DISSERTATION

HYDRAULIC EFFECTS OF UNDERGROUND NUCLEAR EXPLOSIONS, AMCHITKA ISLAND, ALASKA

Submitted by

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In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Summer, 1977

CED76-77DDG31

ABSTRACT OF DISSERTATION

HYDRAULIC EFFECTS OF UNDERGROUND NUCLEAR EXPLOSIONS,
AMCHITKA ISLAND, ALASKA

An intensive field study was undertaken as part of the U.S. Geological Survey Nuclear Hydrology Program to determine the response of drainage basins and groundwater aquifers to underground nuclear explosions. Measurements of streamflow and groundwater fluctuation were made over the period of underground nuclear testing on Amchitka Island. These observations were only minimal for the Long Shot event in 1965 but were expanded considerably for the Milrow and Cannikin events in 1969 and 1971, respectively.

A conceptual model describing the phenomena that relates surface water and groundwater reaction to ground shock, was confirmed when field data supported the main features of the model. Slapdown, an effect of rock failure in tension, results in the greatest response during the event, the effects generally dissipating soon after their occurrence; however, the effects of cavity collapse are long lasting and, in many respects, permanent. Drainage areas surrounding ground zero as well as the groundwater reservoirs beneath them have undergone permanent changes. Distant groundwater effects are documented and are attributed to changes in aquifer porosity as a result of seismic response generated by the explosions. The most outstanding hydrological feature on Amchitka Island, Cannikin Lake, is a result of the collapse of the Cannikin cavity.

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ACKNOWLEDGMENTS

Sincere thanks to the members of the committee, Dr. Everett V. Richardson, major professor, Dr. James P. Waltz, and Professor Robert A. Longenbaugh for their review of the thesis and to Dr. Carl F. Nordin, Jr. for his consistent encouragement and assistance which led to the completion of this work.

To Dr. William W. Dudley, Jr. and Richard K. Blankennagel, present and past coordinators for the Nuclear Hydrology Program, U.S. Geological Survey, gratitude for their support and encouragement during the completion of the thesis.

Thanks are extended to Leonard E. Wollitz for his dependable assistance in the field and in the fabrication of the monitor systems used during data collection. The data used in the thesis was obtained as part of a field project of the U.S. Geological Survey in support of the Energy Research and Development Administration's underground nuclear testing program.

Finally, to my wife, Corine, who through her persistence this work was completed, this thesis is dedicated.

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LIST OF SYMBOLS

		Units
°C	degrees Celsius	°C
DOB	depth of burial	m
P	confined fluid pressure	bars
R	horizontal range	Km
R_c	cavity radius	m
R_s	slant range	Km
RSC	relative specific capacity	m^3/dy/m
SC	specific capacity	m^3/dy/m
T	transmissivity	m^2/dy
TD	total depth	m
U_s	average sonic velocity in rock	cm/s
U_v	vertical component of particle velocity	cm/s
W	device yield	kilotons
ρ	rock density	gm/cm^3

LIST OF ABBREVIATIONS

ERDA	Energy Research and Development Administration
GZ	Ground Zero
NTS	Nevada Test Site
TNT	Trinatrotoluene
USGS	United States Geological Survey
WP	Working Point

Chapter 1

INTRODUCTION

This report presents the results of a unique study, the objectives of which were to determine the effects of an underground nuclear explosion on the hydrologic environment of a remote island in the Aleutians. The selection of Amchitka Island as the supplemental test area for high yield testing provided the opportunity to conduct a hydrological surveillance and effects program in an area that is one of the most hydraulically active in the continental United States. The island exhibits near saturated groundwater conditions and a unique drainage system that reacts almost instantaneously to rainfall.

As part of the ERDA (Energy Research and Development Administration) overall effects program, a hydrological data network was established on Amchitka Island in 1967. Streamflow gaging stations were constructed and instrumented with the cooperation of the Alaska District, U.S. Geological Survey. Several observation groundwater holes were also established in several deep boreholes drilled under the exploratory program.

In 1970, the writer assumed the responsibility of maintaining those existing observation sites and subsequently spent a considerable amount of time and expense to upgrade and expand the entire hydrological network. Logistics were a major problem and expense. Field trips originated from Denver, Colorado, lasting two to three weeks with some visits up to nine weeks in duration. Instrumentation was designed, fabricated, and implemented to operate under the most unusual conditions and circumstances experienced by this writer.

Weather was totally unpredictable, restricting field work days at a time. Equipment was designed to withstand adverse weather conditions and to run maintenance-free for periods of three months up to one year. The field contribution from those that participated on this project was year-round, many times lasting for days at a particular site.

Hydraulic testing of groundwater boreholes and the initial establishment of the hydrologic network was accomplished by the Nuclear Hydrology Program, USGS (U.S. Geological Survey), W. C. Ballance, principal investigator. Confined fluid pressure measurements taken in local aquifers for the Milrow event in 1969 were supervised by W. W. Dudley, Jr., of the same office. From 1970 until its conclusion in 1974, the effects program, which principally emphasized measuring the response of the groundwater and surface water systems to the Cannikin event, was under the direction of the writer.

Cannikin, nearly 5 megatons in yield, presented many problems in design that were necessary to overcome to insure that recording systems would survive the impact of ground shock as high as 30 g's. Borehole packers and strain gage transducers were selected and fabricated into a measurement package able to withstand 350 bars of pressure. At some sites it was necessary for support of drilling rigs to install monitor packages in holes close to GZ (ground zero) and their removal after the detonations.

After the Cannikin event the observation sites were kept in operation in order to document the long term effects of the testing program. The results of these measurements, including those collected prior to 1970, are presented in this thesis for the first time, in their entirety. They are the basis for the results presented herein which describe the general response of the hydrologic system on Amchitka Island to underground nuclear testing.

Background

The first nuclear explosion, Trinity, at Alamogordo, New Mexico, in 1945 occurred in the atmosphere at the top of a 30 meter tower and produced seismic waves that were recorded in the southwestern portion of the United States (USAEC, 1962). The fifth nuclear explosion and the first underwater test, Baker, at Bikini in 1946 produced signals that were detected in the United States. The first contained underground nuclear explosion was the Ranier event, a 1.7 kiloton event detonated in tuff at the NTS (Nevada Test Site), in 1957. Nome, the first experiment of the plowshare program with a nuclear explosive was detonated in salt, near Carlsbad, New Mexico, in 1961. It was a 3.1 kiloton explosion that generated seismic signals detected throughout the United States and Canada, Sweden and Finland (Romney and others, 1962).

Since the advent of high-yield testing in the early 1960's where yields were greater than 100 kilotons and as much as one megaton, the devices were buried so that the cavity formed would be contained either wholly or partially beneath the water table, requiring hydrologic investigation of emplacement holes. These investigations are aimed at determining hydrologic parameters within the saturated zone. These parameters which include permeability, porosity, transmissivity and specific capacity are used in evaluating a potential emplacement hole as to the safety and containment of the device and water inflow into the chamber.

Studies related to containment and safety over the past 20 years have been directed towards identifying the geologic and hydrologic environments of specific explosion sites, describing the regional geologic and hydrologic system, and predicting radionuclide migration. In recent years, all of the tests have been conducted underground in compliance with the test ban treaty of 1963. Most of the United States' underground nuclear tests have been conducted at the NTS, about 65 miles northwest of Las Vegas, Nevada. Other underground tests conducted throughout the United States were experiments involving plowshare projects and Department of Defense programs for detecting, locating and identifying underground nuclear explosions. Two other test areas were of prominence--Hot Creek Valley, Central Nevada and Amchitka Island, Alaska. These supplemental test sites were locations for calibration tests conducted in order to determine the response of that area to a nuclear device of higher energy yields than were feasible at the NTS. As a result of the tests conducted in Hot Creek Valley in 1968 and in Amchitka Island in 1969, Amchitka Island was chosen as a supplemental test area for safely conducting the largest envisioned nuclear tests (Fig. 1).

Purpose and Scope

The selection of Amchitka Island as a site for conducting a five-megaton experiment code-named Cannikin initiated an extensive hydrologic study to assess changes to the hydrologic environment that occurred on Amchitka as a result of the experimental nuclear testing.

Three tests were conducted on Amchitka between the period 1965 and 1971. These were the following:

1. Long Shot--an 80-kiloton explosion detonated October 29, 1965,

2. Milrow--with a yield of about a megaton detonated October 2, 1969, and

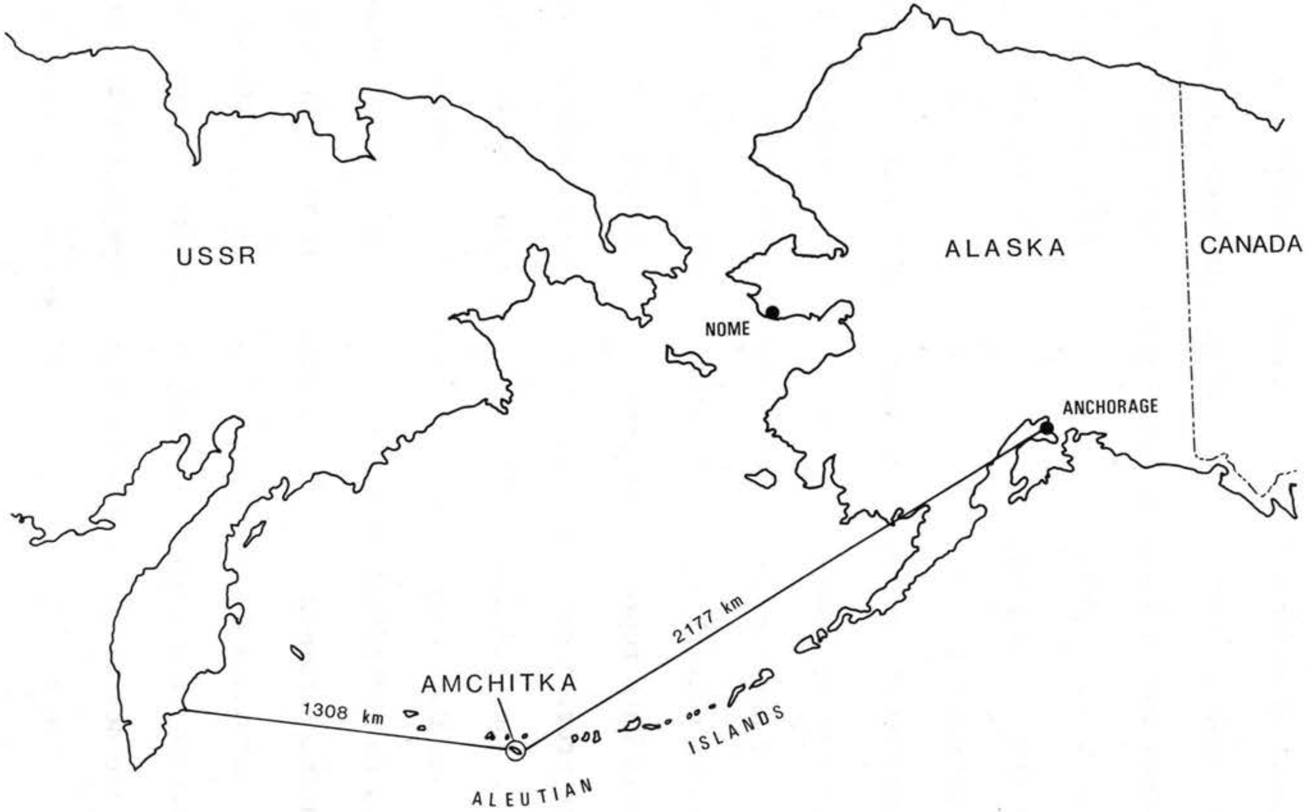

Figure 1. Alaska and the Aleutian Islands, showing the location of Amchitka Island.

3. Cannikin--about a five-megaton explosion detonated November 6, 1971.

Long Shot, detonated at a depth of 701 meters, was part of the Department of Defense's program the Vela Uniform series. The experiment was designed to improve the techniques in detecting underground nuclear explosions and in differentiating them from natural underground signals produced by earthquakes. Milrow was the calibration test for Cannikin in the first of high yield explosions on the island. It was detonated 1,218 meters below land surface. Cannikin, the largest nuclear explosion conducted by the United States was detonated at a depth of 1,792 meters.

This study encompasses the hydrologic investigations, both subsurface and surface, centered around these experiments. The data collection network was established in 1967 and was abandoned in 1974. The field data represent the results of the most extensive hydrologic effects program ever conducted for a specific underground experiment.

The approach used in this study was to identify from the basic hydrologic data changes in the hydrologic systems and to relate these changes to the effect of the explosions and the subsequent collapses of the cavities formed by the explosions. In the following, a discussion of the mechanics of underground explosions is presented, followed by a description of the area of interest, Amchitka Island. The observation sites are described and the basic data are summarized in graphs and tables. Finally, the observed hydrologic changes are related to the effects of the nuclear explosions.

Chapter 2

MECHANISMS OF NUCLEAR EXPLOSIONS

Basic Concepts

Prior to 1940, the most important sources for explosive energy were from chemical reactions. Major applications were for mining, quarrying, excavations, flow stimulation in gas or oil wells and military uses. These types of conventional explosives such as the chemical-high explosive TNT (Trinitrotoluene) depend on rearrangement of only electrons among atoms with the nuclei of the atoms being unaffected. By contrast, nuclear energy arises by rearrangement (splitting or combining) within the nuclei themselves producing a very concentrated form of energy. As a result a given mass of nuclear explosives will produce several million times as much energy as the same mass of a conventional explosive such as TNT. The yield of a nuclear explosion is a measure of the amount of energy released and is in terms of the quantity of TNT that would produce the same amount of energy. The yield of nuclear experiments are therefore expressed in terms of TNT equivalent. The common convention for describing energy yields (TNT equivalent) of nuclear detonations are as follows: low, less than 20 kilotons; low to intermediate, 20 to 200 kilotons; intermediate, 200 kilotons to one megaton; high, more than one megaton (Glasstone, 1971).

Two general methods are known for explosive release of nuclear energy. They are nuclear fission and fusion. In the fission process (splitting) the nuclei of certain heavy atoms are made to break up into lighter particles resulting in a net loss of mass in the reaction. In nuclear fusion, a pair of light nuclei combine to form a nucleus of a heavier atom also resulting in a net loss of mass. The conversion of lost mass into energy accounts for the large amounts of energy released in both fission and fusion processes. The device to be detonated may either be a fission or a fusion process depending on the experiment's application.

An Underground Nuclear Experiment

At the NTS, hundreds of nuclear devices of the low to intermediate range in yield have been detonated in vertical boreholes ranging up to 3.77 meters in diameter and as much as 1500 meters in depth. The test media have been alluvium, tuff, basalt, granite, carbonate rocks, rhyolite, sandstone and salt.

The emplacement hole, after being drilled to the desired TD (total depth), generally is lined throughout its entire depth with a cemented steel casing up to 137 centimeters in diameter. After completion, a canister containing the device and certain diagnostic instruments are lowered into the hole and emplaced at the desired DOB (depth of burial). The DOB is highly dependent on the maximum yield of the device. GZ is then readied for detonation by sealing the casing with a sequence of plugs and stemming materials simulating the density of the surrounding medium. An example of a typical emplacement hole used for underground nuclear experiments is illustrated in Fig. 2. After the emplacement hole has been plugged and stemmed, the device set at the WP (working point) is ready for firing.

An underground nuclear explosion produces sudden and violent changes in the environment surrounding the device. These changes are primarily a function of yield, overburdened pressure, geologic environment and the degree of saturation.

At the time of firing, there are several phases that are useful in describing the nuclear detonation. During the nuclear phase the energy

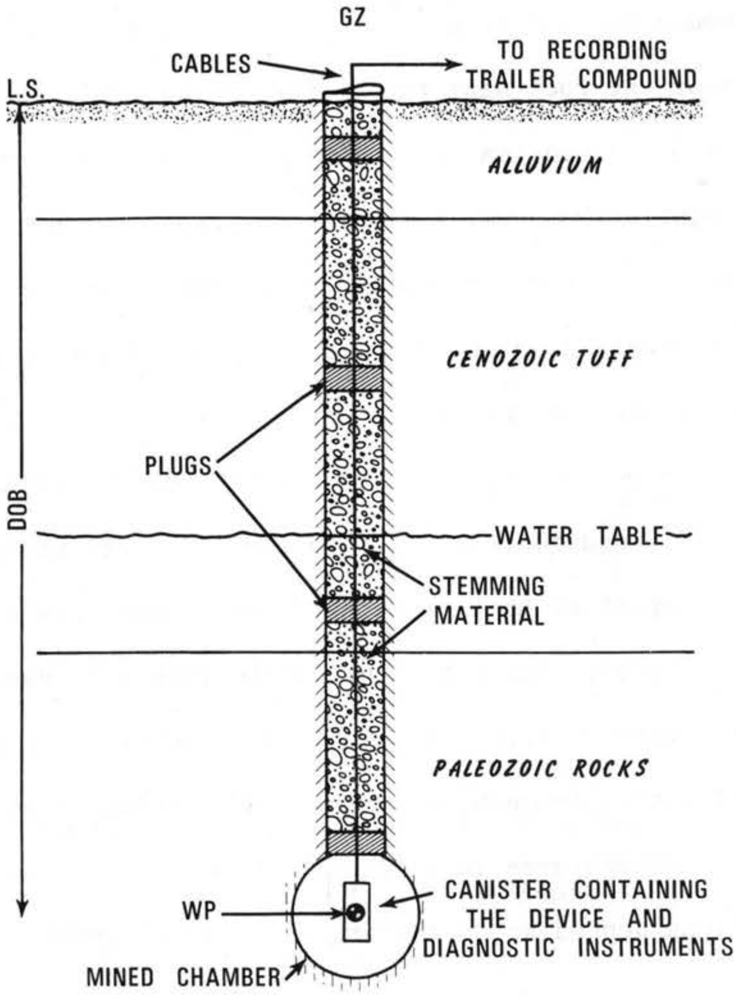

Figure 2. Idealized section of an emplacement hole readied for an underground nuclear experiment.

of the nuclear explosion is generated in a few tenths of a microsecond vaporizing the assembly materials and forming a rapidly growing fireball (Fig. 3). Temperatures may reach 6 x 10^6 degrees celcius and pressures may reach 10^7 bars. In the hydrodynamic phase lasting milliseconds, a shock wave proceeds outward vaporizing, melting and crushing the surrounding medium (Fig. 4). The cavity is formed by the outward motion of the rock near the center of the explosion. Cavities reach their final dimensions in a matter of hundreds of milliseconds. In the quasi-static phase which may last seconds to hours, the cavity cools and collapses when the internal pressure can no longer support it. When a great pressure drop occurs, fissures open allowing gases to escape and thus a release of internal pressure. It is here that the roof of the cavity fails under the weight of overburden material and a chimney of rubble is produced (Fig. 5). In the long-term phase, days to years, a slow transport of heat through the rock takes place and the radioactive products decay. Water present in the rock will vaporize and distribute the heat over a large volume. Boiling points will be reached from several months to possibly years, then condensation of water vapor will begin. Temperatures in the cavity region will slowly decay to normal conditions depending on the availability of groundwater as a coolant.

Spall

A phenomenal characteristic of the tensile strength of rock some depth below the surface is termed spall. Spall occurs as a result of primary stress conditions communicated through the rock at velocities of several thousands of meters per second, the exact value depending upon the material, the type of stress distribution, the state of stress within the medium and the various boundaries involved. In large earth

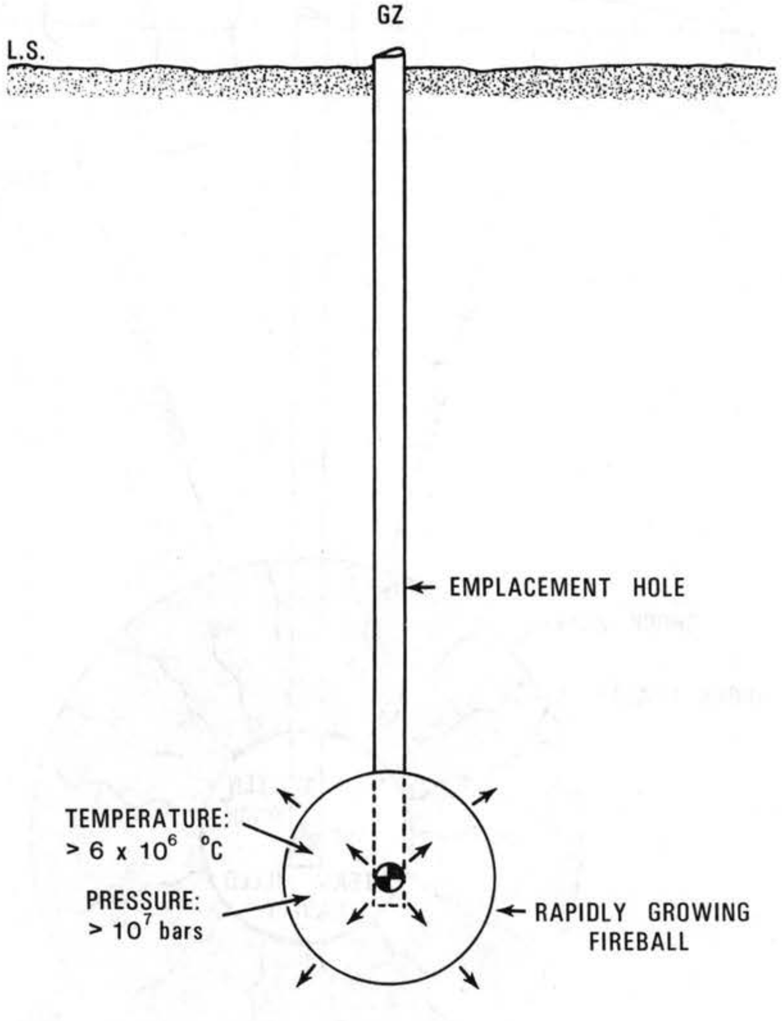

Figure 3. Main features of the nuclear phase during a nuclear explosion.

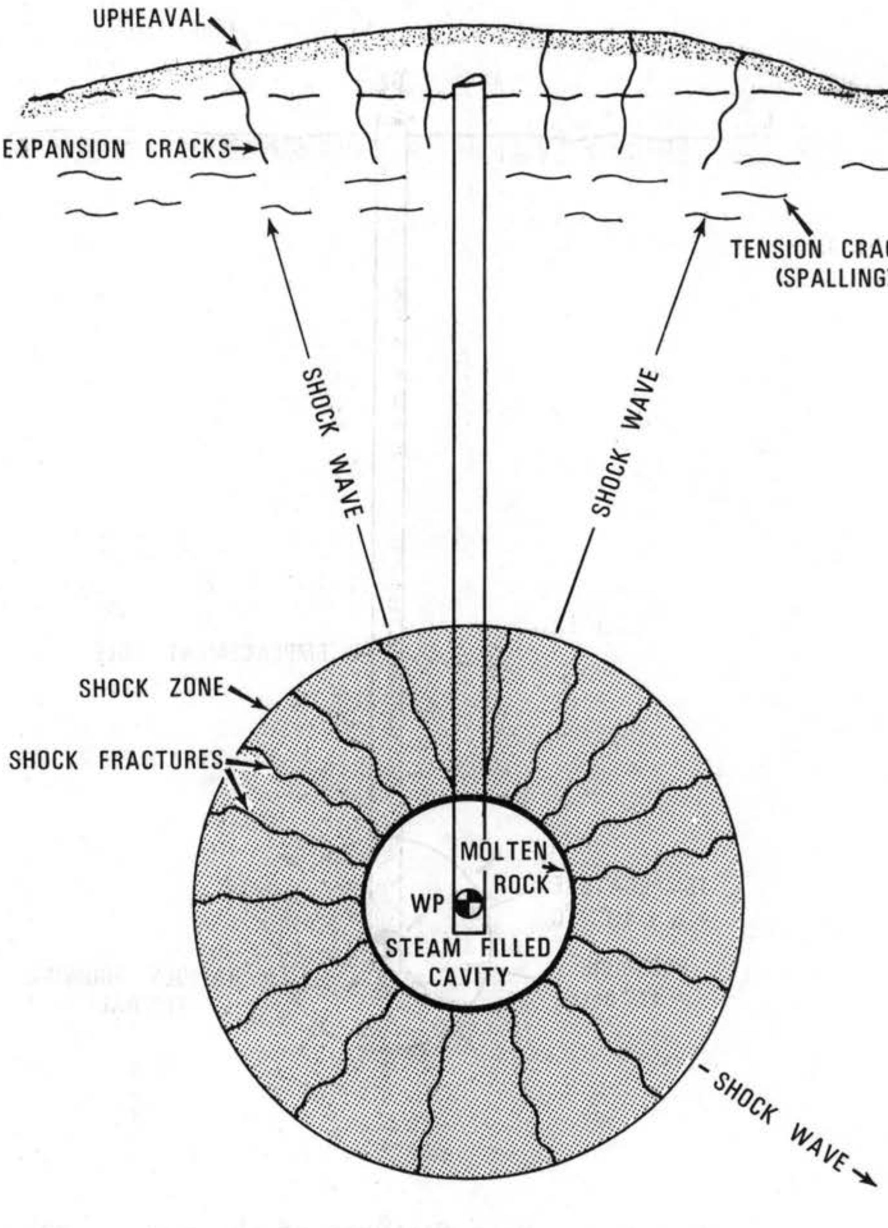

Figure 4. Main features of the hydrodynamic phase during a nuclear explosion.

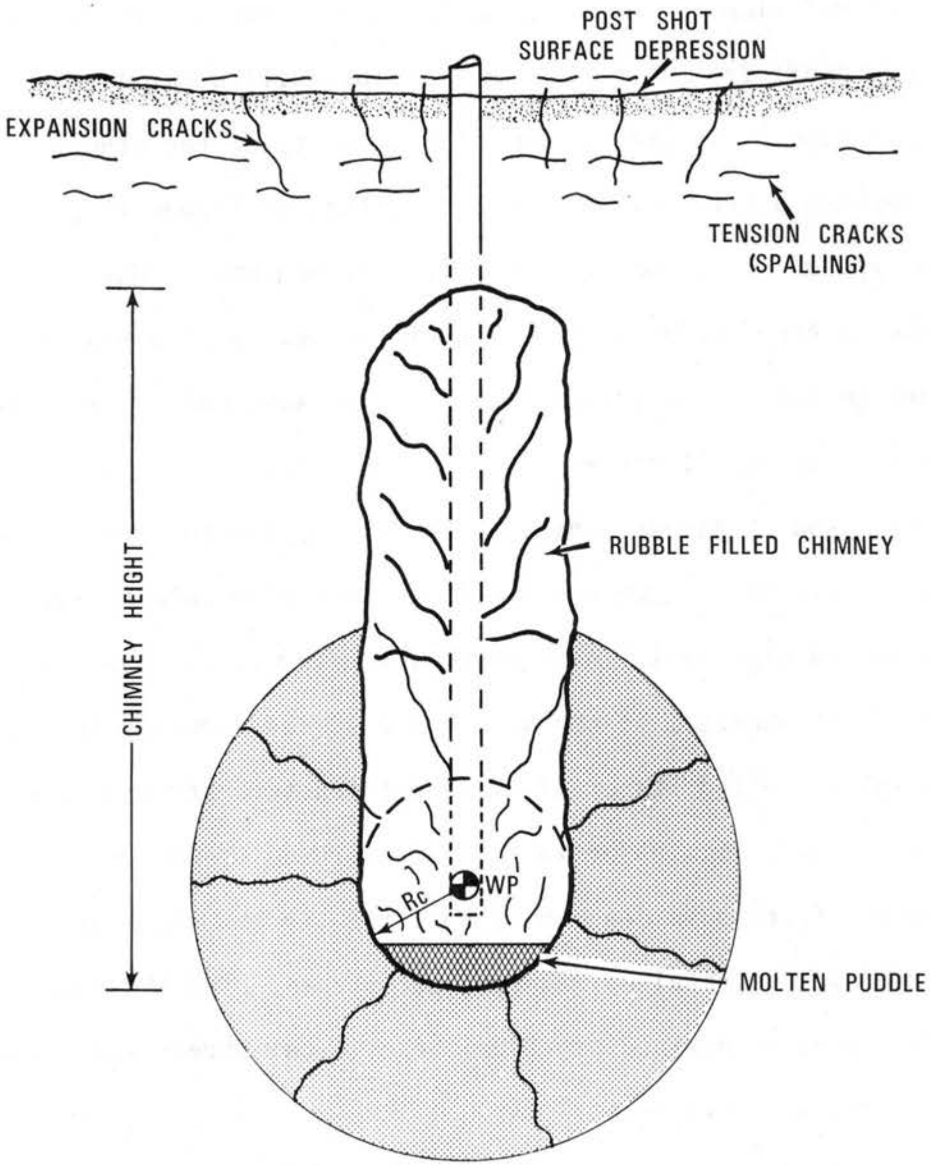

Figure 5. Main features of the quasi-state phase during a nuclear explosion.

masses, velocities of two general types are considered; the compressional rarefactional wave or "P" wave and the transverse, distortional shear wave or "S" wave.

Viewed simply, the material is said to spall when one segment parts and moves off from another segment. This will occur if the velocity of the one segment is greater than the velocity of the other. Stress waves, on reaching a free surface and reflecting, are prone to give rise to this type of partitioning of velocity or momentum. When a disturbance strikes a free surface, it will be reflected as a tension wave without change in form. The incident compression wave and its reflected counterpart (tension) will interfere with each other (Fig. 6). As a result, the distribution of stress changes from compression to tension and the material (rock) at some point will no longer be able to support this tension and will fail. A segment of top layers will spall, trapping much of the momentum of the wave. The stress required to fail the material is called its critical normal fracture stress; in rocks, the stress is quite low being in the neighborhood of 35 bars. The two most important factors in describing spalling are the shape of the stress wave and the critical normal fracture stress. The thickness of the spall may be determined provided the critical stress and the shape of the stress wave are known.

Figure 7 shows the motion of the surface expressed arbitrarily in physical quantities of vertical acceleration, vertical particle velocity, and displacement.

The first arrival of the shock wave results in a relatively sharp pulse of upward acceleration which imparts an upward velocity to the surface formation (Fig. 8a and Fig. 7). Under the influence of this

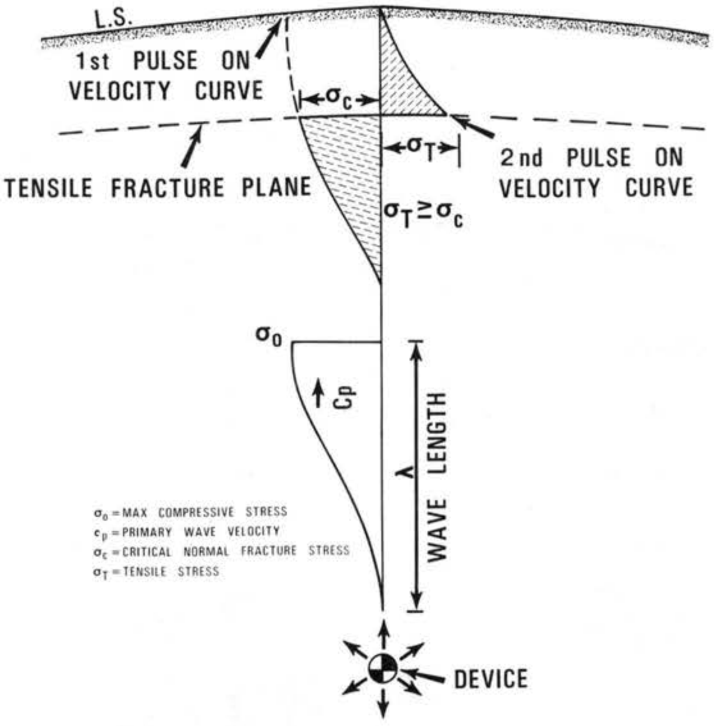

Figure 6. Stress configuration producing tensile failure in rock as a result of an underground nuclear explosion.

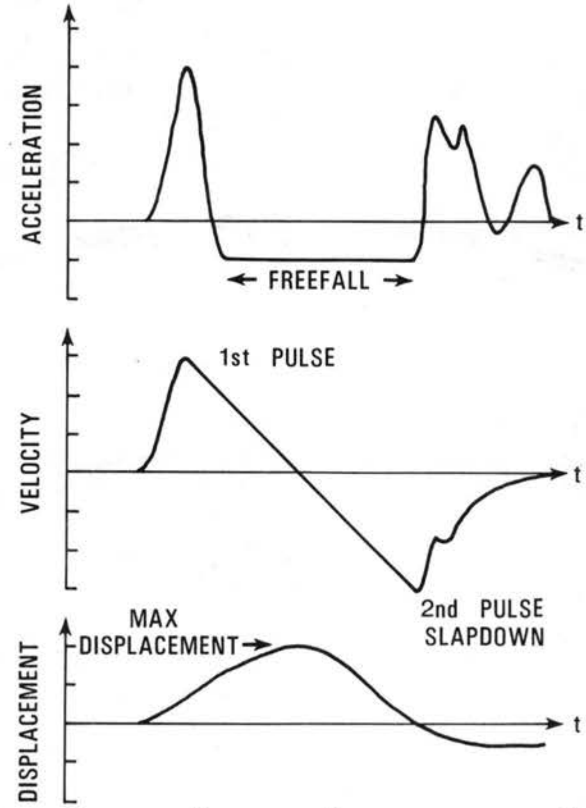

Figure 7. Typical surface motion waveforms as a result of underground nuclear explosions during the hydrodynamic phase.

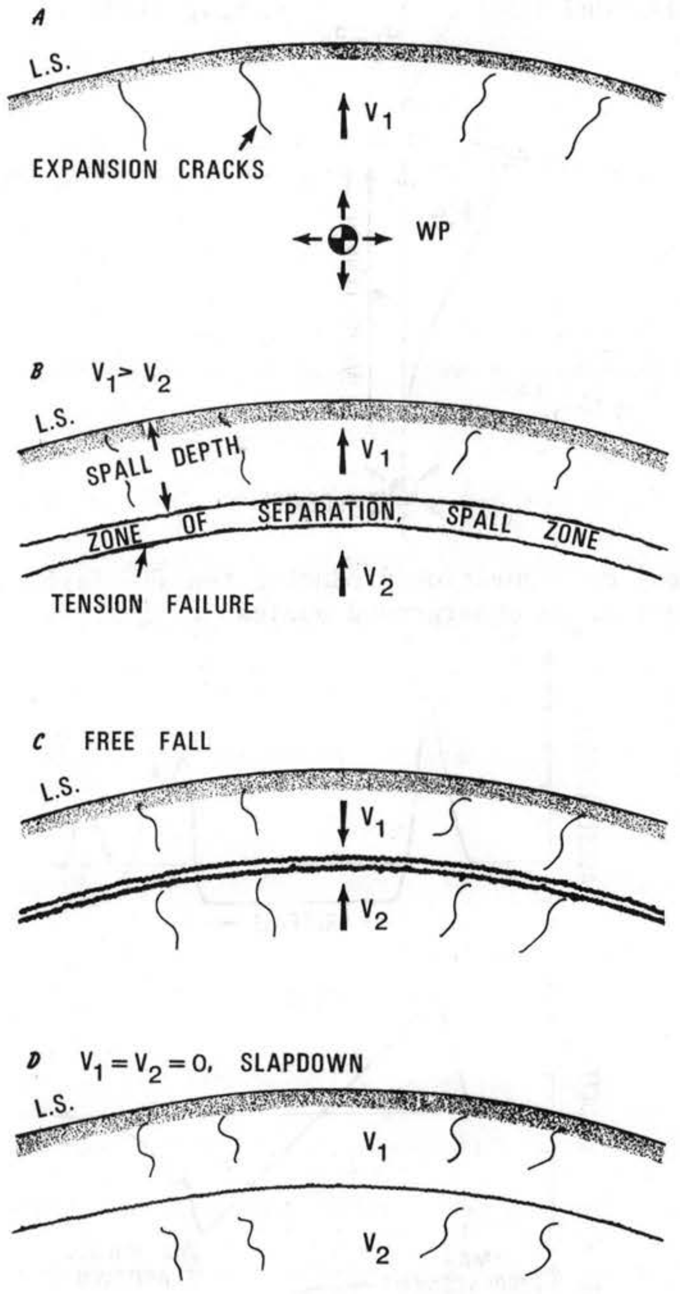

Figure 8. Fundamental concept and features of spall.

velocity, the surface continues upward being decelerated only by the force of gravity so that there is an appearance of a slow upward heave (Fig. 8b). During this upward movement spallation occurs and cracks tend to form in the surface with little tendency toward lateral or vertical displacements across the cracks unless a major discontinuity of the formation intersects the surface. After reaching its peak the hump falls back to its original position during the period of freefall (Fig. 8c and Fig. 7), landing with a second shock referred to as slap-down (Fig. 8d and Fig. 7). At this time most of the cracks close except for those which are somehow wedged apart by loose rocks. In some cases there are distortions producing vertical or lateral displacements across cracks. The final position of points on the surface near GZ has generally been found lower than the original position. The effects fall off rapidly with distance from GZ. The peak accelerations tend to be proportional to the inverse fourth power close in, shifting rapidly to the inverse cube of the range. The peak displacement does not fall off so rapidly because frequency changes as well. At great distances the rate of decline decreases as indirect propagation effects become prominent.

Cavity Expressions

During the quasi-static phase after the cavity ceases to expand, molten rock drains to the bottom to form a puddle at the bottom of the cavity. Pressures and temperatures drop rapidly and eventually the collapse of the cavity roof occurs resulting in a rubble-filled cavity and a rubble chimney extending upward towards land surface. Depending on the DOB, W (the yield of the device), and the competency of the rock, the top of the rubble chimney will end some depth below the surface

(Fig. 5), or will extend to the surface and form what is commonly known as a collapse sink (Fig. 9). In a plan view few sinks are perfect circles but their size, shape and structure are dependent on the geology, the special features of the explosion, and the mode of device emplacement (Houser, 1970). The chimney is fundamentally a right cylinder with a radius equal to or slightly greater than the R_c (cavity radius). If the chimney does not reach the surface, the chimney terminates upward in some form of a dome.

At this time a brief history of collapses and formation of cavities and their dimensions might be in order. As was previously mentioned, the first contained underground nuclear test was a Ranier event in September 1957. The yield of this event was 1.7 kilotons and the nuclear device was detonated in relatively soft nonwelded tuff at a vertical depth of 274 meters in Ranier Mesa on the test site. The cavity formed by the explosion was presumably nearly spherical and had a 19.8 meter radius. This cavity collapsed to form a vertical generally cylindrical chimney with a radius ranging between 21.3 and 27.4 meters and a height of 117.7 meters (Thompson and Misz, 1959). The first surface subsidence of a nuclear explosion resulted from the collapse of the Blanca cavity on October 30, 1958. The collapse occurred in tuff within 26 seconds of the explosion. The irregularly elongated surface depression is estimated to be 30.5 meters wide, 121.9 meters long and not more than 4.57 meters deep (Wilmarth and McKeown, 1960). The largest sink that formed completely in tuff is at the Boxcar site which subsided on April 26, 1968, 106 minutes after detonation and created a sink 152.4 meters in radius and 37.8 meters deep. The first sink to form in alluvium did so 27.5 minutes after the Fisher event on December 3, 1961. The explosion had

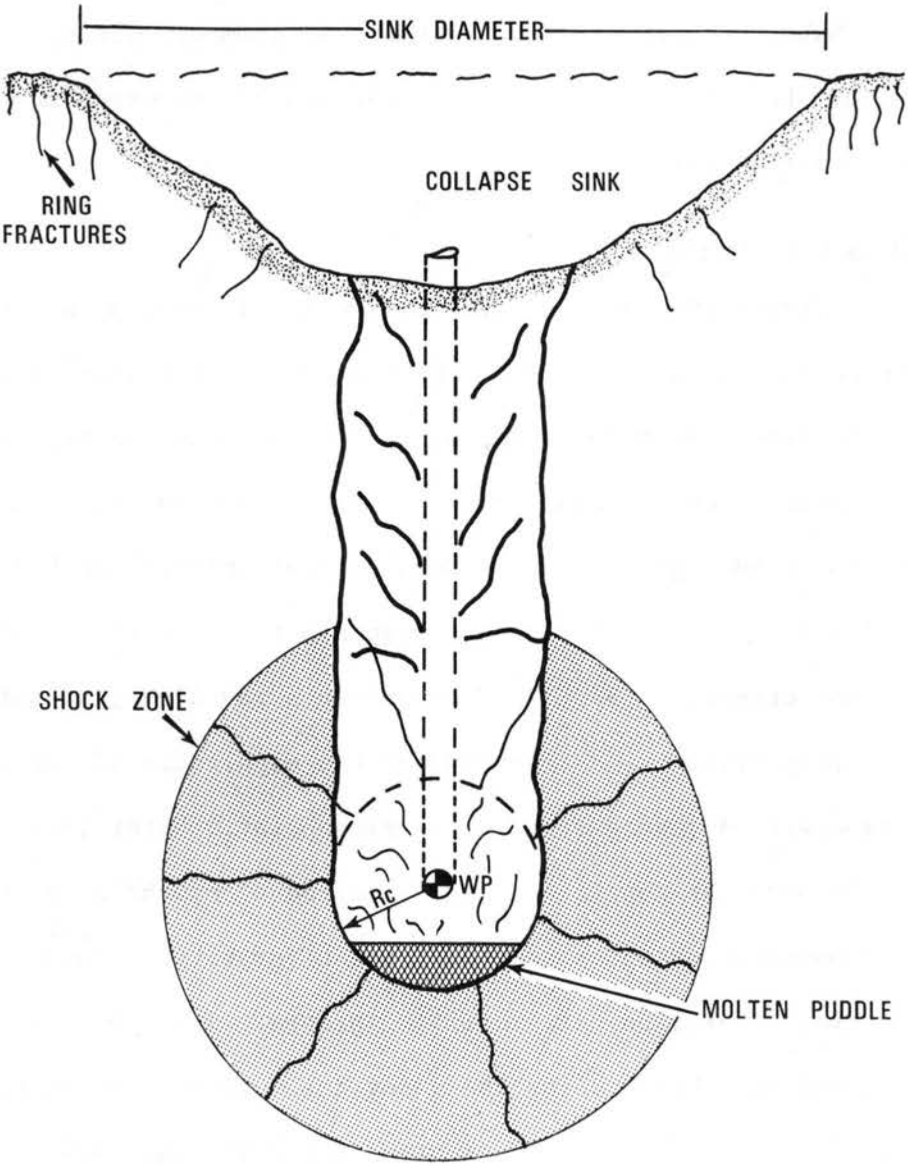

Figure 9. Main features of a cavity collapse producing a rubble chimney extending to the surface, resulting in a collapse sink.

a yield of 13.5 kilotons centered at a depth of 363.6 meters. The sink measured 86.6 meters in radius and 15.2 meters deep. Most of the explosion cavities at the NTS have collapsed within a few minutes or a few hours. Subsidence at the surface has most commonly accompanied this collapse. Less commonly surface subsidence has occurred months or years later or not at all.

Hydrologic Response

In October 1963 a 40 kiloton device was detonated in zeolitized tuff beneath the water table at the NTS. The experiment, code name Bilby, provided the first opportunity to postulate the typical reaction of a saturated zone or aquifer to an underground nuclear explosion. During the event, groundwater levels in four observation holes around the Bilby site were measured as a response to the detonation (Hale, W. E., and others, 1963). The measurements revealed that water levels rose shortly after the detonation and the magnitudes of the rises decreased with distance from the working point. Water levels decayed slowly to pre-shot conditions over a period of months as a result of outward movement of water and the force of gravity.

During several re-entry drilling programs a sharp drop in potentiometric head was observed for those devices detonated below the water table, presumably as a result of groundwater filling those voids created by the collapse.

Subsequent chimney infill programs for several detonations beneath the water table (Gonzalez, D. D., file data) show that upon collapse a cone of depression is formed around the rubble chimney, followed by a period of water infill simulating the recovery of a water well after pumping has ceased. Figure 10 illustrates hypothetical positions of

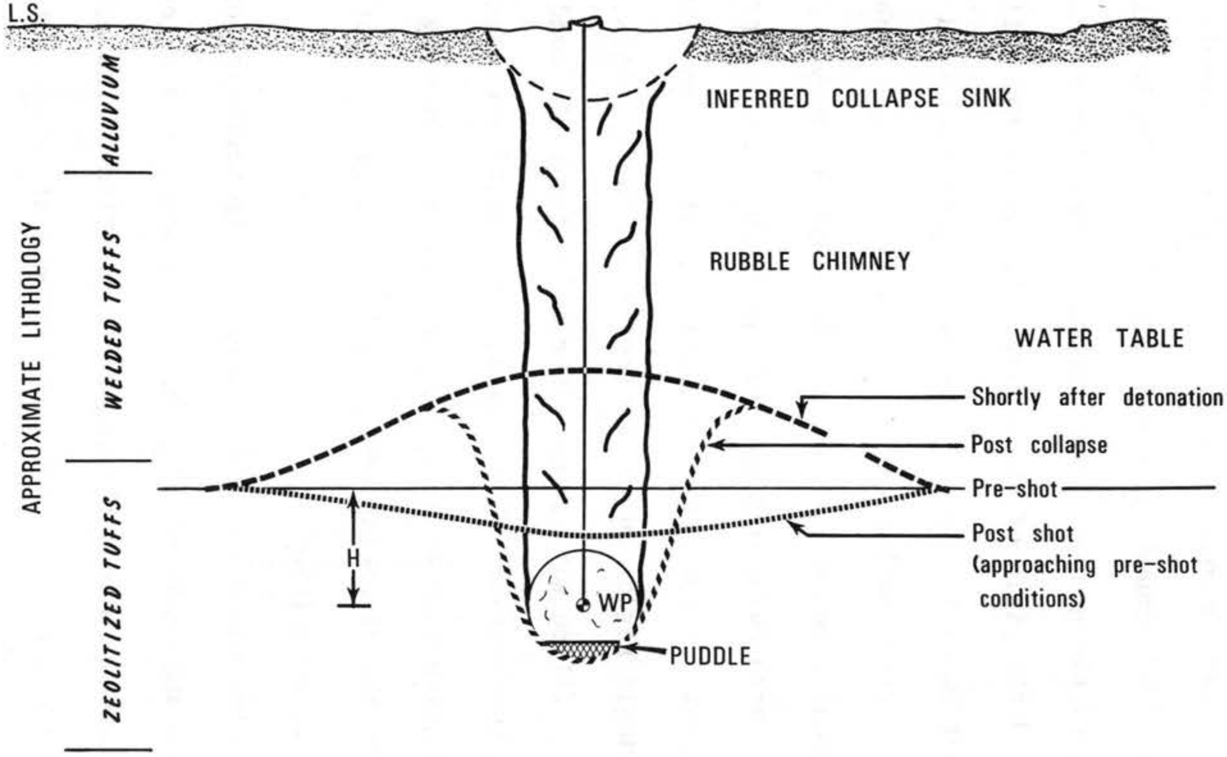

Figure 10. Water table response to a detonation in the saturated zone, Yucca Flats, NTS, Nevada.

the water table following a nuclear explosion in the saturated zone based on available data.

Prior to the explosion, the pre-shot water level is shown in a state of equilibrium at a height above the working point. Shortly after detonation the surrounding medium is compressed resulting in a groundwater mound centered around the emplacement hole. The height of the mound is a function of the geologic and hydraulic character of the surrounding medium and the yield of the device. Following the collapse of the cavity and formation of the rubble chimney the potential head drops sharply to some point near the bottom of the cavity forming a cone of depression and an annular mound surrounding the rubble chimney. Finally, inflow from the surrounding groundwater aquifer becomes the primary cooling and mixing agent for the hot, radioactive cavity region. In time, as the molten puddle region in the bottom of the cavity cools, the rubble chimney is filled with groundwater and water table conditions are restored to their pre-shot levels. At this time contaminents resulting from the detonation achieve the potential to move away from the rubble chimney in the direction of the groundwater gradient at a rate of local groundwater velocities.

The previous discussion concerning the mechanics of nuclear explosions and their after effects will serve as a brief summary of the important points following the detonation of the nuclear explosions that are critical in studying the effects of these explosions.

Chapter 3

AREA OF INTEREST

Geography

Amchitka Island in the west central part of the Aleutian Arc is part of the Rat Island group and lies just west of the 180° meridian and north of the 51°N latitude (Fig. 11). The island is about 65 kilometers long in a northwest direction and 5 to 8 kilometers wide. It has a surface area of 296.3 square kilometers and is the fifth largest Aleutian Island (Coats, 1956, p. 86). The island is in a region of turbulent winds and waters with the Bering Sea to the north and the Pacific Ocean to the south.

The island can be divided into various land forms: a mountain segment, a high plateau, the Chitka point segment, lowland plateaus and in an intertidal bench (Powers and others, 1960). All the Aleutians are of volcanic origin and are seismically very active. Amchitka itself has no volcanoes. The island is foggy and windswept much of the time and is mostly covered with heath and dotted with many ponds and lakes in its lower elevations and bare on the mountainous west.

The Aleuts settled on the island more than 4,000 years ago, and until Russian occupation, more than 40 villages were occupied by the relatively large native population (Guggenheim, 1945). The island was later taken over by the Russians, following Bering's discovery of the Aleutians in 1741 (Hrdlicka, 1945). The Russian expeditions were primarily for the purpose of obtaining the furs of the sea otter. A village inhabited by the Aleuts and Russian trappers was established in Constantine Harbor during the 18th century and flourished for many years (Hutchinson, 1937, p. 145); however, when Hutchinson visited the island

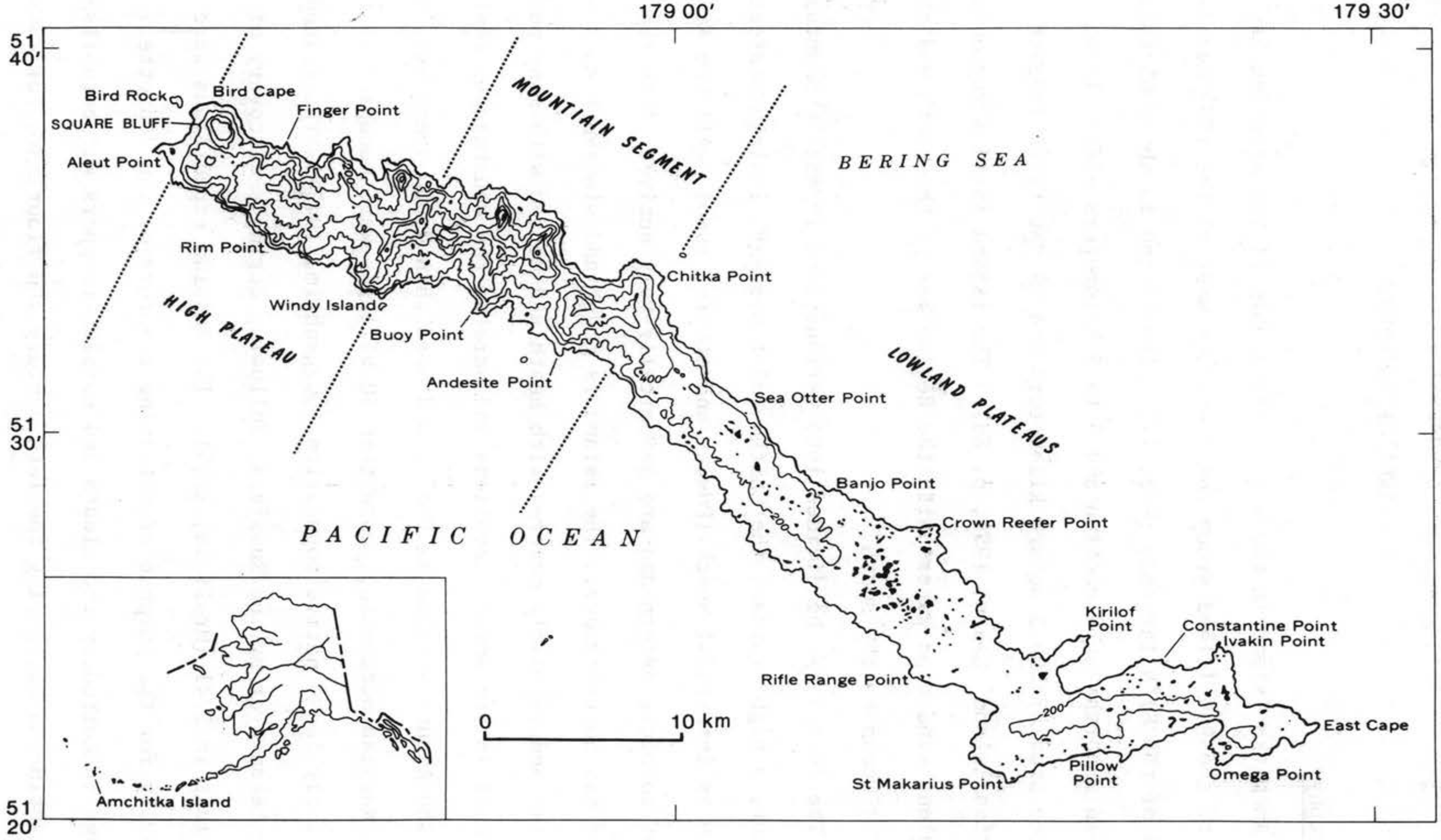

Figure 11. Amchitka Island, showing various landforms and points of interest.

in 1935, the village was entirely uninhabited with only a Russian church in a state of good preservation. To date, the only evidence of this early inhabitation is a 1930 datemark on a tombstone in a small cemetery near Constantine Harbor.

In 1913, the Aleutian chain was set aside as a wildlife preserve under the supervision of the Fish and Wildlife Service, Department of the Interior. From 1943 to 1950, the island was used as a military base where as many as 10,000 troops occupied the island at one time. Most of the eastern part of the island is littered today with uninhabitable ruins of military buildings. During the military occupation, an extensive network of roads, airplane runways and hangars were constructed throughout the general area surrounding Constantine Harbor. One main road, Infantry Road, was constructed from this area to the northwest tip of the island a distance of approximately 50 kilometers. There have been no permanent establishments on the island since military occupation, which ended in 1950.

The island has been visited since then by the Fish and Wildlife Service, the U.S. Weather Bureau, and the U.S. Geological Survey (Coats, 1956; Powers and others, 1960). In 1964, the island was again inhabited when work was begun in preparation for detonation of a low-intermediate yield experiment, Long Shot, for the Vela Uniform Series. In May 1967, the island was again inhabited to complete an exploratory drilling program initiated for the high-yield calibration shot, Milrow. It was at this time that hydrological, biological, and seismic effects programs were also initiated on the island. As a result of the success of Milrow, Amchitka Island was selected as a site for the high-yield test, Cannikin. Exploratory drilling and effects programs therefore continued at an accelerated rate necessitating the inhabitance of the island until at least completion of the experiment in November 1971. During this period, the island was inhabited by as many as 1,000 men at one time.

Climate

Amchitka Island has a pronounced maritime climate, being cool, stormy, and cloudy throughout the year (Arctic Weather Central, 1950). The Aleutian weather is basically a result of large-scale pressure systems and their associated weather fronts.

Barometric pressures fluctuate frequently and often abrupt changes in weather occur as a result of these changes. In the northwest highlands, the weather is expected to be more severe than in the lowlands where the data were collected. Temperatures are usually lower with increasing elevation and commonly all weather conditions are more severe in the highlands than in the lowlands. Partial to complete cloud cover occurs almost constantly (98 percent of the time). During the summer, fog occurs 50 percent of the time and in the winter, there is less fog and overcast. Summer fog persists days at a time; clear skies are extremely rare at Amchitka.

Geology

The U.S. Geological Survey has been actively engaged in extensive studies during the period 1964 to 1972 to better understand the hydrogeologic environment on and around Amchitka Island. Previous to this, the island had been described by Coats (1956) and by Powers and others (1960). The following discussion is a summary of these studies.

The Aleutian Arc includes a curving submarine trench as deep as 7,600 meters which extends 3,200 kilometers from the Gulf of Alaska across the north Pacific and a parallel ridge rising to the north

3,660 meters above the Pacific floor. The eastern third of the ridge comprises the Alaska Peninsula and the western two-thirds is an almost completely submerged mountain range whose exposed peaks represent the Aleutian Islands (Gard, 1974, written communication, U.S. Geological Survey). Formation of the Aleutian trench was initiated during the Tertiary period.

The Aleutian ridge can be divided into a series of physiographic blocks in which each appears to be a seismic entity where aftershocks occurring as a result of earthquakes in that block are generally confined to that same block (Jordan and others, 1965; Engdahl, 1971). Amchitka lies in the Rat block, containing the Rat Islands. According to Anderson (1971), the abundance of tectonic features on the islands, such as dikes, normal faults, grabens, etc., all suggest the island was formed under tensional stress. Faulting was initiated in middle Tertiary time and continued into late Pleistocene time. Faulting generally strikes in a northeastward direction and dips steeply northwest (Fig. 12).

Carr and others (1970) defined and dated rocks on Amchitka Island deriving from three periods of vulcanism: the Amchitka Formation, Banjo Point Formation, and the Chitka Point Formation (Fig. 12).

The five prominent land forms that divide the island (Powers and others, 1960) are, (1) the mountain segment, a remnant of the Chitka Point volcano that rises as high as 366 meters above mean sea level and lies between Chitka Point and Windy Island, (2) a high plateau, northwest of the mountain segment, ranging in altitude from 214 to 275 meters extending to square bluff, (3) the Chitka Point segment, an area south of Chitka Point Bluff and a small area north of Windy Island, (4) the

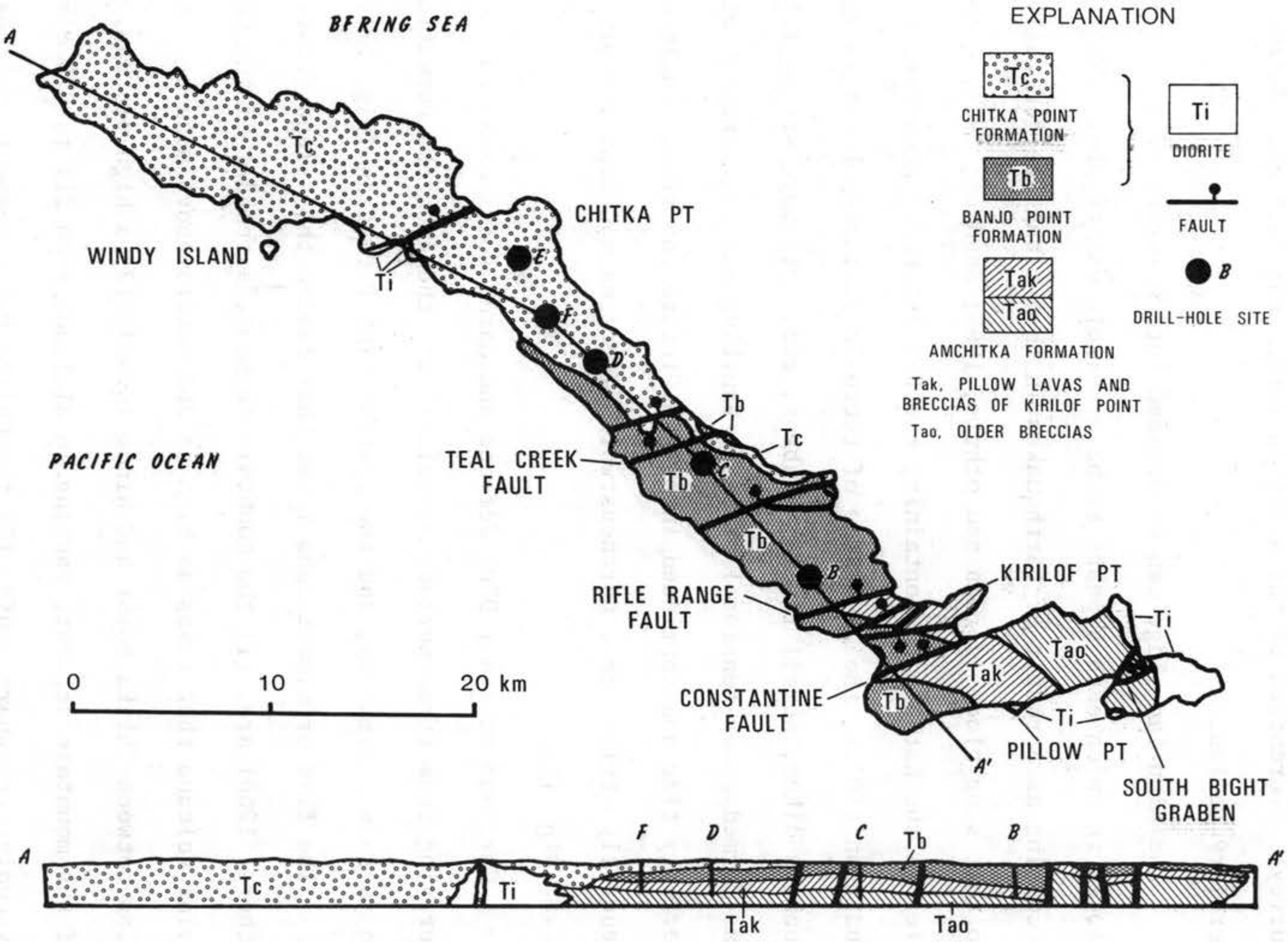

Figure 12. Geologic sketch map and cross section of Amchitka Island, Alaska Carr and Quinlivan, 1969).

lower plateaus which are prominent of the eastern half of the island, and finally, (5) the intertidal bench, currently being developed at about mean sea level around most of the perimeter of the island.

The four major stratigraphic units present on the island from oldest to youngest (Fig. 12) are as follows: (1) the older breccias and hornfels, (2) the Pillow Lavas of Kirilof Point, (3) the basaltic rocks of the Banjo Point Formation, and (4) the Andecitic rocks of the Chitka Point Formation (Carr and Quinlivan, 1969). The oldest rocks on the island are the altered older breccias and hornfels which are exposed in the area east of Constantine Harbor and Pillow Point. The Kirilof Point rocks exposed on the eastern part of Amchitka, east of Rifle Range Fault were probably deposited in a submarine environment with some of the breccia occurring as a result of fragmentation by rapid chilling of hot lava. The pillow lavas range from 7.5 to 60 meters thick and consist of 1- to 2-meter pillow-shaped bodies. Most of the rocks of Kirilof Point are less basic than any others on the island.

The Banjo Point Formation consists of basaltic rocks of submarine deposition and is estimated not to be over 1,550 meters thick. The Chitka Point Formation covers almost the northwest one half of Amchitka Island. It consists almost entirely of subaerially deposited hornblend andesitic volcanic rocks and is estimated to vary in thickness up to 600 meters.

In addition to the major stratigrahic units, there are a group of intrusive igneous rocks present on the island that are divided into two groups on the basis of composition and time of intrusion. The oldest includes basaltic dikes and sills common to the Banjo Point Formation and the youngest is a complex of diorites and andesites exposed on the eastern part of the island. Unconsolidated sand and gravel are noted in fault depressions and are probably beach deposits. Landslide areas are present on the island and in several locations where steep slopes predominate the land surface.

Hydrology

Prior to 1964, little had been documented on the hydrology of Amchitka Island. It was the advent of nuclear testing that prompted hydrologic studies to be initiated at that time. When Amchitka Island was selected as a potential location for high yield testing, a long-term hydrologic network was established to assess the effects of underground nuclear testing on the surface water and groundwater systems of the island. The network was begun in 1967 and continued through August 1974. Surface water gaging stations and groundwater observation wells were established early in the program to define the hydrology of the island, specifically around potential sites for high yield implacement holes. Precipitation was recorded during the military occupation from February 1943 to June 1948 and from October 1967 to June 1972 during the implementation of the high yield test programs. These data show that precipitation on Amchitka Island ranges from about 80 to 90 centimeters per year at the southeastern part of the island near Constantine Harbor and probably increases to as much as 120 centimeters at other locations. The topography of Amchitka is composed of small drainage basins and hundreds of small lakes and ponds cover the lower plateaus.

Surface water base flow is sustained by groundwater discharge from thick surficial materials covering most of the lowland plateaus and the underlying bedrock. Storm events occur with regularity and result in short term runoff events highly dependent on the amount and intensity of precipitation. Comparison of precipitation and runoff altitude relationships show that most of the precipitation results in surface water runoff.

The lakes that dominate the eastern two thirds of the island are generally round in configuration and range in width from 30 to more than 100 meters and are shallow in depth. The depths of these lakes are probably dependent on bedrock configuration and the thick vegetation underlain by peat that completely surrounds many lakes. Depths range from less than 1 meter to more than 3 meters. Their bottoms are composed of bedrock with some organic materials, silts, and clays of low permeability. Many lakes are interconnected and flow into each other, eventually spilling into streams during rainy periods and conversely going dry during the dry season, usually in May and June. Many lakes are fed by perennial springs which are numerous on the island. The largest lake on the Island is Cannikin Lake, which was created as a result of the collapse associated with the Cannikin event. The lake has a surface area of twelve hectares, a depth of 9.5 meters and a volume of 4×10^5 cubic meters (Gonzalez and others, 1974).

The chemical quality of surface water and lakes on Amchitka Island is reported as excellent (Dudley, written communication, 1976). The concentration of dissolved solids is less than 200 milligrams per liter. Sodium and chloride are the dominant cations and anions. Studies of sodium chloride ratios for inland surface waters, ocean water, and precipitation, show that the precipitation occurring on the island is markedly affected by ocean salt spray. The chemistry of streams, lakes, and springs are affected by the surrounding soils, rocks, peat, and vegetation as indicated by the marked differences in increased conductivities and relative proportions of ions in each of these environments (Balance and Beetem, 1972). During periods of low precipitation when groundwater discharges into streams and lakes, an increase in dissolved solids and sodium chloride and bicarbonate chloride ratios can be distinguished.

The groundwater system on Amchitka has been defined by data collected from shallow to deep bore holes, some as deep as 2,200 meters. These data include fluctuation of water levels with time, hydraulic testing of specific intervals within boreholes, surficial observation, and quality of groundwater including temperature profiles taken at depth in drilled holes.

The land surface over most of the lowland plateaus on Amchitka Island is nearly saturated throughout most of the year resulting in a water table at or very near land surface. Exceptions to this are in the highland plateau and mountain regions where observed depths to water are on the order of 50 meters. Water levels and shallow holes respond to periods of infiltration from precipitation and those short-term periods associated with aerial strain and creep episodes. Hydraulic tests and temperature surveys in shallow holes and exploratory holes show that hydraulic head decreases with depth penetration and that the direction of groundwater flow beneath most of Amchitka is downward. Tests also indicate that transmissivities determined from packer tests range from 30 to 0.0002 m^2/dy, or 5 orders of magnitude difference. The thickness of zones tested was generally about 60 meters (Dudley, 1976, written communication, USGS). The basic conclusion from these tests is that groundwater movement is primarily restricted to fracture intensity which appears to decrease with depth because of a tendency of fractures to close under greater lithostatic loads. Groundwater movement is also affected by the Ghyben-Herzberg relationship which is present around coastal areas and beneath oceanic islands (Todd, 1959). Studies made by Dudley and others (1976, written communication), show that a Ghyben-Herzberg freshwater-saltwater interface exists and the groundwater system may have approached static conditions, therefore very little groundwater is flowing through the system. There is, however, sufficient permeability to allow some percolation of groundwater to depths of 1,000 meters or more in response to the downward gradient of flow. Flow is directed laterally and upward along the interface where it discharges at the ocean floor. It is estimated that at depth in the lowland plateau, groundwater velocities are on the order of .05 and .005 meters per day. The bulk of groundwater flow occurs at shallow depths discharging as seeps, springs, and into lakes and streams.

Chapter 4

DESCRIPTION OF OBSERVATION SITES AND DATA

Background

The data presented in this chapter represents a seven-year effort of collecting precipitation, groundwater and surface water data on a continuous basis under the most adverse conditions found anywhere. The problems associated with logistics, weather conditions, supplies, transportation and equipment were at times overwhelming. Recording equipment had to be designed to operate, maintenance free, for periods of at least three months and at times up to 10 months.

Precipitation records were collected intermittently at the airport control tower (Fig. 13). The data are only fair and are discontinuous for the most part. Those data collected during the military occupation of the island are however a good representation of precipitation variations that occur at the southeast part of the island and are used in this report as a basis for distinguishing between wet and dry periods.

Groundwater data were collected from eight sites located primarily on the lowland plateau of Amchitka. The selection of these holes for observation was based on completion, access and of course availability of the hole for monitoring. Completed depths ranged from very shallow, 11.4 meters at the White Alice borehole to 2133.6 meters at the exploratory hole, Site D.

Four holes have at least 10 months of pre-event record for Project Cannikin and of these four, two have at least seven months of pre-event record for Project Milrow. Four other boreholes were monitored post-Cannikin and are used here to show infill rates in the Cannikin rubble chimney and effects due to precipitation.

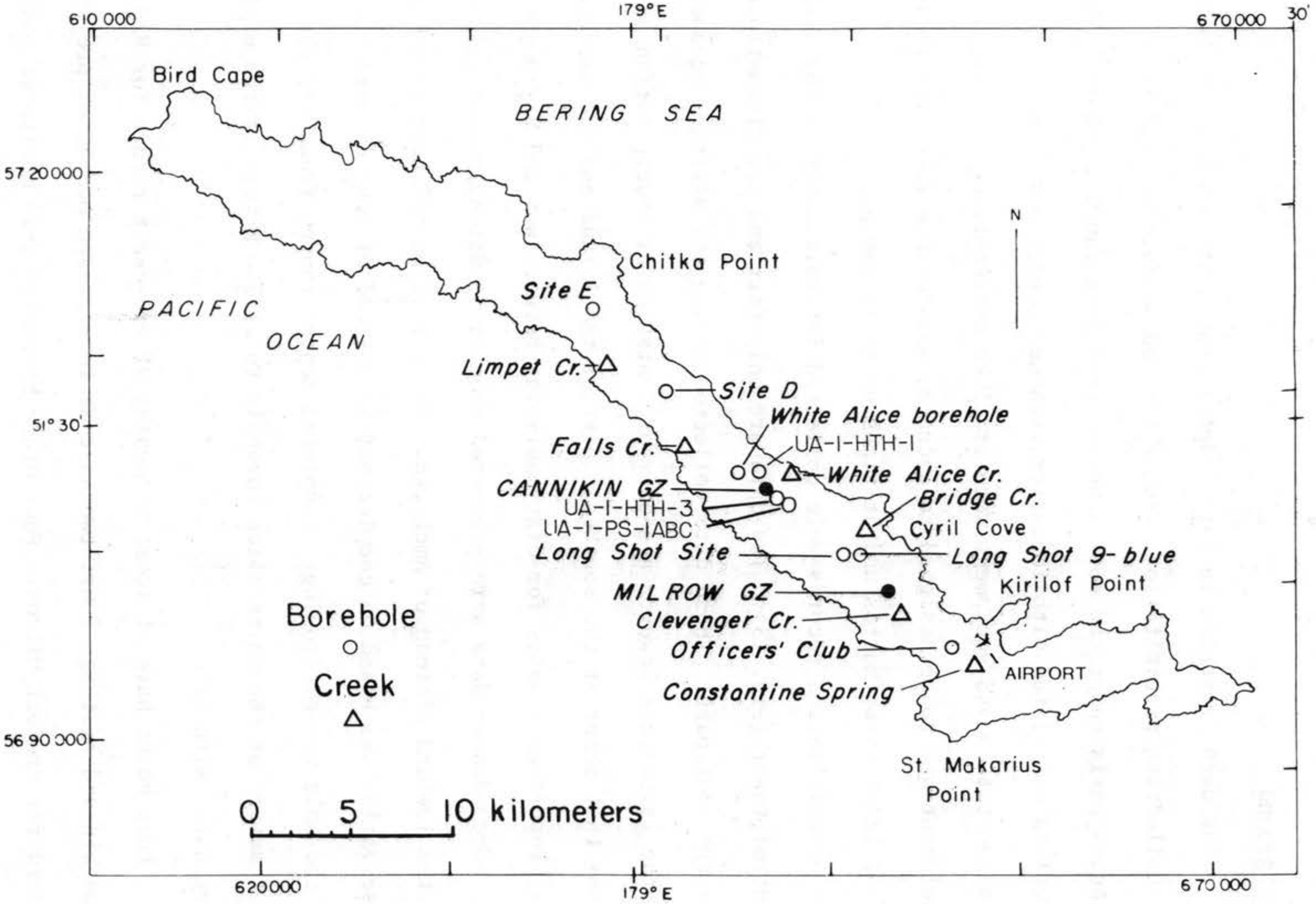

Figure 13. Map of Amchitka Island showing locations of hydrololigcal observation sites.

Surface water gaging stations were established at six locations, all within the lowland plateau. They were established to document the effects of nuclear testing on the drainage basins surrounding potential emplacement hole locations. The drainage areas ranged from 0.73 square kilometers to 7.85 square kilometers. One spring, which served as the base camp water supply, was also monitored. All gaging stations were in operation by April 1968 and some continued in operation until July 1974.

The hydrological observation sites are described in the following sections along with a brief summary of the data collected. Analysis of the data is reserved for a subsequent section. The locations of all pertinent observation sites are shown in Fig. 13.

Climatological Data

Climatological data were collected on Amchitka Island during two periods--from February 1943 to June 1948 during the military occupation of the Island and then again from October 1967 to June 1972. The entire set of data is believed to have been collected at the airport in the southeastern portion of the Island (Fig. 13). On the basis of these records, annual precipitation for the military data is about 83 centimeters (Table 1), and 97.8 centimeters for the records collected by Reynolds Electrical Engineering Company during the period 1968 to 1971 (Table 2). Maximums and minimums during military observations were all exceeded during the later period of record. The time series of daily precipitation at the airport for the period 1968 to 1972 is shown in Fig. 14.

Average daily mean temperatures range from -0.6°C in January to 8.9°C in August with a record low of -10°C in February and a high of 18.3°C in July (Table 1). The maritime climate is evidenced by noting

Table 1. Climatological Data February 1943 through June 1948 Amchitka Island, Alaska
(Compiled by the United States Air Force)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
Temperature (°C)													
Record High	7.2	6.1	9.4	8.3	9.4	13.9	18.3	15.0	13.9	10.6	10.6	7.2	18.3
Mean Daily Max.	1.1	1.7	2.8	4.4	5.6	7.8	9.4	10.6	9.4	7.2	4.4	2.2	5.6
Daily Mean	-0.6	0.0	1.1	2.2	3.9	5.6	7.8	8.9	7.8	5.6	2.8	0.6	3.9
Mean Daily Min.	-2.2	-1.7	-1.1	0.6	2.2	3.9	6.1	7.2	6.1	3.3	1.1	-1.1	2.2
Record Low	-8.9	-10.0	-6.7	-6.7	-1.1	0.0	2.2	3.3	2.2	-2.2	-5.6	-5.6	-10.0
Av. No. of Days													
Minimum <-4.4	3	2	2	1	0	0	0	0	0	0	*	1	9
<-2.2	12	9	6	2	0	0	0	0	0	0	1	6	36
≤ 0.0	28	24	22	13	3	*	0	0	0	2	10	22	124
Maximum ≤ 0.0	9	6	4	1	0	0	0	0	0	0	1	6	27
Precipitation (mm)													
Mean Monthly	71	51	33	58	41	25	89	104	74	97	71	114	828
Av. No. of Days													
with ≥ .25	19	17	13	13	11	13	16	20	16	20	20	20	198
≥ 6.35	4	2	1	2	3	1	4	6	4	5	2	6	40
>12.70	1	*	0	1	1	0	3	3	1	2	1	3	16
% of Hr with rain	9	11	13	24	28	29	40	41	26	21	23	14	-
" " snow	18	24	16	9	2	*	*	0	0	1	5	15	-
Snow Depth at 0800 LST													
Av. No. of Days													
≥ 2.54 cm	17	13	1	*	0	0	0	0	0	0	3	7	41
Depth: ≥ 5.08 "	15	10	0	*	0	0	0	0	0	0	2	5	32
>15.24 "	4	3	0	0	0	0	0	0	0	0	0	1	8
>30.48 "	1	0	0	0	0	0	0	0	0	0	0	0	1
Surface Wind													
Mean Speed (mps)	11	11	11	9	8	7	7	8	8	9	9	11	9
% of Hours with Speed ≥ 14 mps	29	28	26	19	6	4	3	4	9	16	19	28	16

*Less than 0.5 days or percent.

Table 2. Mean Monthly Precipitation, cm, October 1967 through June 1972, Amchitka Island, Alaska (Collected by Reynolds Electrical and Engineering Co., Inc.)

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1967	--	--	--	--	--	--	--	--	--	5.92	9.91	9.32
1968	6.55	9.80	3.02	3.78	0.28	1.73	7.59	4.32	7.34	4.27	12.29	6.07
1969	13.46	13.28	7.98	7.41	2.84	1.90	3.22	14.27	10.72	17.55	11.00	5.49
1970	8.69	5.92	6.32	9.07	3.78	5.23	11.61	17.40	6.48	14.20	10.54	16.59
1971	9.88	5.26	14.73	5.76	4.09	4.27	7.77	5.61	9.83	8.79	7.47	15.77
1972	10.08	1.93	3.48	9.68	2.49	5.92	--	--	--	--	--	--
Totals	48.66	36.19	35.53	35.70	13.48	19.05	30.19	41.60	34.37	50.73	51.21	53.24
Average	9.73	7.24	7.11	7.14	2.70	3.81	7.55	10.4	8.59	10.15	10.24	10.65

Average annual precipitation for the period 1968 to 1971 is 97.8 cm

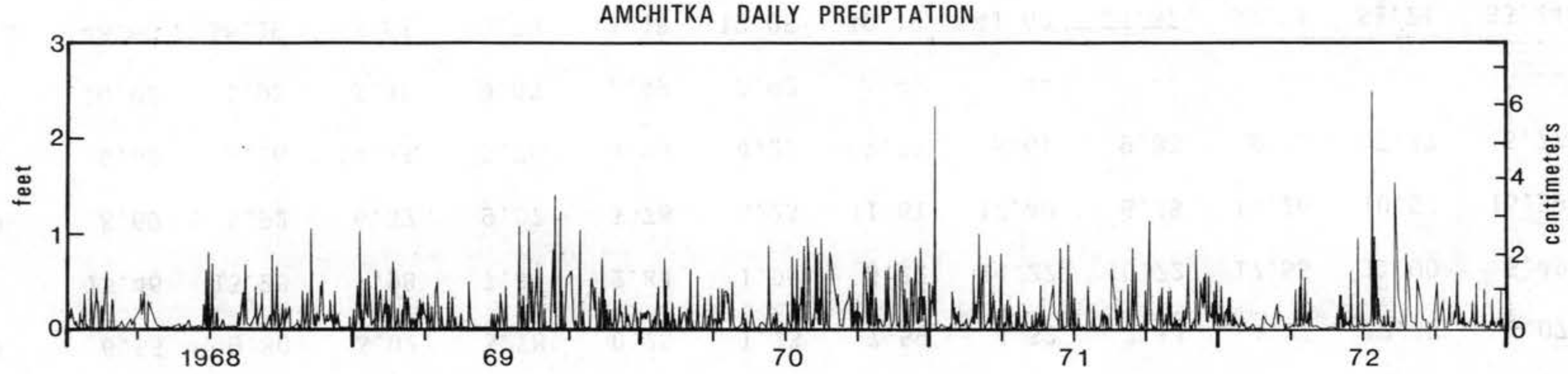

Figure 14. Precipitation at the airport, 1968 to 1972, Amchitka.

that the mean daily range for all months is 3.9°C and the annual range of the mean daily temperature is 9.4°C. Average wind speeds ranged from 22 knots in January to 14 knots in June and July, with maximums reaching 100 knots. Clear skies are rare on Amchitka Island.

Groundwater Observation Holes

UAe-7h, Site E

UAe-7h, located at Site E is in the north-central part of Amchitka on the flanks of the mountain region (Fig. 13). The hole was spudded on June 9, 1968 at an altitude of 159.3 meters above mean sea level and was completed to a total depth of 1912 meters below land surface. Drilling was done using conventional circulation and mud-base drilling fluids. The exploratory hole was drilled specifically for obtaining geologic and hydrologic information in order to assess its potential for containing a high-yield explosion.

The drill hole penetrated 54.9 meters of hornblende-rich volcanic breccia of the Chitka Point Formation, then entered a hydrothermally altered aureole to a large intrusion believed to underlie the highland area northwest of site E (Snyder, 1969). The aureole was comprised of altered andesites, metamorphosed breccias, hornfels and intrusive diorites. No large fault zones were recognized; however, the rock is strongly fractured within many zones and many fractures are open and permeable.

Hole UAe-7h was completed as shown on Fig. 15. A 21.9 centimeter casing was cemented to a depth of 624.5 meters. The remainder of the hole was drilled with difficulty because of the unstable hole conditions. After hydraulic testing was completed, a drill bit and pipe were stuck in hole, and the hole was plugged with cement from 1234 meters to TD.

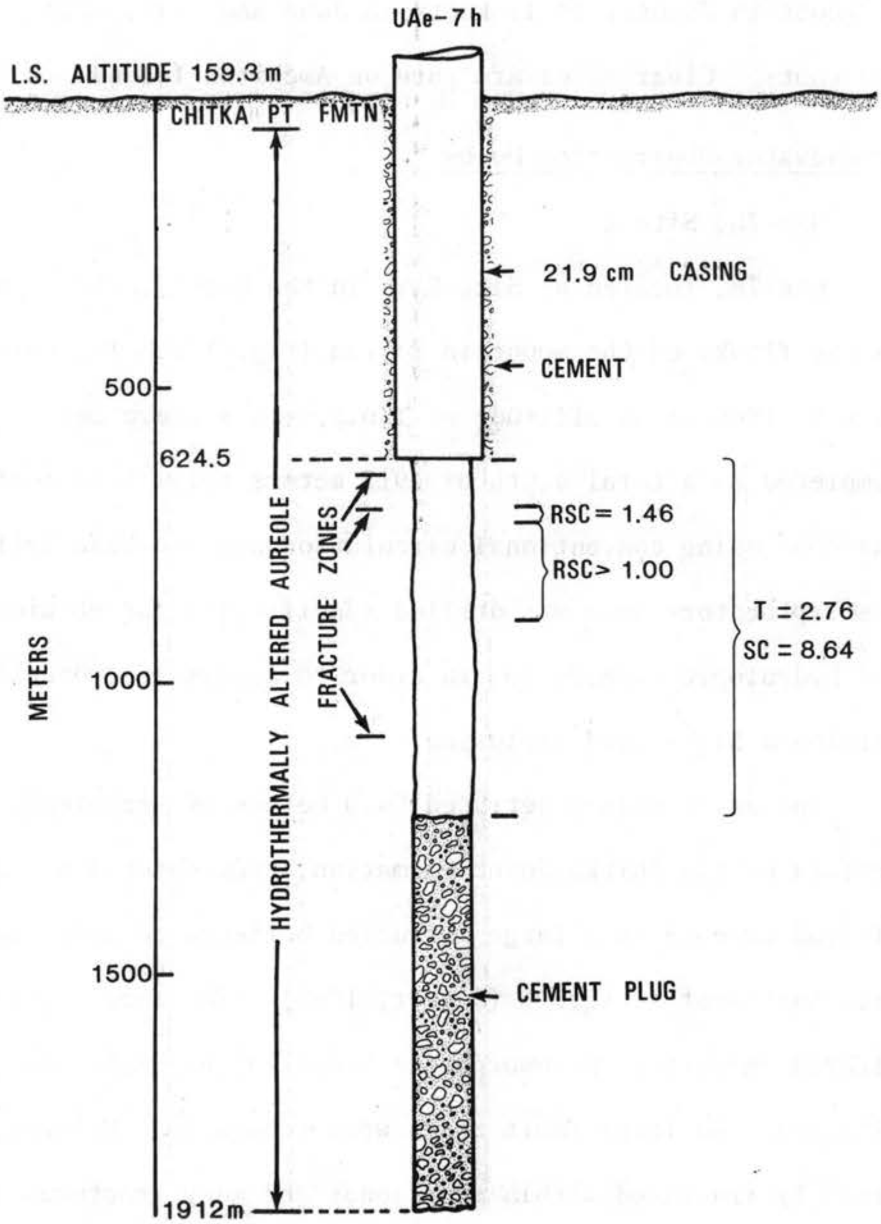

Figure 15. Completion sketch, UAe-7h, site E, Amchitka Island.

After cementing, the hole was cleaned of drilling mud and retained as an observation well whose water level represents the composite head across the zone 624.5 to 1233.5 meters.

Five zones were tested by either injecting or swabbing water across a specific zone isolated by straddle packers. The hydraulic characteristics were determined from an analysis by Cooper and others (1967). The values shown in Fig. 15 are maximum values for RSC, SC, and T (Ballance, 1970).

A pumping (jetting) test was performed across the interval 624.5 meters to 1248.5 meters and these results indicate a T of 2.76 m^2/dy and an SC of 8.64 m^2/dy/m for early recovery data. The estimated effective porosity is about 0.01 percent. A tracejector survey showed most of the water flowing into a fracture zone at about 700 meters and a zone across 960 to 1402 meters.

On March 15, 1969, a water level recorder was placed on the hole and a continuous record of water levels was obtained until it was removed August 27, 1974. Fluctuations of mean daily water-levels for the years 1969 to 1973 are shown on the hydrograph of Fig. 16. The hydrograph represents the composite head across the zone 624.5 meters to 1233.5 meters which is highly fractured in three intervals and whose average T is about 3 m^2/dy.

UAe-6h, Site D

UAe-6h, located at site D, is in the northwestern edge of the lowland plateau (Fig. 13). The hole was drilled in conjunction with the exploratory program designed to determine the geologic and hydrologic characteristics of Site D. The hole was spudded on April 7, 1968 and completed to a depth of 2133.6 meters.

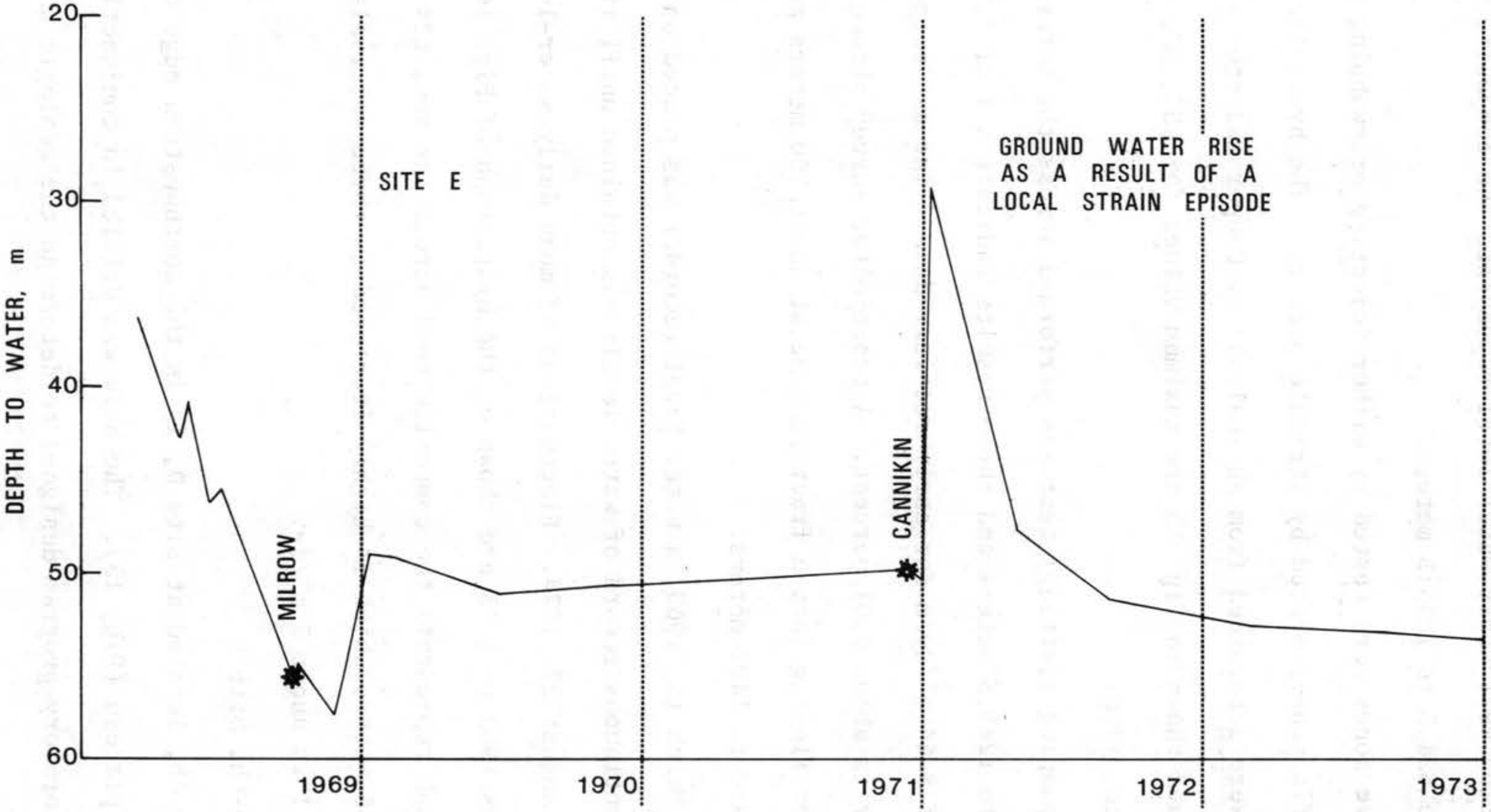

Figure 16. Groundwater hydrograph, UAe-7h, site E, Amchitka Island.

The surface rocks at Site D were the volcanic breccias of the Chitka Point Formation and were penetrated to a depth of 146.3 meters. Underlying the Chitka Point Formation are 884 meters of rocks of the Banjo Point Formation. These rocks are basaltic breccias with poorly sorted and stratified marine sandstone and siltstone. Below the Banjo Point Formation are the rocks of the Kirilof Point. These are basaltic pillow lavas and breccias which attain a thickness of 494 meters. The upper part of the formation is characterized by the pillow lavas while the lower contains breccias of pumiceous tuff. The remainder of the hole penetrates 610 meters of older breccias composed of various lithic fragments of basalt with andesite and aplite dikes and silts intruding the unit (Morris, 1969).

Hole UAe-6h was specifically drilled to determine the hydraulic character of Site D and was completed as shown on Fig. 17. The hole was thoroughly tested by either injection or swabbing methods across 14 zones. The results of these tests show that head decreases with depth and that most of the rocks have very low permeabilities, indicated by the very slow recovery of water levels after testing. Average depths to water across specific zones in the upper interval measured 35 meters below land surface down to a depth of about 1495 meters. In the lower interval, down to about 2120 meters the heads were estimated at 90 meters below land surface.

A pumping (jetting) test was performed across the entire interval, 85 to 2133.6 meters, resulting in a T of 0.60 m^2/dy and a RSC of 1.94 m^2/dy/m (Ballance, 1972). A summary of these tests is shown on Fig. 17.

UAe-6h was equipped with a water level recorder on July 12, 1968, until its removal on August 27, 1974. The continuous record of water

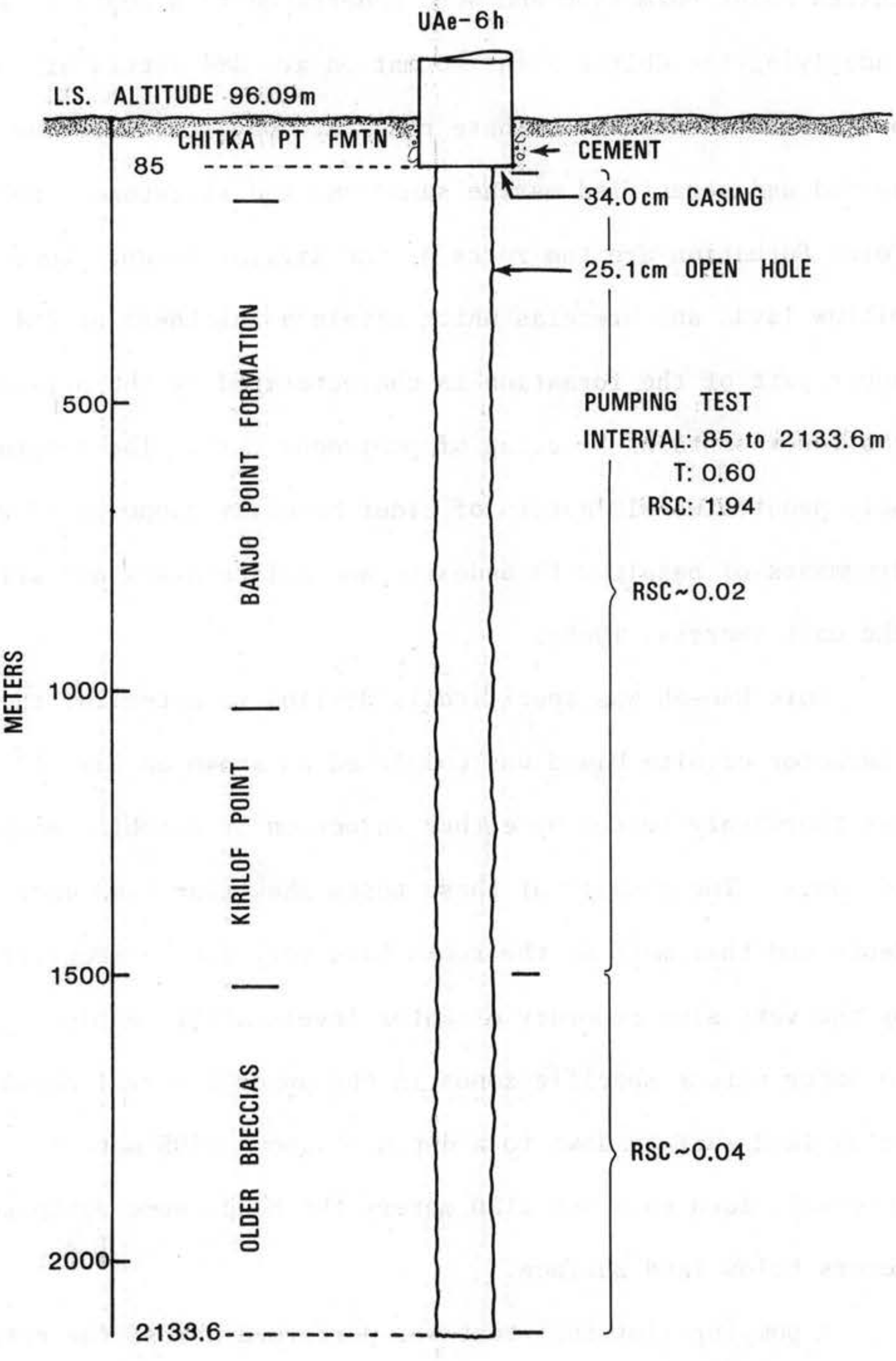

Figure 17. Completion sketch, UAe-6h, site D, Amchitka Island.

levels represents a composite head across the four major stratigraphic units on the island. The lithologic log of the hole does not show any major fracture zones, however a comprehensive analysis of rock properties shows that porosity decreases with age and depth of burial of these rocks along with a general increase in saturated bulk density (Lee, 1969). These data also show that porosity has a marked decrease near the interface between the Banjo Point Formation and the rocks of the Kirilof Point so most of the groundwater response would be from the Chitka Point and Banjo Point Formations.

Figure 18 shows the mean daily fluctuation of water levels for the entire period of record.

White Alice Borehole

White Alice Borehole was probably drilled during the military occupation of island in the 1940's. It is located in the northern part of the lowland plateau (Fig. 13) and was apparently a shallow exploratory hole or water-supply well. It was spudded at an altitude of 88.4 meters, and drilled to an apparent depth of 96.3 meters (Fig. 19). The hole was cased to a depth of 11.43 meters and was apparently left uncemented. The surface rocks are the volcanic breccias of the Chitka Point Formation and it is almost certain that the hole penetrates these rocks (L. M. Gard, 1977, personal communication, USGS).

There was no available hydrualic information on the White Alice Borehole regarding the characteristics of the aquifer until the hole was instrumented just prior to the Cannikin event. The hydrograph (Fig. 20) shows that the depth to water is very shallow and susceptible to recharge from precipitation. The mean monthly depth to water varies only tenths of a meter throughout the year. The hole is located near the divide of

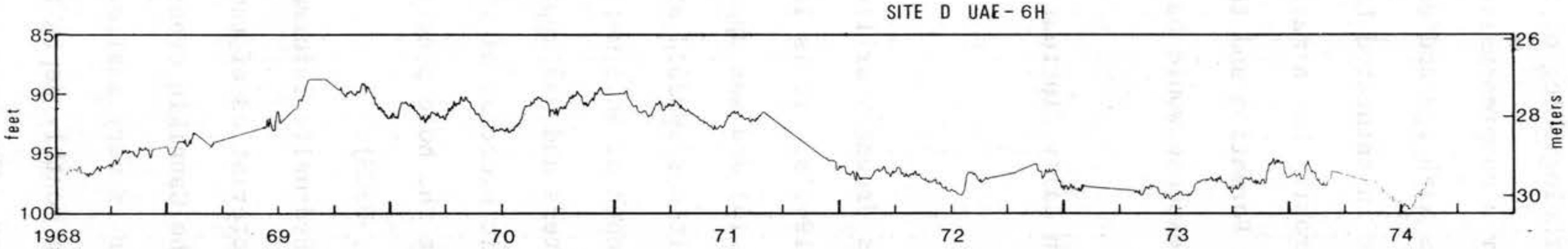

Figure 18. Groundwater hydrograph, UAe-6h, site D, Amchitka Island.

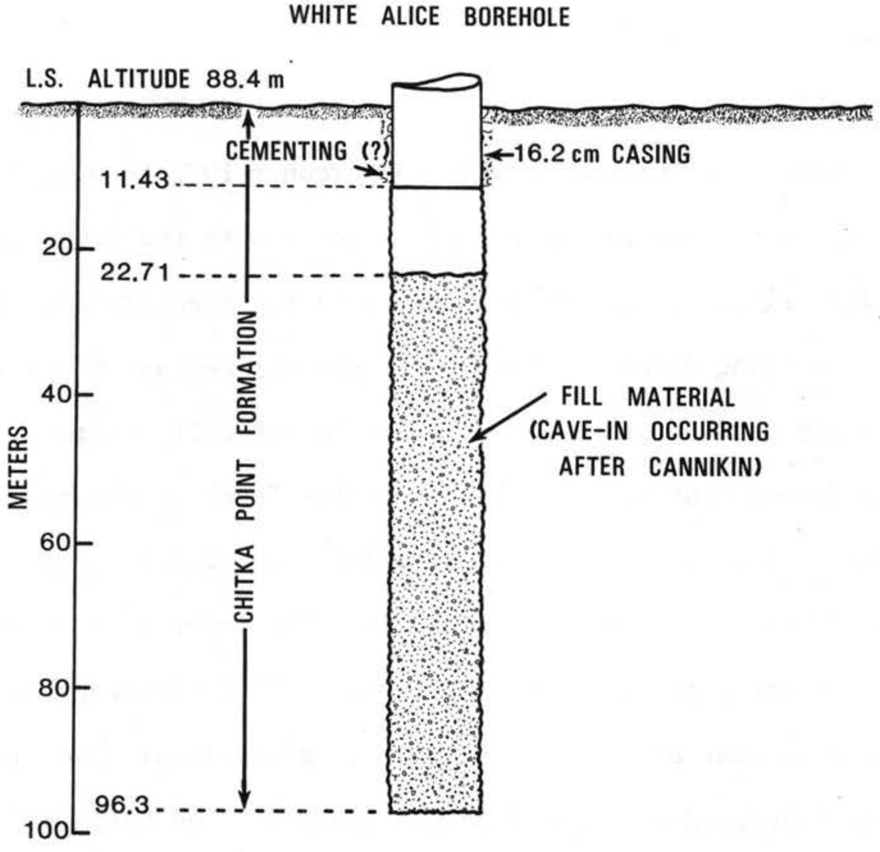

Figure 19. Completion sketch, White Alice Hole Borehole, Amchitka Island.

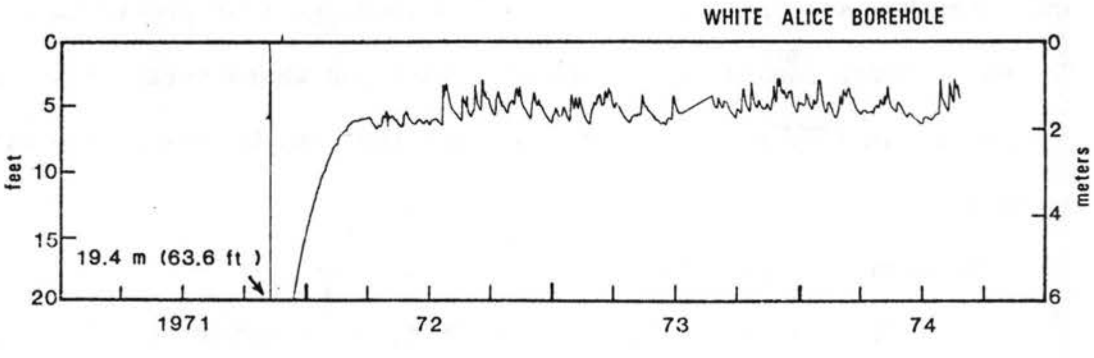

Figure 20. Groundwater hydrograph, White Alice Borehole, Amchitka Island.

the island only about one meter lower in altitude. The station was discontinued on August 30, 1974.

UA-1-HTH-3

The HTH-3 borehole was completed November 1972 to provide a better insight as to the overall hydrologic process with the Cannikin collapse zone. The primary objective was to obtain representative water-samples from inflow being directed into the rubble chimney and to establish the relationship between groundwater levels in the collapse zone, lake levels in newly formed Cannikin Lake and the water level in the re-entry hole.

HTH-3, at an altitude of 52.5 meters, was drilled to a depth of 51.2 meters and cased the entire length. The lower 30.5 meters of the 17.8 centimeter pipe was slotted (Fig. 21). The lithology of the site is similar to that of UA-1 except that as a result of Cannikin, the rock is highly fractured because of ground shock and the collapse. No real problems were associated with drilling HTH-3. A water-level recorder was installed on November 5, 1972, and continued in operation until its removal on August 28, 1974. The hydrograph for this period (Fig. 22) indicates how susceptible the area is to recharge from precipitation. The water level record correlates well with the characteristic wet and dry periods and exhibits very sharp rises that may be associated with areal strain.

Cannikin UA-1-PS-1ABC

Soon after the detonation of Cannikin, on November 6, 1971, a re-entry hole was drilled primarily to retrieve critical rock samples from the cavity produced by the device. These samples were necessary to complete the diagnostics of the Cannikin experiment. Upon completion of rock sampling the drill hole was retained by ERDA as a hydrologic

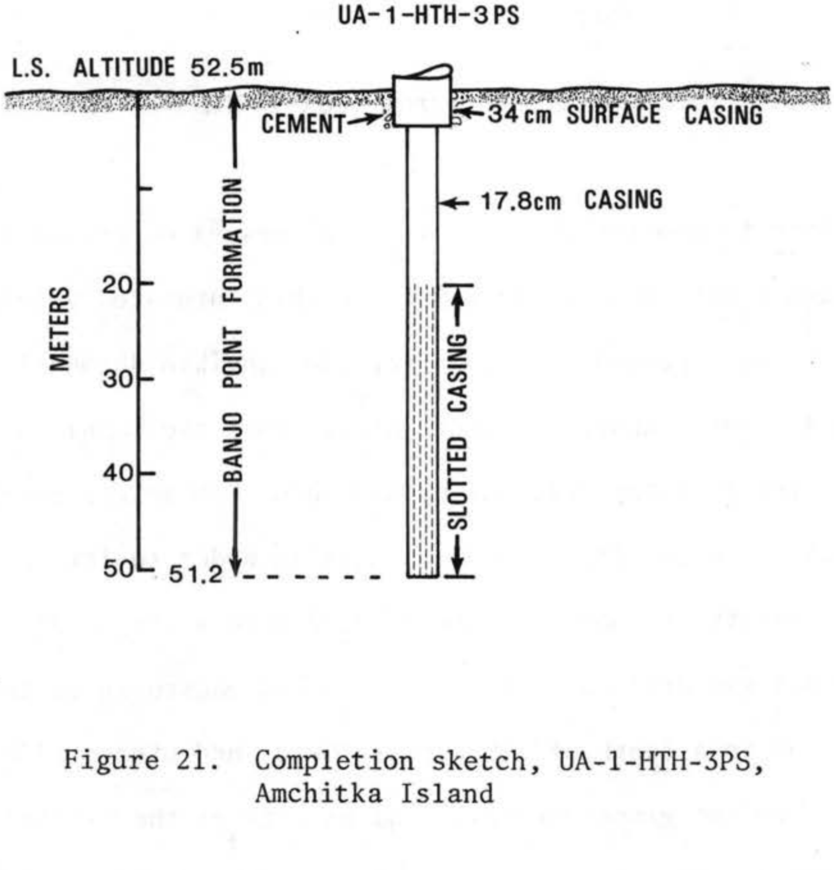

Figure 21. Completion sketch, UA-1-HTH-3PS, Amchitka Island

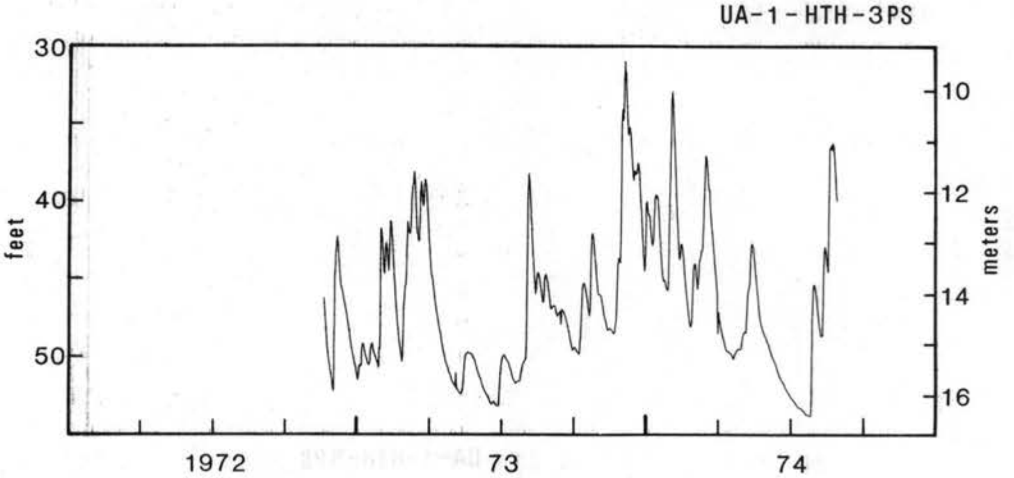

Figure 22. Groundwater hydrograph, UA-1-HTH-3PS, Amchitka Island.

test hole to monitor the hydrologic processes occurring in an explosion-produced cavity and rubble chimney within saturated volcanic rocks. The re-entry was spudded 21 days after the Cannikin detonation at an altitude of 76.4 meters, about 13 meters higher than the Cannikin emplacement hole, UA-1. The re-entry hole was offset about 730 meters south of UA-1 and was drilled using directional methods in order to intersect the bottom of the cavity at about a depth of 2000 meters (Fig. 23).

UA-1 was drilled in the breccias and mudstones of the Banjo Point Formation to a depth of 380 meters (Gard, and others, 1967). Below these depths are the glassy breccias and basalts of the Kirilof Point. At 1525 meters the emplacement hole is probably entirely within the older breccias and basalts of the Kirilof with some basalt dikes and flows noted (Lee, 1969) (Fig. 23).

Hydraulic testing of UA-1 and UAe-1, an exploratory hole 91 meters southwest of UA-1, show that there are four principle aquifers that would contribute to crossflow or inflow into the cavity and rubble chimney regions (Ballance, 1970, 1972). The dimensions of the cavity and rubble

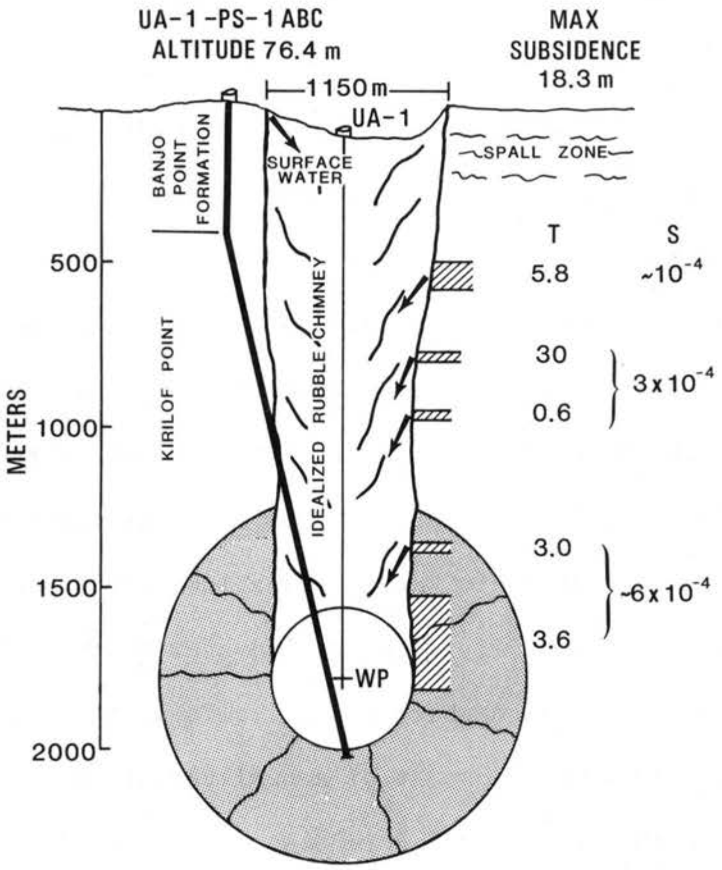

Figure 23. Completion sketch of UA-1 and UA-1-PS-1ABC showing the main features of the Cannikin event and collapse.

chimney produced by Cannikin are currently classified restricting any dimensions placed on the cross section of the rubble chimney and cavity shown on Fig. 23. The re-entry hole was completed with 11.4 centimeter internal flush drill pipe to permit water level monitoring and water sampling through several perforated intervals.

On February 20, 1972, 106 days after the detonation, the re-entry hole was completed as a hydrologic test hole and periodic water samples were taken as well as depth to water readings, thereafter.

A continuous water-level recorder was installed on May 8, 1972, when the water level in the re-entry had risen to 87.8 meters below land surface. The water sampling and water monitoring continued until May 1, 1973, when the re-entry hole was plugged in compliance to containment and safety regulations. The hydrograph for the infill of the Cannikin chimney is shown on Fig. 24.

Long Shot 9-Blue

Long Shot 9-blue was drilled about 50 meters northeast of Long Shot GZ as a water sampling hole. After the completion of the water sampling program, the hole was equipped with a water stage recorder on January 14, 1971. The hole is 152.4 meters deep and penetrates the Banjo Point Formation. The depth to water is shallow, about 5 meters, and varies only 0.5 meters annually. The groundwater hydrograph (Fig. 25) shows the effect of recharge which is typical near the island divide, that is, there is only a minor amount of annual variation. The record is similar to that in the White Alice Borehole. The sharp decrease in water level occurring in November of 1971 is a result of the Cannikin event.

Officers Club

The Officers Club borehole was drilled during the military occupation of the island in the 1940's. It is located in the southeastern part of the island near Constantine Harbor. The hole penetrates the Banjo Point Formation to a TD of 112.8 meters and is cased to a depth of 24.4 meters. The borehole was equipped with a water stage recorder from August 20, 1970, until August 28, 1974. Groundwater levels fluctuate over 7 meters in short periods of time and are very responsive to recharge (Fig. 26). Some characteristics of the change in water level indicate an effect due to strain. The hydrograph exhibits the characteristic lows in May and June and, of course, the highs during periods of high precipitation.

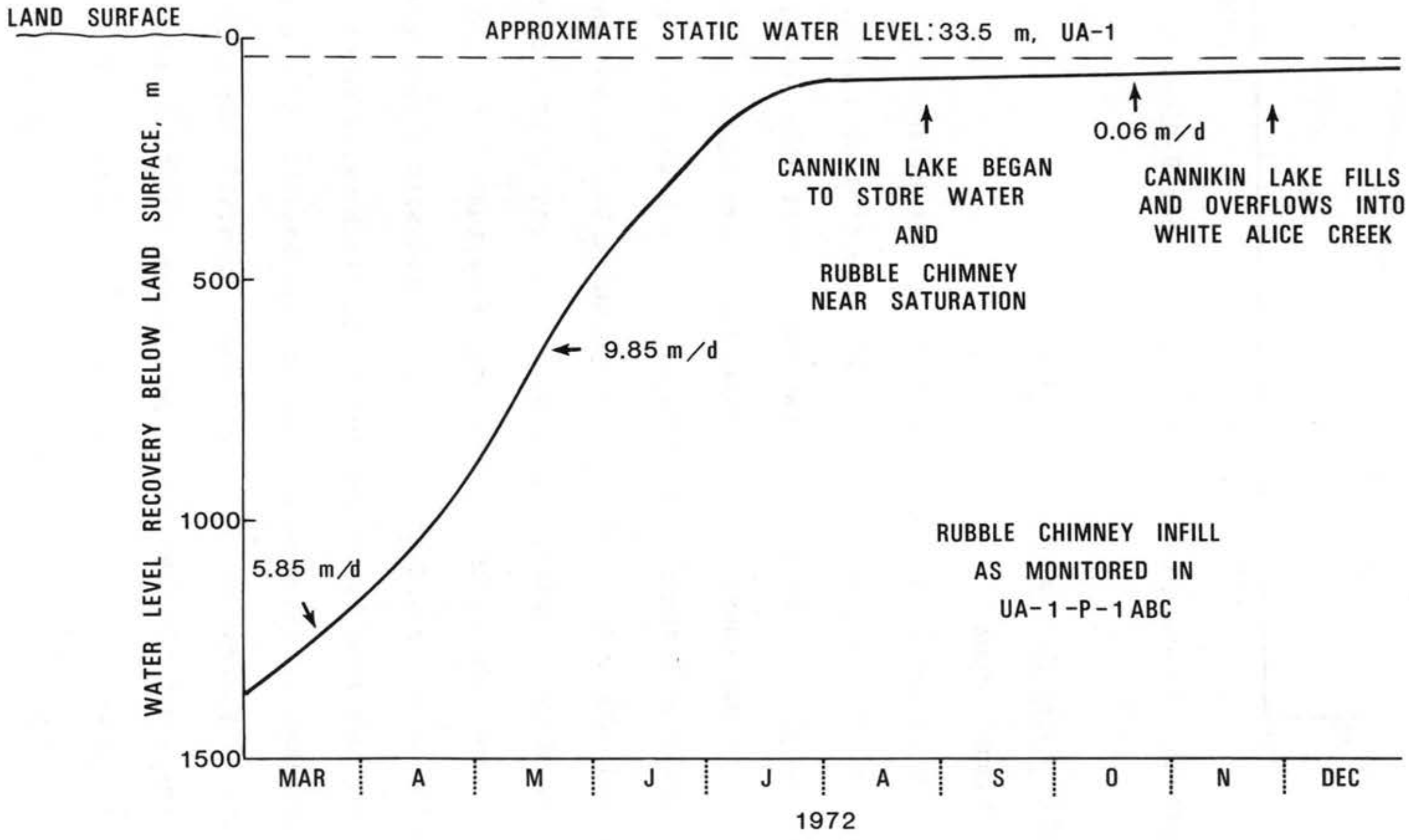

Figure 24. Infill history of the Cannikin rubble chimney, Amchitka Island.

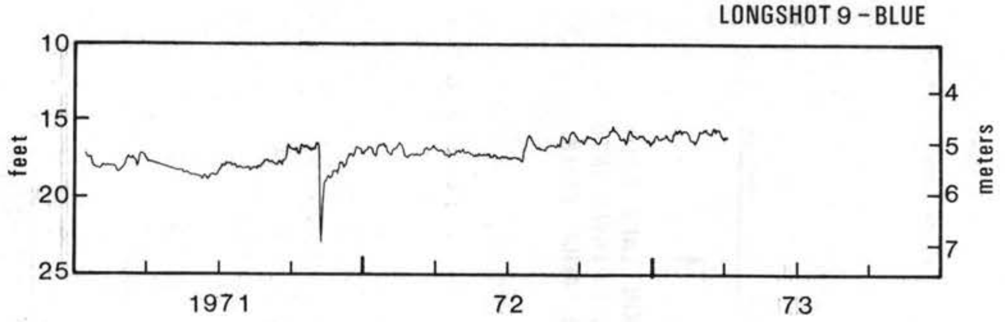

Figure 25. Groundwater hydrograph, Long Shot 9-Blue, Amchitka Island.

Surface Water Stream Gaging Stations

Limpet Creek

The Limpet Creek gaging station was established in November 1967 to record any effects within its drainage area as a result of testing. The drainage partially drains two emplacement hole sites, E and F. Site F was not considered for extensive hydrological monitoring and is not mentioned further in this report. Site E was a potential emplacement hole and after the completion of hydraulic testing was instrumented with a water-stage recorder. The Limpet Creek gaging station was about 300 meters above the mouth and monitored flow that discharged from an area of 4.38 km^2. The drainage area is covered with a lush growth of tundra and responds readily to precipitation, discharging runoff into the Pacific Ocean. The mean altitude of the basin is 89.0 meters and lakes comprise 7 percent of the total area. Rainfall over this area probably averages about 120 centimeters per year on the basis of cumulative runoff and mean altitude versus runoff observations (Figs. 27 and 28). Mean monthly runoff is listed in Table 3 for the period of record (USGS, 1968-72). Mean annual runoff is about 108 centimeters. No anomalous effects were noted at this site as a result of the nuclear testing program. The gage was discontinued in September 1972.

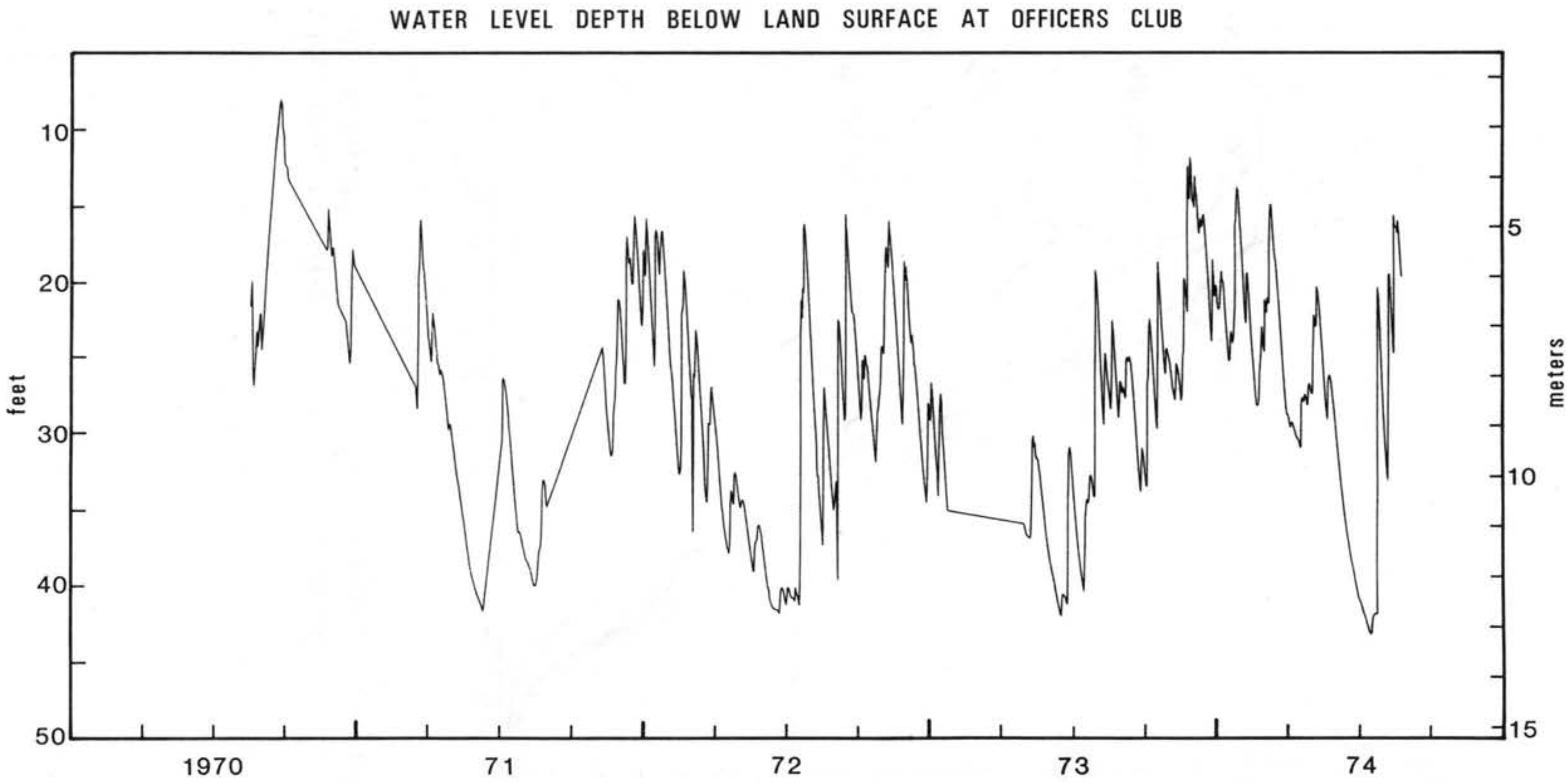

Figure 26. Groundwater hydrograph, Officer's Club, Amchitka Island.

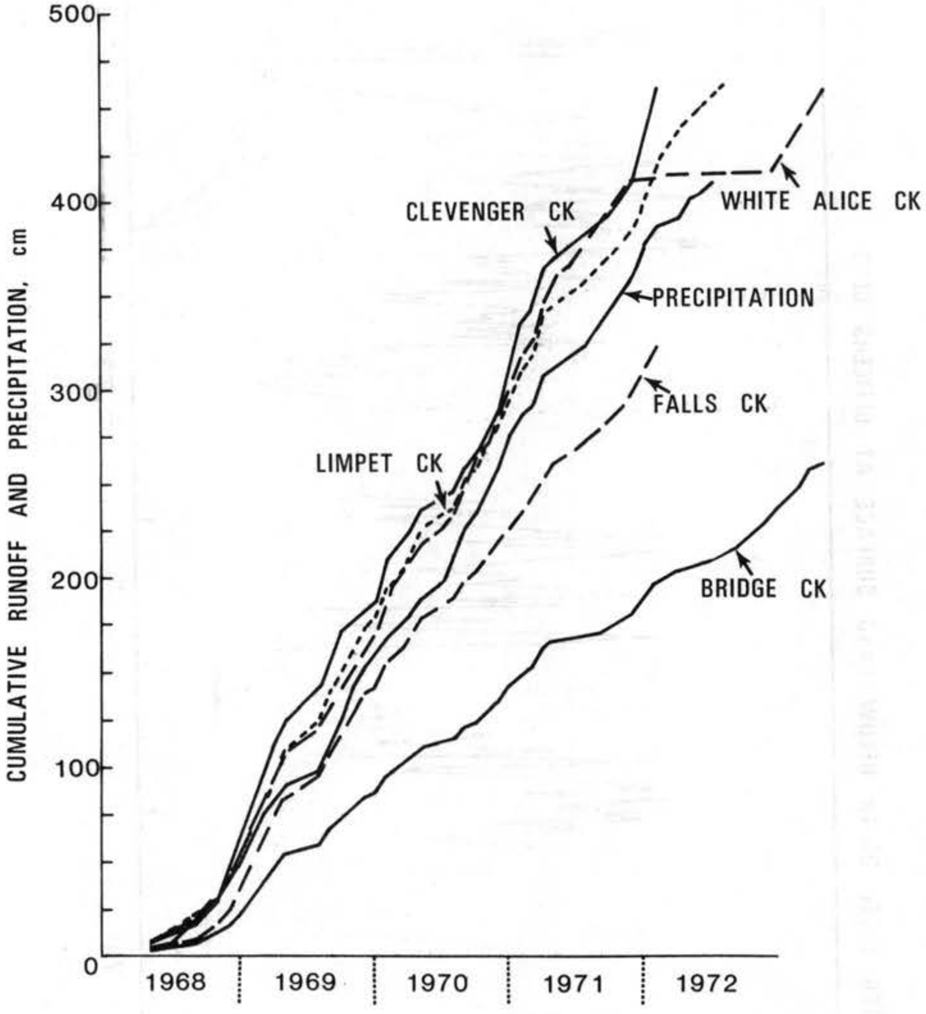

Figure 27. Cumulative runoff for major drainage areas and precipitation at the airport, Amchitka Island.

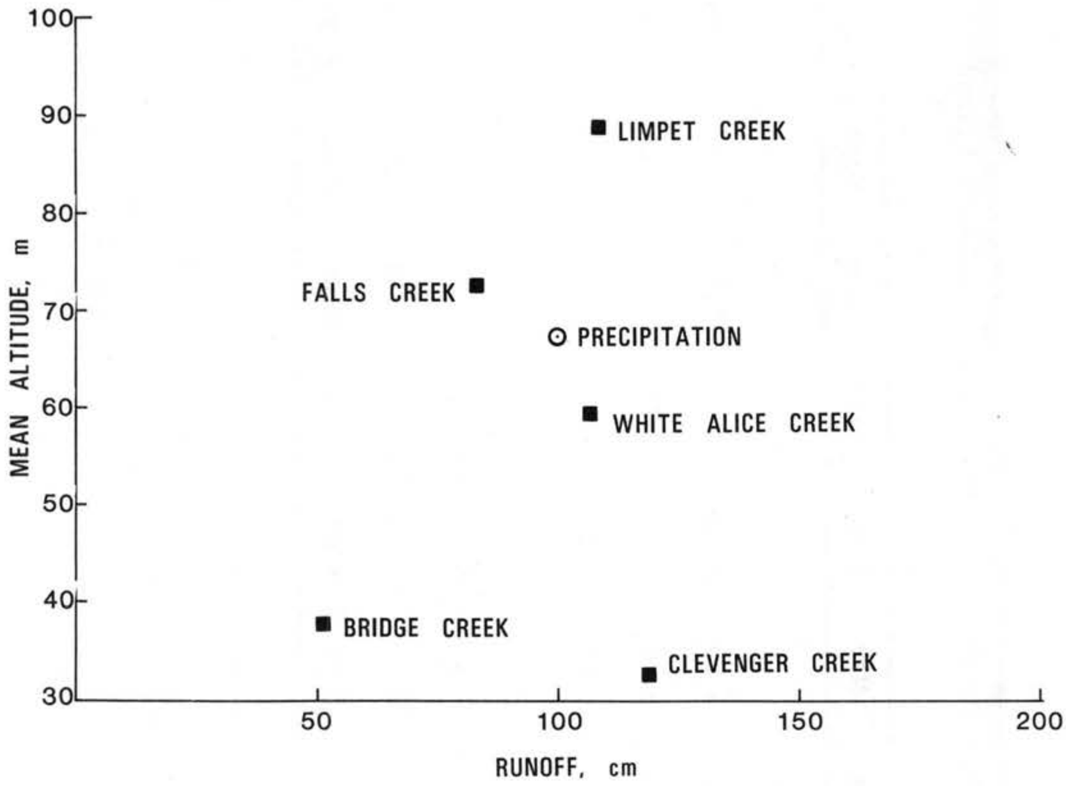

Figure 28. Mean altitude versus mean annual runoff for major drainage areas and precipitation at the airport, Amchitka Island.

Table 3. Mean Monthly Runoff, cm, Limpet Creek, Amchitka Island

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1967	--	--	--	--	--	--	--	--	--	--	13.74	9.47
1968	12.90	5.72	7.80	7.92	3.28	3.45	3.94	3.73	4.37	5.66	9.93	12.42
1969	11.46	11.66	14.78	14.76	5.64	4.70	6.30	14.66	10.06	11.23	12.34	4.65
1970	15.77	4.98	8.79	14.91	5.69	3.38	5.21	13.51	6.40	11.84	9.91	17.12
1971	12.62	7.16	21.59	6.55	3.18	3.73	6.15	5.64	6.32	7.11	9.07	13.28
1972	17.20	9.58	9.70	6.68	5.92	4.42	9.45	7.77	12.57	--	--	--
Totals	69.95	39.10	62.66	50.82	23.71	19.68	31.05	45.31	39.72	35.84	54.99	56.94
Average	13.99	7.82	12.53	10.16	4.74	3.94	6.21	9.06	7.94	8.96	11.00	11.39

Falls Creek

The Falls Creek drainage area drains the area around Site D, a major consideration for an emplacement hole. The gaging station was 183 meters above the mouth and monitored flow from an area of 2.23 km^2. The drainage basin, like that of Limpet Creek, has a thick cover of tundra and drains into the Pacific Ocean. The mean altitude of the drainage area is 72.5 meters and receives about 100 centimeters of rainfall annually (Figs. 27 and 28). About 5 percent of the area is covered by lakes. The channel exhibits the steepest slope of all major drainages, 40.5 meters per kilometer. Mean annual runoff at this site is 83.3 centimeters and a tabulation of mean monthly runoff is in Table 4 (USGS, 1968-72). The gage was discontinued in February 1972.

Clevenger Creek on Amchitka Island

Clevenger Creek drainage area was the major drainage for Site B where Milrow was detonated on October 2, 1969. The gaging station was established in April 1968 and drains an area of 0.73 km^2, the smallest of the major drainages. The mean altitude is also the lowest, 108 meters, and the basin has the shortest channel length, 0.96 kilometers. The gage is 1.21 kilometers above the mouth at the Pacific Ocean and is 800 meters from Milrow GZ. The drainage has 7 percent of its area covered with lakes and an annual runoff of 118.5 centimeters, the highest of the drainages. The drainage responds quickly to rainfall averaging about 125 cm/yr. A listing of monthly mean runoff is in Table 5 (USGS, 1968-72). The flow of Clevenger Creek was altered for a period of about three months after the firing of Milrow. Flow has recovered to normal and did not show any adverse effect as a result of the Cannikin event (November 6, 1971) (Figs. 27 and 28). The gage was discontinued in May 1974.

Table 4. Mean Monthly Runoff, cm, Falls Creek, Amchitka Island

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1968	--	--	--	3.35	1.24	.97	1.55	1.73	3.20	5.00	7.32	11.15
1969	12.75	10.44	12.45	10.82	4.32	3.18	5.00	12.01	9.98	9.91	10.08	3.84
1970	12.88	5.00	7.34	11.15	4.70	3.12	3.33	8.74	4.34	8.05	7.04	8.89
1971	8.23	7.09	11.10	6.81	3.96	3.45	4.80	4.24	6.05	7.39	8.79	12.04
1972	10.46	--	--	--	--	--	--	--	--	--	--	--
Totals	44.32	22.53	30.89	32.13	14.22	10.72	14.68	26.72	23.57	30.35	33.23	35.92
Average	11.08	7.51	10.30	8.03	3.56	2.68	3.67	6.68	5.89	7.59	8.31	8.98

Table 5. Mean Monthly Runoff, cm, Clevenger Creek, Amchitka Island

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1968	--	--	--	7.47	1.04	0.79	3.96	2.72	5.66	7.75	13.97	15.93
1969	20.22	15.75	17.53	10.24	5.36	6.48	5.94	15.67	13.72	3.84	5.08	3.18
1970	25.60	6.02	9.96	9.83	3.99	2.87	3.23	12.88	5.82	12.27	10.67	26.21
1971	19.43	6.96	20.70	8.23	3.66	3.23	5.28	4.65	6.81	8.38	12.12	19.46
1972	23.72	11.63	11.43	7.34	6.99	5.18	12.27	8.48	15.65	6.60	8.31	8.20
1973	7.65	9.60	10.39	3.94	4.04	3.71	3.86	7.49	5.46	7.39	9.04	13.69
1974	10.13	8.92	10.57	6.45	--	--	--	--	--	--	--	--
Totals	106.75	58.88	80.58	53.50	25.08	22.26	30.58	51.89	53.12	46.23	59.19	86.67
Average	17.79	9.81	13.43	7.64	4.18	3.71	5.10	8.65	8.85	7.71	9.87	14.45

Constantine Spring

Constantine Spring was used as a base camp water supply since early Long Shot preparation and may have been used during the military occupation. The groundwater boundaries are unknown and probably deviate considerably from the island's divide about 400 meters away. The gage at Constantine Spring was established in November of 1967 and discontinued April 1973. Average annual flow was about 1.56×10^{-2} cubic meters per second for the period of record and appeared to vary with rainfall, the lowest monthly flows occurring during May, June and July (USGS, 1968-72). No real abnormal effects were noted as a result of nuclear testing except for an apparent increase in turbidity occurring immediately after detonations and lasting for several days.

Bridge Creek

The Bridge Creek drainage area drains the largest area amongst the major basins, 7.85 km^2, and contains the greatest percentage of lakes, 35 percent. This large percentage of lake surface area accounts for the low yield in runoff, about 51 centimeters annually (Figs. 27 and 28). Channel slope is low, 59 meters per kilometer and the mean altitude of the basin is 37.8 meters. The gaging station was established in November 1967, 320 meters from the Bering Sea. The area is adjacent to the drainages of the Long Shot site and Site C (Cannikin site). The drainage area probably receives about the same amount of precipitation annually as other basins, about 90 cm per year. Table 6 lists the mean monthly runoff for the period of record (USGS, 1968-72). No anomalous effects were noted as a result of the testing program. The gage was discontinued in August of 1974.

Table 6. Mean Monthly Runoff, cm, Bridge Creek, Amchitka Island

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1967	--	--	--	--	--	--	--	--	--	--	7.01	8.31
1968	6.76	2.69	4.27	3.28	0.76	0.66	1.52	1.09	2.16	2.54	4.50	5.66
1969	7.80	8.13	9.96	5.66	1.55	1.55	2.62	7.01	5.54	4.90	5.84	2.41
1970	9.19	4.65	4.62	5.13	1.47	1.32	2.31	5.89	2.54	6.15	4.90	8.31
1971	5.49	3.07	11.73	3.07	.56	.61	1.96	.89	2.92	3.76	4.24	8.74
1972	6.68	3.02	2.54	1.93	1.93	1.09	4.80	2.46	5.87	4.09	7.87	4.50
1973	5.31	6.05	8.13	2.01	2.16	2.13	2.72	5.11	3.53	5.03	5.97	12.88
1974	7.52	8.79	7.21	3.07	3.81	1.14	3.07	--	--	--	--	--
Totals	48.75	36.40	48.46	24.15	12.24	8.50	19.00	22.45	22.56	26.47	40.33	50.81
Average	6.96	5.20	6.92	3.45	1.75	1.21	2.71	3.74	3.76	4.41	5.76	7.26

White Alice Creek

The White Alice drainage area is of importance because of its relationship to Cannikin which was detonated on November 6, 1971. The gage was established in April 1968 and monitored flow from an area of 2.05 km^2. The basin cover is a thick mat of tundra and the basin is only 2 percent covered by lakes. Flow drains into the Bering Sea and averages 107 centimeters of runoff annually. The area probably receives an average of 115 centimeters of rain annually with a mean altitude of 59.1 meters. As a result of Cannikin, the drainage was drastically altered and as a consequence of the collapse, the largest lake on the island is now contained within the drainage area. Flow in White Alice Creek remained far below normal for about a year before returning to normal flow rates (Figs. 27 and 28). Mean monthly runoff is listed in Table 7 (USGS, 1968-72). The gage was discontinued in August 1974.

Summary

A resume of the principal drainage characteristics for each drainage area is given in Table 8 and annual runoff totals and averages are in Table 9.

Table 7. Mean Monthly Runoff, cm, White Alice Creek, Amchitka Island

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1968	--	--	--	6.10	2.62	2.21	4.37	3.81	5.61	6.96	10.03	11.30
1969	13.44	12.45	15.49	12.07	4.93	3.12	4.22	11.13	8.69	9.50	10.52	8.28
1970	18.87	9.96	9.04	10.64	4.37	3.43	7.14	17.42	7.75	12.70	11.51	18.77
1971	15.27	9.22	19.66	11.20	6.88	5.92	8.36	9.12	8.69	10.29	4.14	0.56
1972	1.02	.43	.33	.18	.18	.10	.43	.20	.46	.18	.53	5.61
1973	9.02	9.60	10.80	5.89	5.51	4.45	4.57	6.91	8.86	10.92	11.25	23.22
1974	15.70	13.08	15.42	6.91	9.45	4.95	5.31	--	--	--	--	--
Totals	73.32	54.74	70.74	52.99	33.94	24.18	34.40	48.59	40.06	50.55	47.98	67.74
Average	12.22	9.12	11.79	7.57	4.85	3.45	4.91	8.10	6.68	8.43	8.00	11.29

Table 8. Principal Drainage Basin Characteristics for the Major Drainage Basins on Amchitka Island, Alaska

Streamflow Site	Drainage Area km^2	Slope m/km	Length km	Mean Altitude m	% Lakes	Distance from GZ km	Site Drainage
Limpet Creek	4.38	34.5	3.54	89.0	7	11.17	Site E
Falls Creek	2.23	40.5	2.25	72.5	5	7.06	Site D
Clevenger Creek	0.73	21.0	0.96	32.9	7	8.70	Site B
Bridge Creek	7.85	11.2	4.18	37.8	35	5.86	Longshot
White Alice	2.05	17.4	2.57	59.1	2	1.50	Site C
Constantine Spring	--	--	--	27.8	0	14.07	Camp Water Supply

Table 9. Annual Runoff for the Period of Record, Major Drainages on Amchitka Island, Alaska

Annual Runoff--centimeters

Site	Cal. Yr.	1968	1969	1970	1971	1972	1973	1974	Average
Airport Alt. = 67 m		67.06	109.14	115.82	99.24	33.58 1/	--	--	97.82 cm/yr 1968-71
Limpet Creek D.A. = 4.38 km^2 Alt. = 89 m		81.1	122.2	117.5	102.4	53.5	--	--	105.8 cm/yr 1968-71
Falls Creek D.A. = 2.23 km^2 Alt. = 72.5 m		35.51 2/	104.8	84.6	84.0	--	--	--	91.1 cm/yr 1969-71
Clevenger Creek D.A. = 0.73 km^2 Alt. = 32.9 m		59.3 2/	123.0	129.2	118.9	119.2	86.31	34.6 3/	115.3 cm/yr 1969-73
Bridge Creek D.A. = 7.85 km^2 Alt. = 37.8 m		35.9	63.0	56.5	47.0	46.8	61.0	34.6 4/	51.7 cm/yr 1968-73
White Alice D.A. = 2.05 km^2 Alt. = 59.1 m		53.0 2/	113.8	131.6	109.3	9.65	111.0	70.8 4/	118.2 cm/yr 1969-71

1/ 6 months of record Jan.-June

2/ 9 months of record Jan.-Sept.

3/ 4 months of record Jan.-April

4/ 7 months of record Jan.-July

Chapter 5

HYDRAULIC EFFECTS

General

The geologic and hydrologic effects of underground nuclear explosions have been investigated and documented for devices implaced in either the unsaturated zone or the partially and saturated tuffs and rhyolites of the NTS. The advent of high yield nuclear testing on Amchitka Island gave the opportunity to investigate these effects on the saturated volcanic rocks of Amchitka. Three major nuclear experiments have been successfully conducted on Amchitka Island; these are (1) the Long Shot event, an 80 kiloton explosion detonated on October 29, 1965, at a depth of 701 meters, (2) the Milrow event, about 1 megaton, detonated on October 2, 1969, at a depth of 1218 meters, and (3) Cannikin, the largest underground explosion detonated by the United States which was less than 5 megatons in yield. It was emplaced at a depth of 1792 meters and detonated on November 6, 1971.

All three events were conducted on the lowland plateau of the island; all within 6 kilometers of each other (Fig. 13). The geologic and hydraulic character is generally the same for all three sites. A thick cover of turf ranging from a few centimeters to several meters thick is dominant over the entire area. Annual precipitation of over 90 centimeters collects temporarily in an abundant number of lakes and underlying turf before discharging to streams and finally into the oceans. The runoff that occurs within drainage basins almost simultaneously with rainfalls suggests that the rocks underlying the turf and shallow lakes are either low in permeability, or are saturated to land surface. There is a significant amount of groundwater storage within the shallow flow system, as evidenced by the amount of base flow in streams during dry periods.

The groundwater system throughout the island is probably saturated, especially in the lowland plateau. The groundwater table is near land surface, hardly below 15 meters. The circulation of groundwater is controlled principally by fractures, interstitial rock permeability being very low in unweathered rocks. The water levels in the deep exploratory holes are on the order of 35 meters deep or more and represent composite heads of several producing zones whose hydraulic potential decreases with depth. Probably only a small amount of precipitation infiltrates into fractures of deeper rocks. Carbon 14 analyses of samples of groundwater from UAe-1 at Site C reveals that the unadjusted age of this water is 11,000 years at a depth of 960 meters. Wells are responsive to barometric changes, aerial strain, and loading by tidal fluctuation, and in shallow wells, there are rapid responses to infiltration from precipitation.

The lowland plateau is saturated with many interconnected lakes in the lower elevations and distinct small drainage areas in the higher elevations. The average width of the island in these regions is 5 kilometers with divides up to 80 meters in altitude.

Upon firing of an underground device, there is an almost instantaneous release in energy that produces extremely high temperatures and pressures that vaporize the device and surrounding rock. Within a fraction of a second a generally spherical cavity is created around the device. The cavity radius is primarily dependent on the yield of the device and its depth of burial. The initial effects on geology and hydrology are reflected in the arrival of seismic waves producing visible changes in land form and the shallow groundwater and surface water systems. It is the ground shock which produces most effects on the geologic and hydrologic systems within a certain radius of GZ. Ground shock is primarily a function of energy release and distance. Other contributing factors are the type of rock porosity and saturated conditions along the travel path.

Compressive wave trains reflected at land surface result in the tensil failure of subsurface rock commonly referred to as spall. Doming of the land surface above the WP is another immediate ground feature dissipating rapidly with distance from GZ. In the near-saturated environment of Amchitka, geysers of groundwater erupt from faults and lineations as a result of compressive stresses imposed on both sides of fault surfaces. Upheaval of water stored in lakes, ponds, and streams will also occur because of the initial ground motion and spall. Because of severe ground shock and compressive stress there will occur an increase in pore pressure, resulting in possible fault motion. Other typical visible effects may include rock slides, disrupment of surficial turf, mud flows, etc.

The initial effect on the groundwater is a cyclic fluctuation of pore pressure as a result of the compression and relaxation of the surrounding medium by seismic waves. The overall product of this fluctuation is a sustained increase in pore pressure, simulating a water mound ideally centered around GZ. In nearly saturated groundwater conditions, where the water table is near the surface, groundwater is forced out the shallow turf, discharging into streams and infiltrating into the subsurface. In time, the mound decays to some equilibrium either above, below, or at pre-shot conditions depending upon the effect of shock on specific aquifer characteristics.

As a result of changes in the fracture openings, there are localized changes in pore pressure affecting the character of the aquifer.

The surface water initially reacts to upward ground motion, compressive stress and slapdown. Water stored in lakes and ponds in the vicinity of GZ is thrown into the air, either falling back into storage or discharging into the surrounding turf. Streamflow also is heaved upward, and depending upon its closeness to GZ, migrates downstream in a form of a floodwave as a result of an increase in channel slope and in groundwater discharge. Narrow deep channels may experience temporary damming due to sloughing of banks or slides restricting flow. Any lakes or ponds in the vicinity of GZ might experience tilt or fracturing causing water storage to be either shifted or partially or entirely depleted.

After the spherical cavity is formed, at the depth of burial, temperature and pressure begin to decrease and a puddle of radioactive molten rock forms at the cavity bottom. As the temperature and pressure within the cavity void continue to subside, the roof of the cavity collapses under the weight of the overburden material. The collapse of the cavity roof produces a rubble filled chimney extending to ground surface for most high yield detonations. A subsidence crater is formed at the surface, its configuration dependent on the type of rock and local structure. The dimensions of the subsidence crater are a function of yield and the depth of burial. The collapse of the cavity is of significant importance particularly in Amchitka's saturated environment because of the creation of new unsaturated interstitial porosity. The collapse initiates the beginning of groundwater and surface water infill into the newly created void space within the rubble chimney. High temperatures in the cavity regions preclude any infill into the cavity until condensation of the steam. At the time of condensation, infill water within the rubble chimney and surrounding rock begins to flow into the cavity region initiating the refilling of the cavity and rubble chimney. Associated with infill is the mixing and distribution of radioactive nuclides, principally tritium. During the period of infill, groundwater and surface water is temporarily diverted in total or partly into the rubble chimney regions until they become full. The period of infill is dependent on aquifer characteristics and the availability of surface water. Experience at the NTS indicates the periods of infill to vary between months and several years. On the island of Amchitka, these infill periods would probably be short by comparison. Upon the completion of infill, groundwater and surface water conditions should return to normal or nearly so depending on changes within the groundwater aquifer or drainage basin.

The Long Shot Event

Long Shot, part of the Velo Uniform Series, located south of Bridge Creek (Fig. 13) was an 80 kiloton explosion detonated within the Banjo Point Formation with volcanic breccia constituting the bulk of the formation. Preparation and planning to document the effects of Long Shot was minimal because the objectives of the experiment were not oriented to high yield testing. The experiment was conducted for the purpose of investigating seismic wave propagation in the complex Aleutian Arc structure of the Aleutian chain (DeNoyer and Frosch, 1966).

Groundwater observations made during the drilling of exploratory holes indicate that the bedrock of the site is nearly saturated at depths ranging from 1 to 6 meters below land surface. The effects of Long Shot were determined principally by mapping and photographing surficial effects. The most common effect was fractured ground occurring mostly in unconsolidated areas such as roads, paths, etc. These fractures occurred as far away as 2,260 meters from GZ (McKeown and others, 1967). Other visual effects noted were rock falls and the displacement of buildings and other structures near GZ. Measured vertical velocity and accelerations indicate that surface spall occurred between 30 and 150 meters in depth and extended laterally about 1220 meters from GZ (Day and Murrell, 1967).

Observation of streamflow at two sites gave no indication of any variation in flow due to the detonation, slapdown or after-shot effects. Slumping of stream banks and ponds was common to a distance of about 900 meters. No observation of groundwater effects were made. Mud geysers occurred as a result of compaction and closing of saturated lineations but did not commonly occur. Level and geodemeter surveys indicated maximum displacements of 0.43 meters vertically and 12 centimeters laterally across a fault 245 meters from GZ. There were no apparent effects on the hydrologic regime as a result of the Long Shot 80 kiloton detonation.

The Milrow Event

Milrow, about one megaton in yield, was a calibration shot for Cannikin, to be detonated at a later date. It was fired on October 2, 1969, at a depth of 1218 meters in the Pillow Lavas and Breccias of the Kirilof Point. The Milrow emplacement hole, UA-2, was located at Site B (Fig. 13).

Site Hydrology

The area surrounding Site B is covered with a thick mat of tundra dotted with lakes and streams. The principal hydrologic features are three large lakes within 300 meters of GZ and the Clevenger Creek drainage which flows into the Pacific Ocean (Fig. 29). The drainage area outlined in Fig. 29 includes GZ and covers an area of 0.73 square kilometers. It receives at least 90 centimeters of rainfall annually, based on precipitation records collected at the airport. The average runoff for the period 1969 through 1973 is 118.5 centimeters per year based on records collected at the Clevenger Creek gaging station (Table 5). The drainage area is relatively flat at higher altitudes with slopes steepening toward the gaging station. Lakes comprise 7 percent of the drainage area that temporarily collect and store rainfall that either eventually percolates into the shallow groundwater system or drains into adjoining streams. The groundwater storage within the thick mat of tundra, peat and shallow rocks provide the base flow for Clevenger Creek that varies from 1.13×10^{-2} to 0.56×10^{-2} cubic meters per second. There have been several days of recorded no flow during the period of record. Clevenger Creek has been noted to discharge more runoff per square kilometer than other major drainage areas on the island (Fig. 27). The drainage area, channel slope, and length-width ratio are the primary basin characteristics contributing to high runoff per square kilometer.

The groundwater is about 4 to 5 meters below land surface as indicated by the total composite measured head in UAe-2, an exploratory test hole at Site B (Ballance, 1973). The hydraulic tests conducted by Ballance showed that hydrualic conductivity ranges from 2.86×10^{-5} to 6.41×10^{-2} meters per day in 25 selected zones ranging from 380 to 1981 meters in depth.

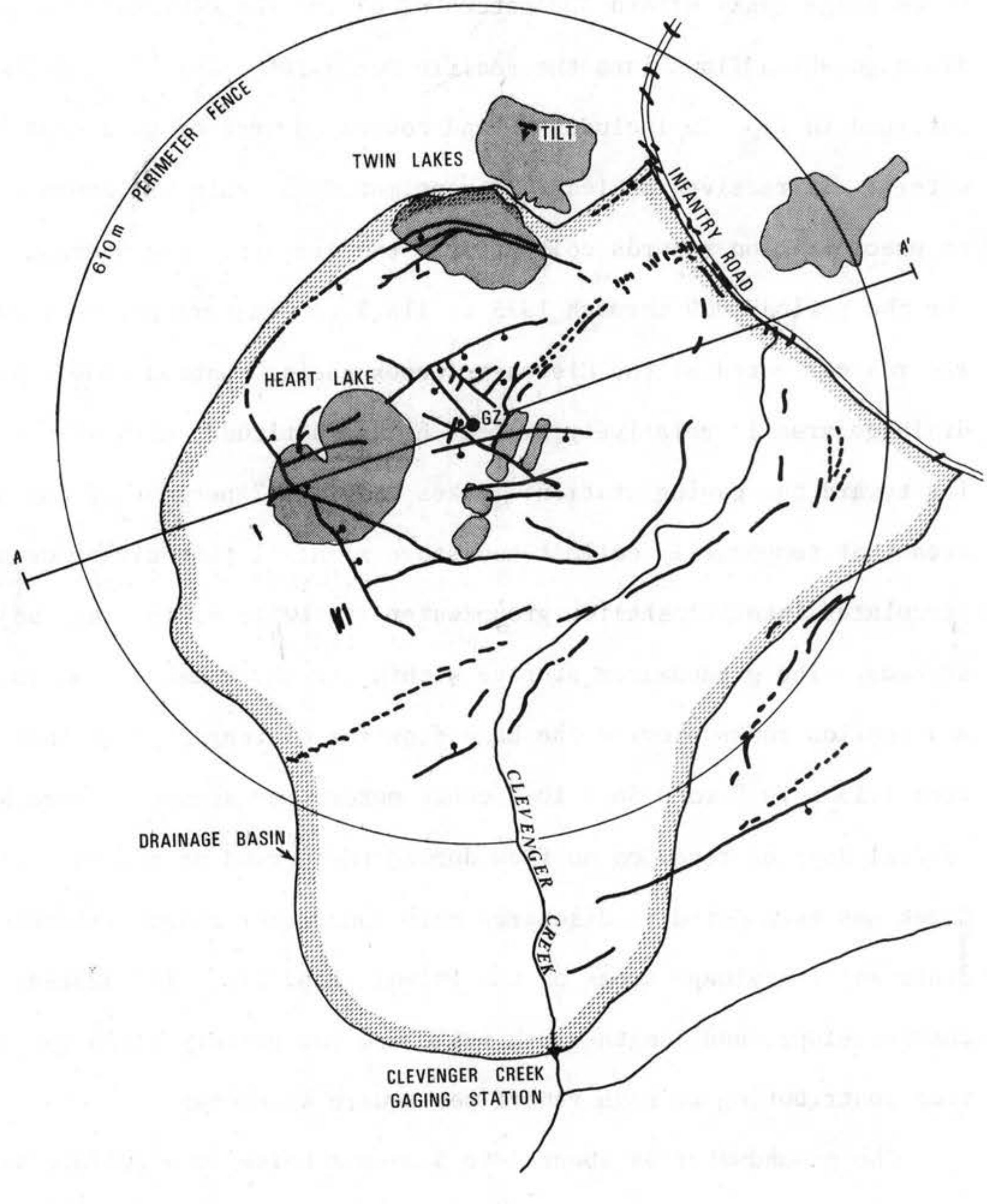

Figure 29. Hydrolgic features of site B and the primary geologic and hydrologic effects resulting from the Milrow event.

The zones that exhibited the highest average hydraulic conductivity were at about 750 meters (Banjo Point Formation) and 1,050 meters (Kirilof Point) (Fig. 30), and would be expected to contribute considerable inflow to Chimney infill. These zones had conductivities of 0.07 and 0.01 meters per day. The results of the hydraulic tests throughout 25 selected zones between 380 and 1980 meters indicated that the rocks between 380 and 1128 meters contain most of the permeability. The hydraulic gradient decreases with depth and ranges between 14 to 34 meters below land surface. Flow is downward as is typical throughout the island. The discharge areas are probably near the shoreline.

The effects program conducted by the U.S. Geological Survey for the Milrow event included visible geologic changes, ground displacement measurements, stress determinations, and hydrologic changes in the surface water and groundwater regimes.

Milrow Zero Time

Visible effects--The visible geological effects produced by the firing of Milrow were a result of the upward displacement (doming) of the land surface caused by peak accelerations and particle velocities produced by the one-megaton device. Seconds after the firing, a nearly spherical cavity with a radius of about 105 meters was formed with radial fractures extending several cavity radii around the working point (Fig. 30). Accelerations attained 35 gs and peak-particle velocities were measured at about 4.5 meters per second, 600 meters from GZ. Ground motion studies were conducted by A. E. Electronics Defense Research Laboratories and Sandia Laboratories in two holes near GZ and in surface canisters 9.7 kilometers from GZ (Merritt, 1970). Analysis of vertical

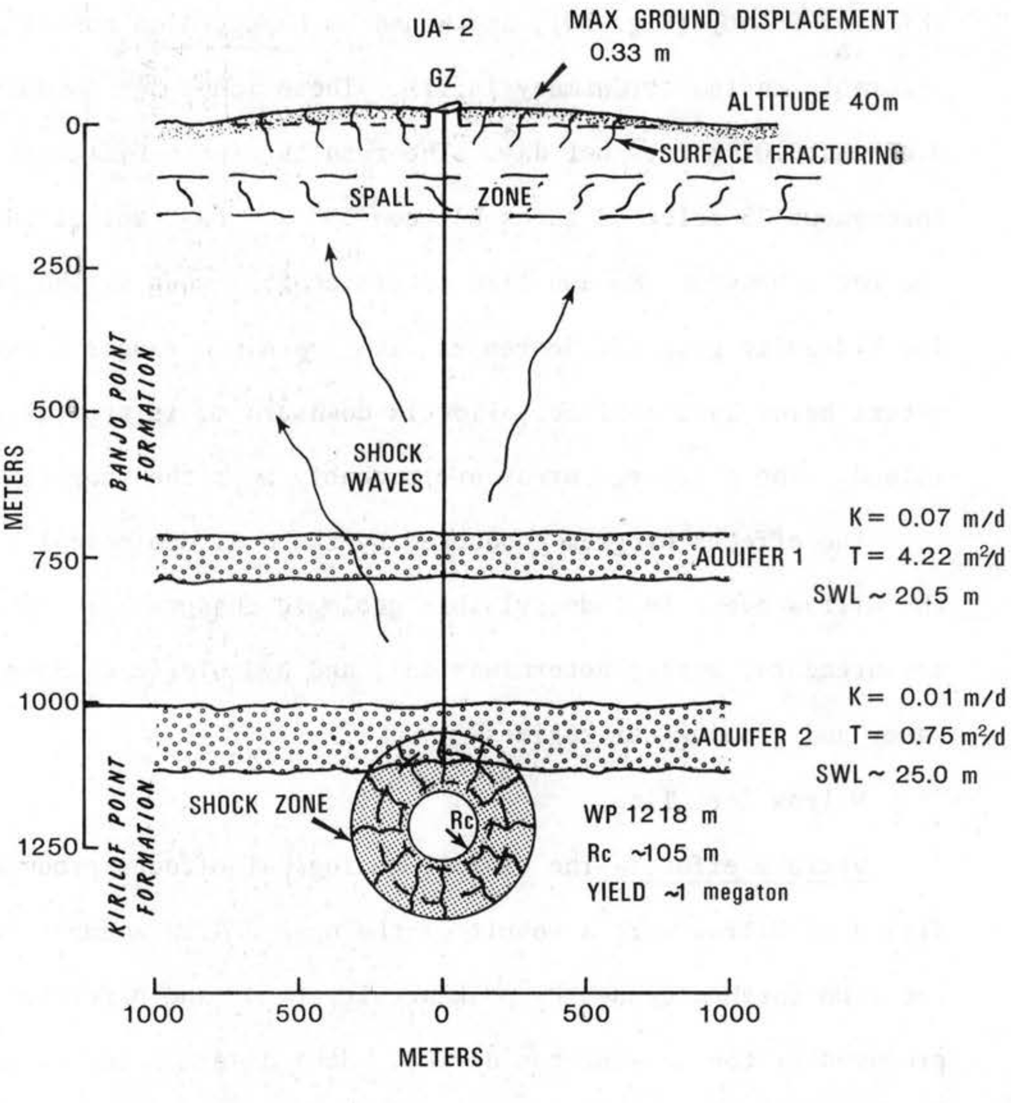

Figure 30. Cross section of UA-2 during the Milrow detonation, Amchitka Island.

velocity and acceleration wave forms indicate that spall occurred between a depth of 90 and 150 meters below land surface (Fig. 30), and extended laterally 5.12 kilometers from GZ (Environmental Research Corporation, 1970). Probably, a great deal of surficial deformation occurred as a result of spall. Wave form analysis showed that during the period of free fall, accelerations dropped to minus 1g, and at impact the resulting positive peak was stronger than the first. The visible effects of Milrow were few and limited in extent similar to those occurring during project Long Shot. These typically included rock falls, turf falls, slumping, cracking and soil disturbance. Known faults were examined for displacement with no appreciable cracking or displacement along them. There was evidence of minor tilt in small ponds near GZ along with evidence that pond water had been displaced as a result of ground motion. There were numerous rock falls along the Bering and Pacific Coast especially in areas where there were steep cliffs. Slumps of unconsolidated sands and gravels also occurred along steep shore lines. Geysers of water and mud were observed from photography taken at shot time and probably were a result of upheaval and compressive stresses closing shallow lineations and fractures. These were seen along streams, across lakes and along the beaches on the Pacific side as far as 1.3 kilometers from GZ. The surface of the soil was disturbed up to 6 kilometers from GZ. Surficial cracking and displacement of rock and turf were the typical results from the associated ground motion at shot time. Milrow, teleseismically, had a body wave magnitude of 6.5 on the Richter scale.

Surface water--The Effects of ground shock on the shallow ground water system was indicated in the response of flow at several gaging stations on the island. Clevenger Creek, of course, was the most affected. The effects of doming as a result of cavity formation compressed the medium and forced local groundwater storage from along stream banks into drainage channels, increasing discharge. At Clevenger Creek, flow increased by about 2.23 x 10^{-2} m^3/s (cubic meters per second) and the stage remained almost constant for about three hours before becoming affected by backwater caused by failure of stream banks downstream (Fig. 31). The stage trend indicates that flow would have returned to pre-shot conditions about 10 hours after Milrow and would have continued to decrease below normal until effective bank storage had been replenished to near pre-shot conditions. Then, depending on available recharge from precipitation, the flow would have returned to normal conditions. The discharge trend would have been similar to that of Constantine Spring. The stage record at Constantine Spring 4.4 kilometers southeast of GZ showed a slight increase in flow at shot time followed by a slight decline, possibly a result of dilatation of rock mass (Fig. 31). Discharge then increased slightly and finally dropped below pre-shot conditions. The spring was turbid for two days after Milrow and flow was back to normal the day after the event. There were no apparent changes in streamflow at two other gaging sites, 3.6 and 8 kilometers from GZ. These were Bridge Creek and White Alice Creek, respectively (Fig. 13).

Groundwater--The groundwater response to the Milrow event was monitored in three bore holes located at Sites C, D, and E (Fig. 13). Borehole packers and pressure transducers set below water level were used to monitor the pore pressure response to the seismic stress imposed on the groundwater system. The monitor systems were capable of responses up to 30 hz which were anticipated during the dynamic phase. The

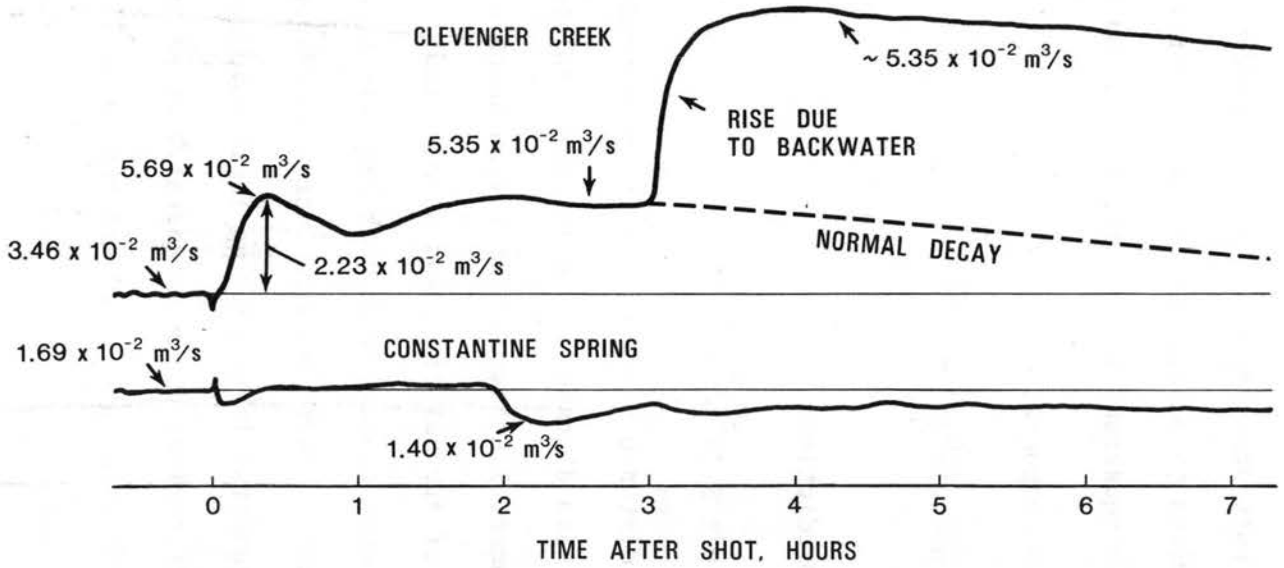

Figure 31. Stage hydrograph showing discharge at Clevenger Creek and Constantine Spring before and after the Milrow event.

frequencies of the hydraulic response in terms of pressure simulates those of seismic wave trains. Peak pore pressures regressed with distance from GZ are similar to those derived from vertical displacements and peak particle velocity measurements. Table 10 lists the pore pressure response to the Milrow event monitored in three bore holes and Fig. 32 shows the pore pressure response regressed with distance from GZ and its comparison to prediction at the NTS for 1 megaton events (Dudley, 1970). The equations for the regressions on Fig. 32 are:

Milrow response:

$$p = 21W^{0.33} R^{-1.54} \quad (1)$$

and

NTS prediction:

$$p = 3.2W^{0.33} R^{-1.32} \quad (2)$$

The -1.54 distance exponent for the pore pressure regression compares favorably with distance exponents for displacement regressions measured by Environmental Research Corporation which were calculated as -1.64 on the basis of arrival times and wave periods. The peak fluid pressures correlate more closely with peak particle velocities than with peak displacements. Pore pressure increases resulting from the event may have been instrumental in triggering fault movement by reducing normal stresses along fault surfaces. Unfortunately, there are no data to correlate fault displacement within 10 kilometers of GZ with increased pore pressure. Each well returned to pre-shot water level conditions two minutes after the event. Several days after the event, Sites D and E were equipped with stage recorders to document any long term changes within these local groundwater systems.

Table 10. Fluid Pore Pressure Response from the Milrow Event

Site	C	D	E
Well number	UAe-1	UAe-6h	UAe-7h
Distance from GZ, km	8.7	16.0	22.7
Direction from GZ	NW	NW	NW
Depth of well, m	2134.2	2133.3	1233.0
Depth to water, m Sept. 1969	35.1	29.0	45.7
Max pressure bars	+7.4	+3.7	+1.7
Min pressure bars	-4.3	-2.4	-1.7

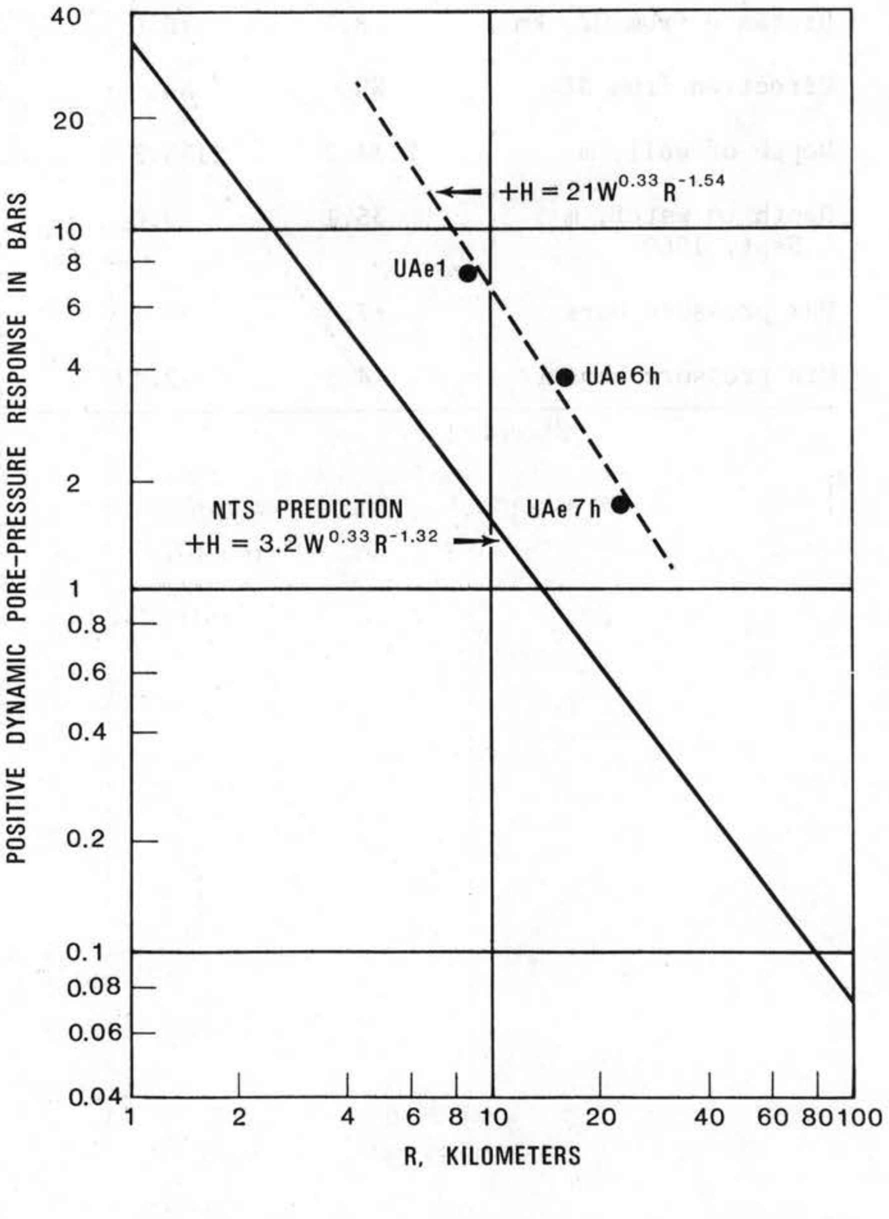

Figure 32. Fluid pore pressure response to the Milrow event compared with the NTS prediction for one-megaton events (Dudley, 1970).

Milrow Collapse

Visible effects--Following the firing of Milrow, there were hundreds of small shallow-focus earthquakes all occurring within a 5 kilometer radius of GZ (Engdahl and Tar, 1970). Previous experience at the NTS associates this phenomenon as aftershocks common of high yield explosions. The aftershocks are generally deemed as precursors to the main collapse that ultimately produces a rubble chimney to land surface. The frequency of aftershocks decreased for the first 12 hours after Milrow and then increased prior to the collapse 37 hours after the detonation (Fig. 33) (from Engdahl and Tar, 1970). The body magnitude, M_b, of the collapse was 4.3 on the Richter scale, two units lower than Milrow itself. The aftershock activity after the collapse decreased dramatically to almost no activity. The collapse of the Milrow cavity produced a rubble chimney extending to land surface. The collapse caused significant changes in surficial geologic structure within a 600 meter radius of GZ, and significantly altered drainage area characteristics and stream flow of Clevenger Creek. The ground surface at GZ sank as much as 6.1 meters forming a rectangular shaped depression with an average width of about 540 meters (Fig. 29). Aerial photography taken over GZ indicated that no fracturing or subsidence had occurred prior to collapse, and three major lakes around GZ had no apparent deformation. All the surficial geologic effects shown on Fig. 29 occurred as a result of the collapse (Morris and Gard, 1970). Heart Lake and South Twin Lake tilted towards GZ and partially drained into the sink area; North Twin Lake drained to the west prior to collapse but now discharges toward the collapsed zone as a result of tilt. Figure 34 shows the main features associated with the Milrow collapse. The line profile A-A' across the

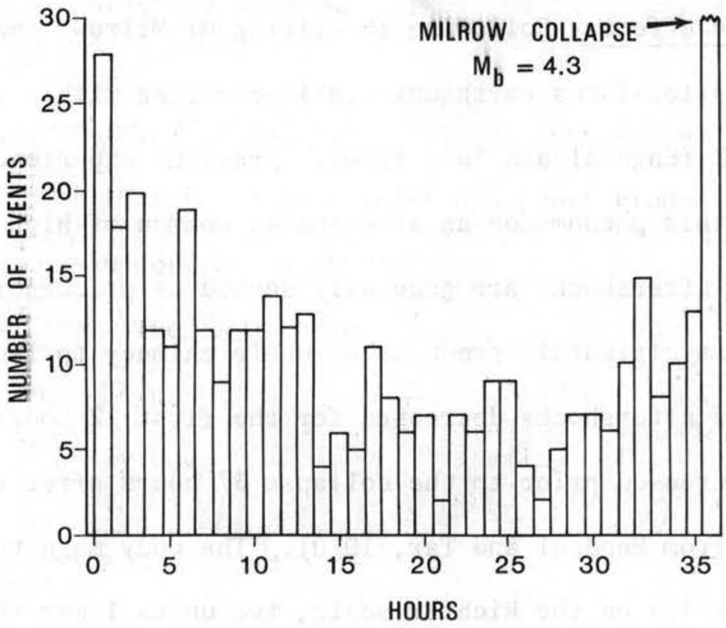

Figure 33. Frequency of aftershocks following the Milrow event culminating with the Milrow collapse (Engdahl and Tar, 1970).

sink through GZ (Fig. 29 and Fig. 34), was surveyed under the supervision Holmes and Narver, Inc., a test-related support group. The width of the sink is about 850 meters and its depth is 4.5 meters relative to pre-shot land elevations. The lips of the sink are a result of upheaval and doming during the formation of the cavity. The differences in lip elevation is probably due to asymmetrical doming. The sink is approximately 540 meters wide and 2 meters deep and has a volume of about $5.83 \times 10^5 m^3$ cubic meters.

Hydraulic effects--The collapse of the cavity formed a rubble chimney that intercepted several zones of high horizontal hydraulic conductivity and created new unsaturated pore volume equivalent to the difference of the near spherical cavity volume and the surficial sink volume. The resulting vertical permeability within the rubble chimney is probably about equal to the horizontal permeability, inducing a strong

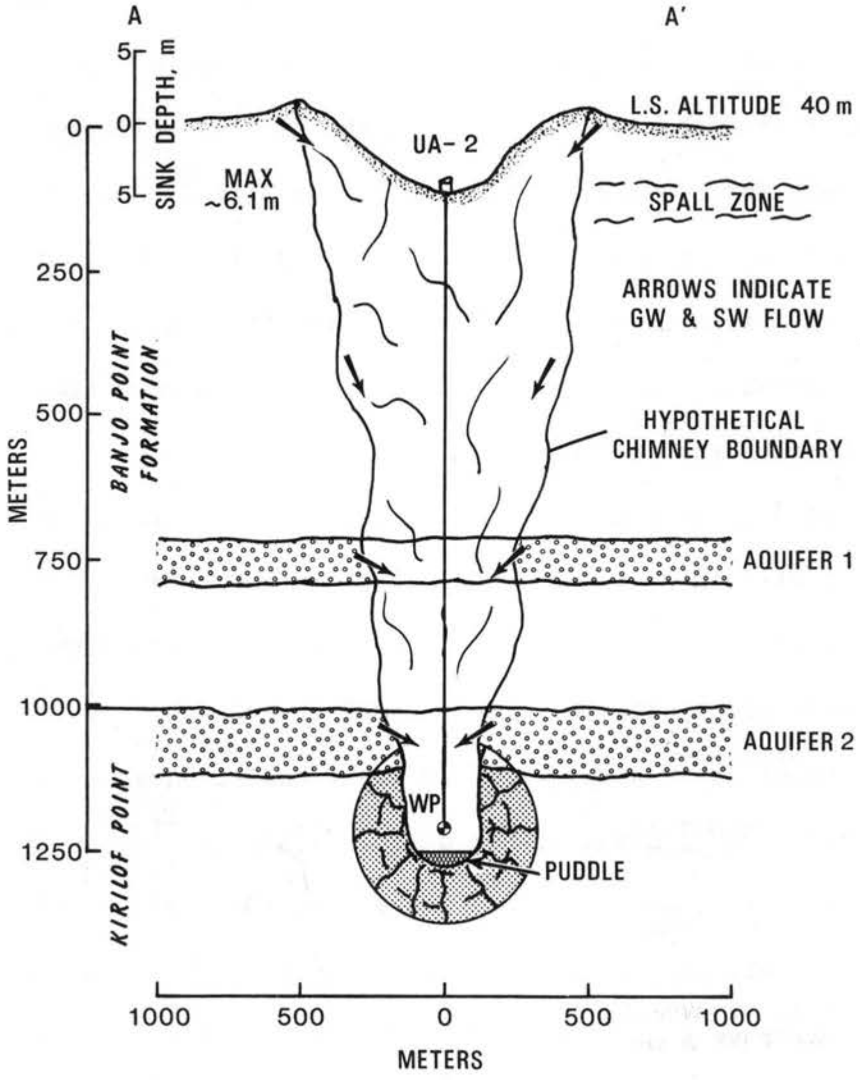

Figure 34. Cross section of A-A' after the Milrow collapse.

vertical component for downward flow. Fracturing due to the collapse and spall during shot time intercepted local surface water and shallow groundwater and diverted this flow toward the rubble chimney. The alteration of surface water discharge is evidenced by the dramatic drop in runoff from the drainage area at the time of collapse. The discharge hydrograph for Clevenger Creek during the period June 1967 to March 1970 (Fig. 35), illustrates the effect of the collapse on stream flow. Runoff peaks are a result of varying intensities of rainfall verified by records of precipitation collected at the airport and stream flow records from four other basins on Amchitka.

Intermittent runoff events during October through December 1969 are a result of rainfall. The magnitudes of flow events during this period are considerably lower than those of the remainder of the record because local fracture systems diverted runoff towards the rubble chimney.

A double mass analysis of rainfall collected about 6 kilometers southeast of GZ and runoff per unit area for five major drainage basins is shown in Fig. 36. Interception of runoff from Clevenger Creek and diversion into the rubble chimney is indicated by an increase in slope at the Milrow collapse on October 3, 1969. The regression back to a normal trend on January 4, 1970, indicates that chimney infill is nearly complete. The exact dates for interception and infill completion were determined by hydrograph analysis of daily discharges. Further investigation of the double mass analysis shows the general slope of the Clevenger Creek plot has slightly shifted to the left after the period of apparent filling. This shift is a result of increased infiltration rates induced by local fracturing and possibly changes in total porosity within the shallow groundwater system. The shift in the plot may also indicate

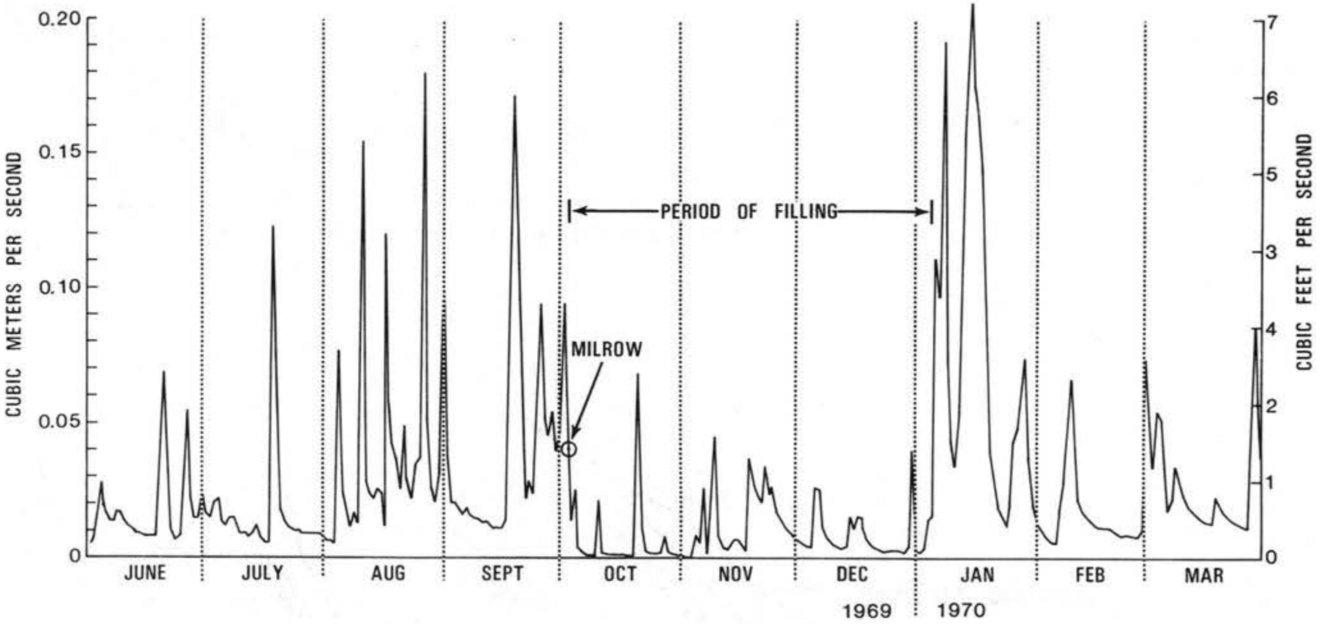

Figure 35. Mean daily discharge at Clevenger Creek for the period June 1969 to March 1970 showing the effect of the Milrow collapse.

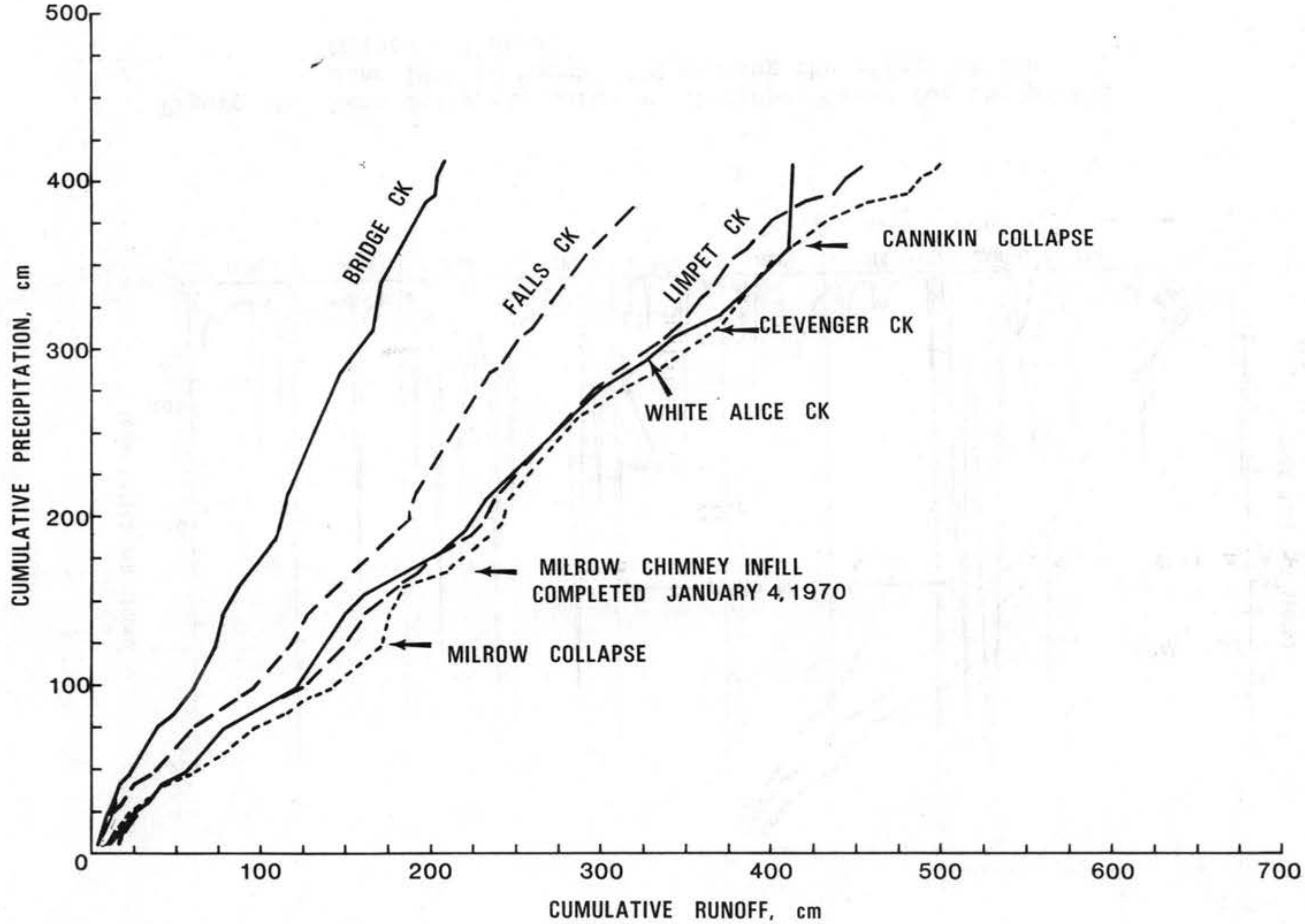

Figure 36. Double mass analysis for precipitation and major drainage areas, Amchitka Island.

that the chimney has not reached complete saturation, resembling the slow recovery of drawdown in a well as it is approaching static conditions.

These analyses are the basis for estimating the time required to nearly saturate the newly formed porosity of the rubble chimney. The period of filling began on the day of collapse and lasted for 95 days, ending on January 4, 1970.

Assuming that a near-spherical cavity was formed, with a radius of about 105 meters (Merritt, 1970), the volume of the cavity is about $4.8 \times 10^6 m^3$. As mentioned previously, the newly formed unsaturated porosity created by the collapse should equal the difference between the volume of the cavity and that of the sink. The sink volume was 5.8×10^5 m^3; so the new pore volume is about 4.2×10^6 m^3. Upon collapse, as a result of an immediate drop in potential due to the newly formed unsaturated zone within the entire rubble chimney, inflow into the rubble zone began immediately, as indicated by stream flow records. Both surface water and groundwater (mostly from aquifers 1 and 2) contributed to the infill of the rubble zone but not necessarily into the cavity, where flow may have been retarded because of the presence of steam due to high temperatures and pressures. Upon condensation of the steam, estimated to occur at least 60 days after the detonation of Milrow, (Claassen, 1976, personal communication, USGS) inflow into the cavity would begin. The infill rate was rapid, taking only about 94 days to fill a column of rubble at least 105 meters in diameter and extending from below the DOB to land surface. If the infill rate was constant from the start of infill, it had to average 15 meters per day and probably approached 100 meters per day during the initial stages of filling. The contribution to infill from surface water is estimated on the basis of average monthly runoff for the entire period of record at the Clevenger Creek gaging station (Table 5). On the basis of average runoff for the months of October to December, the surface water contribution to infill was about 3.3×10^5 m^3, leaving a pore volume of 3.9×10^6 m^3 to be supplemented by groundwater infill, principally from aquifers 1 and 2. Groundwater infill is about 80 percent of the total contribution to infill. Figure 37 illustrates the deficiency of runoff during that period of infill and compares monthly runoff to long-term averages for the years 1969 and 1970. Rainfall for the same period was deficient as compared to long term averages, however, the comparisons with runoff indicate that runoff for 1969 and 1970 was not as sub-par as precipitation would indicate.

Milrow Long Term Effects

Hydraulic effects--Long term changes in hydrologic systems are generally detected by comparison of long term hydrologic data with time. On Amchitka Island two groundwater boreholes and six stream flow stations were equipped with water stage recorders in order to assess long term effects due to the seismic response generated by Milrow. As mentioned previously the shot-related response from the hydrologic system was a dynamic one and pre-shot conditions were restored to normal a short time after firing. The collapse of Milrow affected only the hydraulics of the local area with no apparent effects at distances greater than 4 kilometers from GZ.

A correlation between changes in groundwater fluctuation, surface-water discharge and precipitation has revealed some changes that are shot-related.

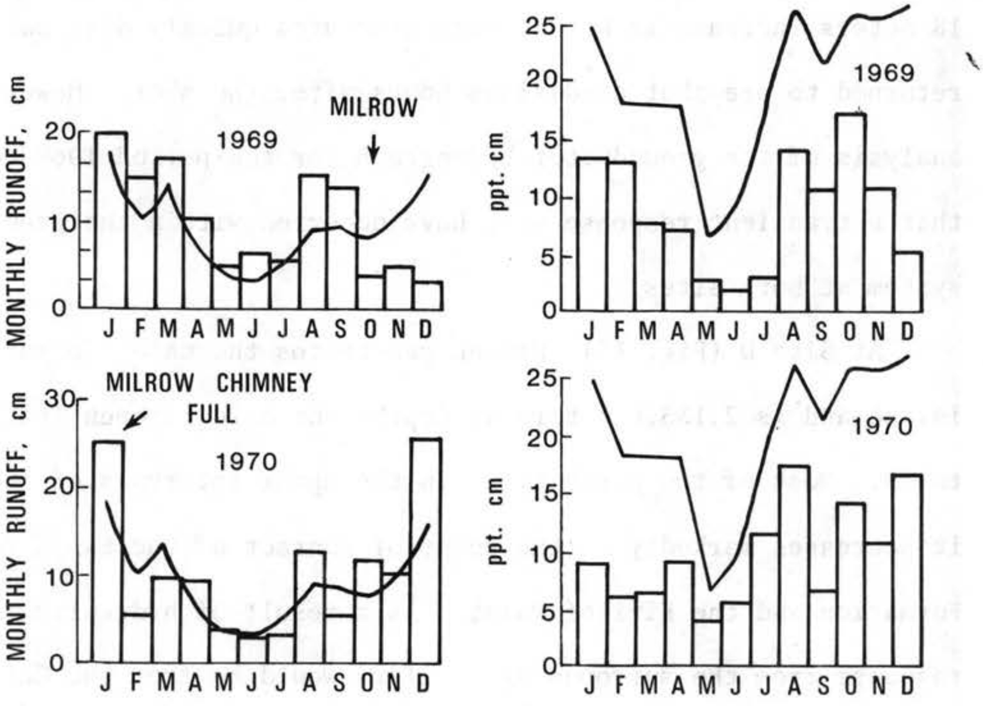

Figure 37. Histograms of monthly runoff for Clevenger Creek and monthly precipitation, 1969-1970; solid lines are long-term averages.

The double mass analysis (Fig. 27) does not show any adverse changes in patterns of stream flow at any of the five drainage areas other than those mentioned previously for Clevenger Creek. The dynamic pore pressure measured at Site D, 16 kilometers northwest of GZ, was 3.7 bars, equivalent to an increase of about 38 meters in hydraulic head. At Site E, 22.7 kilometers northwest of GZ, the response was 1.7 bars, or about 18 meters increase in head. Pore pressures quickly dissipated and returned to pre-shot conditions hours after the shot. However, an analysis of the groundwater hydrograph for the period 1968 to 1970 shows that a transient response must have occurred within the groundwater system at both sites.

At Site D (Fig. 13), UAe-6h penetrates the major formations on the island and is 2,133.6 meters in depth; the hole is open from 85 meters to TD. Most of the porosity is in the upper intervals of the hole and it decreases markedly at the point of contact of the Banjo Point Formation and the Kirilof Point. As a result of hydraulic testing, any response from the surrounding aquifers would be from the Chitka Point and Banjo Point Formations. A hydrograph of mean monthly depth to water for Site D is shown on Fig. 38. Shown also for comparison is runoff from Falls Creek, the principal drainage for Site D and precipitation at the airport 22 kilometers southeast from Site D. During the last half of 1968, and up to Milrow, groundwater levels in UAe-6h had been rising following the pattern of stream flow and precipitation until March of 1969. Following Milrow, the water level rose slowly until mid-November, then continued its downward trend. The rise is a result of compression forcing a transient pulse through the most transmissive zones. The hydrograph during 1970 seems to correlate well with runoff from Falls

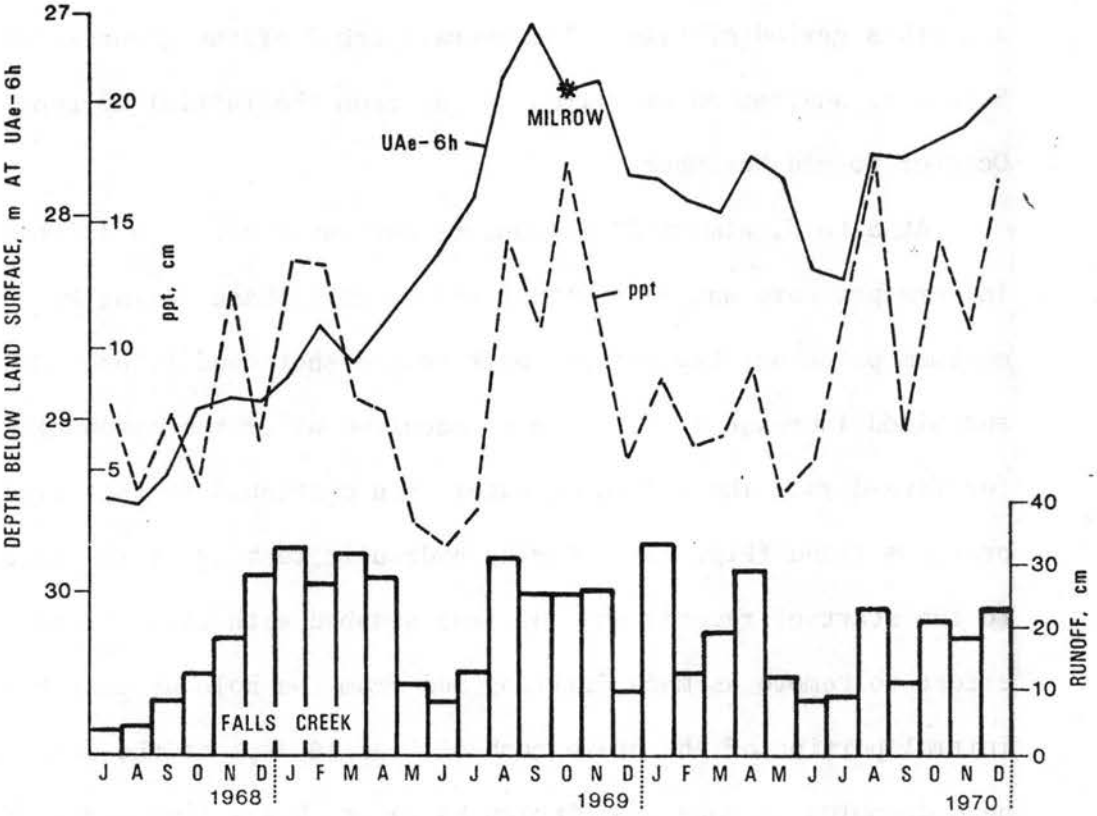

Figure 38. Mean monthly water levels, UAe-6h, site D, runoff for Falls Creek and precipitation at the airport.

Creek and with precipitation. It is a mild surprise that the deep borehole whose head decreases with depth reacts to infiltration over such a short time. The response to infiltration due to precipitation does not occur simultaneously as does the runoff from Falls Creek, but occurs over a month's period of time. The overall trend of the groundwater level at Site D is unaffected by Milrow, aside from the initial response from October to mid-November.

At Site E, almost 23 kilometers northwest of GZ, a 1.7 bar increase in pore pressure was a result of the dynamic phase during Milrow. The maximum pulse quickly decayed back to pre-shot conditions. However, a sustained increase in water level occurred after the detonation, lasting for five days. The column of water then continued to fall along the previous trend (Fig. 16). During hydraulic testing of the hole, prior to the start of record, the hole was swabbed with clean fluids in an effort to remove as much drilling mud from the hole as possible. The initial portion of the hydrograph of Fig. 16 depicts the potentiometric head dropping to some equilibrium 58 meters below land surface. The downward trend is interrupted by three abrupt changes in direction; the last induced by project Milrow. The first two are probably rises due to local strain episodes in compression as they appear too sharp to be a result of recharge. About a month after Milrow, the water-level rose about 8.5 meters reaching a state of equilibrium late in 1970. Figure 39 shows mean monthly values of groundwater potential, precipitation and runoff from Limpet Creek which partially drains Site E. Careful analysis did not clearly bring out any correlation for the abnormal changes in groundwater level and recharge due to precipitation, as was the case at Site D. It is possible that rise and fall in groundwater are severely lagged behind any input from rainfall.

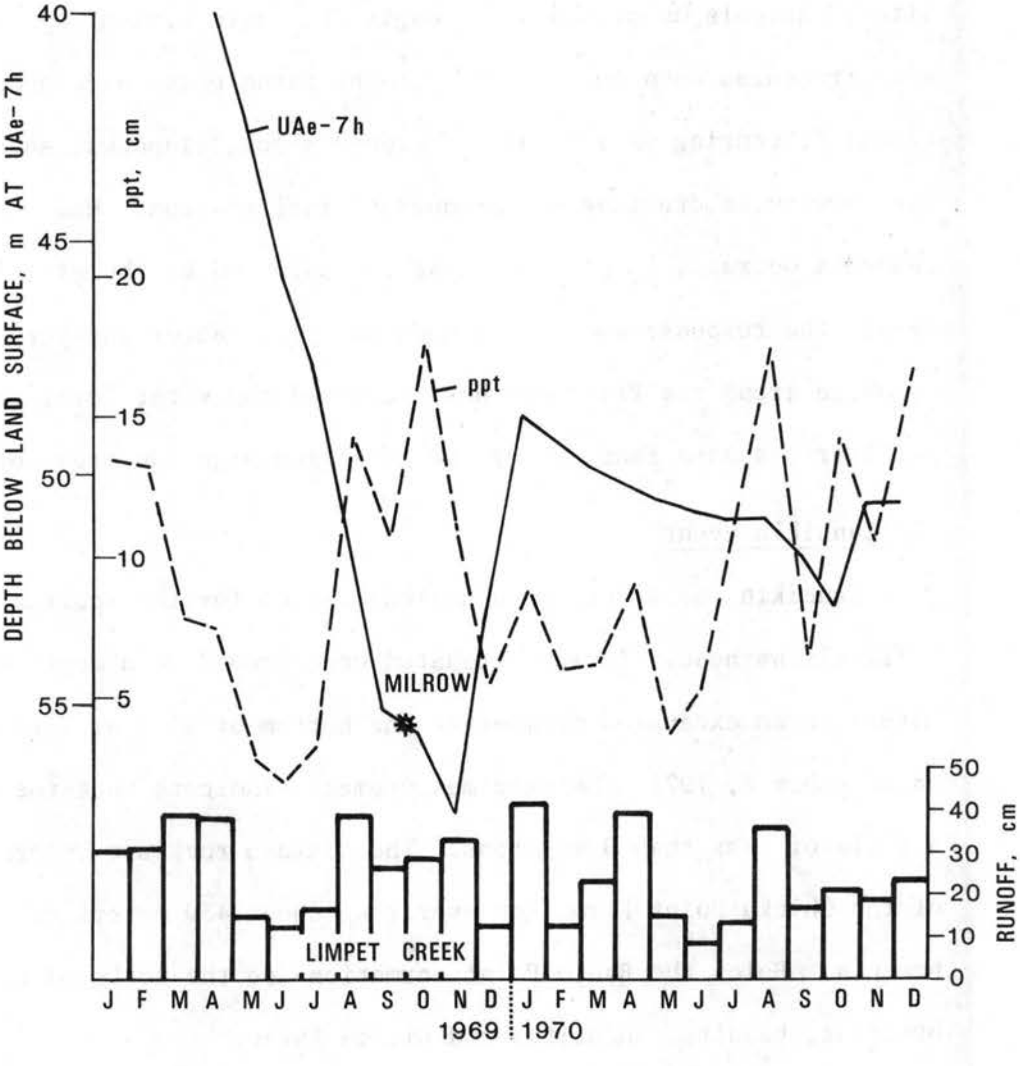

Figure 39. Mean monthly water levels, UAe-7h, site E; runoff for Limpet Creek and precipitation at the airport.

The rise in water level, if not related to tectonic activity, may be an indirect effect of Milrow. UAe-7h was drilled in a hydrothermally altered aureole described as strongly fractured within may zones with many fractures open and permeable. The aureole may have undergone additional fracturing as a result of ground shock, slapdown, and increased pore pressures creating new avenues of infiltration. Had the shock caused a decrease in pore space as is indicated by the rise in water level, the response would have been sharper. Water infiltrating from recharge areas via fractures has increased the water level to new equilibriums as a function of available recharge and areas of discharge.

The Cannikin Event

Cannikin was a test of a nuclear device for the spartan anti-ballistic warhead. It was detonated underground at a depth of 1792 meters in an excavated chamber at the bottom of UA-1 at Site C (Fig. 13) on November 6, 1971. Seismic measurements indicate that the device had a yield of less than 5 megatons. The surface rock are volcanic breccia of the Chitka Point Formation overlying about 430 meters of Banjo Point breccia. Below the Banjo Point Formation are the rocks of Kirilof Point: breccias, basalts, andesites and pillow lavas.

Site Hydrology

The Cannikin site is almost on the divide of the island where the terrain is relatively flat at an altitude of about 63 meters. The width of the island is about 5 kilometers and the surface materials of the whole area include several meters of tundra and peat overlying clay detritus of weathered volcanic breccia. The mean annual precipitation is probably in excess of 110 centimeters based on cumulative precipitation and runoff comparisons. There are many lakes and streams that are an important part of the local basin hydrology. Site C is entirely contained within the White Alice Creek drainage basin which covers 2.05 square kilometers (Fig. 40). The saturated tundra and underlying weathered rocks are reason for almost instantaneous response of runoff to bursts of precipitation. This shallow aquifer also provides base flow for White Alice Creek during those months of low precipitation, particularly May through July. Base flow is about 0.028 m^3/s during these periods. The drainage area extends from about the divide of the island to the Bering Sea, has an average width of 1 kilometer, and ranges in altitude from 15.2 to 85.3 meters. Lakes comprise only two percent of the drainage area which drains northeastward toward the Bering Sea. The shoreline near the White Alice Creek gaging station is characterized by steep cliffs ranging from 12 to 18 meters high. Stream flow records collected near the shoreline show that the mean annual runoff is about 0.08 m^3/s for the period of record.

The water table is very near the land surface throughout most of the drainage area. The correlation of water levels in shallow boreholes with precipitation trends indicates that the shallow groundwater system is quite permeable and susceptible to infiltration (Fig. 41). Typically, hydraulic heads decrease with depth of penetration indicating downward flow. The depth of water in four boreholes within 2 kilometers of GZ ranges from 2 meters near the divide to about 35 meters in UA-1.

Hydraulic tests conducted in UAe-1 (Ballance, 1973) show that four principal transmissive zones exist within the saturated rock to a depth of about 1800 meters. The highest transmissivity was calculated to be 30 m^2/day at a depth of about 775 meters. All four zones were expected to contribute significantly to chimney infill. The salinity of water

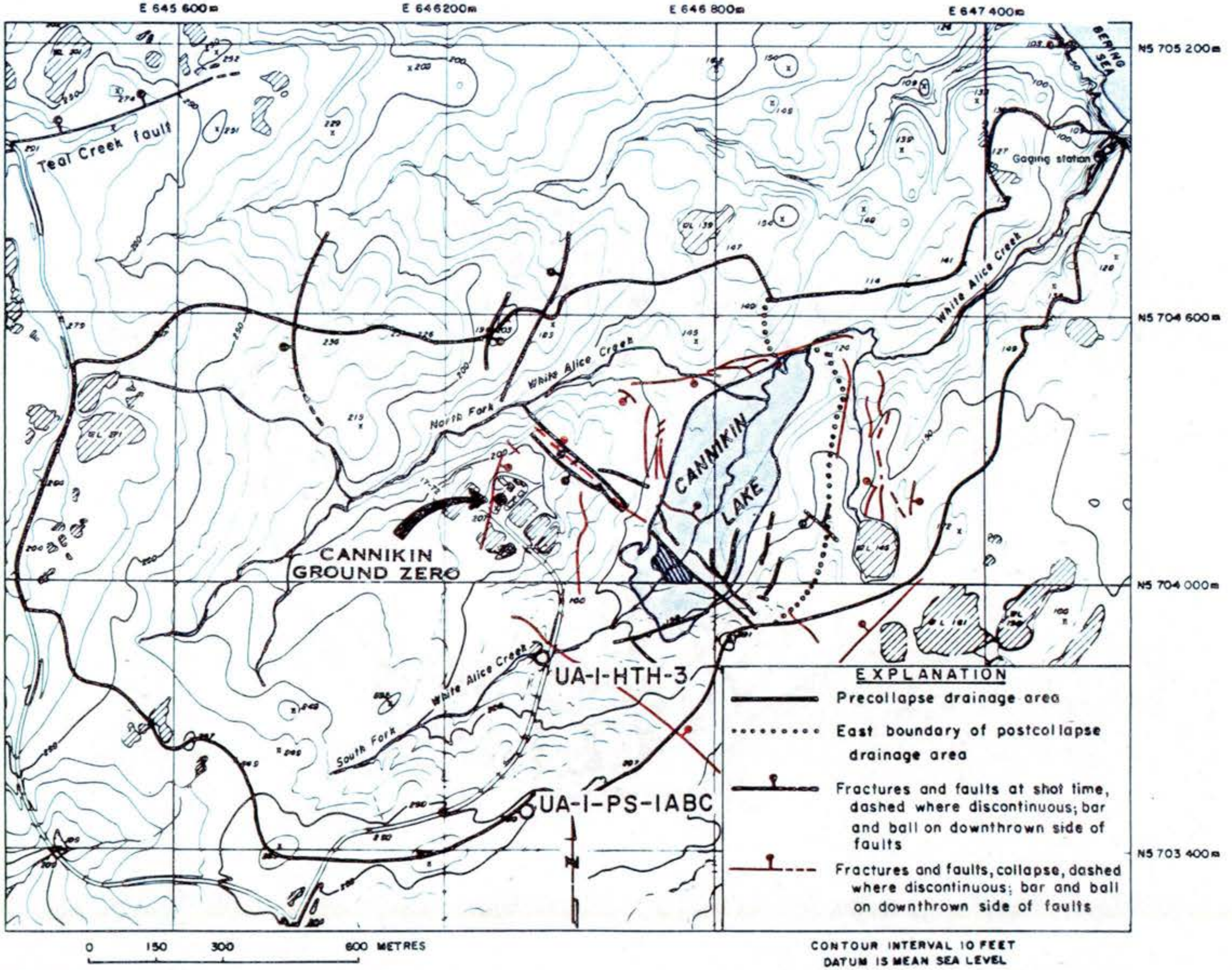

Fig. 40. White Alice Creek drainage basin and the primary geologic and hydrologic effects resulting from the Cannikin event (Geology by Morris and Snyder, 1972).

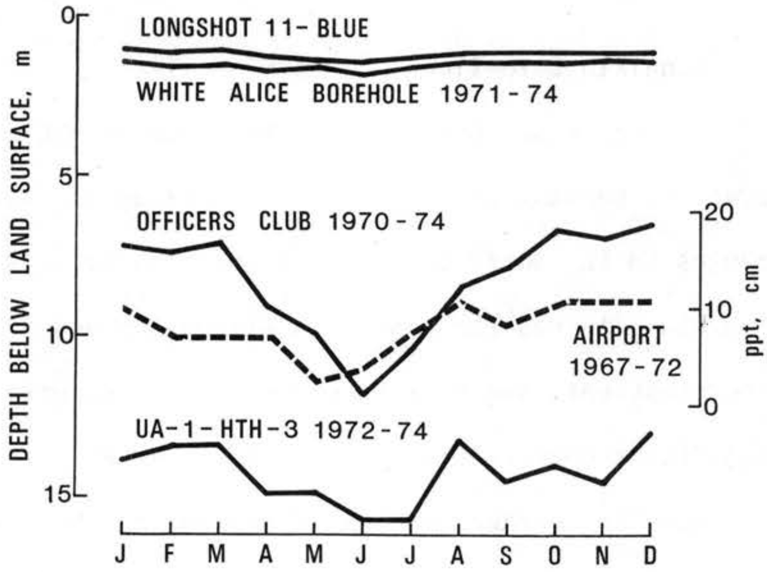

Figure 41. Mean monthly variation in groundwater levels and precipitation, Amchitka Island.

increases with depth indicating fresh water-salt water interface at depth. Dudley (1976, verbal communication, USGS) states that the Ghyben-Hersberg interface probably exists below the working point of the Cannikin device.

Cannikin Zero-Time

At zero time, preparations had been made by the U.S. Geological Survey to monitor at six stream flow sites and five groundwater boreholes changes in the surface water and groundwater systems as a result of Cannikin. As was the case with Milrow, ground displacement, stress determinations, and visible geologic changes were also monitored and significant changes measured and documented.

Adverse weather conditions existed on the island hours prior to the explosion. High winds and precipitation caused high runoff within major drainage basins, but the flow was approaching normal conditions at the time of firing. Groundwater conditions were impossible to assess because boreholes had been instrumented with monitoring equipment insensitive to minute changes in water levels.

Visible effects--Cannikin was successfully detonated on the morning of November 6, 1971, after nearly four years of preparation. Immediate observations of concern were that there had been no radioactive release or triggering of major earthquakes or tsunamis as a result of Cannikin. Teleseismically, the shock produced by Cannikin had a body wave magnitude of 6.8 and a surface wave magnitude of 5.7 (Orphal and Smookler, 1972).

Surface and subsurface motion studies by Sandia Laboratories found Cannikin data equal to or slightly greater than motion peaks predicted for Milrow. Maximum surface motion accelerations approached 36 g's as a result of slapdown which were equal to or greater than initial shock values. Spallation occurred at least 60 meters deep and extended laterally 5.5 kilometers (Perret, 1972), about the same as observed for the Milrow event, which occurred between the depths of 90 and 150 meters and extended laterally 5.2 kilometers. A power malfunction at 1.8 seconds prevented any recording at stations over 10.6 kilometers from GZ. Maximum vertical displacements were over 6 meters in the vicinity of GZ.

Aerial photography taken during Milrow and Cannikin revealed approximately the same visible effects, that is, geysers of water spewing from land surface, eruptions of mud and water from lineations and fractures (seen along stream channels, lakes and in the oceans) and water being heaved upward from lakes and streams.

In an effort to document these phenomena in shallow water, pressures and accelerations were measured in numerous lakes and ponds on Amchitka. The results were similar to those wave forms recorded during surface motion programs in that each showed an initial pulse, a period of free fall during spall, and an impact shock. An example of vertical accelerations, velocities and displacement wave forms measured 1.3 kilometers from GZ are shown on Fig. 42 (Perret, 1972). These surface ground motion measurements illustrate the seismic force that results in the change in water pressure over a local area. The acceleration pulse at 0.55 seconds is at shock arrival. Velocity reaches 520 cm, then decreases into a state of free fall at a rate of 1g, typical of spallation some 60 meters below land surface. When the spall material hits bottom at about 1.6 seconds, there is a second acceleration pulse due to slapdown of 18 g's. At this time the velocity soon returns to zero. Ground displacement at this range was in the order of 1.7 meters. The power malfunction at +1.8 sec prevented recording of any over-pressures in shallow lakes or

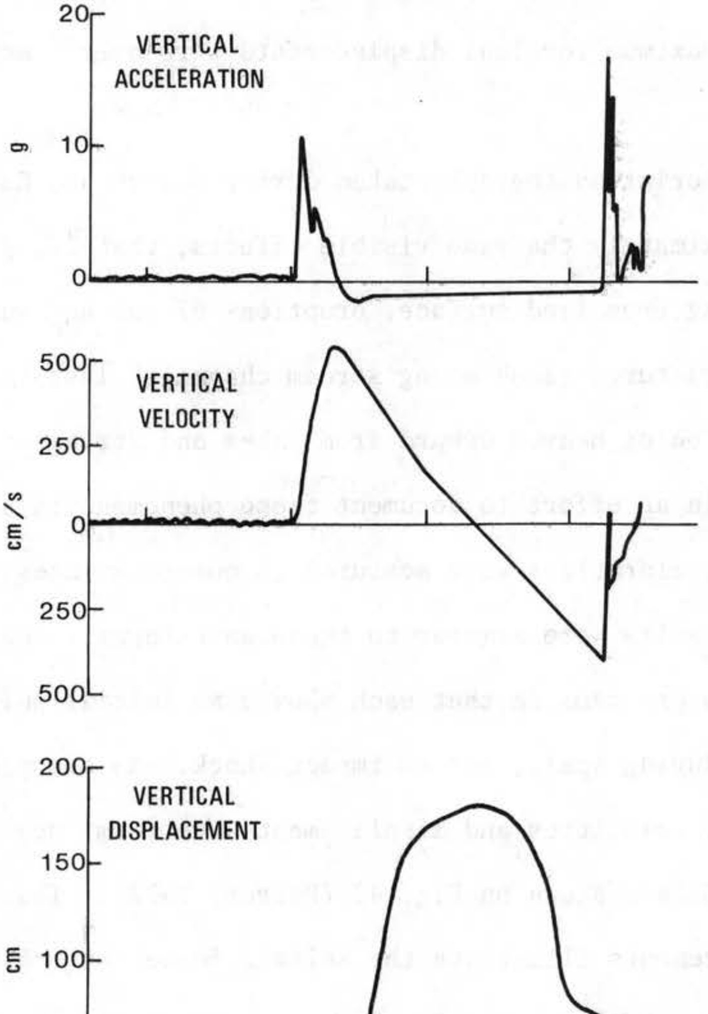

Figure 42. Surface motion measurements 1.3 kilometers from Cannikin GZ (Perret, 1972).

ponds beyond this time. However, an explanation to the configuration of the upheaval of surface waters on the basis of appearance on aerial photography and available wave form is appropriate.

A set of Milrow deep-pressure records measured in 24 meters of water at a distance of 2.6 kilometers from Milrow is shown on Fig. 43 (Merritt, 1971) and is used for comparison. The Milrow deep-water records result in peak pressures of about nine atmospheres and drops below pre-shock ambient pressures to -3 atmospheres. Inspection of aerial photography indicated large areas of white spray around this gage. Merritt interprets this as cavitation.

Pressure measurements in a shallow lake DK-2 (Cannikin) shown on Fig. 44 (Merritt, 1973) are seen to exhibit characteristics similar to surface motion measurements. The reaction of ponds and small lakes to Cannikin ground shock was also recorded from photography of lake DK-2 as were the deep pressure measurements taken for Milrow. The photographs show the surface as an initial white flash, a darkening, a long interval of a white appearance and at slapdown an agitated surface. These descriptions are coincident with measured pressures: whitening appears at shock arrival; the darkening during the period of positive pressure and upward acceleration; the long white period is during free fall in which air is decelerating the water and finally instability at slapdown. Merritt interprets the pulses recorded in the pond as real and suggests that pressures in shallow or shore waters resulting from ground shock are related to the acceleration of the rock surface. He reports that each pond history exhibited a shock duration pulse less than an atmosphere of pressure. Then surface water, per se, became in the state of upheaval in pressure or pressure relief and when spall occurred beneath the surface

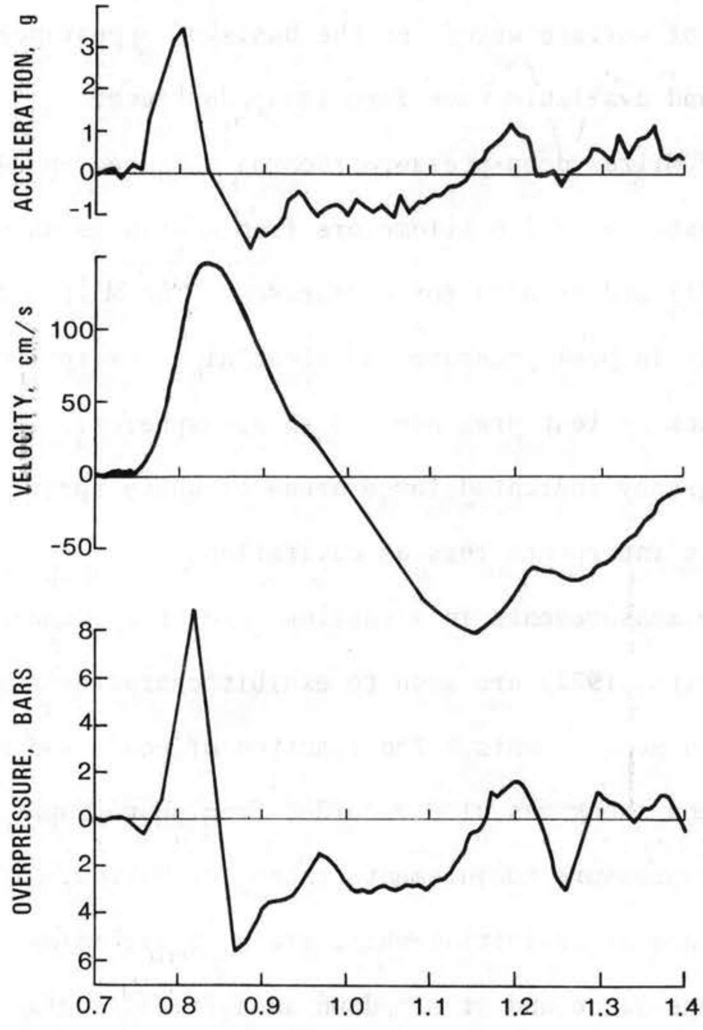

Figure 43. Deep water motion and over pressure measurements as a result of Milrow (Merritt, 1973).

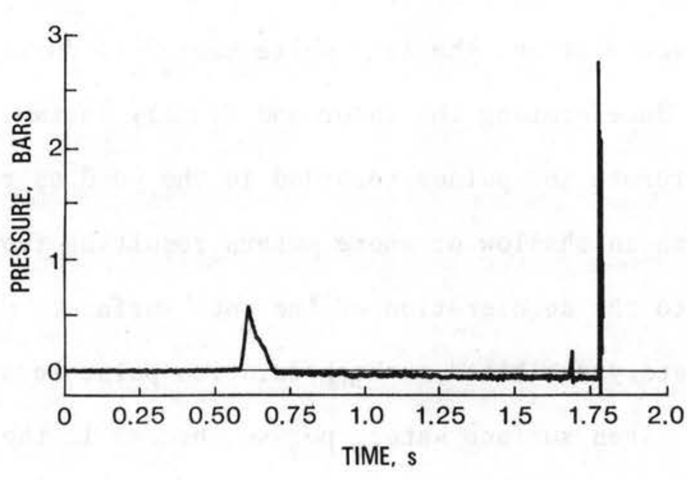

Figure 44. Pressure in a shallow lake, 1.3 kilometers from Cannikin GZ (Merritt, 1973).

waters of the island, sharp second pulses of greater amplitudes of pressures occurred resulting in agitation and displacement of fluids. Kirkwood (1972) attributes this phenomena to the amount of small fish kill at the time of detonation.

Most fractures associated with the Cannikin experiment occurred along previously mapped structures that exhibited a trilateral pattern oriented northeasterly, northwesterly and northerly (Morris and Snyder, 1972) (Fig. 40). Teal Creek Fault, 1070 meters northwest of GZ and that fracture zone 200 meters northeast of GZ were the main geologic features that occurred as a result of Cannikin. Those fractures closest to GZ had 2 to 3 meters of displacmeent while the Teal Creek Fault was downthrown to the north a maximum of 0.6 meters.

Uplifting as much as 1.1 meters along the intertidal platform southeast of Banjo Point suggests movement of a structural unit or block along the Bering coast. Rock falls occurred, more so than for Milrow, primarily because of energy differences between events and the steep structure of those cliffs closest to Site C on the Bering side. The bulk of rock falls, slumps and landslides occurred on the Bering Sea side. One ancient landslide east of Banjo Point showed evidence of dropping about 3 meters. Turf disruptions were common within 1.6 kilometers of GZ and were readily detectable. Ground shock caused turf to uplift and shear resulting in local disrupted piles of turf mats. On steep slopes turf mats would fail along the surface of underlying rock and slump into depressions and streams creating temporary blockage of these channels.

A group of lakes east of GZ (Fig. 40), underwent significant changes as a result of fracturing, causing them to be drained or tilted. Several lakes were drained completely and effects as far as 10 kilometers from GZ were noted. Many observations of fill material failure were noted along roads, pads, foundations, etc. There were no major structural failures as a result of these disruptions.

Strain measurements (Dickey and others, 1972) indicate that maximum principal strains greater than 1 kilometer from GZ tend to be extensional and oriented northeast-southwest. They appear related causally to cavity growth because of similarity to radial and tangential strains expected from cavity growth. However, because of the magnitude ratio of radial and tangential stress and estension rather than compression, the real direction and cause of principal strain are related to local linear structure and release of local tectonic strain triggered by the explosion. The release of tectonic strain also may have been a result of increased fluid pore pressures across fault planes.

<u>Surface water</u>--The response of surface water and groundwater was dramatic and predictable, based on the Milrow and NTS experience, but the magnitudes of the response generally exceed predictions.

Surface water response was recorded from five drainage areas at five sites ranging from 1.5 to 14.07 kilometers from GZ (Fig. 13). An additional site which was observed was Constantine Spring, the island's major source of water supply. The integrity of the monitor system was maintained throughout the dynamic and transient phases of ground shock despite adverse weather throughout the island and unfortunate malfunctions at two primary sites. Continuous records of stage were collected at all stream gaging sites with no interruption in record. All the major drainage areas within 14 kilometers of GZ reacted to the impact of seismic wave trains generated by Cannikin. Some detail has already been discussed in the previous section of those measurements of over pressures taken in several lakes and ponds. References will be made occasionally to the measurements of ground motion, 1.3 kilometers from GZ (Fig. 42).

The result of upheaval, spall and successive reflections of compressive wave trains radiating from the working point was a semi-instantaneous supply of water available for runoff. Most of this surplus was a result of compaction of the shallow groundwater reservoir forcing groundwater to the surface in the form of geysers, sheets of flow, eruptions along lineations and an ooze from the overlying thick tundra mat similar to an effect that one could simulate by squeezing a saturated sponge. This surplus of surface water found its way to stream channels in the form of overland sheet flow, with some quantities infiltrating back into the shallow unsaturated mat of turf. Some ponds and lakes were partially or completely drained as a result of upheaval, tilt or fracturing. Water in streams was heaved upward during the initial shock of increased acceleration and at slapdown. As a result of ground upheaval, an abrupt increase in channel slope occurred around the vicinity of GZ increasing the rate of flow in a downstream direction in numerous drainage areas. The effects of ground displacement probably reached as far as 13 kilometers from GZ (Perret, 1972).

The principal drainage areas tabulated on Table 8 responded similarly except for Bridge Creek which had no appreciable response. The drainages responded to an abrupt change in slope and an excess of water due to upheaval and compaction. Excess runoff was principally of shallow groundwater origin which sustained the initial flood peak for varying times resulting in a depletion of the reservoir. The sustained flow lasted upwards to an hour before falling into a recession below normal conditions. With exception of White Alice Creek and Bridge Creek, flow was back to normal two days after the detonation.

At Falls Creek, principal drainage for Site D, natural recovery was interrupted by the failure of several mud pits containing drilling fluids used in drilling UAe-6h (Fig. 45). There were no adverse effects with the Site D drainage area as a result of this spillage.

Flow in Limpet Creek, 11.17 kilometers from GZ, increased slightly at zero time and recovered to normal conditions within five hours (Fig. 45). Flow remained normal with no appreciable changes in flow pattern.

Bridge Creek, the largest of the five drainage areas (7.85 km^2), had no appreciable response to the explosion. The character of the basin, such as flat slopes, length and percentage of lakes within the area (35 percent), probably reduced the effects of the explosion to an undetectable response.

White Alice Creek drainage area, the principal drainage for Site C, responded to ground shock as expected. Extreme accelerations and ground displacement severely altered the drainage area and, of course, the flow. The discharge history shown on Fig. 46 indicates a maximum peak flow of record of over 1.13 m^3/s as a result of initial shock and slapdown. Streambed material was found strewn along the main channel as a result of slapdown. After the recession of the floodwave, flow dropped significantly below normal conditions and remained so as a result of fracturing occurring in the upper basin and turf slides restricting normal flow (Fig. 40). Normal flow did not resume at White Alice Creek for nearly a year after the Cannikin event.

Clevenger Creek, 8.7 kilometers from GZ, sustained an increase in flow lasting for nearly two days. The increase may have been supplemented

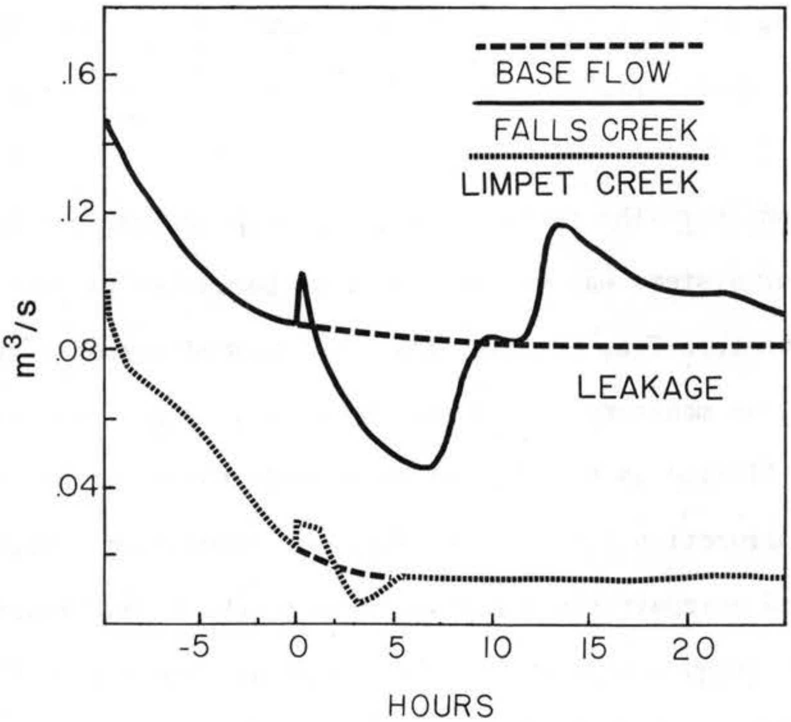

Figure 45. Discharge at Falls Creek and Limpet Creek before and after the Cannikin event.

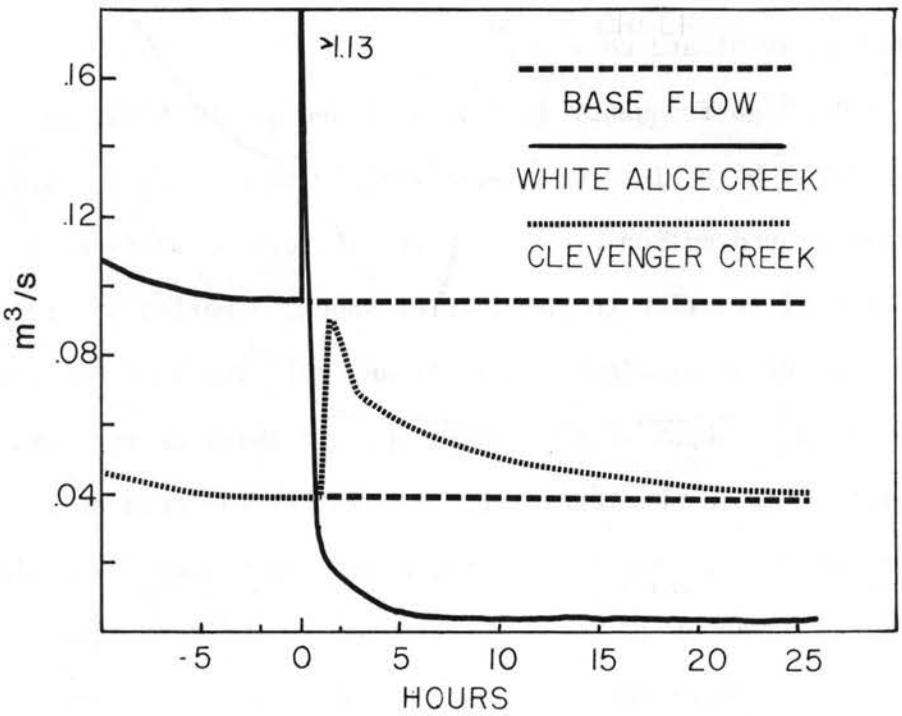

Figure 46. Discharge of White Alice Creek and Clevenger Creek before and after the Cannikin event.

by drilling fluids released from old storage pits around Milrow GZ (Fig. 45). There were no appreciable affects two days after the explosion.

Groundwater--The response of confined pore pressure in local groundwater systems was recorded in five boreholes ranging from 1.18 to 14 kilometers from GZ (Fig. 13). Unconfined response at the Long Shot Site was monitored in an open borehole. High frequency data were very limited as a result of high winds the night before firing and a power malfunction 1.8 seconds after the detonation. High winds and rain caused unrepairable damage to signal cables that would have triggered high frequency recording systems at all sites except the Officers Club borehole. At UA-1-HTH-1 only 1.8 seconds of data were recorded because of power failure. Table 11 contains the principal characteristics and response data from the boreholes that were monitored during the Cannikin event and collapse.

The high frequency records obtained at the Officers Club and UA-1-HTH-1 boreholes were quite similar to wave forms typically recorded during ground motion programs. The history of confined pressures showed an initial reaction to the initial shock, a period of free fall, and a large spike at slapdown (Figs. 47 and 48). The UA-1-HTH-1 record is truncated at about +1.8 seconds, but its short history exhibits characteristics of an accelerometer. UA-1-HTH-1 was at a slant range of 2.14 kilometers from the working point and measured a maximum pore pressure of about 207 bars in response to the detonation.

The pressure recorded at UA-1-HTH-1 is significant. These measurements represent confined pore pressures that are contained in the upper crust and distributed locally as a function of distance.

Table 11. Fluid Pore Pressure Response from the Cannikin Event

Borehole Site	Total Depth m	Cased Depth m	Distance from GZ km		Direction from GZ	Confined Pressure Response, Bars				
						Cannikin Event			Collapse	
			Horizontal	Slant		Max	Min	Residual	Max	Min
UA-1-HTH-1	426.7	80.8	1.18	2.14	N	207	-25	-5.2	3.45	-2.41
White Alice	96.3	11.0	2.06	2.73	NW	>6.21	-9.66	0	Sharp decrease in water level	
Long Shot 9-Blue Open Hole	152.4	--	6.42	6.66	SE	.274 m	-.152 m		Sharp decrease in water level	
Site D	2134.	85.0	7.45	7.66	NW	9.65	0	-.69	.52	.45
Officer's Club	112.8	24.4	12.97	13.09	SE	3.11	-2.07	.015	.25	-.24
Site E	1231.	624.5	14.00	14.11	NW	>5.75	-1.86	.26	.12	-.05

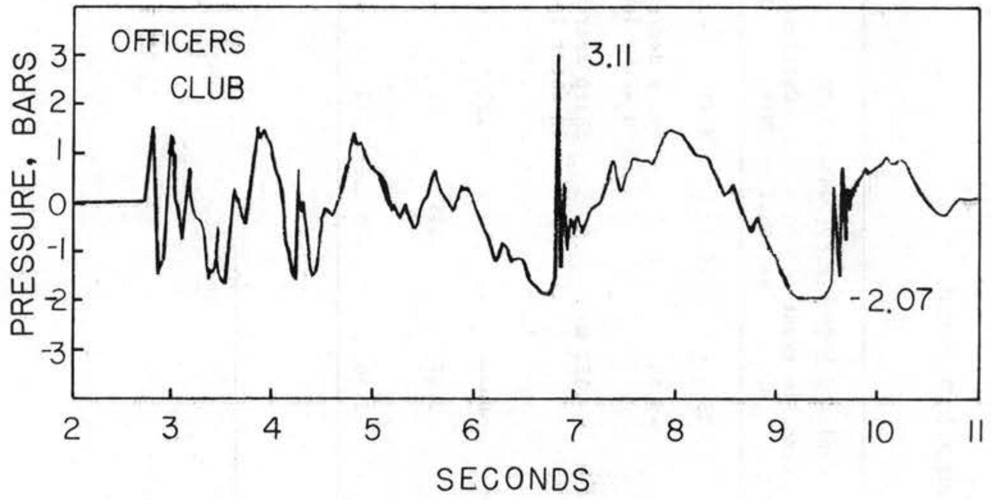

Figure 47. Fluid pore pressure response to the Cannikin event at Officers Club borehole, Amchitka Island, Alaska.

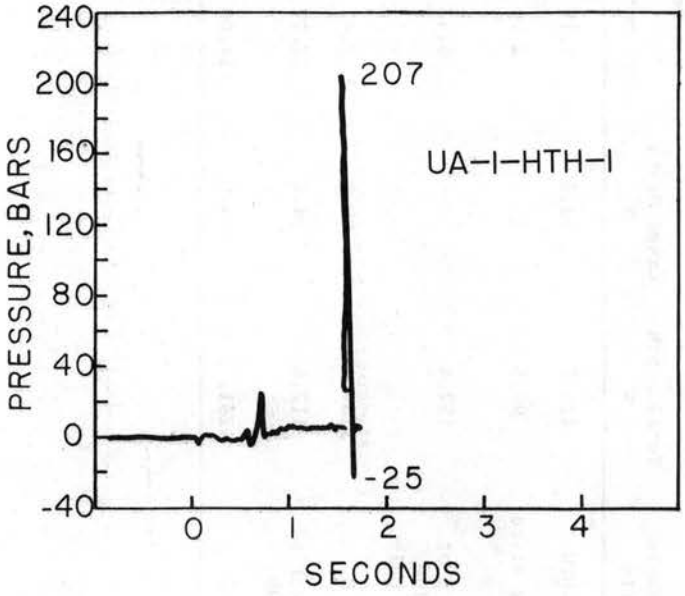

Figure 48. Fluid pore pressure resonse to the Cannikin event at UA-1-HTH-1, Amchitka Island, Alaska.

Principal fault movements were observed in close proximity and were related to a short term interaction of the explosion and the local ambient tectonic stress of the island. The release of energy resulted in small scale tectonic events that were characteristically high frequency and confined to the upper crust. These events exhibited focal mechanisms similar to those under natural conditions and near major faults on the island (Engdahl, 1972). The short term interaction between explosions and local ambient stress could possibly result from the explosion-generated seismic waves (elastic body waves) or changes in fluid pore pressure as observed during the event.

Officers Club, at a slant distance of 13.09 kilometers, was the only other groundwater hole where high frequency monitoring was successfully employed (Fig. 47). The first arrival time was about +2.7 seconds with initial shock producing low frequency over pressures ranging from 1.5 to almost -2 bars. The period of free fall appears to be between +5.6 to +6.8 seconds when the characteristic slapdown spike occurs. Pressures then oscillate and decay to pre-shot conditions at about +11 seconds taking on the appearance of vertical particle motion. The fluid pore pressure history for Officers Club contains many characteristics similar to those of ground motion measurements performed by West and Christy (1971) near the borehole site. Initial arrival times for these studies were measured at +2.28 and +2.80 seconds, respectively, at sites 14.7 kilometers from the working point. Peak particle accelerations were measured between 0.24 and .85 g's arriving at about +5.5 seconds. It must be noted that time of arrival data are within certain limitations for all fluid pore pressure measurements and probably contain appreciable error. However, the data show that fluid pressures follow the general pattern of particle propagation.

White Alice borehole, only 2.06 kilometers from GZ, sustained casing failure as a result of initial shock and high pore pressures. It reacted as a geyser following the failure of the annulus around the casing.

Long Shot 9-Blue, 6.42 kilometers from GZ and monitored as an open hole, fluctuated about ambient conditions as a result of ground motion, then began a decline in water level in response to subsurface fracturing, probably spall (Fig. 49). At the time when water levels began to recover after almost two meters of decline, the collapse occurred resulting in an additional drop in head. Shortly after the collapse, water levels again resumed their recovery and reached normal conditions nearly 45 days later (Fig. 25). The effect of ground shock at this location may have stimulated further collapsing of the roof of the rubble chimney formed by Long Shot (October 29, 1965). There is no surface expression of the collapse at this site and there have been no determinations as to what extent, if any, a rubble chimney was created. In any event, it is possible that by the stimulation of ground shock produced by Cannikin, rearrangement or further collapse of the Long Shot chimney occurred creating additional pore space reflected in the decline of water levels in Long Shot 9-Blue. The record also points out that the occurrence of the Cannikin collapse also had an effect on the alteration of local aquifers. Assuming interstitial porosity in the order of two to three percent, saturated groundwater conditions, and transmissivities that probably range from 0.1 to 4 m^2/day, over a depth of 400 meters, the volume of water that was depleted over some unknown areal extent may have been considerable, especially on the basis of the two meter drawdown around the local Long Shot area.

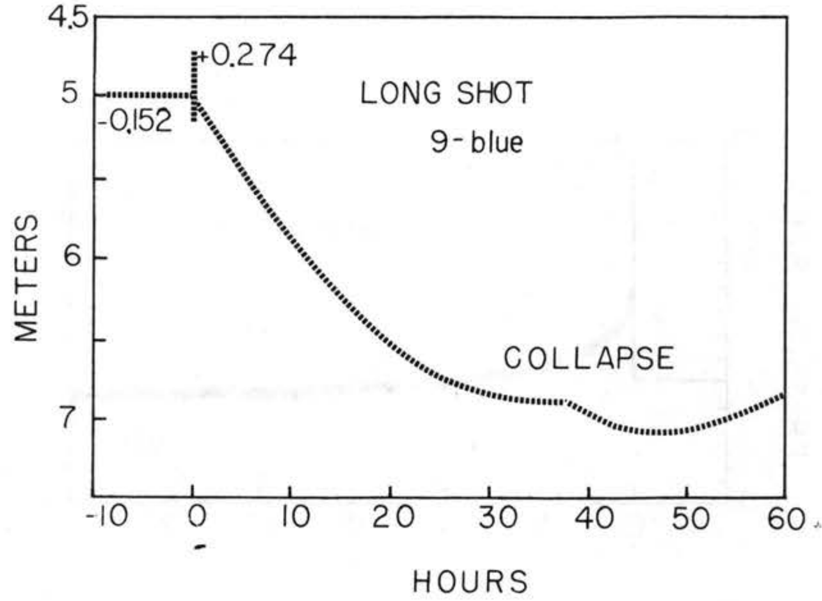

Figure 49. Water-level response to the Cannikin event at Long Shot 9-Blue, Amchitka Island, Alaska.

The shot time responses for Site D and E (Figs. 50 and 51), were measured on low frequency, slow speed recorders through the detonation and collapse and only maximum responses were obtained. Fluid pressures responded sharply to initial ground shock and slapdown. However, both sites did not fully recover to pre-shot conditions and sustained residual pressures. These residuals are probably a result of excess stress conditions in the aquifer which resulted in a change of porosity. At Site D (Fig. 50) there was no observable response below ambient pressures which is unexplained and only occurred at this location.

The relationship of fluid pressure response to the Cannikin event and slant distance to the working point is presented on Fig. 52. Several correlations also were made with particle motion data collected by Sandia Corporation and Environmental Research Corporation (ERC). The vertical components of particle velocities were transformed into over pressures by the relationship:

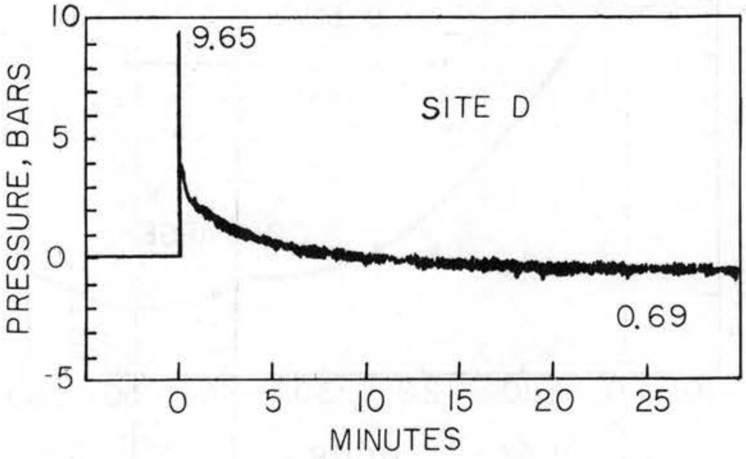

Figure 50. Fluid pore pressure response to the Cannikin event at Site D, Amchitka Island, Alaska.

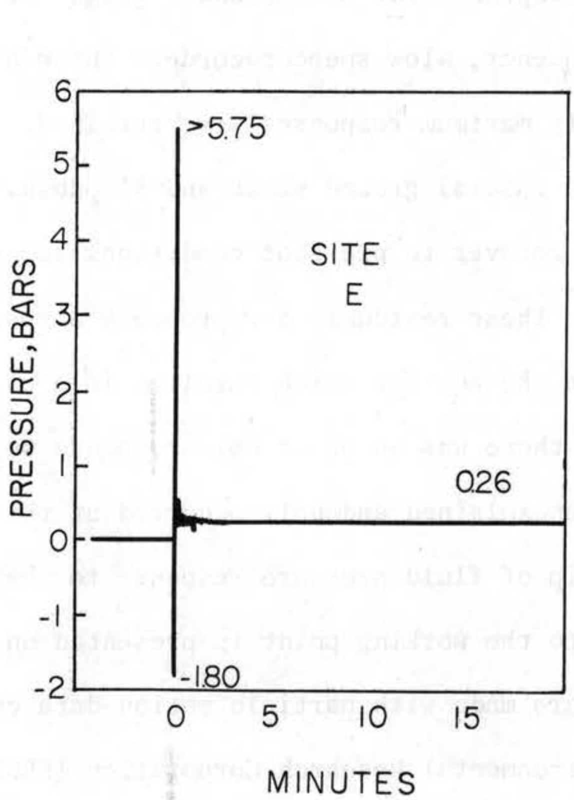

Figure 51. Fluid pore pressure response to the Cannikin event at Site E, Amchitka Island, Alaska.

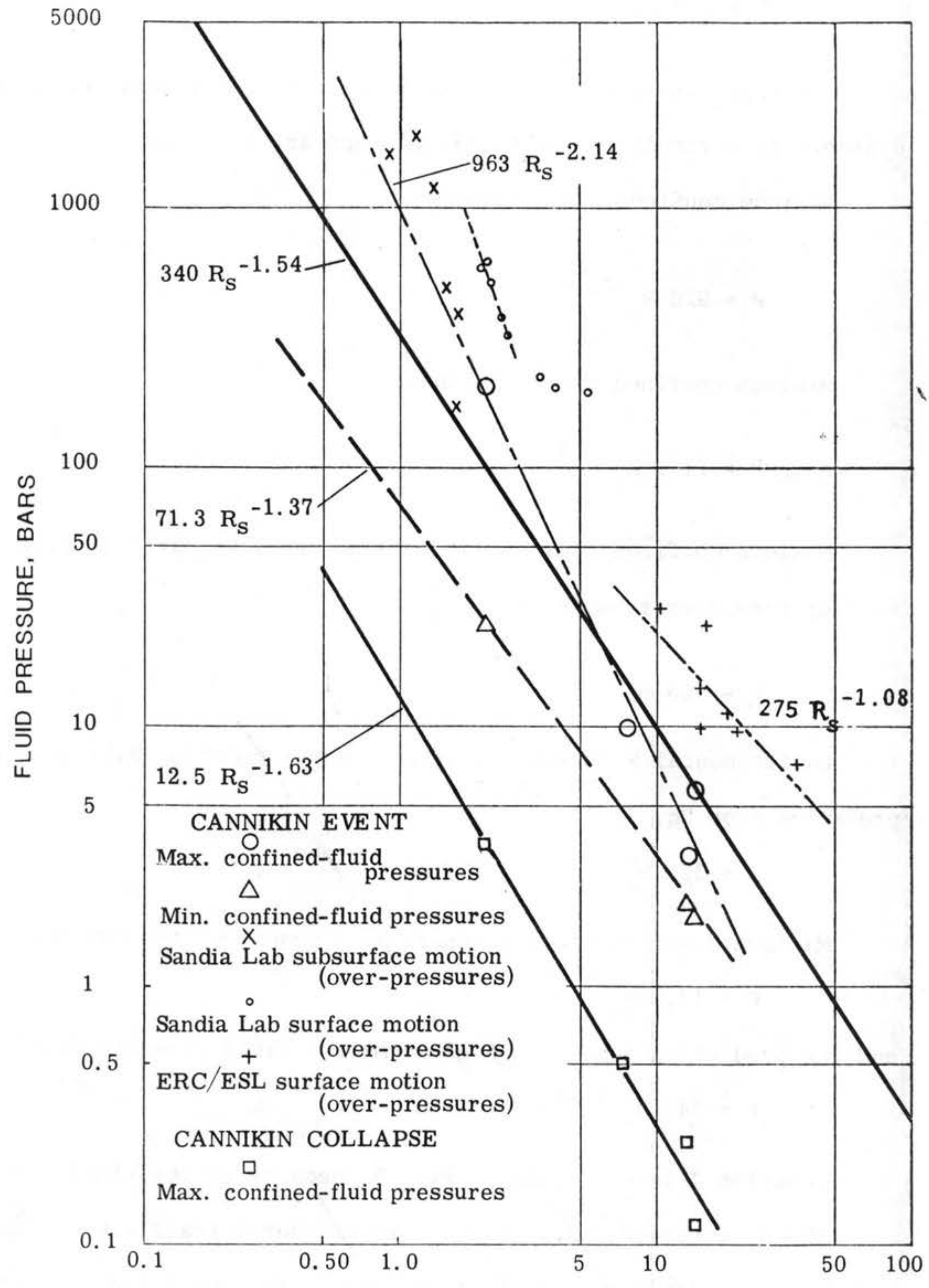

Figure 52. Fluid pressures resulting from the Cannikin event and collapse.

$$P = \rho U_V U_s \quad (3)$$

The regressions based on statistically best-fit data versus slant distance as a result of the Cannikin event are as follows:

Maximum confined fluid pressure:

$$P = 920 R_s^{-2.10} \quad (4)$$

Minimum confined fluid pressure:

$$P = 71.3 R_s^{-1.37} \quad (5)$$

Maximum confined fluid pressures and vertical particle velocities as over pressures from Eq. 3:

$$P = 963 R_s^{-2.14} \quad (6)$$

Environmental Research Corporation surface motion data as over pressures from Eq. 3:

$$P = 275 R_s^{-1.08} \quad (7)$$

Maximum confined fluid pressure as a result of the Cannikin collapse:

$$P = 12.5 R_s^{-1.63} \quad (8)$$

and the prediction equation based on Milrow fluid pressure data:

$$P = 340 R_s^{-1.54} \quad (9)$$

Equation 4 is not shown on Fig. 52 because of its similarity to Eq. 6.

The data suggests that fluid pore pressures react with ground motion and follow traditional wave form patterns. Maximum fluid pressures are a result of peak accelerations associated probably at slapdown and their magnitude is proportional to slant distance from the working point. Any residual pressures that occur are a measure of an alteration of some local aquifer property, probably porosity.

Cannikin Collapse

As in the case of Milrow, there was considerable aftershock activity following the firing of Cannikin (Fig. 53) (Engdahl, 1972). The frequency of small scale events was initially high followed by a low about 10 to 13 hours after Cannikin. The seismic response was a characteristically low frequency signal occurring in the overburden above the cavity. When the cavity could no longer support the overburden, the aftershock activity intensified ending with a large multiple event coinciding with the collapse of the cavity and the formation of the subsidence sink at land surface. The collapse occured 38 hours after the detonation and was reported as an earthquake with a body magnitude of 4.9.

Visible effects--As a result of the collapse, a rubble chimney was formed extending to land surface creating a large collapse sink with newly formed fractures and faults. The deepest part of the triangular-shaped sink was offset about 460 meters east of GZ and controlled by three principal directions of faulting, east-northeast, north and west-northwest (Fig. 40). The maximum subsidence was about 18 meters and the volume of the sink was calculated to be about 4.45×10^6 m^3 (Holmes and Narver, 1972, written communication).

The Cannikin collapse altered the hydrologic regime over a large area surrounding GZ. The effects were similar to those of Milrow, however on a much larger scale. Surficial effects were predominantly associated within the collapsed sink and along the White Alice Creek channel. Those surficial effects along the channel included large disruptions of turf and landslides that occurred near the coast lines.

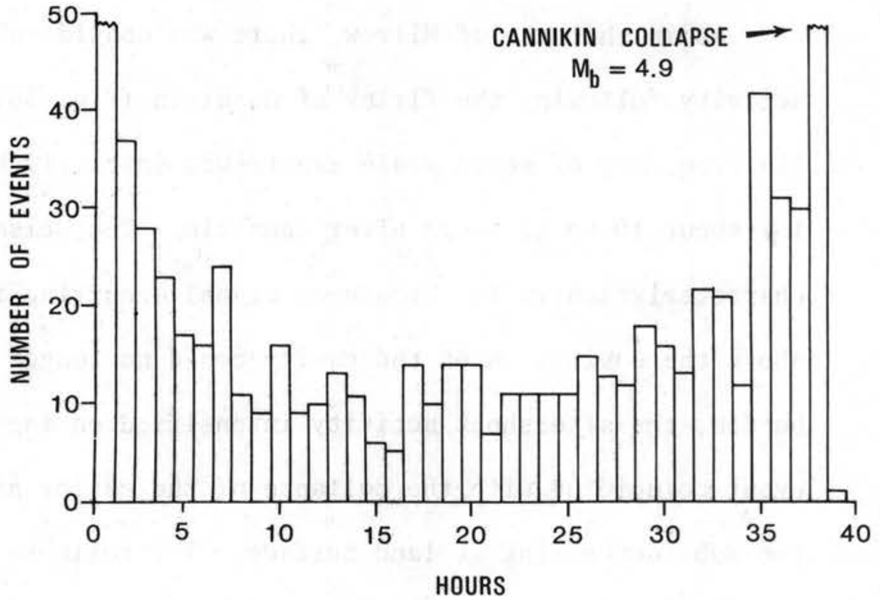

Figure 53. Frequency of aftershocks following the Cannikin event culminating with the Cannikin collapse (Engdahl, 1972).

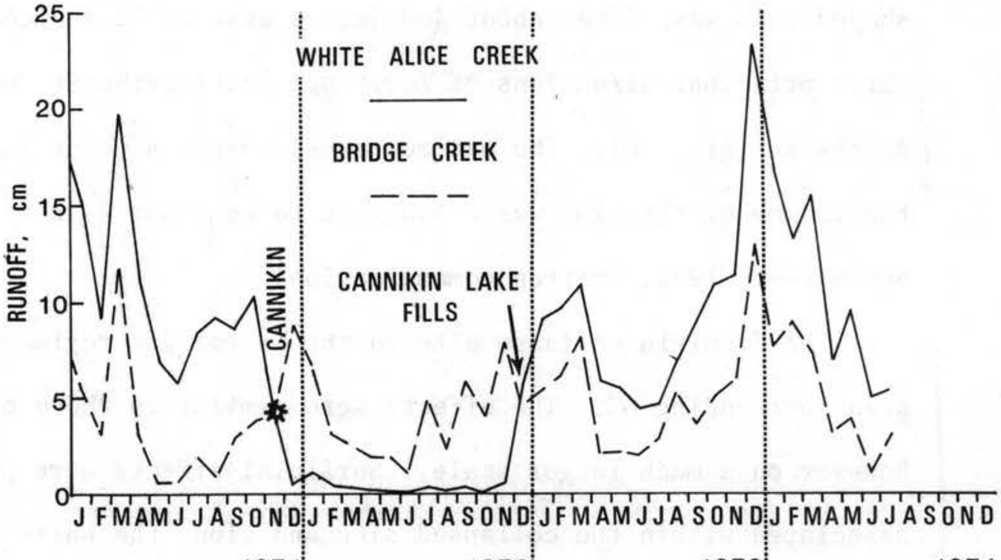

Figure 54. Monthly mean flow for White Alice and Bridge Creeks, Amchitka Island.

Hydraulic effects--The drainage area surrounding GZ was severely altered primarily because of faulting. Eighty-four percent of the drainage area was temporarily transformed into a closed basin (Fig. 40) and nearly all the flow was diverted towards the cavity as a result (Gonzalez and others, 1974). The formation of the rubble chimney which reached to land surface intercepted groundwater flow from major aquifers as a result of increased vertical permeability. Groundwater levels were in a state of drawdown for at least a radius of two kilometers as evidenced by the hydrographs for White Alice borehole (Fig. 20). The flow in White Alice Creek was reduced to almost zero as a result of interception through fractures diverting the flow towards the rubble chimney. Figure 54 is a hydrograph of mean monthly flow for White Alice Creek showing the effect of the collapse on runoff. Double mass analyses showing the effects of the collapse on three major drainage areas, Bridge, Clevenger, and White Alice Creeks, are shown on Fig. 55. The plot shows the change in cumulative flow corresponding to the time of collapse in the White Alice Creek drainage and its ultimate return to normal conditions at least one year afterward. For comparison, the hydrograph for Bridge Creek also is shown. Under normal conditions, the hydrographs for the two streams are very similar.

The dynamic response to the collapse of the cavity was recorded at all boreholes and their regression with slant distance is shown on Fig. 52. At HTH-1 the maximum response was 3.45 bars, probably a result of a shock-produced pressure mound generated by the main collapse. Figure 56 illustrates the fluid pressure response received at four sites with time zero referenced to the time of the collapse.

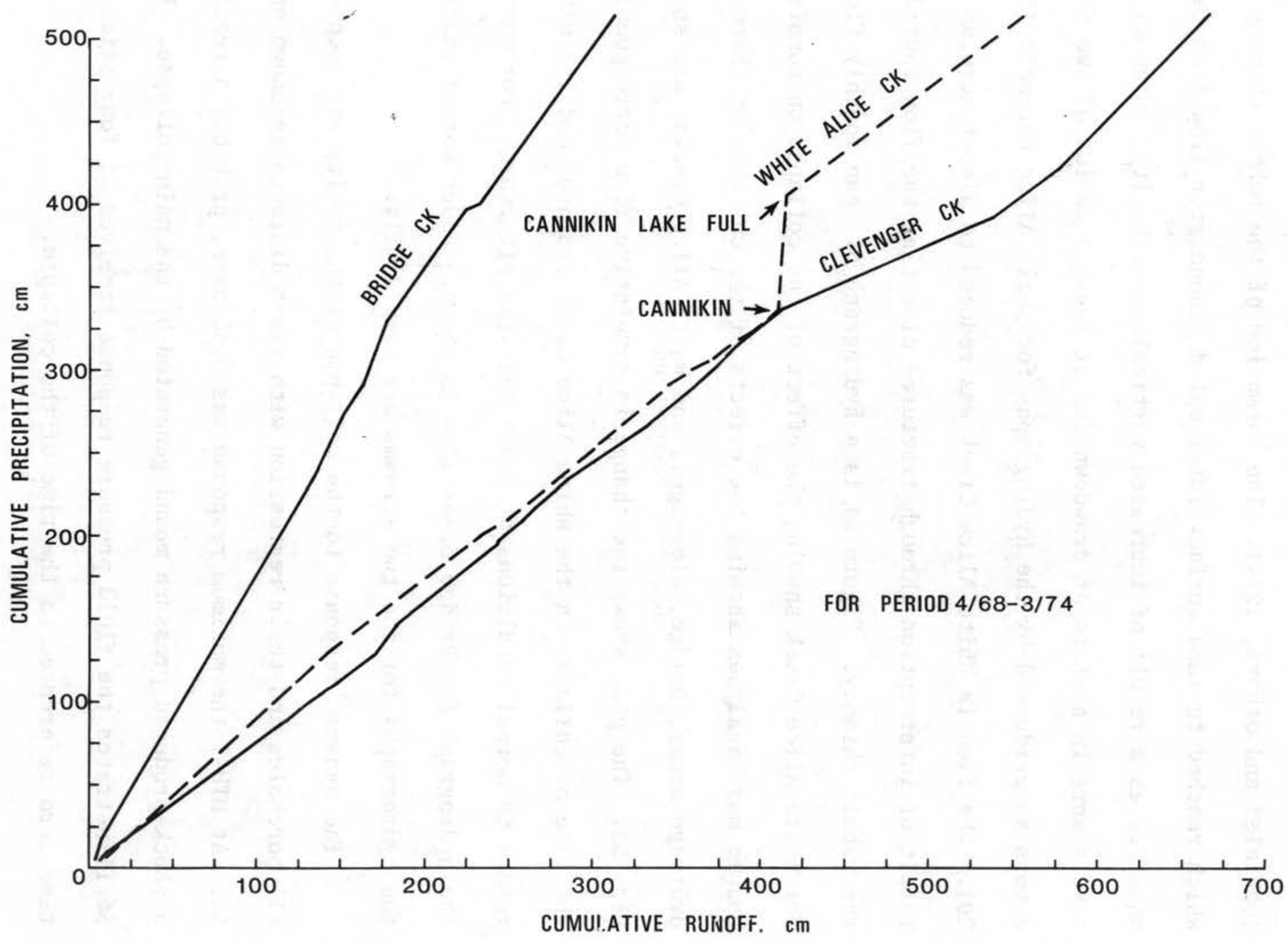

Figure 55. Double mass analysis for White Alice, Bridge and Clevenger Creeks, Amchitka Island.

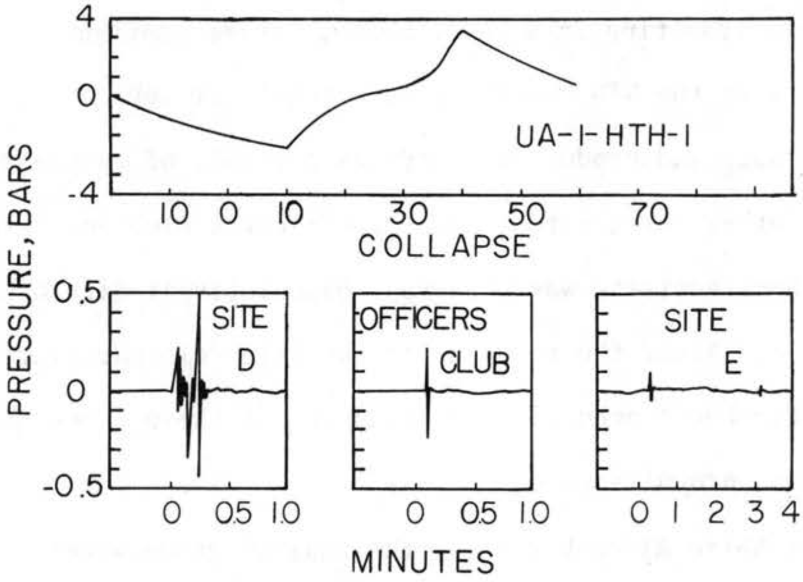

Figure 56. Fluid pore pressure response to the Cannikin collapse at sites UA-1-HTH-1, D, Officers Club, and E, Amchitka Island.

At UA-1 HTH-1 the response was a slow buildup of pressure that began about 10 minutes after collapse lasting for 30 minutes. The pressure then slowly began to decay to some equilibrium near preshot conditions. The response is unusual in that it is not a sharp peak as exhibited at other sites, however, it is similar to a slow migration of pressure resulting in a water mound. These configurations have been observed at the NTS occurring as a result of devices set beneath the water table and producing mounds as a result of compressive stress. At the other three sites, Site D, Officer's Club and Site E, the intense aftershock activity was observed, especially at Site D before the main collapse. After the response to the main collapse (largest spike), a few aftershocks occurred and pressures at these sites quickly returned to normal precollapse conditions.

At White Alice borehole, the shallow groundwater table (1.82 meters below land surface) was saturated to ground surface as a result of Cannikin. At the time of collapse, the water level in the hole dropped nearly 20 meters over a period of five days, then began to slowly recover to preshot conditions 145 days later (Fig. 20). The effect of spall and of course the collapse were instrumental in diverting this groundwater towards the collapse zone and into those newly-created zones of unsaturated porosity.

At Long Shot 9-Blue, after the water level began to recover from the effects of Cannikin, the effect of the collapse was noted by a reversal and subsequent drawdown (Fig. 25). We assumed that the collapse must have affected the Long Shot rubble Chimney in addition to those effects of the event and created additional unsaturated porosity. Shortly after the effect of the collapse, the water level began a period of recovery lasting 45 days.

There were no observable effects recorded at any streamflow sites other than at the White Alice gage as a result of the Cannikin collapse.

Cannikin Long Term Effects

The long term effects for the Cannikin event as well as for previous events were assessed on the basis of long term records of surface water discharge, groundwater level changes, and available records for rainfall.

Hydraulic effects--The most outstanding effects were those associated with the collapse of the Cannikin cavity. After the event, the cavity created by the explosion was filled with gases and superheated steam. Approximately 38 hours after the explosion, pressures and temperatures had dropped sufficiently to allow the weight of overburden to collapse into the cavity, forming a rubble chimney to land surface. The surface expression resulted in a collapse sink that severly altered the White Alice drainage and intercepted most of the surface water flow. The rubble chimney in its collapse induced flow from the surrounding aquifers by increased vertical conductivity. At the time of collapse, surface water and groundwater immediately began to fill the newly-saturated rubble chimney. Cavity infill is retarded, however, until temperatures and pressures in the cavity region are lowered sufficiently to permit condensation of water vapor produced by heated rock. At the time of condensation, calculated to be 60 days after the detonation (Claassen, 1976, communication, USGS), the filling of the cavity occurred and chimney infill resumed. The rubble chimney infill history shows that several rates of filling occurred during this period. After the time of condensation, about January 5, 1972, water levels in the rubble chimney were declining while the cavity was being filled. At the time that the reentry hole was completed and perforated on February 20, 1972, the water levels in the rubble chimney were rising at a fairly constant rate and varied relative to input from White Alice Creek and the various contributing aquifers (Fig. 24). H. C. Claassen (1976, written communication) computed the distribution of explosion-created porosity in the rubble chimney. His analysis was based on rate of chimney infill and estimates of surface water inflow, hydraulic aquifer characteristics and chimney dimensions. The distribution of chimney-created porosity varies from about 10 percent near the bottom to 4 percent near the top.

The near saturation of the rubble chimney was indicated by the formation of Cannikin Lake in the deepest portion of the subsidence area. Water level instruments set in the deepest portion of the sink show that the lake began to fill on August 20, 1972, about 290 days after the detonation. The lake filled in 74 days and flow in White Alice Creek returned to preshot conditions. The natural spillway for Cannikin Lake is formed by an east-northeast trending fault where it intersects the north fork of White Alice Creek (Fig. 40). At the highest known level of 35.4 meters altitude, the lake covers 12.1 ha and stores 401 x 10^3 m^3 of water (Gonzalez, D. D., and others, 1974). The lake is 655 meters long, has an average width of 198 meters and attains depths of 9.45 meters. Cannikin Lake is probably the most outstanding hydrological feature on Amchitka Island.

The filling of the collapse zone with water and eventually spilling into the lower reaches of White Alice Creek mark the approximate time when the hydrological system around GZ was near normal conditions. It may be that the system will never fully recover from the impact of the

Cannikin event, but by May 1974, there were no appreciable deviations from the standard conditions. Groundwater levels within the collapse area as observed in White Alice borehole, HTH-1, and HTH-3, indicate that no aftereffects are present at these sites. In UA-1-PS-1ABC, infill into the chimney was still in progress, with water levels rising slowly at a rate of about 1.22 meters per month. On May 1, 1973, when the hole was abandoned, the water level was about 20 meters below preshock conditions. It appears that preshot conditions in UA-1-PS-1ABC would be reached in about two years from the time of abandonment. The double mass analysis of Fig. 54 shows that White Alice Creek was adversely affected by the explosion and subsequent collapse and that upon filling of Cannikin Lake the mean flow from this drainage returned to near normal conditions. Any deviations from pre-event trends are attributable to changes in basin or some groundwater aquifer characteristic. The apparent deviations in trend for Clevenger and Bridge Creeks in this analysis are a result of the effect of reduced flow at White Alice Creek since the correlation is made against a pattern of runoff from all three creeks. The negligible effects of Cannikin on other drainages are also apparent by examining cumulative runoff versus time (Fig. 27). White Alice, of course, is affected as shown.

Long-term records of surface water and groundwater indicate that some changes in trend have occurred at distant sites. These changes are due to internal variations within aquifer systems as they slowly adjust to structural changes, primarily a result of ground shock and possibly tectonic events that may have been produced or triggered by increased fluid pore pressures.

At Site E, groundwater levels were declining at a very slow rate after the explosion when the water level was affected by a large-scale strain event in compression (Fig. 16). After rising about 22 meters, the water level decayed back to its normal trend, approximately six months later. Site E has had a very poor history of representative water levels because hole conditions have hampered recording true aquifer conditions. At the end of the period of record, the groundwater level was in a state of decline seeking some equilibrium below those levels before Milrow. Milrow had an apparent effect, improving recharge rates within Site E, resulting in a higher static head; however, it does not appear that Cannikin had any adverse affects on the water levels in UAe-7h.

Site D, UAe-6h, exhibits changes that are a result of the nuclear testing program. Figure 57 is a hydrograph of mean monthly water levels for Site D and runoff in the adjacent drainage area, Falls Creek. UAe-6h is responsive to infiltration as noted by the correlation with runoff from Falls Creek. There are only a few periods when runoff highs and lows do not compare well with the trend of the groundwater level. It is apparent that most of the response is from the upper zones in this hole, where on the basis of core analysis, porosity is the greatest at shallow depths at least down to 500 meters.

After Cannikin, water levels dropped about two meters over a period of a year. During the event and collapse, the fluid pressure response was slightly higher at this range and the signals from the collapse event were very clear. An alteration of some aquifer property may have occurred as a result of ground shock and increased fluid pore-pressures around the local area. Fractures may have been

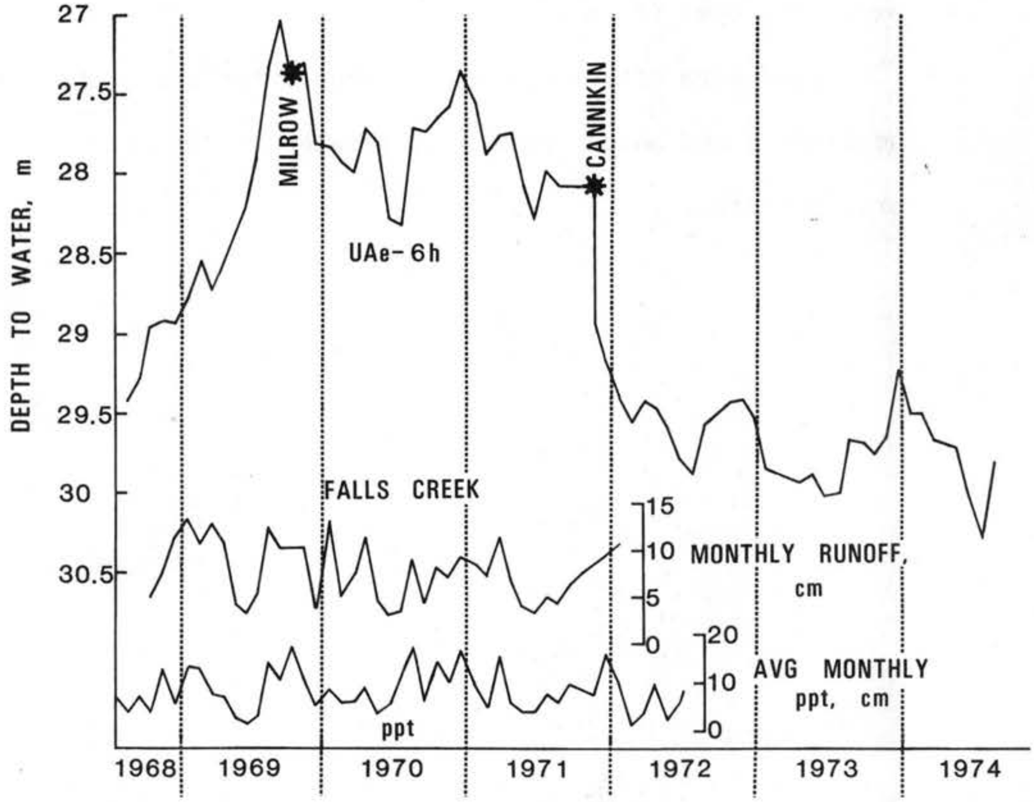

Figure 57. Mean monthly water levels for UAe-6h, runoff for Falls Creek and precipitation at the airport.

restructured providing new areas of discharge or increased porosity. Water levels indicate that new porosity was created in the vicinity of the borehole resulting in a drop of water level. The trend appears to have stabilized establishing a new equilibrium about two meters below pre-event conditions.

Long term effects at other groundwater observation sites were negligible and appear normal as related to runoff and average precipitation.

Chapter 6

SUMMARY AND CONCLUSIONS

Summary

Basic hydraulic data were used to determine the effects of underground nuclear explosions on the hydrologic environment of Amchitka Island. In the early stages of underground testing at Amchitka Island, a minimum of effort was placed on evaluating the effects of explosions on the natural environment. In preparing for Milrow, a hydrologic surveillance program was initiated in 1967 by the U.S. Geological Survey. A network of drainage areas and groundwater observation holes that were hydraulically related to several potential emplacement holes was established.

The results of the Milrow effects program prompted the U.S. Geological Survey to upgrade and expand the existing hydrologic data network in anticipation of the upcoming Cannikin event. The emphasis of the effects program, however, was predominantly seismic, and compared to the majority of the effects programs on the island, the hydrology studies were low-key. Instruments were specifically designed to operate maintenance-free for long periods of time in the high-stress environments, but weather conditions and logistics presented great obstacles to the proper maintenance and servicing schedule for the system in operation and consequently, some invaluable data were lost.

Continuous records of streamflow and fluctuation in groundwater levels were the basis for evaluating the effect of underground explosions on the local hydraulic environment. Dynamic and transient fluid pore-pressures were measured as a response to initial shock, slapdown and the eventual collapse of the cavity to evaluate the impact on the local groundwater system and to establish any correlation with seismic signals generated by the explosion.

Relationships of maximum fluid pore-pressures with distance from the working point were established to show that there is a relationship to particle motion and to illustrate that excess fluid pore-pressure may have a primary role in triggering earthquakes. The changes to the local hydrologic system around collapse areas were documented and proved to be the most visible effect of explosions. Discreet effects were those borne out by long term records of discharge and groundwater where offsets in equilibrium levels were noted by examination of hydrographs, cumulative plots and double-mass relationships.

Conclusions

In conclusion, these observations may be made about the hydrologic data measured during the underground testing program conducted on Amchitka Island:

(1) The dynamic and transient fluid pore-pressures measured at shot time and during the collapse of the Cannikin cavity are consistent with surface particle motion measurements conducted by Sandia Corporation and the Environmental Research Corporation in that the pulse forms exhibit two peaks separated by a low plateau (free fall), the second peak being the larger in magnitude.

(2) An apparent relationship exists between acceleration and surface water reaction as evidenced by aerial photography, shallow water measurements made by Merritt (1973) and surface water records.

(3) A relationship for maximum fluid pore-pressures was established which relates maximum fluid pore-pressure and distance for the Cannikin and Milrow events, and the Cannikin collapse. This

data proved to be consistent with vertical particle velocities measured by Sandia Corporation (Perret, 1972).

(4) Anomalous increases in surface water discharge at shot time were attributed to compressive stress as a result of initial shock. These were also evidenced by photography of lineations of spray and geysers emitting from saturated fractures that squeezed shut. The increase and duration in flow varied at all sites and was primarily a function of basin character. The decrease in discharge that followed the initial surge was an indication of the volume of shallow groundwater storage depleted as a result of compaction. The duration of this deficiency was dependent on available recharge and lasted no more than several days.

(5) Strain measurements by the U.S. Geological Survey which measured small-scale tectonic events in the upper crust on major island faults point to the fact that there may exist a short-term interaction between detonations and the tectonic stress field of the island resulting from high fluid pore-pressures occurring near major faults. The measurement of fluid pore-pressure at HTH-1 (207 bars) indicates that fluid pressures are certainly a possibility to induce fault movement. Unfortunately, there was not a sufficient amount of fluid pressure data to substantiate this hypothesis.

(6) The confined fluid columns in bore holes on Amchitka reacted to aftershock activity, the main collapse and subsequent aftershocks.

(7) The collapse events of both Milrow and Cannikin were the most significant episodes which affected the local hydrology. Drainage basins and the groundwater aquifers were altered, some permanently, as a result of the disruption of rocks from the cavity to land surface. Most

drainage areas resumed their normal flow trends after filling of the rubble chimney was complete. Aquifers underwent permanent changes at several sites, especially those around ground zero.

(8) Surface water and groundwater data can be used to determine when the filling of rubble chimneys was complete by observing cumulative plots in a double mass analysis.

(9) Long-term changes in groundwater that are attributed to testing are a result of a change of aquifer porosity affecting the level of groundwater.

(10) The most significant effect associated with the Cannikin event was the formation of the largest body of water on the island, totally contained within the collapse zone. Cannikin Lake was offset several hundred meters west of ground zero as a result of subsurface stratigraphy. At its highest known level, the lake covers 12.1 hectares and has a volume of 4.01×10^5 cubic meters. The lake is 655 meters long, has an average width of 198 meters and attains depths of 9.45 meters.

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