressure pulse damage
D+20		x	Dead	- -	Only part of skeleton found; cause of death not known
D+20		x	Dead	- -	Skeleton only; cause of death not known
Total	16	7			

(a) Autopsy performed (Rausch, 1973)
(b) Lactating

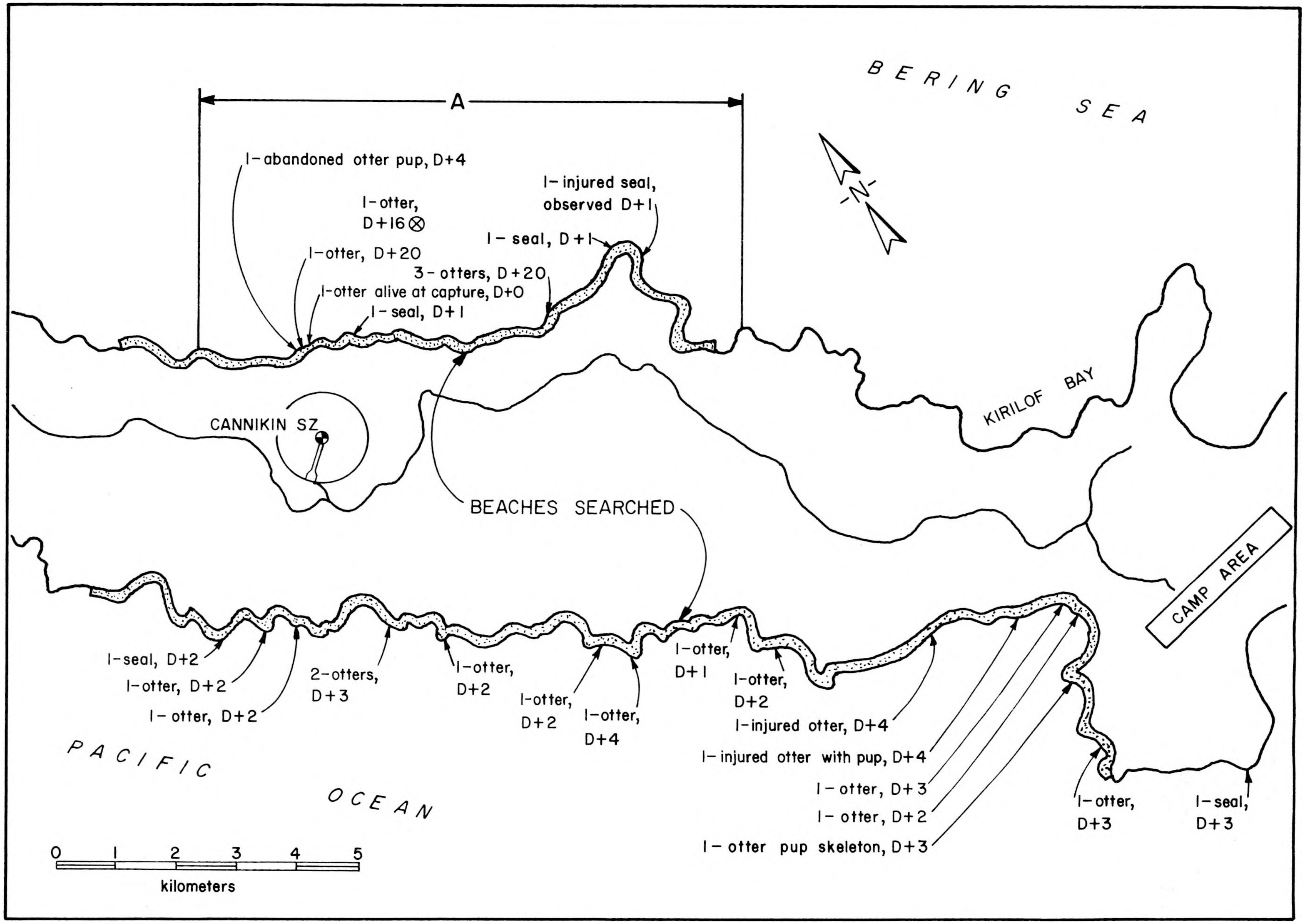

FIGURE 27. Locations of dead and injured sea otters and seals found during beach searches post—Cannikin. (Kirkwood and Fuller, 1972)

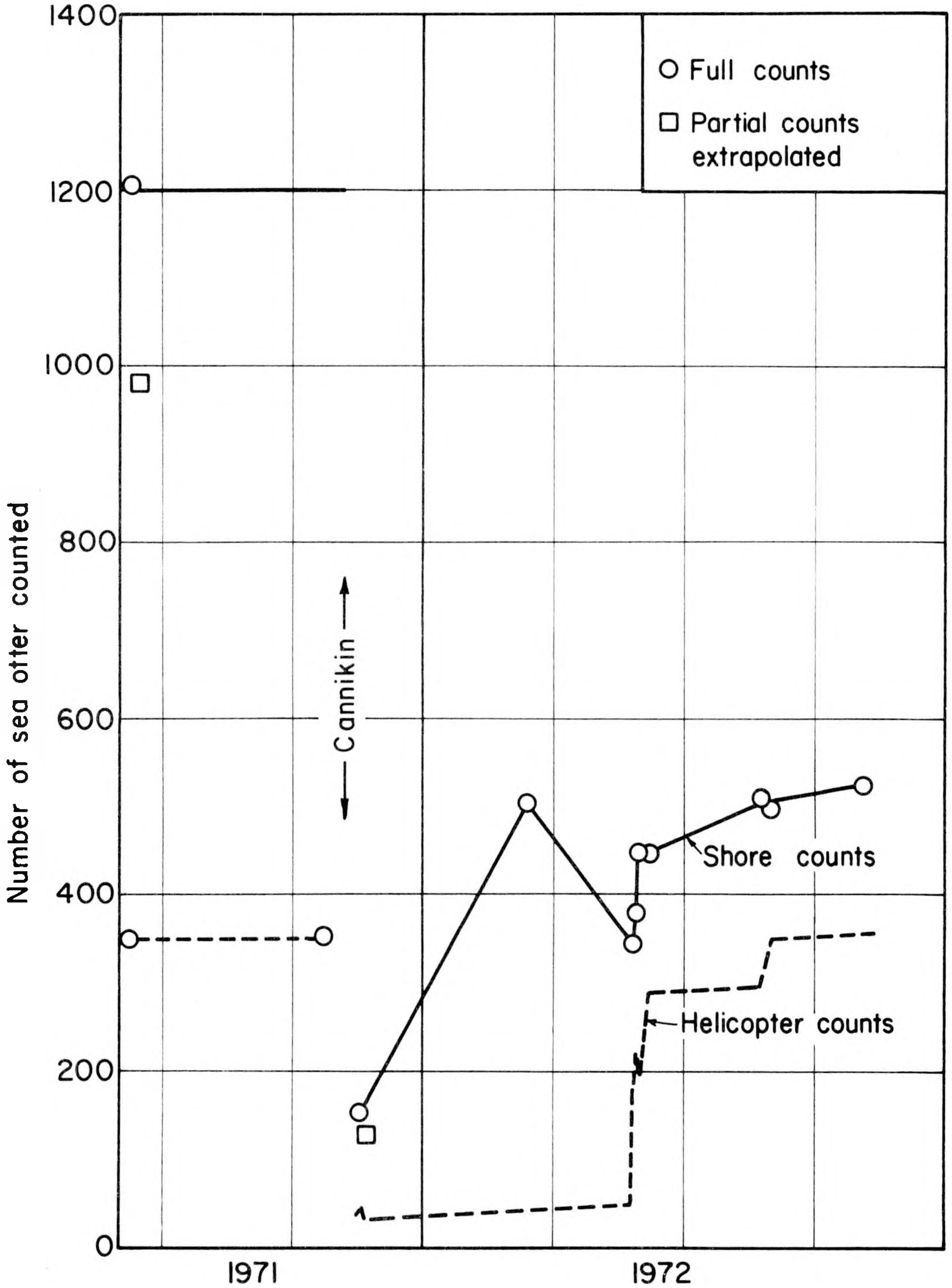

FIGURE 28. Sea otter counts in the area of the Bering Sea nearest surface ground zero by two methods.

November 1971 is very large indeed. However, the weather in late November 1971 was bad: the November numbers are given only because they are the only ones available from just after the shot. Counts in similar good weather to that in June 1971 were made in March, June, August, and November 1972. Taking the maximum numbers at each time, the reduction in numbers in the study area on the Bering coast appears to be about 60 percent or 700. It remains to be determined whether this decrease in numbers was due to Cannikin-caused mortality or whether other factors such as redistribution may have intervened. Redistribution should result in increased counts elsewhere, but counts in subareas at the edges of Area A have not increased. In contrast to this, the results shown in Figure 26 indicate that on a whole-Island basis, there has been no net reduction of numbers detectable by present census methods. Further, scuba examination of subtidal and benthic fauna has not revealed the magnitude of damage and resultant limitation of carrying capacity opposite the Cannikin site that would be necessary to force redistribution. Nevertheless, the reduction in numbers of sea otter seems real. It is probable that we shall never know how much of it is due to death and how much to other factors. In either case, we must assume that the changes are a direct consequence of Cannikin.

It thus appears that the prediction of 20 to 240 kill was low in absolute terms. In relative terms, the prediction of a kill of 240 out of 4000 was a prediction of 6 percent casualties; the possible casualty level of 700 out of 7000 is 10 percent, again higher than prediction although not so much so. Nevertheless, for various reasons but especially because the Island's sea otter population was already pushing its limit, as indicated inter alia by reduced size and weight of Amchitka sea otters relative to those in areas of sparse population (Kenyon, 1969, p. 21-23), all authorities agree that there has been no permanent harm done to the Amchitka sea otter population (Sea Otter Panel, 1973; Estes and Smith, 1973).

As respects the other two species of sea mammals that are found at Amchitka, four seals and no sea lions were found dead after Cannikin, the former with the massive lung hemorrhages indicative of overpressure pathology. Although no detailed censuses have been taken, it has appeared to competent observers that there have been no changes in gross numbers of either species at Amchitka.

6.6 EFFECTS ON OTHER MARINE LIFE

Sea otters have received the most public attention from among the varieties of life that live in the sea surrounding Amchitka, but other life, especially fish, are equally important in all respects except the aesthetic. Indeed, it is safe to say that almost all life on Amchitka is dependent on the sea and its resources. No local resources are presently being exploited, the nearest approaches being the harvesting of sea otters for fur that the state of Alaska has occasionally carried out, a seasonal crab fishery operating out of Finger Cove, Adak, and a small potential for halibut. The University of Washington has done exploratory fishing nearby, but neither their results nor those of the Bureau of Commercial Fisheries and its successor, NMFS, are definitive about the size of the fish stocks nearby.

The University of Washington's Fisheries Research Institute (FRI) has carried out the bulk of the investigations on marine resources about Amchitka, supplemented by scuba observations by NMFS. As to fish, their research has consisted of exploratory fishing with various types of gear operating at various depths; examination of the interdependence of the various species with each other and with other marine biota, particularly by examining stomach contents and natural associations; and habitat studies. The FRI studies have also included studies of inshore and intertidal communities. The results of these studies are amply reported in the literature (e.g., Burgner et al., 1968, 1969, 1971; Burgner and Nakatani, 1972; and various articles in BioScience 21, No. 12 (1971)).

To determine Cannikin shot-time effects, FRI made pre- and postshot fish catches in nearshore and offshore waters, searches along beaches by helicopter and on foot looking for dead or dying fish, and pre- and postshot examination of specific study plots on the intertidal bench in the Bering Sea off the Cannikin site. Their plan also included ten cages at five positions in the Bering Sea, each of which would contain fish such as greenling, cod, or Dolly Varden, and would be instrumented to measure the pressure pulse incident there. However, the day of the shot was preceded by several days of bad weather that culminated with a violent storm on the day before Cannikin. This storm forced the abandonment of the cages except for one string of two cages emplaced in Constantine Harbor about 15 km (9.3 mi.) from SGZ. This was so far from the shot that nothing happened to the fish in them, except for one cod which had a bubble in its right eye and appeared to have some difficulty in maintaining equilibrium. The fact that only one out of ten cod (34 fish altogether) had such symptons suggests damage during handling, probably during setting or retrieval operations, rather than shot-caused damage.

The beach searches produced the most immediate results. Dead fish found consisted of 277 rock greenling, 7 Pacific sandfish, a long-nose lancet fish, a great sculpin, 8 skeletons of Pacific cod, and the skull of an unidentified rockfish. Except for the cod skeletons and the rockfish skull, all were found on the uplifted Bering tidal bench described in Chapter 2. These fish are ones that can normally be expected to be found in shallow water: the lancet fish being one often driven ashore in storms, the sandfish commonly burrowing into intertidal sand, and the greenling being a fish that characteristically forages in the shallow water that lies over tidal benches at high tide (Kirkwood and Fuller, 1972).

Of the 277 greenling recovered, 23 were autopsied. About half had internal hemorrhages; the rest had no evident injury and are assumed to have suffocated on being stranded out of the water (Nakatani et al., 1973, p. 14-15).

The eight cod skeletons and the rockfish skull, all freshly cleaned by amphipods, were found on Pacific beaches. Since such finds are uncommon, they, too, are almost surely Cannikin-caused casualties. The preshot prediction had been that "some fish, mainly members of cod and rockfish species, will probably be killed in the marine environment." (Kirkwood and Fuller, 1971, p. 26). The reason for the emphasis on cod and rockfish is that they are species with closed air bladders and hence great suspectibility to shock pressure damage, as contrasted to salmon and Dolly Varden which have air bladders that open into the mouth, or to halibut and sole, which have no air bladders at all.

As with sea otters, it is probable that only a fraction of the fish kill was found in these beach searches. One notes that just as more sea otters were found dead on the Pacific side than on the Bering side, fish such as cod which might be expected to be killed away from shore were found only on the Pacific side, presumably because there was a wind and tide set towards that coast. Again we must turn to other sampling to extend the picture.

Inshore sampling by trammel nets only caught rock greenling in numbers sufficient to give pre- and postshot comparisons. After shot time, their populations dropped, then recovered to a level that appears to be somewhat lower than preshot, though this is hard to ascertain because there were only two comparable samples taken. The postshot population was of the same size distribution as preshot; this implies the kill mechanism was nonselective, and that any postshot immigration from adjacent areas was of the same general size distribution (Nakatani et al., 1973, p. 12-14).

Offshore fish populations were sampled pre- and postshot by bottom and midwater trawls and by salmon longlines. In the bottom trawls, only rock sole were caught in numbers sufficient for statistical analysis, and these did decline from 100.70 ± 86.14 to 8.73 ± 28.81 (sic, Nakatani, priv. comm.) fish caught per hour of trawling. Seasonal movement was found not to be a probable reason for the decline. Pre- and postshot salmon catch data were not comparable because the species composition changed: sockeye were not caught before the test, but only sockeye were caught after the test. In any case, the likelihood of damage to salmon was remote because of their small numbers off Amchitka in the fall and their tendency to stay far offshore (Nakatani et al., 1973, p. 6-9; priv. comm.).

FRI biologists conclude that this reduced catch of rock sole per unit effort and the dead cod found on the Pacific beaches indicate that some thousands of bottom fish may have been killed.

In the intertidal zone, it necessarily follows from the unexpectedly large uplift along the Bering Coast that there were larger than predicted consequences to the life inhabiting that zone.

Intertidal life on Amchitka, as elsewhere, is highly specialized and adapted to tidal fluctuations of water cover and exposure to the air.

This results in a changing set of communities as one walks out from the shore, each characterized by different brown algae, from Fucus, to Halosaccion-Hedophyllum, to Alaria, to Laminaria (Burgner et al., 1969). An uplift of a meter means that these algae must shift outward, and since the flat bench is now entirely out of the water for a 2 km (1.2 mi.) stretch of coastline and has been raised to a lesser extent for several kilometers on either side of that, the new habitation zones are necessarily narrower. Subtidal life now lifted into the intertidal zone, on the other hand, will be much less affected by the uplift.

Of 40 quarter square meter plots established on the bench before Cannikin, 7 were buried by rockfall. After Cannikin, 11 additional plots were added in subtidal areas uplifted into the intertidal zone. In the remaining original areas, die-off began very soon after the shot. Very obvious were the effects on corraline algae, an encrusting growth that is a light pink when alive and vigorous, but turns white when it dies. Normally, this lines the edges of rock pools and surge canals in the intertidal bench. A month after the uplift, these edges appeared snowlike in their whiteness. On top of the tidal bench, the low algal growths had changed from their normal browns, greens, and dull reds to black, and were beginning to die off, except where spray retarded the die-off. Though less affected, these areas, too, were deteriorating. As of October 1972, only 4 percent of the original plots at the intertidal area having the greatest degree of uplift and about one-third of the original plots at an area of lesser uplift had live algae on them. These species of algae were ephemeral, annual species that had replaced the original populations that had died off. Algal succession to intertidal species was starting in the 11 new plots with most of the original species dead (Nakatani et al., 1973; priv. comm.).

Early stages of recolonization are already in evidence on the new rock surfaces exposed where rocks have broken off the vertical edges of some surge channels. On these, a dense mat of new growth can often be seen. This contrasts with areas on which preevent algae are dying or absent; there is little or no new growth in such areas.

The invertebrate animal life of the intertidal zone has followed the fate of the plant life on which it depends. Thus, for instance, the uplift meant greater exposure of limpets on the tidal bench. Black Oystercatchers feed on limpets, and their increased predation was indicated by the large number of limpet shells overturned and empty on the beach. In late February 1972, I still saw exceptional numbers of these birds in the uplift area, though in fall 1972, their numbers were reported to be smaller than preshot. The narrowing of intertidal algal habitat implies a reduction in the number of macroinvertebrates; and this, in turn, is likely to have an effect on nearshore fish populations, particularly greenling.

Subtidal and near inshore waters have been explored by scuba divers from the NMFS. Their observations on sea urchin populations have shown no change in numbers. However, they have found several areas of physical damage on the sea floor, principally in the western half of the damage study area. Typically, these consist of spalling from steeply sloping or vertical surfaces of prominent bedrock outcrops. They are clearly new, Cannikin-caused breaks, as evidenced by bare rock surfaces in regions where vegetative cover should be everywhere, and by kelps and other algae dying in shaded areas where insufficient light penetrates to support that kind of plant life (Figure 29).

Undersea, too, the newly exposed mineral surfaces are beginning to be recolonized. The mobile invertebrates such as sea urchins come first, then minute pink spots of coralline algae become visible, then the kelp Alaria, and then the kelp Laminaria. NMFS biologists estimate that within a few years, these new surfaces will be so encrusted with organisms that they will be indistinguishable from undisturbed areas (Merrell and Barr, NMFS, priv. comm.).

A final effect on the marine habitat is that due to the break of a mud pit at D-site, 7.5 km (4.7 mi.) northwest of Cannikin SGZ. It is estimated that some 30,000 barrels (4800 m^3) of mud and water escaped before the breach was closed, flowing down Falls Creek to the sea. This is by far the greatest mud spill that has occurred on Amchitka during the AEC occupation. The flow of this mud to sea could be seen for several weeks as a plume in the ocean outlining the normal outflow of the creek. Later, on February 27, 1972, an additional 20,000 barrels (3200 m^3) were released to the creek to reduce the volume of stored mud (Cater, Fish & Wildlife Service, quoted in Helm & Valdez, 1973, p. 10). The effects of this material on local marine life have not been determined, although they cannot be but deleterious.

6.7 EFFECTS ON TERRESTRIAL VEGETATION

Landform and surficial changes we took up in Chapter 2, and these necessarily have effects on the vegetal cover of Amchitka. These effects are under study by the University of Tennessee. The immediate effects were most prominently loss of grassy cover on beach slopes, as shown in Figures 7 and 8, as well as some suppression of growth where blocks of peat have been overturned and thrown about in several regions of tundra rupture and at the larger fault shifts about SGZ. Long-term shifts in vegetation patterns are to be expected from changes in drainage and from flooding by Cannikin Lake, but it is much too early to know what these will be. Even around Milrow where some of these same effects occurred three years ago, changes are hardly evident, one of the earlier signs being grass coming up plentifully on overturned peat blocks (Amundsen, U. Tenn., priv. comm.).

A year of weathering and possible change has occurred since Cannikin. On the beach and rocks below some of the slide areas on the Bering

FIGURE 29. Rockfalls along the face of an underwater escarpment. (Photo: Barr, NMFS)

coast, one can see where fine silt is coming down. A few slide paths that originally looked bare have turned out to have been merely dirt-covered grass and as this washes off, there is an appearance of re-greening. In numerous places, there were multiple breaks and tears, and rhyzomes of Elymus grass are sending up new shoots. Nevertheless, the general impression is that these slopes will only revegetate slowly.

One subtle effect of Cannikin is to be found on crowberry (Empetrum) covered slopes within a kilometer south of SGZ. One sees low (15 cm--5.9 in.) ridges of crowberry oriented down slope. If one pulls on the tops of this vegetation, it feels loose below as if one were pulling up on a fold in a blanket, as if there were numerous sub-surface root breaks. In some instances, a strip of material has been ejected wedgewise along the axis of these ridges (Amundsen, ibid.).

Generally, however, any changes in the distribution of vegetation as a result of Cannikin have yet to occur.

6.8 EFFECTS ON FRESHWATER PONDS AND STREAMS AND FISH IN THEM

The freshwater ecology on Amchitka has been studied by BCL scientists as respects limnology (the study of physical, chemical, and biological factors in fresh waters) and by Utah State University scientists as respects the higher trophic levels of life, especially freshwater fish.

In Milrow, the principal limnological effects, in addition to lake drainage and perturbations of stream flow, were that one lake (and not the closest one at that) had a 25 cm (10 in.) drop in level, a 15 percent decrease in alkalinity, a decrease in zooplankton, and an increase in suspended organic material. On this basis, Cannikin effects were predicted to be small, the only specific prediction being that plankton abundance might be changed in some lakes near SGZ (Kirkwood and Fuller, 1971, p. 26).

As discussed in Chapter 4, there were a number of lakes fully or partially drained as a result of Cannikin, and White Alice Creek ceased flowing until Cannikin Lake filled in late November 1972. As to the more strictly limnological effects, the changes expected would have been subtle, and whatever may have been strictly shot related was obscured by the severe storm that struck Amchitka just before the shot.

Changes in lake chemistry were almost random: pH changes of ±0.55 units, with little relationship between changes and distance from SGZ. Two lakes within 1.4 km (4590 ft.) (DH and DO, see map in Figure 15) increased in alkalinity by about a factor of two. Suspended organic matter increased from mid-October to mid-November by an average third; with close-in lakes increasing more than this (3.4 to 9.9 mg/ℓ) and more distant ones decreasing (from 14.0 to 6.5 mg/ℓ). To say that these changes were Cannikin caused is problematical: the storm and seasonably poorer weather were enough to stir the bottom of lakes. Nevertheless, the close-in increases in alkalinity and suspended matter are probably real and event related. As to phyto- and zooplankton, no meaningful results emerge (Birch, 1973).

Thus, limnologically speaking, any changes in surviving lakes were little more than those characteristic of storms such as occur several times each winter. Studies of Cannikin Lake are still underway and have produced no results yet.

Freshwater fish on Amchitka are limited to six species: Dolly Varden char (Salvelinus malma), three-spined stickleback (Gasterosteus aculeatus), Aleutian sculpin (Cottus aleuticus), pink or humpback salmon (Onchorhyncus gorbuscha), silver or coho salmon (O. kisutch), and red or sockeye salmon (O. nerka). The greatest in number are the stickleback; the greatest in biomass are the Dolly Varden. Sculpin are uncommon. The three species of salmon spawn in small numbers in Amchitka streams, their young returning to the sea according to the habit of each species (Neuhold and Helm, 1968). Pinks are the most common salmon: in 1970 they spawned in 21 of 30 streams with an estimated total of 674. In 1971, an estimated 100 fish used only four streams. In 1972, an estimated 743 fish used 12 streams (Helm and Valdez, 1973, priv. comm.). It is well known that pink salmon have a strict two-year life cycle (Bailey, 1969) so that this pattern of alternate years of abundance is not unexpected. Silver salmon are less common at all times; in 1970, they used only five streams on Amchitka. Red salmon are rare.

Milrow effects on freshwater fish were greatest among stickleback. An estimated 85 percent and 50 percent of their numbers were killed in two lakes within a kilometer of SGZ, mostly from pressure effects though also partly from being thrown out onto the banks. Sticklebacks in streams suffered similar fates, in smaller percentages. Dolly Varden at similar locations suffered no pressure casualties, though some were killed by being stranded out of water. Therefore, the Cannikin predictions were that "Dolly Varden and salmon in freshwater should not be harmed, except for a few individuals that may be tossed out of water," and that "stickleback may be killed or injured in lakes near Cannikin SGZ" (Kirkwood and Fuller, 1971, p. 26).

The shot-related Cannikin program carried on by Utah State scientists consisted of 23 cages holding stickleback or Dolly Varden in various ponds and streams, 16 salmon-egg-holders in four streams, and pre- and postshot seining and other observation at almost every close-in pond and stream. This experiment was another one adversely affected by the preshot storm. For instance, all of the stickleback in 7 out of 15 pens died before Cannikin, probably as a result of being beaten against the walls of the pens. Two-thirds of the fish in another pen died before the shot, and a ninth pen was found upside down with the lid off and the fish gone.

Examination of the fish in the remaining pens and of the lakes and their surroundings has led to an estimate of 10,000 stickleback and

700 Dolly Varden killed as a result of Cannikin. Seventy-two percent of these were the result of four lakes being drained. Twenty-seven percent, all stickleback, died of pressure effects, the evidence of this being internal hemorrhages, ruptured air bladders, and disrupted kidneys. A small number, 1 percent of the total, died from being thrown out of the water. The maximum proportion of stickleback kill was 15 percent in pond DK (Kirkwood and Fuller, 1972; Helm and Valdez, 1973).

Not all of the salmon-egg-holders put in the streams survived the physical effects of the shot; four broke and lost their contents. In the remaining 12, all eggs were alive on recovery three days after the shot. Hatching tests on survivors indicate a very slight tendency--and only significantly so at a low confidence level--for a smaller hatching success on eggs that had been closer to SGZ. These closer eggs also had a tendency to die before hatching or to produce deformed fry, symptoms typical of eggs affected by shock.

Thus, the effects on freshwater fish near the Cannikin SGZ were real. The populations that used to be in the drained lakes are, of course, gone forever; however, from the fact that the two lakes that suffered large percentage stickleback losses on Milrow have essentially recovered (Helm and Valdez, 1973, p. 9), we presume that the Cannikin-affected populations in surviving lakes will also recover soon.

Cannikin Lake is new, and the development of its flora and fauna is a matter of great current research interest, but no results are available yet to report.

As to drilling-mud-contaminated streams, the one of longest record is Clevenger Creek, which drains the Milrow SGZ area; it suffered two mud spills before Milrow. This stream was repopulated from unaffected tributaries and from the sea, and is showing a pattern of recovery, even though new oozes of mud came out of the peat as a result of the Cannikin ground shock. For instance, pink salmon and Dolly Varden spawned there successfully in 1970. In the lower reaches of Falls Creek, the stream effected by the Cannikin-caused spill and later deliberate release, Dolly Varden and some invertebrates survive, but the more sensitive mayflies were absent in June 1972. The upper portion of Falls Creek was, like other streams after spillage, devoid of life. However, in a test with penned fish in the spill lake just outside the dike, the fish survived. The fate and time scale of recovery of this stream have to await final disposition of the mud remaining in the D-site mud pits.

6.9 EFFECTS ON BIRDS

The first stated purpose for setting aside the Aleutian Island in 1913 as a wildlife refuge was "as a preserve and breeding ground for native birds." Birds remain a primary refuge value of these islands, especially now that the fur seal and sea otter have recovered from the threat of extinction.

Avian investigations have been undertaken on Amchitka by scientists from the Smithsonian Institution and Brigham Young University. They have thus far identified 103 species of birds on the Island, some permanent residents and some accidental visitors with affinities all about the Pacific Ocean. These include two birds, other subspecies of which are on the Secretary of the Interior's list of rare and endangered species: the Alaskan or Northern Bald Eagle, Haliaeetus leucocephalus alascanus, and Peale's Peregrine Falcon, Falco peregrinus pealei. (The endangered subspecies are H. l. leucocephalus, F. p. anatum, and F. p. tundrius.) One of the non-shot-related findings is that Amchitka peregrines are much less affected by the worldwide dispersion of DDT and consequent eggshell thinning than even peregrines from mainland Alaska (Cade et al., 1971). The basic research conducted has covered species identification, population counts, breeding biology, feeding ecology of selected species, and relation to habitats.

The principal hazard to bird populations from nuclear testing at Amchitka was believed to be the effect on cliff-nesting birds' nest sites. On Milrow, a falcon eyrie about 4 km (2.5 mi.) from SGZ was first thought destroyed, but later found intact. This eyrie was then occupied normally the following spring. The predictions for Cannikin were, therefore, for minimal damage even though a number of eagle and falcon eyries were within 8 km (5 mi.) of SGZ, and for no measurable change in population density of any species of bird (Kirkwood and Fuller, 1971, p. 25). The shot-related program consisted of searches for dead birds, postshot examination of nesting sites, pre- and postshot censuses of selected species of birds, and study the following spring of the nesting success of possibly disturbed birds.

The beach walks already referred to found 15 dead birds as well as sea mammals and fish. A dead bird was also found on an inland lake, and two more on the beach after the intensive search was over. Sixteen were autopsied. One had died of natural causes; eight from pressure effects, as evidenced by severely hemorrhagic lungs with some bleeding from the ears; seven from acceleration effects, as evidenced by fractures of the legs, ribs, and spine, and macerated lungs (Rausch, 1973). These 18 were of the following species:

	Death			
Species	Natural	Pressure	Acceleration	Total
Harlequin Duck	-	2	8*	10
Pelagic Cormorant	-	2	1	3
Horned Grebe	-	1	-	1
Greater Scaup	-	1	-	1
Oldsquaw	-	1	-	1
Common Murre	-	1	-	1
Thickbilled Murre	1	-	-	1
Total	1	8	9	18

*Two not autopsied.

It was the Greater Scaup that was found on a lake (DP, see map, Figure 15), which is consistent with its normal preference for the larger and deeper freshwater lakes (Williamson et al., 1972, p. 14). The other species, with the possible exception of the Horned Grebe, normally are found in the marine littoral habitat, which is to say in nearshore waters. The food habits of these birds are generally consistent with the manner of their deaths. Thus, for instance, Harlequin Ducks principally eat amphipods and isopods found on the reef, while Pelagic Cormorants are diving fish eaters (Williamson and Emison, 1969; Williamson et al., 1972). No dead terrestrial birds were found although there was an unconfirmed report of three about a kilometer west of SGZ.

Of the 16 eagle and 3 falcon eyries within 8 km (5 mi.) of SGZ, 6 eagle eyries and 2 out of 3 sites at a falcon eyrie at Petrel Point were destroyed (Figure 30). In addition, the falcon eyrie 10 km (6.2 mi.) east that had been feared lost from Milrow was further damaged. In spring 1972, it was found that most such displaced breeding pairs tried to reestablish their nests in nearby places and in some instances successfully. This was expected of eagles, which customarily change nest sites from year to year, but was found to be so for falcons as well. A surprising result was that in one or two instances, new sea stacks were formed. Spike ridges broke out in the middle, leaving a patch of grass-covered peat on an isolated rock, which is to say a new stack. Another point of interest is that there were more pairs of eagles attempting nests in 1972 than ever before, 68 pairs (Williamson et al., 1973; priv. comm.).

Censuses showed no population changes not accountable for as normal seasonal changes. There were apparent changes in distribution: the transiently greater and now smaller numbers of Oystercatchers in the uplift area, a decrease in the number of gulls, and an increased number of Cormorants there. These are not considered significant changes.

6.10 SUMMARY

A number of the biologists' shot-related activities were impaired by the preshot storm, and, hence, had less than desired success in their mission. Nevertheless, these conclusions appear to be justified:

1. Since there was no release of radioactivity, there were no effects of radioactivity on the biosphere. All effects seen were the results of ground shock, water pressure, and surficial changes in land forms.

2. Twenty-three dead or dying sea otters were seen and/or recovered. Autopsies of 12 indicate as a major cause of death massive intrathoracic hemorrhages.

3. Sea otter numbers in the local area of the Bering Sea adjacent to Cannikin have decreased about 60 percent, a considerably

FIGURE 30. Sea stack where an eagle eyrie was lost. On the bluff at the right is archaeological site 32, partially excavated in the summer of 1971. (Photo: Pan Am C3640)

greater decrease than predicted. Around the whole Island, there has been no net reduction in numbers detectable by present census methods.

4. New census methods imply that there are twice as many sea otters around Amchitka as had been previously assumed.

5. About 300 dead fish, mostly rock greenling, were found on the uplifted tidal bench near Cannikin, some killed by pressure effects, some by being stranded out of water. All were of species that can normally be expected to be found in shallow water.

6. Decreased catches of rock greenling and rockfish, and unusual finds of cod skeletons on the Pacific beach, indicate that some thousands of bottom fish may have been killed nearby.

7. The gross uplift of 2 km (1.2 mi.) of tidal bench and lesser uplifts beyond has caused a die-off of the algal cover and a death or migration away of the invertebrate fauna associated with those algae. On surfaces newly bared by rock breakage, recolonization is evident.

8. Underwater rockfalls have been observed. The new surfaces are being rapidly recolonized, while growth on newly covered or shaded surfaces is dying.

9. Adjustments in vegetation cover will be required because of the cracks, faults, and turf slides caused by Cannikin; but progress is too slow to be seen yet.

10. No significant limnological changes have been detected in Island ponds and streams.

11. An estimated 10,000 stickleback and 700 Dolly Varden were killed, most of them as the lakes they lived in were drained, some (all stickleback) from pressure effects, a few from being stranded out of the water.

12. Eighteen dead birds were found, all water birds. Apart from one dead of natural causes, half died of pressure effects, half of acceleration effects.

13. Six eagle eyries and two out of three sites at a falcon eyrie were destroyed. Most of the displaced breeding pairs tried new nearby sites in spring 1972, some successfully.

14. The effects of turf slides on slope-nesting birds have not been determined.

15. No significant effects on populations of any species of bird detectable by census techniques have been found.

CHAPTER 7

SEISMIC EFFECTS

7.1 GEOLOGIC AND TECTONIC SETTING AND HISTORY

Amchitka Island is in the southernmost part of the Aleutian arc. Throughout most of its length, this arc consists of a mountainous ridge of volcanic materials flanked on the north by a chain of active and quiescent volcanoes, and on the south by the submarine Aleutian Terrace and Trench.

The Aleutian arc is one of the earth's major structural features and is very active seismically, whereas the Pacific Ocean to the south and the Bering Sea to the north are essentially nonseismic. The high seismic activity in the Aleutians--and along most other shores of the Pacific--is generally explained by plate tectonics. This term refers to the spreading sea floor model in which hot plastic rock rises to the surface along a system of midoceanic ridges in the east-central Pacific, shouldering aside the older crust. As a result, the North Pacific Ocean floor slides as one continuous plate toward the northwest at a rate of about 4 cm per year, impacting at the opposite edge along the Aleutian chain, the Kamchatka Peninsula, the Kurils, and the islands of Japan. Arriving there, the moving crustal material turns downward and is reabsorbed into the underlying mantle, a process accompanied by the buildup and release of enormous strain energies. The Aleutians thus override the Pacific plate and are separated from it by a fault passing under Amchitka and the other islands (Isacks et al., 1968; Stauder, 1968).

The pattern of earthquakes and their aftershocks and evidence from marine geophysical surveys indicates that the plate movement associated with the Aleutian thrust fault is erratic, with motion first in one place and then another. Individual subplates are in the order of 500 miles (927 km) wide, and are separated from each other by transverse faults. Amchitka Pass, just east of Amchitka, is apparently a boundary between such plate sections, interpreted by Stauder (1968, 1972) as a transform fault, and said by Anderson (1971) to be related to the Bowers Ridge in the Bering Sea, which may be an old and no longer active island arc.

Amchitka itself is cut by numerous lesser transverse faults, trending northeast-southwest and dipping nearly vertically. Although these show vertical displacement of as much as 4000 feet (1.2 km) stratigraphically (the Rifle Range fault, 1.25 km (4100 ft.) southeast of Milrow and 9 km (5.6 mi.) from Cannikin), the geological indications are that there has been no appreciable movement on these faults since the late Pleistocene (Carr et al., 1971).

The recorded seismic history of the Aleutians goes back 70 years, but the earlier part of the record is not complete as regards smaller earthquakes because there were few seismographs in existence then, and those few were quite distant from this part of the world. Figure 31 shows the location of recorded earthquakes in Alaska of magnitude six or greater for the period 1899-1964. These included one of magnitude eight in 1906 just south of Amchitka. Of special interest also is Amchitka Pass, at longitude 179° to 180° W. This small area is an historic source of earthquake sequences. The record includes quakes in this area as early as 1912, a group of closely spaced quakes in April-June 1955, another in March 1957, another in August-September 1962, and a sequence which started in May 1969.

7.2 NTS EXPERIENCE

Recent experience has made it clear that all large underground nuclear explosions are followed by small aftershocks. Although this fact was recognized as far back as Press and Archambeau (1962), general awareness only dates back to the Boxcar event of April 1968. Since then, the matter has received extensive coverage at technical meetings and in the literature. At NTS, the largest aftershocks have been one or two units of magnitude less than the magnitude of the shot itself. Typically, aftershocks start off at a high rate immediately after detonation, then slow down, and also often migrate away from the shot point. Aftershocks seem to be associated with local geology in that they lie in patterns aligned with known or suspected faults. All aftershocks are very shallow. Aftershocks at the shot point itself are attributed to cavity collapse, those away to release of tectonic strain energy. The release of tectonic strain is also evidenced by surface fractures and displacements that may occur thousands of meters from the explosion and that are unequivocally related to natural preexisting faults. Repeated shots in the same area give fewer and fewer aftershocks, and less and less surface cracking.

A good deal of attention has also been given to the accompanying strains. Typically, these are a superposition of a sudden step and then a relaxation to a new strain. The step is usually attributed to tectonic adjustment, the slowly changing or quasistatic strain to the pressure in the underground cavity formed by the explosion. Asymmetry in strain is the rule, and is attributed to shear displacements at the source.

Underground nuclear explosions produce seismic signals detectable at very large distances, but which differ from earthquake signals. Explosions generate weaker surface waves than do earthquakes. In other words, surface and body wave magnitudes (M_s and m_b)* are nearly the same for earthquakes, but surface wave magnitudes from large explosions are 1 to 2 magnitude units less than body wave magnitudes (Liebermann and Pomeroy, 1969). Such distinctions are used in distinguishing earthquakes from explosions (Evernden, 1969a).

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*Body wave magnitudes are measured near 1 sec period; surface waves near 20 sec. The magnitude is the logarithm to the base 10 of the amplitude, adjusted for distance from the source and for station biases.

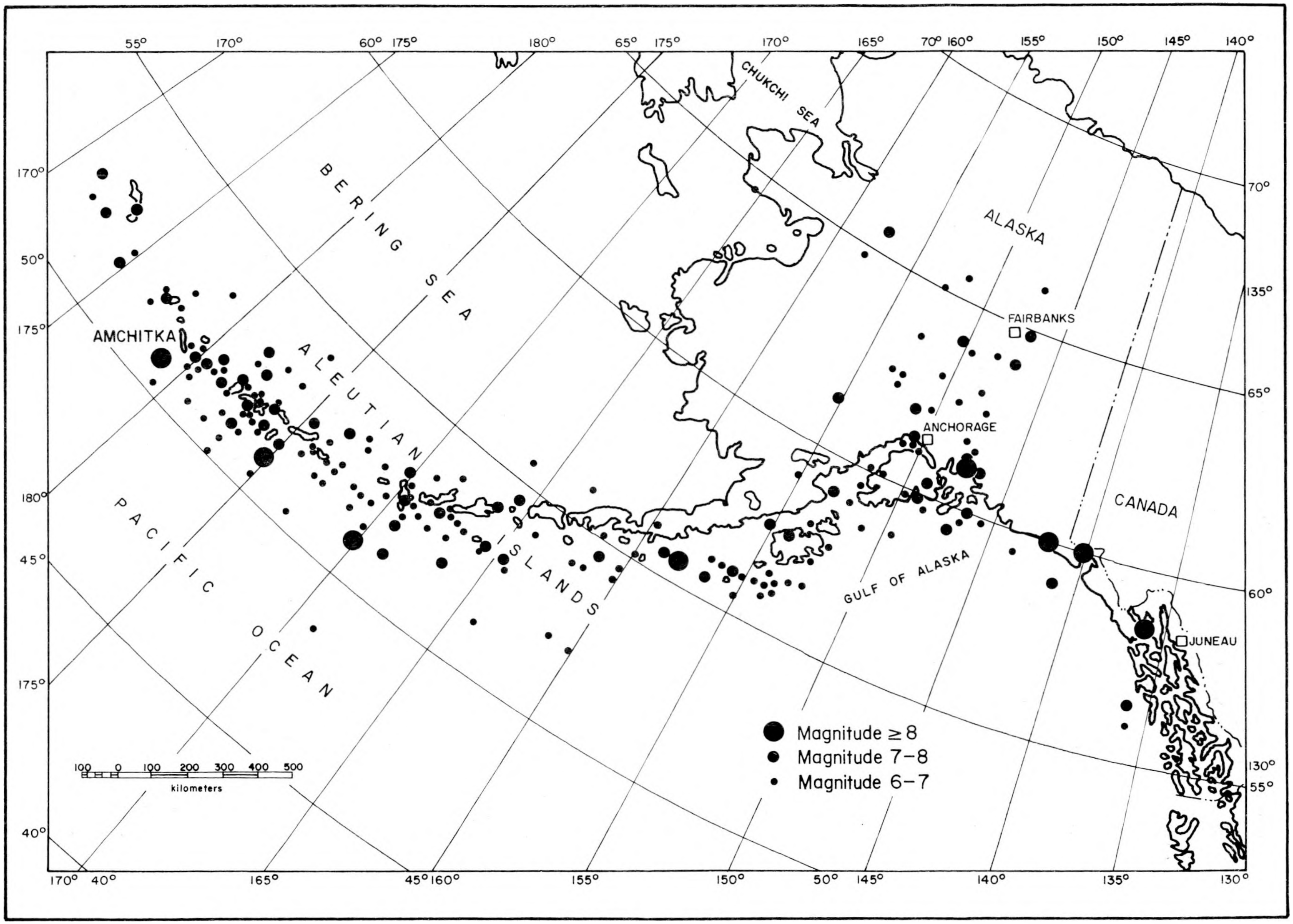

FIGURE 31. Alaskan earthquakes with magnitude over 6, 1899 to 1964. (USC&GS Publication 10-3)

The unclassified portion of the data relating body wave magnitude (m_b) to yield is shown in Figure 32. Evernden (1969b, 1970) states that for explosions above 100 kt in competent rock, the yield versus magnitude curve has the form $m_b = 4.55 + 0.6 \log Y$. This curve is in the figure.

7.3 LONG SHOT AND MILROW EXPERIENCE

Long Shot, at a yield of 80 kt, had a body wave magnitude of m_b = 6.0 as plotted in Figure 32. Its surface wave magnitude was much less, 4-4.5. Milrow's body and surface wave magnitudes were 6.5 and 5.0, respectively. As to aftershocks, the close-in seismic array necessary to detect them did not exist on Long Shot. The threshold for teleseismic detection is about 4 to 4.5 for the Aleutians; the teleseismic records show no aftershocks from Long Shot of this magnitude and no detectable change in nearby seismic activity.

The Milrow shot did have a close-in seismic array. This showed a vigorous aftershock activity, shallow and close to the shot point, that ceased abruptly when the cavity collapsed at 37 hours post-shot. (In contrast, at Nevada, such activity would have lasted for weeks though at a decreased level.) There was no apparent change in regional seismic activity. Surface faulting and cracking were much less noticeable and smaller in size than similar shots in Nevada. There was no apparent interaction between the shot-produced seismic activity and the tectonic activity of the region.

In the light of this experience, Cannikin, though it was to be considerably larger than Milrow, was predicted to have a teleseismic body wave magnitude of 6.8-7.1 and a surface wave magnitude about one magnitude unit lower. It was predicted that it would not interact with the regional seismic activity, and, hence, not trigger an earthquake of magnitude comparable to or greater than the magnitude of its own ground shock. Surface cracks and faults were likely, but would be small in magnitude away from the subsidence area itself (AEC, 1971a).

7.4 SEISMIC ACTIVITY--EXPERIMENT AND RESULTS

The Cannikin seismic experiment consisted of three parts, one involving seismometers, one involving strain and tiltmeters, and one involving magnetometers. All required background level studies and thus portions of the seismometer and strain meter installations are still in place recording data, to be removed in the summer of 1973. The seismometer experiment was installed, operated, and its results analyzed by NOAA. It consisted of 14 land-based seismometers, 11 on Amchitka and 3 on nearby islands (Figure 33). (Ocean bottom instruments were not used, since the Milrow experience indicated that the data gained were not worth the effort they would have entailed.) In addition, the usual Alaskan seismic stations were supplemented with new stations at Shemya, Cape Sarichef on Unimak Island, and Granite

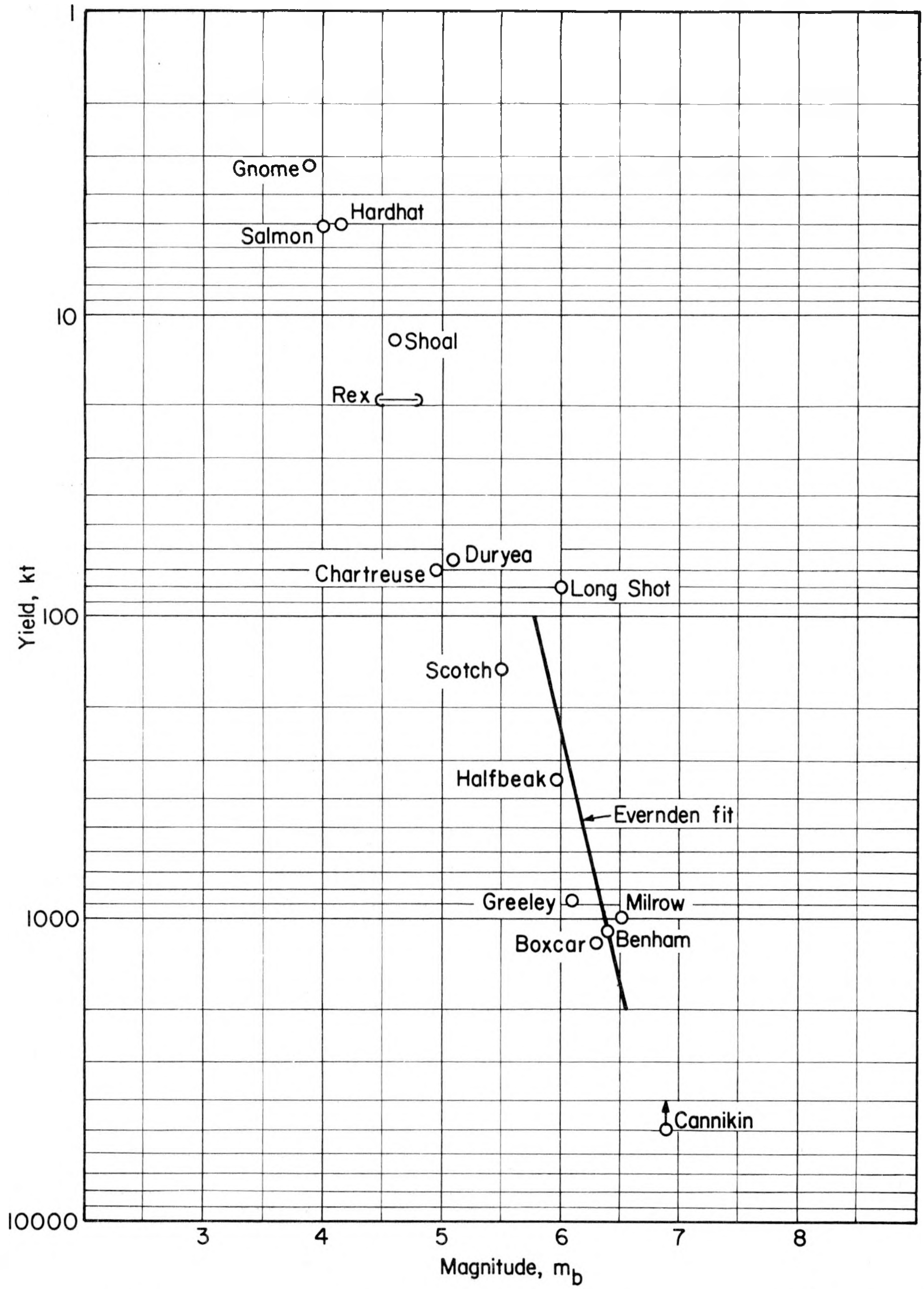

FIGURE 32. Yield versus body wave magnitude for detonations in rock.

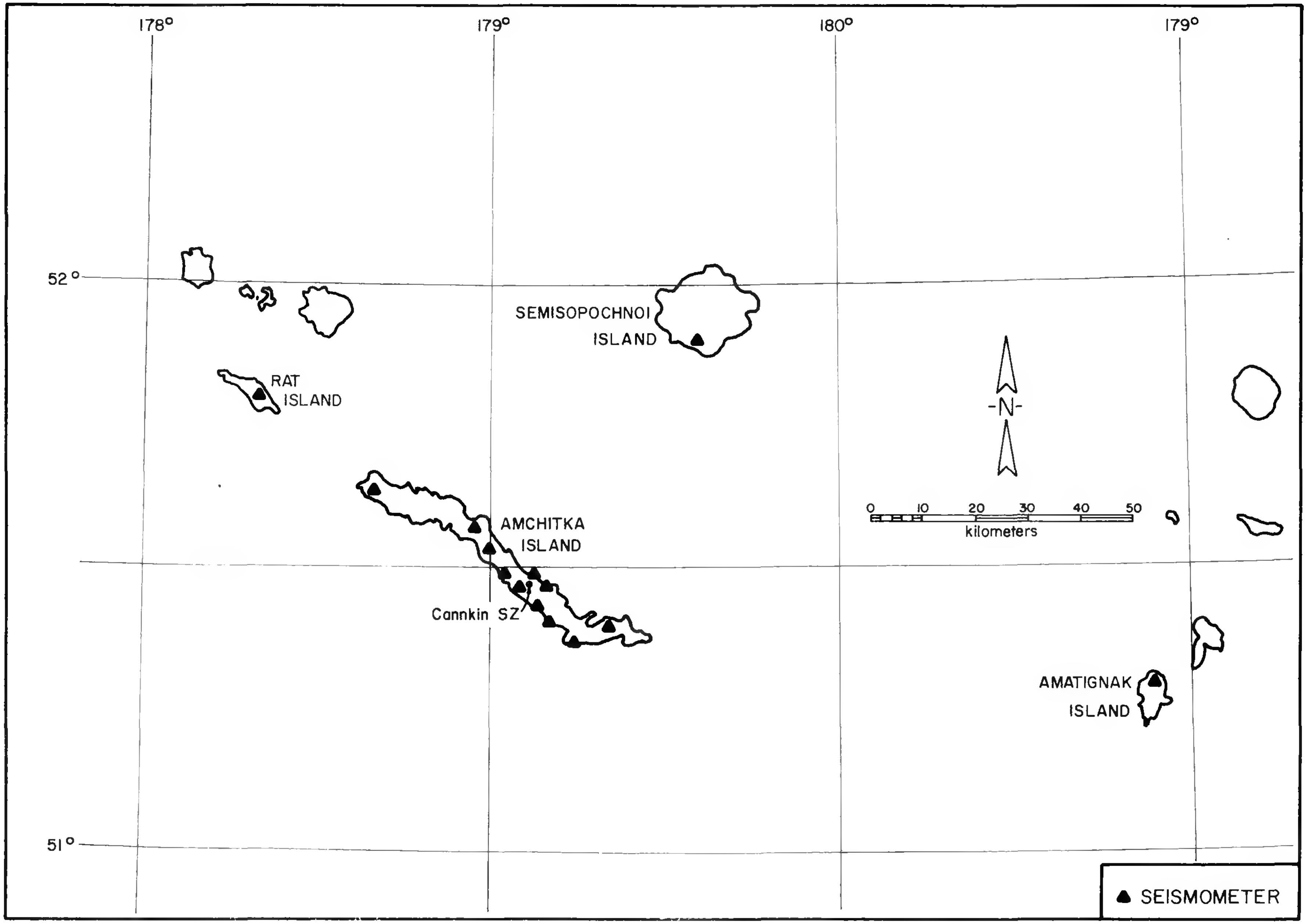

FIGURE 33. Location of seismic instrumentation, Cannikin. (Engdahl, 1972)

Mountain on Seward Peninsula. The five basic stations on Amchitka have been in operation from the latter part of 1969 until removal in mid-1973. Six additional stations were installed in May 1971, and were removed in mid-1972. The three instruments on adjacent islands have operated since late 1970. All are 1-sec velocity sensitive instruments, damped to 65 percent critical. Their readings are transmitted to a central station on Amchitka for recording on oscillographs, tapes, and direct-writing recorders (Engdahl, 1972b).

The direct ground disturbance from Cannikin was felt on instruments around the world. NOAA's National Earthquake Information Center reports a body wave magnitude of $m_b = 6.8$ and a surface wave magnitude of $M_s = 5.7$, with 315 stations entering into the determination (PDE, November 1971). The first of these magnitudes is plotted in Figure 32 and is consistent with the prediction made preshot and with previous experience.

The Cannikin seismic array permits detection of all signals of magnitude (m_b) 3 or greater out to a distance or depth of 50 km (31 mi.). It will detect smaller signals that are closer. As expected, many small signals were observed immediately following Cannikin, and for the 38 hours until the underground cavity collapse took place and a surface subsidence was formed. Seismic activity then effectively ceased, except for a few minor signals (m_b <1) which continued locally for several weeks. These signals were determined to be at the cavity itself. Similar phenomena had been observed at Milrow, intensive activity until collapse at 37 hours postshot. The Milrow activity, too, was essentially at the cavity itself (this is a departure from earlier interpretations (Engdahl, 1971; Merritt, 1970, p. 85-7)). The level of activity of the collapse signals from the two shots is presented in Figure 34. Levels are similar, except that the Cannikin activity was greater: both started and ended at high levels of activity, and in both, the collapse signal itself was the strongest aftershock. Cannikin's collapse shock was of magnitude $m_b = 4.8$.

Concurrent with these collapse signals were a few true tectonic signals. The latter are distinguishable by their different frequency and wave-type content. Collapse signals were of low frequency; tectonic signals of high frequency, about 2 Hz. An additional diagnostic feature is that only the high-frequency signals came from sources away from the cavity. After Cannikin, 22 tectonic events were identified. All were of magnitude less than 4, and all but one came within 23 days of the detonation. Similarly, Milrow, reanalyzed on the basis of Cannikin insights, was found to have had 12 tectonic aftershocks, all of magnitude less than 3. The epicenters of these tectonic signals are shown in Figure 35. They occurred in two general locations. Six occurred near but below the Cannikin underground cavity at depths of 3.7 to 7.5 km (2.3 to 4.7 mi.). Most of the remainder occurred near the Rifle Range fault, 9 km (5.6 mi.) southeast, at a depth of about 2 km (1.2 mi.). The focal mechanisms of the latter shocks suggest right-lateral slip on the fault.

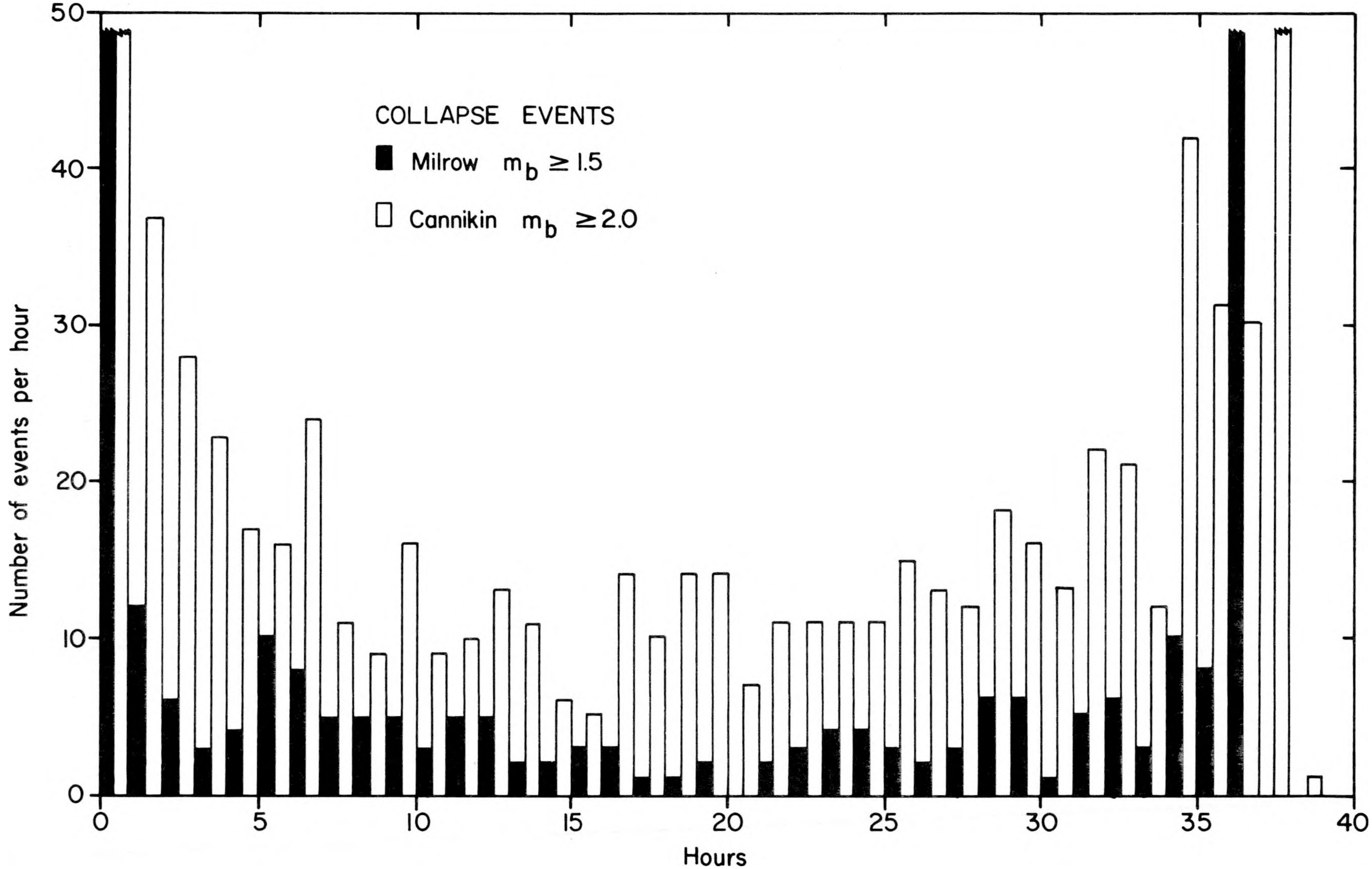

FIGURE 34. Comparison of collapse event activity, Milrow versus Cannikin. (Engdahl, 1972)

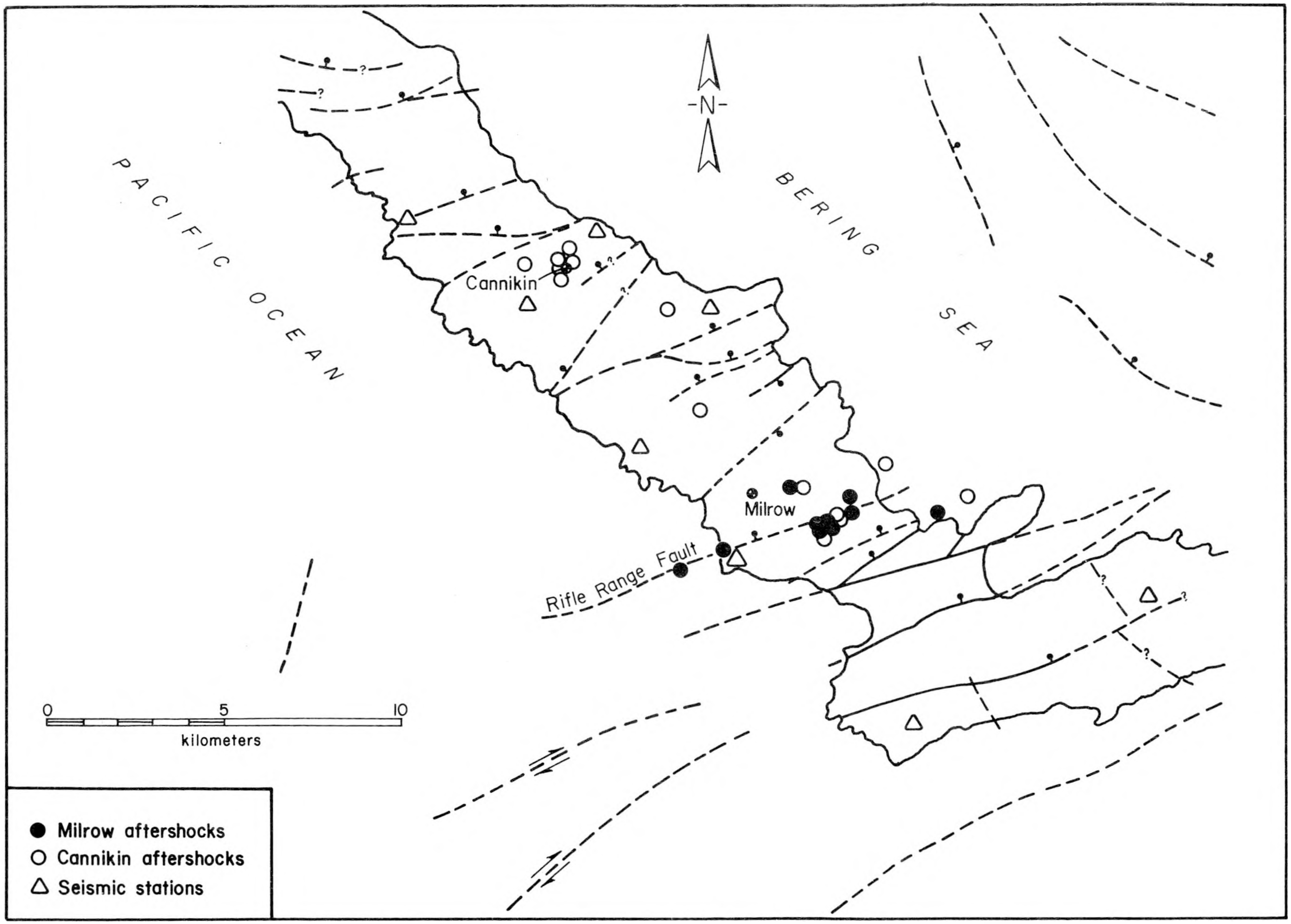

FIGURE 35. Epicenters of tectonic events following Milrow and Cannikin. (Engdahl, 1972)

Regional activity, as at Milrow, had no detectable change in level. This is best seen in a plot of the cumulative number of seismic events detected with hypocenters within 50 km (31 mi.) of Cannikin, of magnitude 3 or more (Figure 36). Also shown is the cumulative strain release, a presentation that gives more weight to the larger seismic events. It appears that the effects of Cannikin were much too local to have any effect on regional seismic activity (Engdahl, 1972a, b).

7.5 STRAINS--EXPERIMENT AND RESULTS

The Cannikin strain and tiltmeter experiment was carried out jointly by NOAA's Earthquake Mechanism Laboratory (EML) and the Colorado School of Mines (CSM). It consisted of nine stations, four on Amchitka, three on nearby islands, and one each on Adak and Cape Sarichef on Unimak. These strain stations have been in operation for various times since late 1969, two on Amchitka and the one on Adak being the oldest in service (Romig et al., 1972).

In addition, the USGS calculated permanent strain from changes in distance determined by geodetic surveys on strain grids before and after Cannikin (Dickey et al., 1972).

Records resulted from all stations except at the Galion Pit station (GPT) where the instruments were badly overranged and scratch gage records had to suffice.

Maximum permanent strain steps measured by EML/CSM and by the USGS are plotted in Figure 37. All data within 10 km (6.2 mi.) are USGS data; all at or beyond 10 km are EML/CSM data. Generally, the data are well fit by a line that decreases as R^{-2}, with two outstanding exceptions at 10 km. These two were GPT and the Mile 19 station (M 19). Station GPT is very near the Rifle Range fault; the relation of M 19 to cross-island faults is not clear. Moreover, the principal strain at GPT is extensional, oriented north-south almost perpendicular to the fault. This suggests that GPT, at least, responded principally to movement on that fault, and may be discounted in plots like that of Figure 37. One notes also that the strain at Cape Sarichef (at 1100 km or 685 mi.) is high, perhaps due in part to low signal-to-noise ratio, perhaps due in part to the coincidence that this station was on a great circle whose initial direction was closely alined with the strike of the cross-island fault structure. In any case, these more distant strains are well below the strains (3×10^{-8}) caused by earth tides (Romig et al., 1972).

Only one of these sets of records has been analyzed with respect to the quasistatic strain, the records from the Amchitka SE station, 15 km (9.3 mi.) from SGZ at an azimuth of 147°. It registered a strain of 4×10^{-7} with a time constant changing from 10 to 18 minutes. This strain is compared to Milrow and Benham data in Figure 38. In spite of a nearly fivefold increase in yield, this Cannikin datum is consistent with the previous data. (It is quite possible that this is a

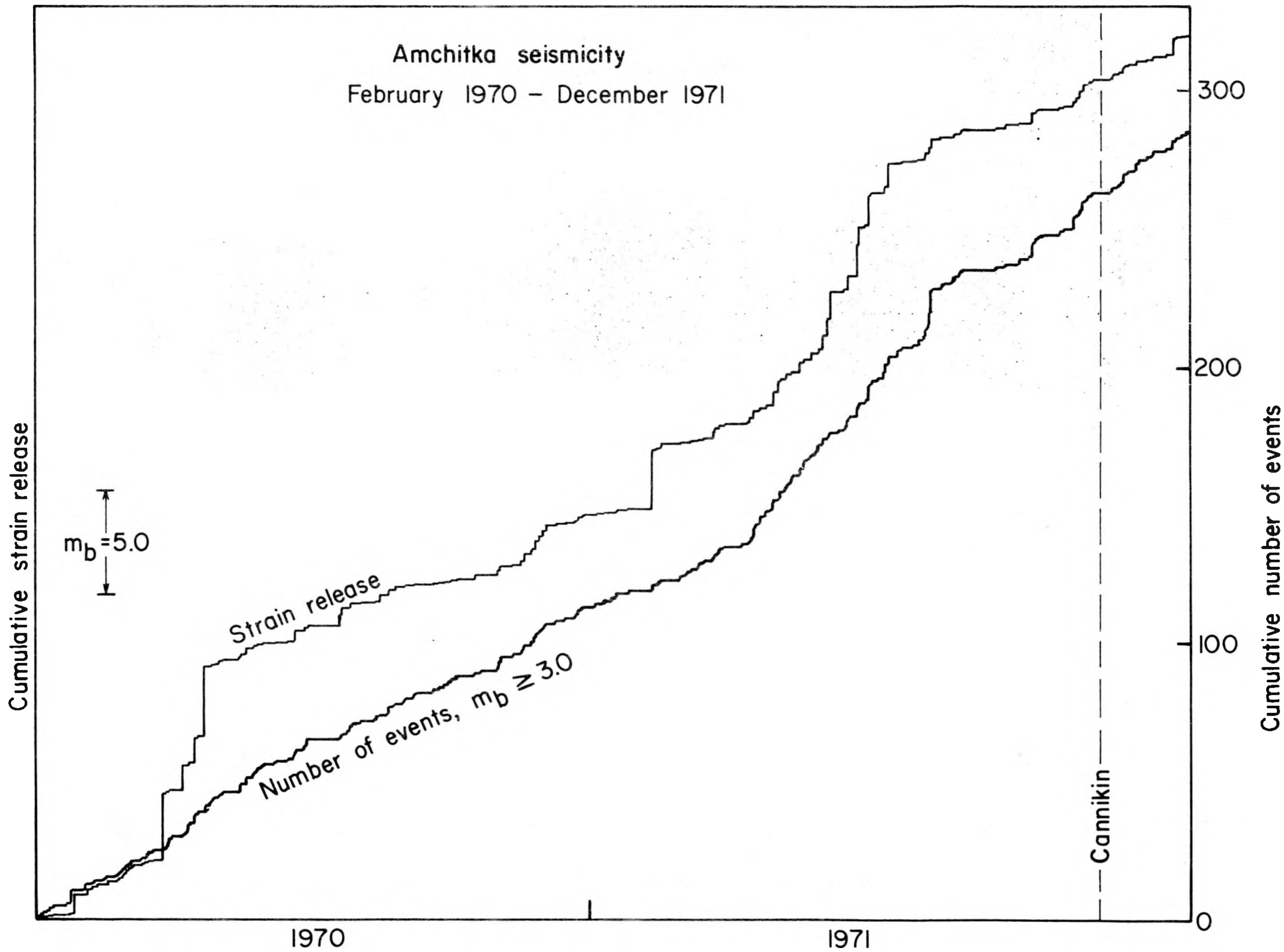

FIGURE 36. Cumulative number of events and strain release before and after Cannikin. (Engdahl, 1972)

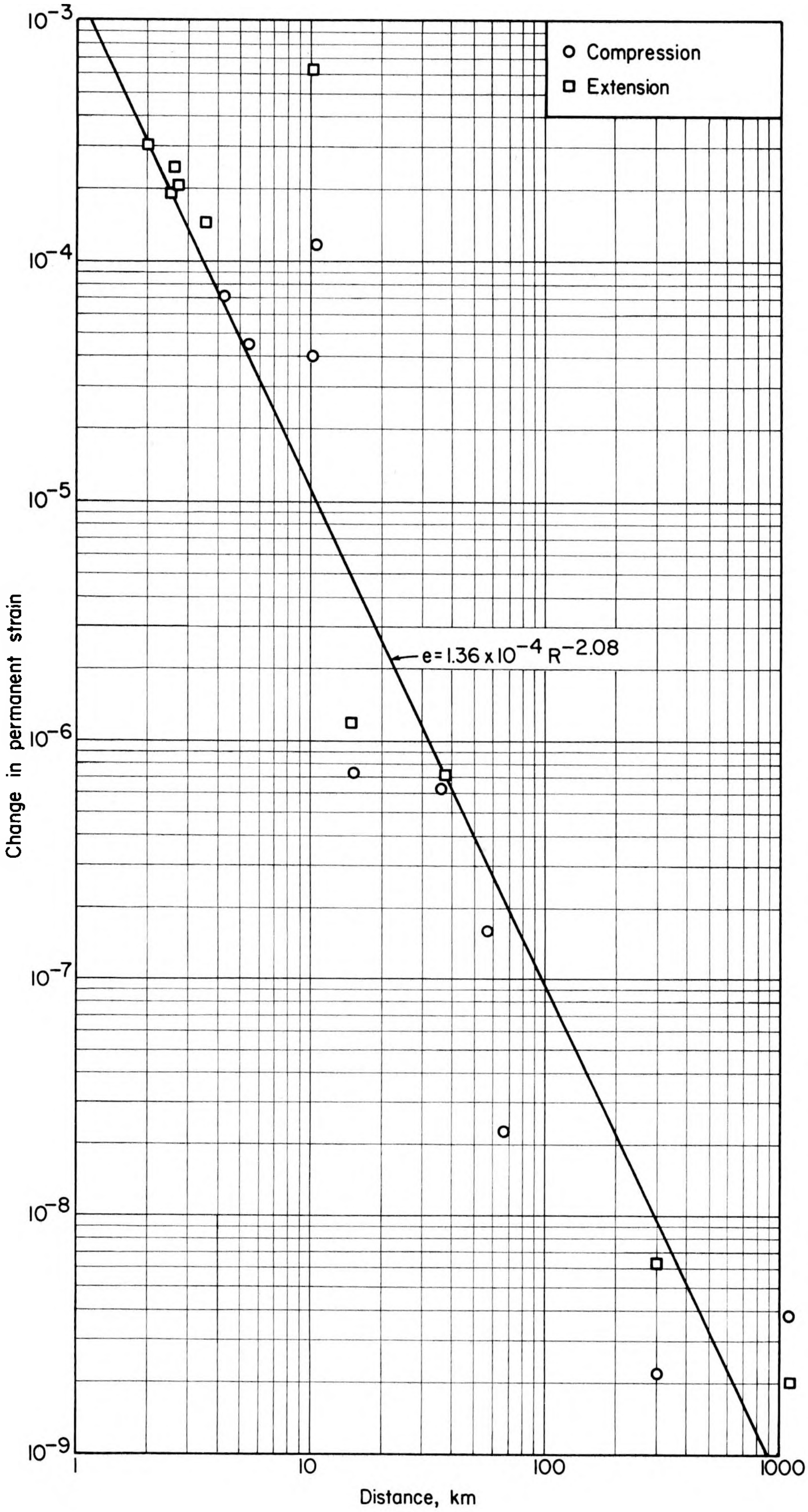

FIGURE 37. Permanent changes in strain versus distance.

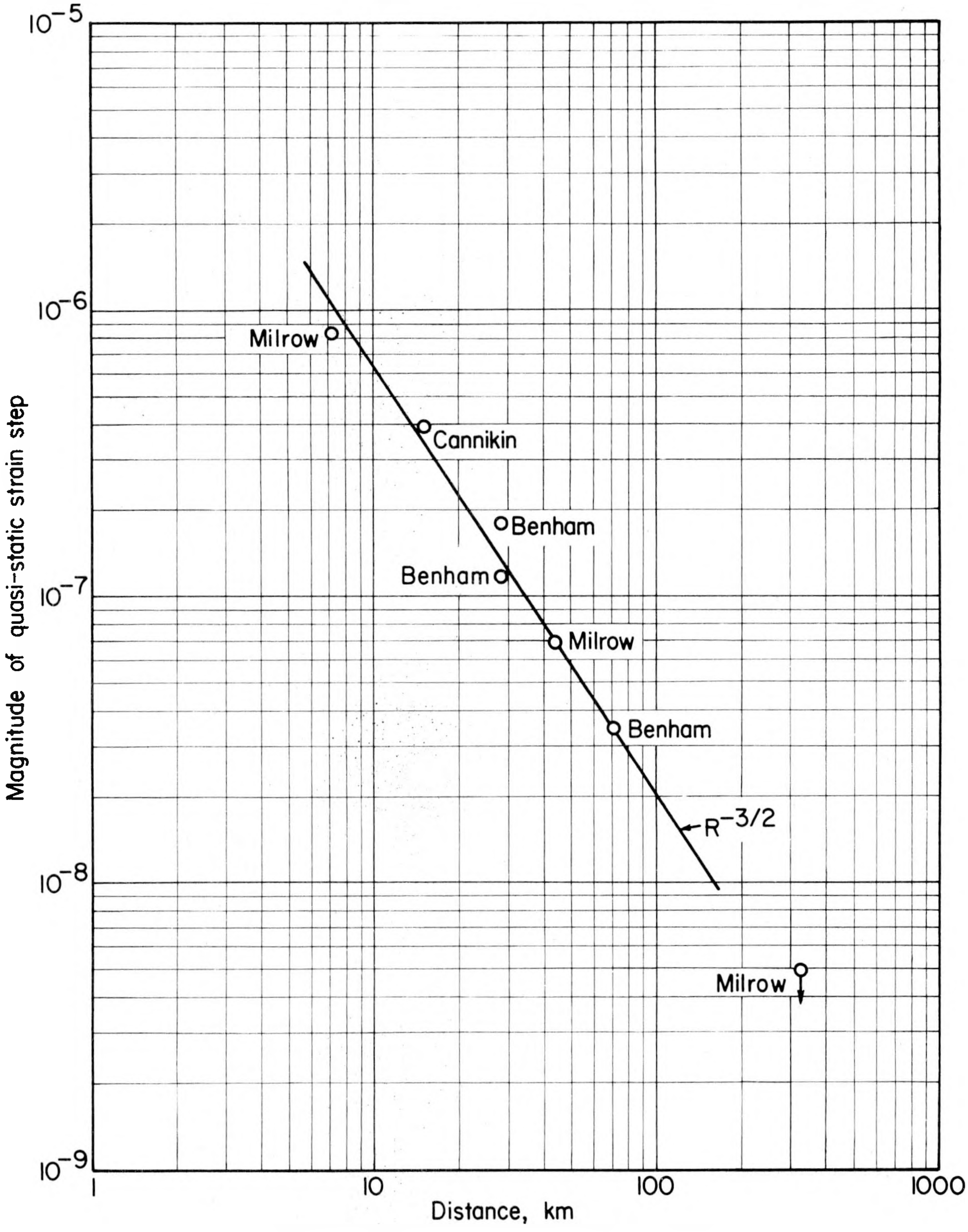

FIGURE 38. Quasi-static changes in strain versus distance compared with results of other large detonations in Nevada.

coincidence that will disappear when the remainder of the quasistatic strains become available.) As a preliminary result, it has been determined that at all stations, permanent strain steps were larger than quasistatic strains. This and asymmetry suggest faulting near surface ground zero, equivalent to that normally associated with an earthquake of (surface) magnitude 6 to 6 1/2 (Romig, 1972). This is considerably larger than the magnitude reported by NOAA (5.7; PDE, November 1971), and no displacements as large as this magnitude would imply are evident on the land surface, which suggests, in turn, that the earthquake to nuclear explosion analogy has again broken down. However, the implication of tectonic energy release is consistent with the results of Toksöz and Kehrer (1972) who used the ratio of Love to Rayleigh wave amplitudes at teleseismic distances to infer a tectonic component of magnitude $M_s = 5.4$ in the seismic signal.

As with the seismometer stations, strain stations have been operated continuously in order to obtain background information, especially a suspected gradual or secular change in strain state. Residual deformations amount to less than 3×10^{-6} per year when a thermally generated annual variation is subtracted (see Butler and Brown, 1972), and the state of strain at the time of Cannikin was little changed from Milrow. This was reassuring, because the only real seismic concern was about an earthquake ready to be triggered. Since the Rat Island earthquake had been so recent (1965), this was not all likely; but the additional evidence of no appreciable new accumulation of strain was good to have.

Very interesting also has been the existence of superimposed changes. These consisted of compressive strains slowly built up over a period of one to three months, relieved in the space of a day. These strain episodes are not local, but can be observed and correlated over distances of several hundred kilometers (Butler and Brown, 1972). This suggests that these episodes may be surficial manifestions of motion on the thrust fault underlying this part of the Aleutians. It further suggests that much of the relative motion of Pacific and Bering Sea tectonic plates this far west is being dissipated by periodic stike-slip rather than accumulating to set the stage for a large earthquake.*

7.6 MAGNETOMETER STUDIES

An experiment new to the Amchitka seismic program on Cannikin was the examination of geomagnetic effects associated with the shot. This experiment was carried out by NOAA/ESL. One part of the experiment was the installation of four magnetometers on Amchitka to operate during the shot at distances of 3 to 36 km (1.9 to 22.4 mi.) from SGZ. The other part was measurement of magnetic field changes near the Teal Creek fault by detailed pre- and postshot magnetic mapping. (This

*In contrast, Barrows (1973) attributes these strain episodes to rain.

was another experiment damaged by the storm on the day before Cannikin. For a while, the magnetometer at the Rifle Range fault was out of order, but it was repaired by six hours preshot. Then the high winds rolled over the hut containing the recording station for the magnetometer at the Northwest Command Point, and that record was lost.)

Only one shot-time change was recorded. At the nearest magnetometer station, 3 km (1.9 mi.) east-southeast of SGZ, there was a 9 gamma (γ) increase in the field (the earth's field is between 10^4 and 10^5 γ) that apparently decreased to 7.2γ in the next week. No other stations showed a shot-time change, the next nearest station being 9 km (5.6 mi.) east-southeast.

The preshot mapping of Teal Creek Fault was done near the main road 1.62 km (1 mi.) west-northwest of SGZ. This showed a magnetic grain parallel to the fault, accumulating to a thousand γ change in a 400 m (1300 ft.) distance. This anomaly is probably related to the fact that Teal Creek fault is the boundary between the Chitka Point and the Banjo Point formations, and there is probably a difference in magnitude or direction of the remnant magnetization of these two formations. The shot produced definite changes in the magnetic field. The rock to the northwest of the fault (Chitka Point rock) that preshot had had a higher magnetic field relative to the other, experienced a 10γ decrease in field strength. The rock to the southeast of the fault (Banjo Point rock) showed a progressive increase from the fault to a +13γ change 300 m (985 ft.) away. Just at the fault, there was a narrow zone of as much as 22γ decrease. Various combinations of changes in field strength or direction with changes in ambient stress are possible to explain these effects (Hasbrouck and Allen, 1972).

7.7 SUMMARY

Cannikin produced a ground shock of body-wave magnitude of 6.8 and surface-wave magnitude of 5.7.

Cannikin caused intense aftershock activity. Most of it was immediately at the cavity and is attributed to collapse phenomena. This activity ceased with cavity collapse at 38 hours.

Cannikin also caused true tectonic shocks, 22 of which have been found. These are characterized by higher frequency content than the cavity collapse signals. All were shallow and within 10 km (6.2 mi.) horizontal range.

There was no discernible change in regional seismic activity as a result of Cannikin.

Associated strains fit previous patterns. They imply release of tectonic strain equivalent to an earthquake of surface magnitude 5.5 to 6.5.

Long-term monitoring of surface strain shows periodic strain episodes larger than the annual accumulation of strain. This suggests continued strain relief and may be associated with the low level of induced seismic activity.

The local magnetic field was slightly but measurably changed by Cannikin. Field changes were particularly evident at the Teal Creek Fault.

CHAPTER 8

TSUNAMI EFFECTS

Tsunamis (or seismic sea waves, also miscalled "tidal waves") are long-period ocean waves which periodically through history have caused tremendous damage around the Pacific basin. They are almost always generated by ocean floor displacements associated with major earthquakes. As a tsunami crosses the open ocean, its wavelength may be a hundred miles or more, but its height from trough to crest will be at most a few feet. It cannot be felt aboard ships in deep water and cannot be seen from the air. When a tsunami enters the shoaling water of coastlines, its velocity diminishes and its wave height increases, while it refracts out of a straight line in response to changing sea floor contours. It is in these shallow waters that tsunamis become a threat to life and property, for they can crest to great heights and strike with devastating force. There are a number of coastal areas in the Pacific whose offshore bathymetry seems actually to focus the destruction and that have repeatedly been badly hit. Hilo, Hawaii, for instance, is notorious for having been repeatedly damaged by tsunamis. In Alaska, the place most repeatedly damaged is Lituya Bay (Pararas-Carayannis, 1969; Cox and Pararas-Carayannis, 1969). (These were really waves in an enclosed bay caused by earthquake-induced rockslides, hence, not true oceanic tsunamis.)

Alaskans are particularly aware of tsunamis because of the water-wave damage that accompanied the 1964 earthquake. In that case, almost all of south-central Alaska was in the source region of one of the largest earthquakes on record. By contrast, the next year, there occurred the Rat Island earthquake (M_s = 7.75) with an epicenter 40 km (25 mi.) southwest of Amchitka. Although observed on instruments numerous places around the Pacific, the resulting tsunami caused only minor damage at Shemya, almost surely in the source region, and was not noticed at all by the common man in south-central Alaska. Similarly, the 1906 magnitude 8 earthquakes near Amchitka caused no recorded tsunami, and even in 1906, the reporting system was good enough that a major tsunami would have been detected and made known. Thus, the historical evidence is that large earthquakes in the western Aleutians cause small waves at most.

Studies of naturally occurring tsunamis indicate that the really damaging ones come from vertical movements of the ocean floor between the continental coasts or island arcs and the bottom of the deep-sea trenches, with the shoreline about at the hinge line separating areas of upward and downward displacement. Thus, for instance, the 1964 Alaska earthquake involved thousands of square kilometers of ocean floor being displaced upward several meters (Plafker, 1965, 1969). The hinge line at the island arc means that Morris and Bucknam's (1972) finding that the western Aleutians have been vertically stable for at least 4000 years (the age of the present tidal bench) is less than completely reassuring about tsunamis not being generated there.

However, because large surface areas must be involved, it is clear that no tsunamis could possibly be generated by the direct effects of a nuclear explosion, but only through the intermediary step of a triggered earthquake.

The Milrow tsunami experiment had been a null experiment: no shot-caused wave was observed above background at any instrument. As a result, on Cannikin, a concerted effort was made to increase the sensitivity of the instruments used, and to place them closer to SGZ. There was no real concern about damaging waves, but what waves might be caused needed to be documented, and there was also a need to have a controlled experiment in which both the motion of the source and the resultant water wave could be measured together.

The Cannikin water-wave experiment was a joint project of the Los Alamos Scientific Laboratory, Delco Electronics of Goleta, California, and the Hawaii Institute of Geophysics. Three kinds of instruments were used: tide gages, run-up gages, and deep ocean gages. All gages measured pressure and, hence, water depth. The tide gages were filtered to respond to long-period waves only (>15 min.). Their sensitivity was ±0.5 cm. Divers anchored them to rocky parts of the bottom, six on the Bering side of Amchitka, and four on the Pacific side (Figure 39). Run-up gages were sensitive to higher frequencies, and with sensitivities of ±0.1 cm. Divers installed them near enough shore that cable-borne signals could be recorded on land. They were installed in four accessible bays on Amchitka and on three neighboring islands, Rat, Semisopochnoi, and Amatignak (Figure 40). Deep ocean gages were free fall gages that rested on the ocean floor and were recalled by coded fathometer signals from a service ship. They were long-period gages with sensitivities of ±.05 cm. Six were installed at various positions around Amchitka in water depths of 800 to 4000 m (450 to 2200 fathoms) (Figure 40) (McNeil et al., 1972; Olsen et al., 1972).

Four of the ten tide gages failed. Of the six remaining, five recorded permanent uplifts (Table 3). At first sight, the uplift at Station 3 seems unreasonably high. However, its position to the east of the Teal Creek Fault (see Figure 39) suggests that this half-meter uplift is real, an extension to sea of the one meter uplift seen a kilometer away on the shore. This result shows that the uplift area goes at least a kilometer to sea. Station 4 is to the east side of the uplifted area. Projected back parallel to the strike of these faults as they probably extend to sea, it is off Banjo Point, where the uplift was 25 cm (9.8 in.). Thus, too, its measured 8.5 cm (3.3 in.) is reasonable. Similarly, on the Pacific side, Stations 7 and 9 measured about half the 10 to 12 cm (3.9 to 4.7 in.) uplift seen on the adjacent shore.

As to water waves themselves, the closer tide gages on the Bering side (Stations 3, 4, and 5) showed a long-period (15 to 20 min.) wave action that lasted for an hour or more. The two run-up gages on the Bering side also recorded a clearly shot-caused wave action, starting 6-10 minutes after zero time. In both cases, the frequencies were those characteristic of the resonances of the bays the gages were installed

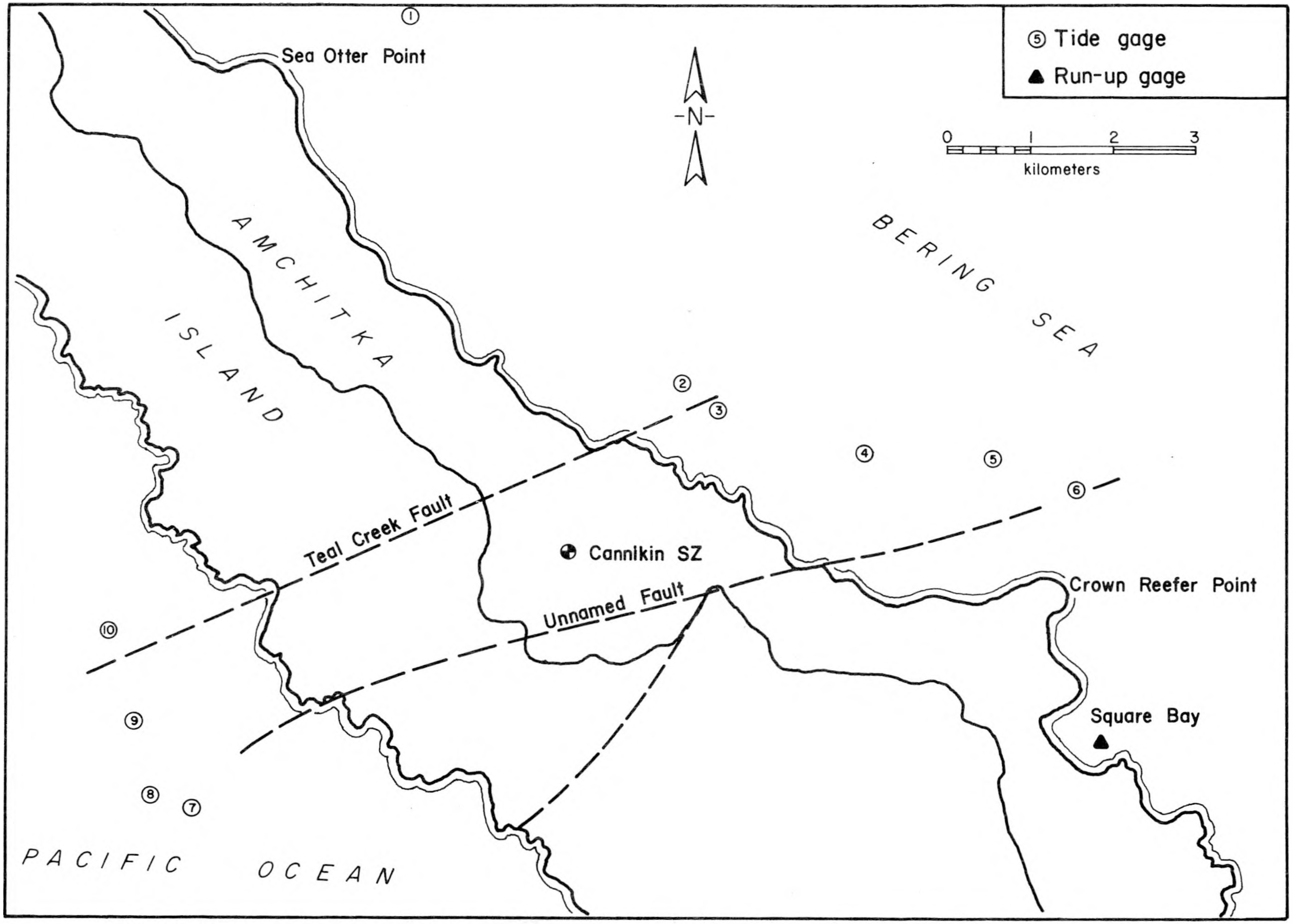

FIGURE 39. Location of tide gages used as ground displacement gages. (McNeil et al, 1972)

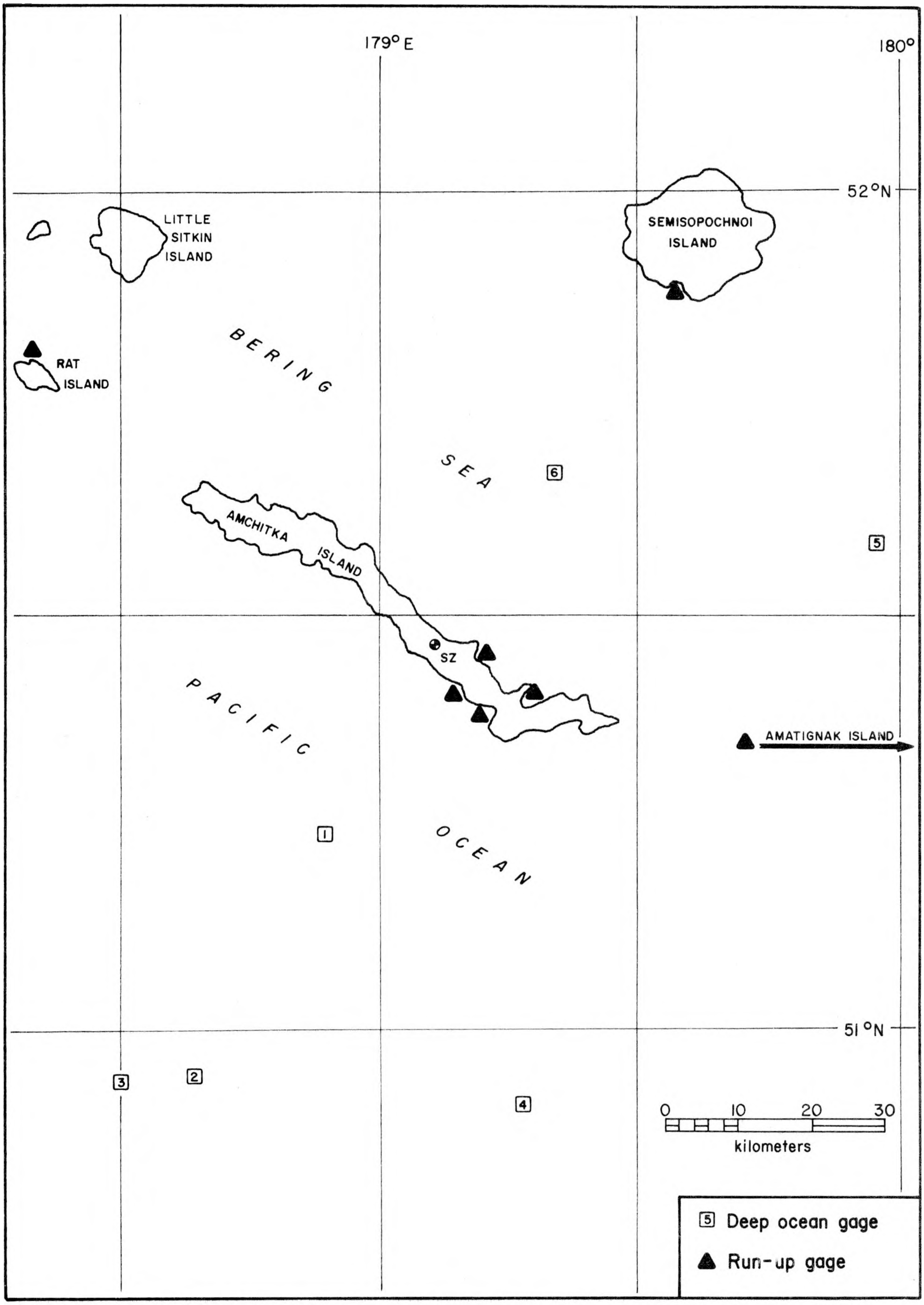

FIGURE 40. Location of run-up and deep ocean gages. (McNeil et al, 1972)

in. At the other run-up stations, no shot-caused waves could be seen against the background of high wave and surf action remaining from the previous day's storm.

TABLE 3--TIDE GAGE INFORMATION

Station	Range km(mi)	Azimuth (deg)	Depth cm(in)	Change in Depth cm(in)
1	6.9(4.3)	344°	20(7.9)	0.0 ± 0.5(0.0 ± 0.2)
3	2.5(1.6)	45°	23(9.1)	56.0 ± 0.5(22.0 ± 0.2)
4	3.8(2.4)	70°	24(9.4)	8.5 ± 0.5(3.3 ± 0.2)
5	5.3(3.3)	76°	23(9.1)	3.5 ± 0.5(1.4 ± 0.2)
7	5.6(3.5)	236°	14(5.5)	5.5 ± 1 (2.2 ± 0.4)
9	5.5(3.4)	249°	20(7.9)	6.5 ± 1 (2.6 ± 0.4)

The results of the deep ocean gages were anomalous in that only at Station 4 was an apparently shot-caused signal seen; other gages closer and farther saw nothing. The investigators suggest "aliasing" of an acoustical reverberation as a possible source of this signal (Olsen et al., 1972).

Concurrent with and even preceding this experimental work, there has been a considerable theoretical investigation on the generation and propagation of tsunamis, mostly by Tetra Tech, Inc., of Pasadena, California. Because of this work, it has long been accepted as an empirical fact that tsunamis tend to be directional in their impact. Their sources are usually elongated, and the highest waves are experienced perpendicular to the long axis of the source. For example, the seismic sea wave accompanying the 1964 Alaskan earthquake was directed along the western coast of North America, while the wave associated with the 1960 Chilean earthquake had its principal effects away from the source, in Hawaii and Japan, not North America (Iida et al., 1967).

This matter of directionality has been examined theoretically, and it has been shown that any tsunami generated in the Amchitka-Shemya section of the Aleutians would be principally directed into the open ocean between Hawaii and Japan (Figure 41) (Hwang et al., 1971, 1972). The theoretical effort has also clarified the matter of bay resonances (Olsen and Hwang, 1971) but examination of the Cannikin data has not proceeded far enough to give a full understanding of them. One can only believe that the absence of waves at deep water instruments and at neighboring islands means that most of the water wave energy generated by Cannikin was trapped in edge modes along the shallow offshore slope along the Bering coast of Amchitka.

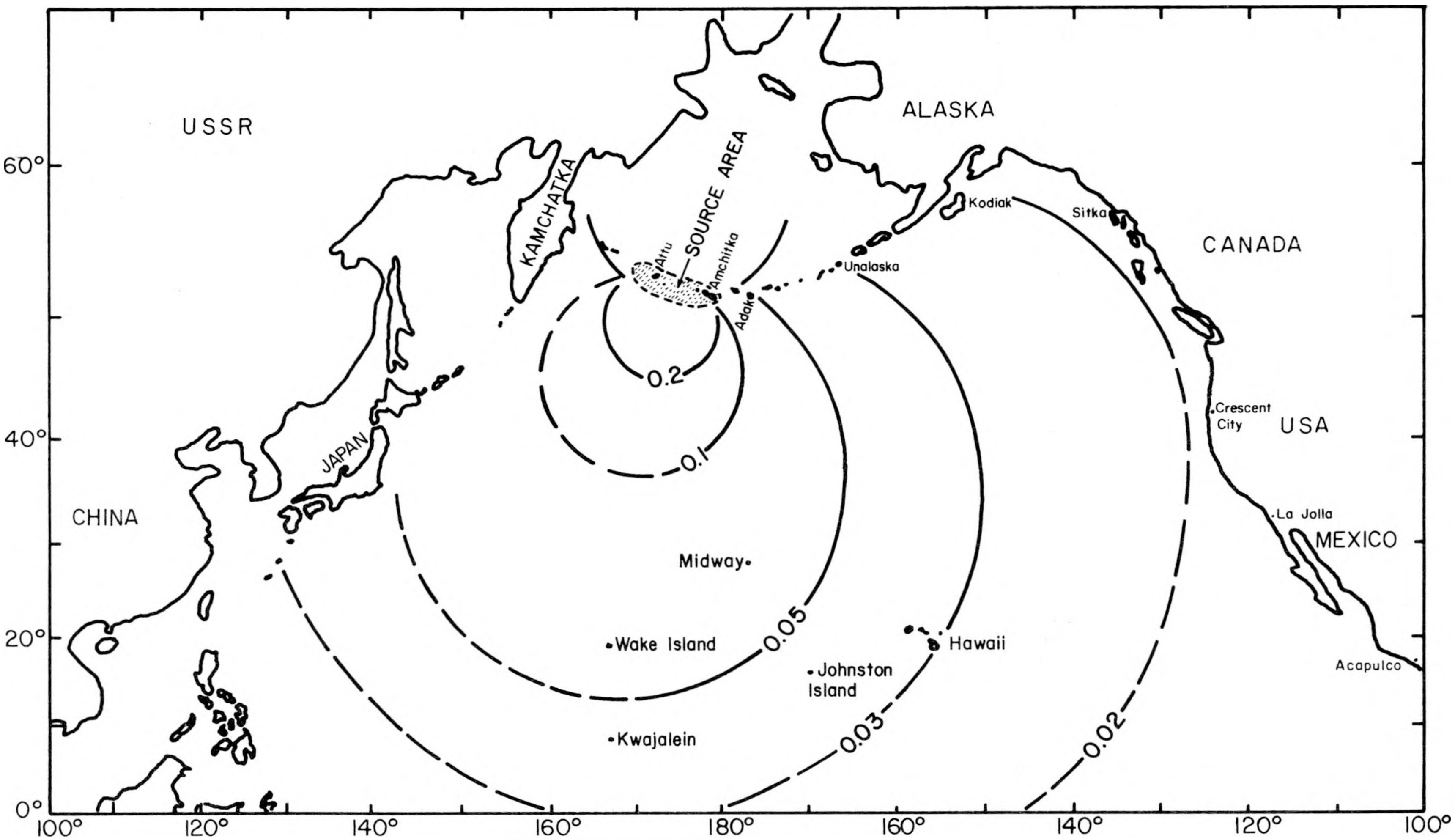

FIGURE 41. Contours of maximum wave heights in the deep ocean from a hypothetical tsunami generated at Amchitka. (Hwang et al, 1971)

In summary,

No water waves were generated on Cannikin strong enough to be measured away from the immediate neighborhood of Amchitka itself.

Tide gages being used as bottom displacement gages indicate that the uplift evident on the tidal bench adjacent to the Cannikin SGZ extends at least a kilometer to sea.

Tide gages and run-up gages on the Bering side of Amchitka give evidence of edge waves and bay oscillations resulting from Cannikin.

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