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MILROW/CANNIKIN SEISMIC EFFECTS

U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
ENVIRONMENTAL RESEARCH LABORATORIES
ROCKVILLE, MARYLAND 20852

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U. S. Department of Commerce
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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ILLUSTRATIONS

ABSTRACT

Seismic effects of the underground nuclear explosions MILROW (October 1969, about 1 megaton) and CANNIKIN (November 1971, under 5 megatons) were monitored by a network of continuously-recording, high-frequency, high-gain seismographs located on Amchitka and nearby islands.

Each explosion was immediately followed by hundreds of small discrete events ($m_B < 4$), of a similar focal mechanism and with a characteristic low-frequency signature, which apparently occurred as a result of the deterioration of the explosion cavity. This activity intensified, then terminated, within minutes of a large complex multiple event and concurrent formation of a surface subsidence crater, signaling complete collapse of the explosion cavity (MILROW, 37 hours; CANNIKIN, 38 hours).

On a smaller scale, apparently unrelated **to** the collapse phenomenon, were a number of explosion-stimulated tectonic events which occurred intermittently for several weeks following each explosion near the explosion cavity and up to 13 km southeast of CANNIKIN ground zero along the Island. These events were confined to the upper crust of the Island, had characteristically high-frequency signatures, and, near the Rifle Range

Fault, had focal mechanisms which correlated with pre-existing faulting. The evidence points to a short-term interaction of the explosions with the local ambient tectonic stresses of the Island through explosion-generated elastic body waves or changes in fluid pore pressure.

Continuous monitoring of the natural seismicity of the region since 1969 reveals no other apparent evidence for an interaction between either MILROW or CANNIKIN and natural tectonic processes. The high level of natural seismicity in the subduction zone 20-60 km beneath the Island and the apparent low level of stress in the upper crust of Amchitka suggest that these zones are effectively seismically decoupled.

INTRODUCTION

Underground nuclear explosions in the megaton range often demonstrate pronounced geologic and geophysical effects, not all of which are clearly understood. It is the purpose of this report to describe as accurately as possible, within the limits of the observational data, seismic effects of the underground nuclear explosions MILROW and CANNIKIN on Amchitka Island.

MILROW, about 1 megaton, was detonated on October 2, 1969, in order to "calibrate" the region, i.e., to establish a baseline from which to predict the effects of larger-yield explosions. A major concern was the effect of these explosions on the natural seismicity, since Amchitka lies in a region of active subduction of the spreading sea floor (Engdahl, 1971) and there existed the remote possibility of triggering an earthquake large enough to generate a tsunami. Another consideration was the possibility of extensive explosion-related seismic activity such as that following several high-yield Nevada explosions (Hamilton et al, 1971).

In view of these questions the National Oceanic and Atmospheric Administration (NOAA) initiated in 1969, at the request of the Atomic Energy Commission (AEC), a seismic study of the region, which included the installation of a network of continuously-recording, high-gain, high-frequency seismographs on Amchitka and nearby islands. With this network it was hoped that by observing extremely low-level seismic activity in the region we could predict the natural patterns normally observed on a larger scale over a longer period of time and could also document any explosion-related effects.

For MILROW this network consisted of seven land-based seismographs supplemented by ten short-term ocean-bottom systems, providing sufficient capability to monitor low-level seismic activity up to 50 km from MILROW ground zero. The test was, in effect, instrumented for seismic effects several times that observed from similar tests in Nevada. The actual effects of MILROW were very small, localized, and difficult to interpret. Nevertheless, the test served to demonstrate that seismic effects of the type observed in Nevada were not as pronounced on Amchitka and to point the way to a successful instrumental program for CANNIKIN.

CANNIKIN, under 5 megatons, was detonated on November 6, 1971. With the benefit of MILROW and more than 2 years of continuous monitoring of the seismic activity of the region, NOAA fielded 14 land-based seismographs, 11 on Amchitka and 3 on nearby islands to record seismic effects from this test. The observed data from CANNIKIN, as will be evidenced in this report, have allowed the seismic effects of MILROW and CANNIKIN to be interpreted in a self-consistent manner. These effects, although lower level, were similar in character to explosion-related activity from Nevada tests and provide important new evidence about this phenomenon. Three main categories of seismic effects will be discussed: (1) Seismic activity related to deterioration of the explosion cavity; (2) Tectonic activity stimulated in the upper crust of the Island; and (3) Effects on the natural seismicity of the region.

CAVITY DETERIORATION

The most dramatic and immediate effect following a high-yield underground nuclear explosion is the high rate of seismic activity concurrent with the deterioration of the explosion cavity which appears to effectively terminate when complete cavity collapse occurs. The data from CANNIKIN provide new evidence about this phenomenon which, in the case of MILROW and some of the larger Nevada tests, has often been confused with explosion-related tectonic activity.

Figure 1 shows a playback of the 48 hour period following CANNIKIN as recorded by an Amchitka seismograph, about 16 km from ground zero at a gain 36 db down from nominal for clarity. Time reads left to right with ½ hour between lines and time marks at 10 second intervals except on the minute. Seismic activity, almost wholly related to deterioration of the explosion cavity or collapse phenomenon, is visible to less than magnitude 2.0. The complete collapse of the CANNIKIN cavity occurred as a large complex multiple event about 38 hours after detonation, concurrent with the formation of a surface subsidence crater. Seismic activity effectively terminated at this time except for some minor events,

ASB 3 RECORD CANNIKIN - COLLAPSE

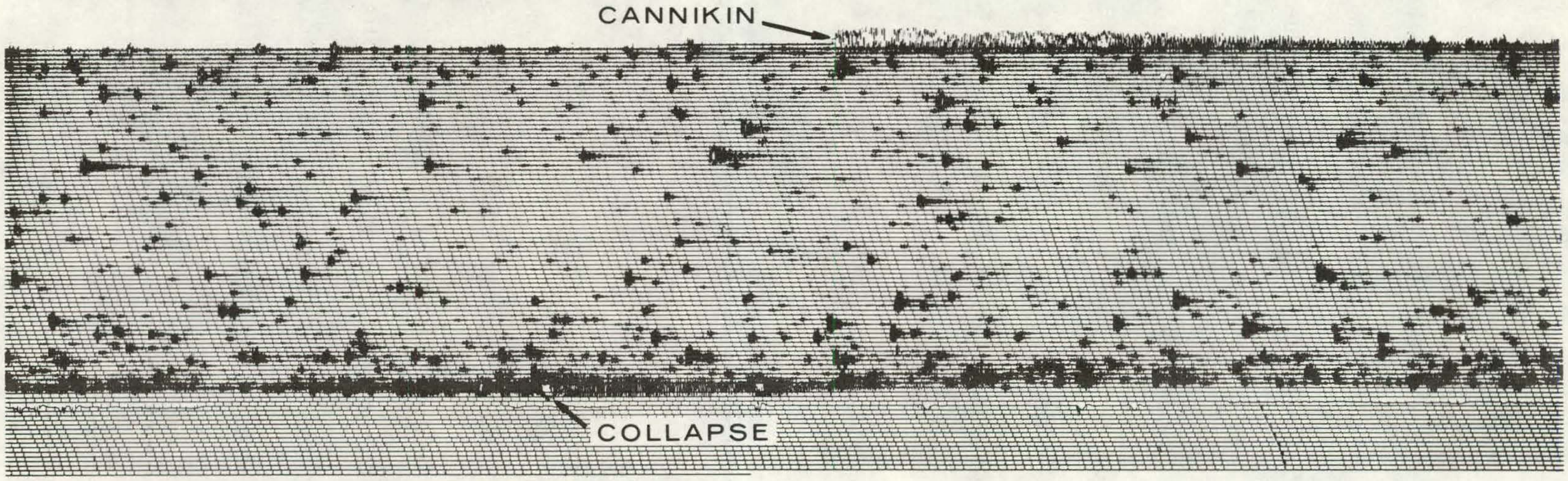

Figure 1

less than magnitude 1.0, which continued for several weeks thereafter in the immediate vicinity of ground zero.

In the case of MILROW similar phenonomena related to cavity deterioration were observed with the collapse occurring about 37 hours after detonation. This represents a departure from an earlier interpretation of the less-reliable MILROW data (Engdahl, 1971) which held that this activity was primarily tectonic. The actual explosion-related tectonic events from MILROW were so small and so few in number that they were not clearly distinguishable from the natural seismicity until it had been established over a longer period of time.

Seismic activity from CANNIKIN related to the cavity deterioration could be easily identified by its characteristic low-frequency signature and by the observed time differences within the network. Because of this low-frequency character these events have been described as emergent, when in actuality they often have clearly discrete first motions. In Figure 2 is shown a typical "collapse" event occurring about 18½ hours after detonation of CANNIKIN as recorded on develocorder film. First and second levels of the five stations recorded on this

ISLAND STATIONS

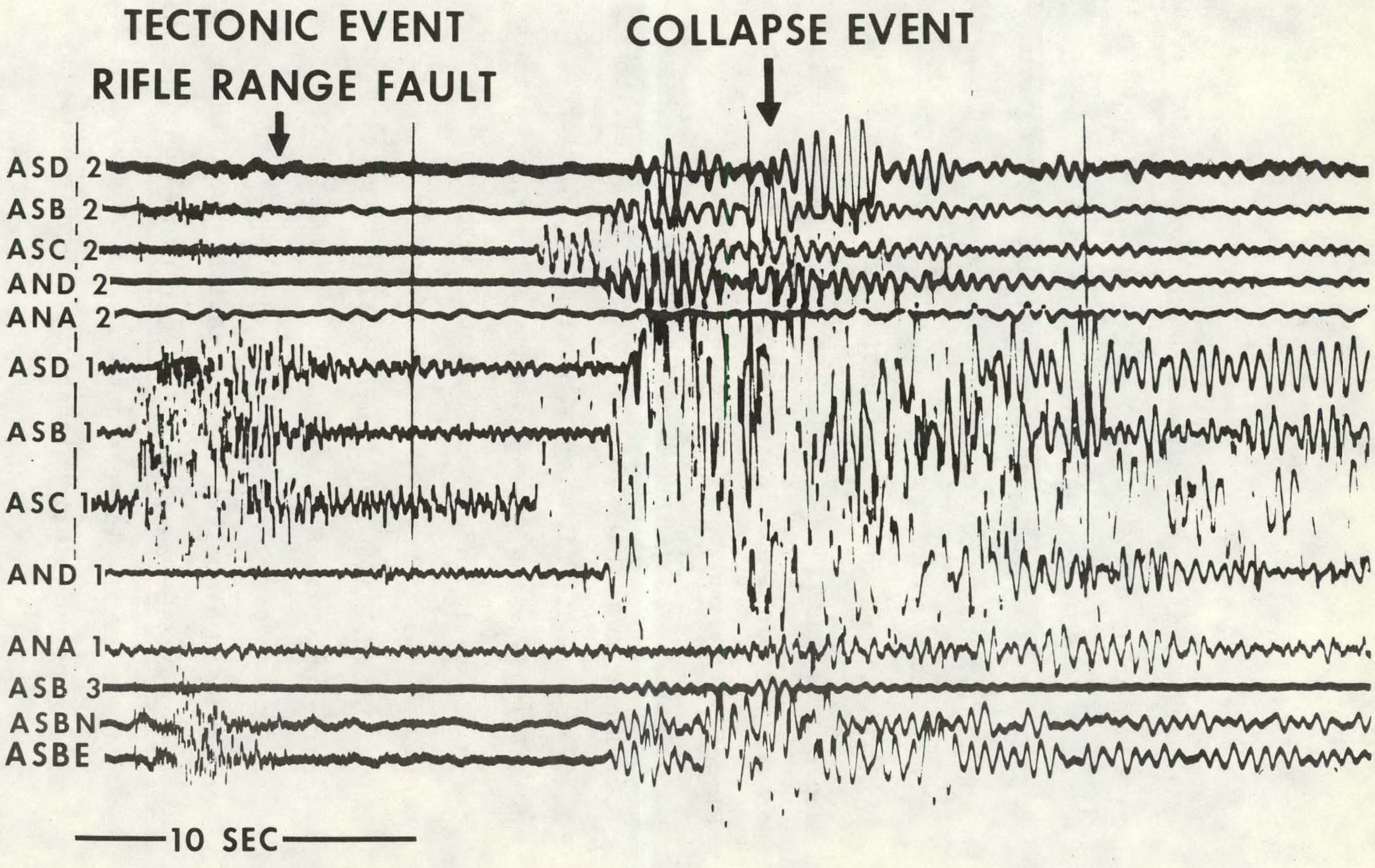

Figure 2

unit have an 18 db separation. A characteristic frequency of 2 Hz easily distinguishes the collapse event from the higher-frequency tectonic event.

Hundreds of collapse events followed MILROW and CANNIKIN, many large enough to be recorded on the nearby islands and some as far away as Adak, about 295 km from CANNIKIN ground zero. For statistical purposes, only those near magnitude 1.5 or greater for MILROW and 2.0 or greater for CANNIKIN were completely scaled. In Figure 3 is shown the incremental frequency of occurrence of collapse events from MILROW and CANNIKIN. Except for higher magnitudes, the CANNIKIN data appear to fit a log normal distribution with slope -1.0. MILROW data are less clear. Figures 4 and 5 summarize the temporal statistics, assuming total detection at magnitude 1.5 or greater for MILROW and 2.0 or greater for CANNIKIN. Although MILROW collapse activity was significantly lower level than for CANNIKIN, the temporal descriptions are quite similar. A high rate of activity occurred immediately after detonation, followed by more regular behavior until about 1 hour before the collapse, when the activity increased to the point that individual events were not distinquishable. All this activity

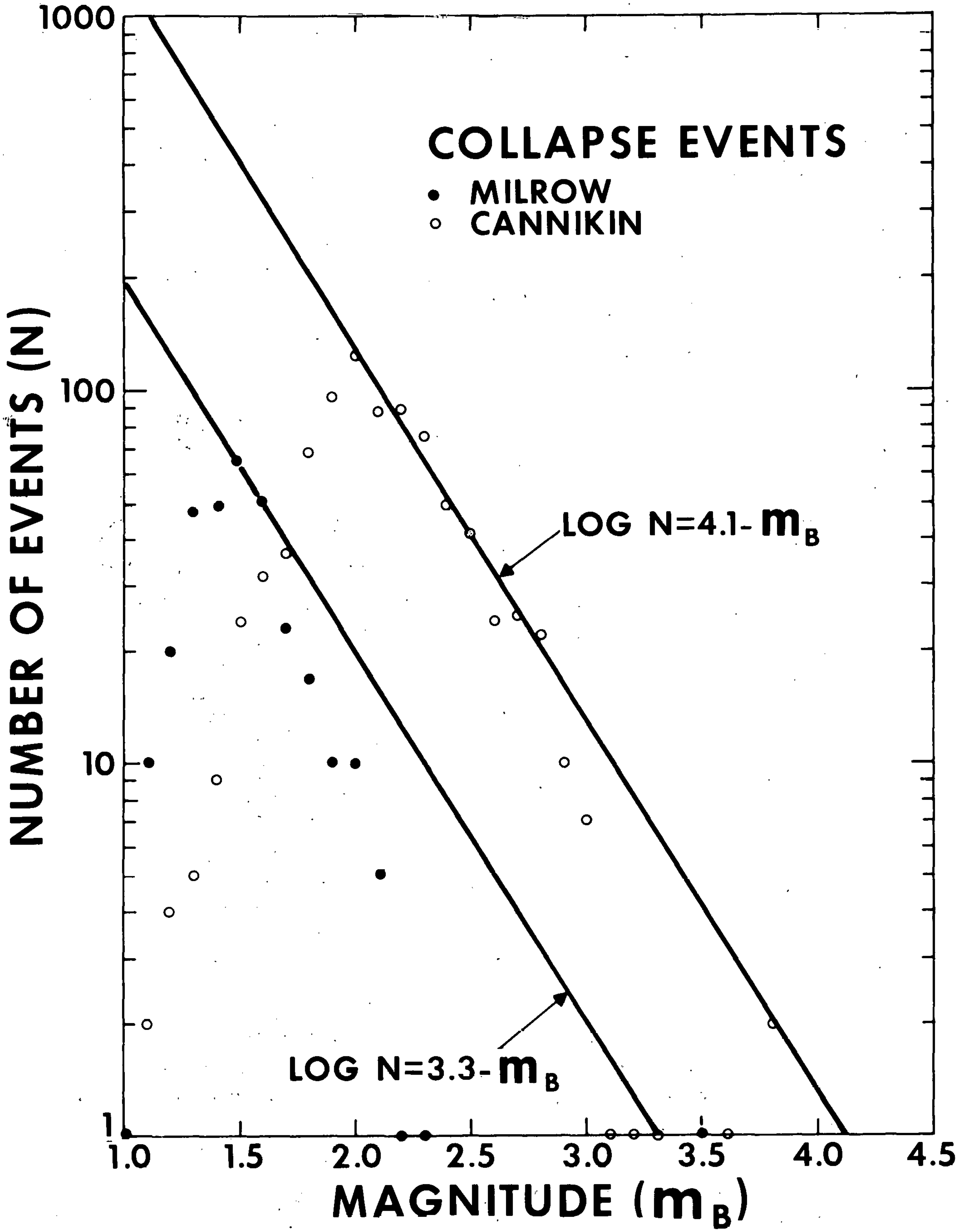
COLLAPSE EVENTS
MILROW
CANNIKIN
LOG N=4.1- m_B
LOG N=3.3- m_B
NUMBER OF EVENTS (N)
1000
100
10
1
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
MAGNITUDE (m_B)

Figure 3

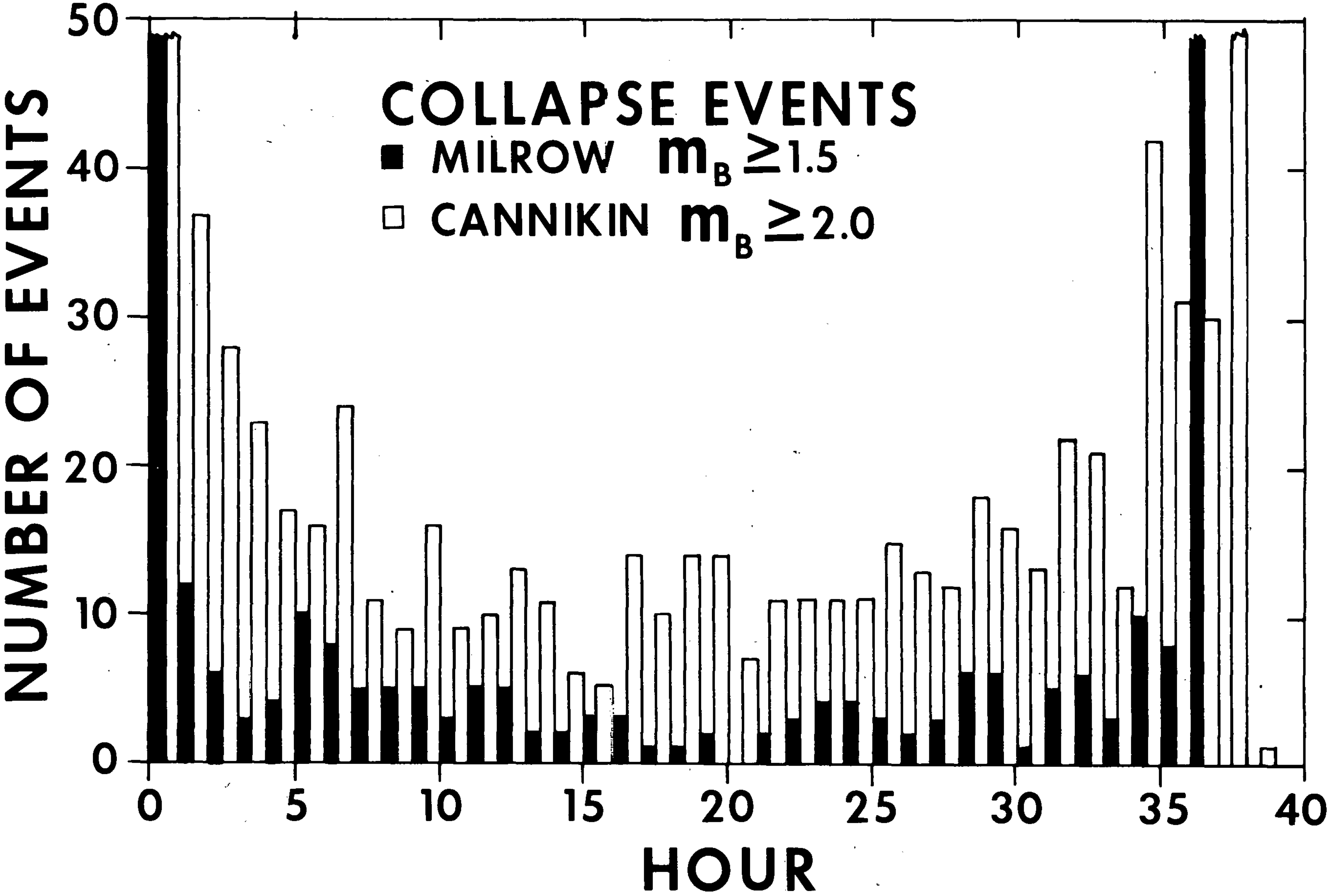
COLLAPSE EVENTS
MILROW $m_B \geq 1.5$
CANNIKIN $m_B \geq 2.0$
NUMBER OF EVENTS
HOUR
0
10
20
30
40
50
0
5
10
15
20
25
30
35
40

Figure 4

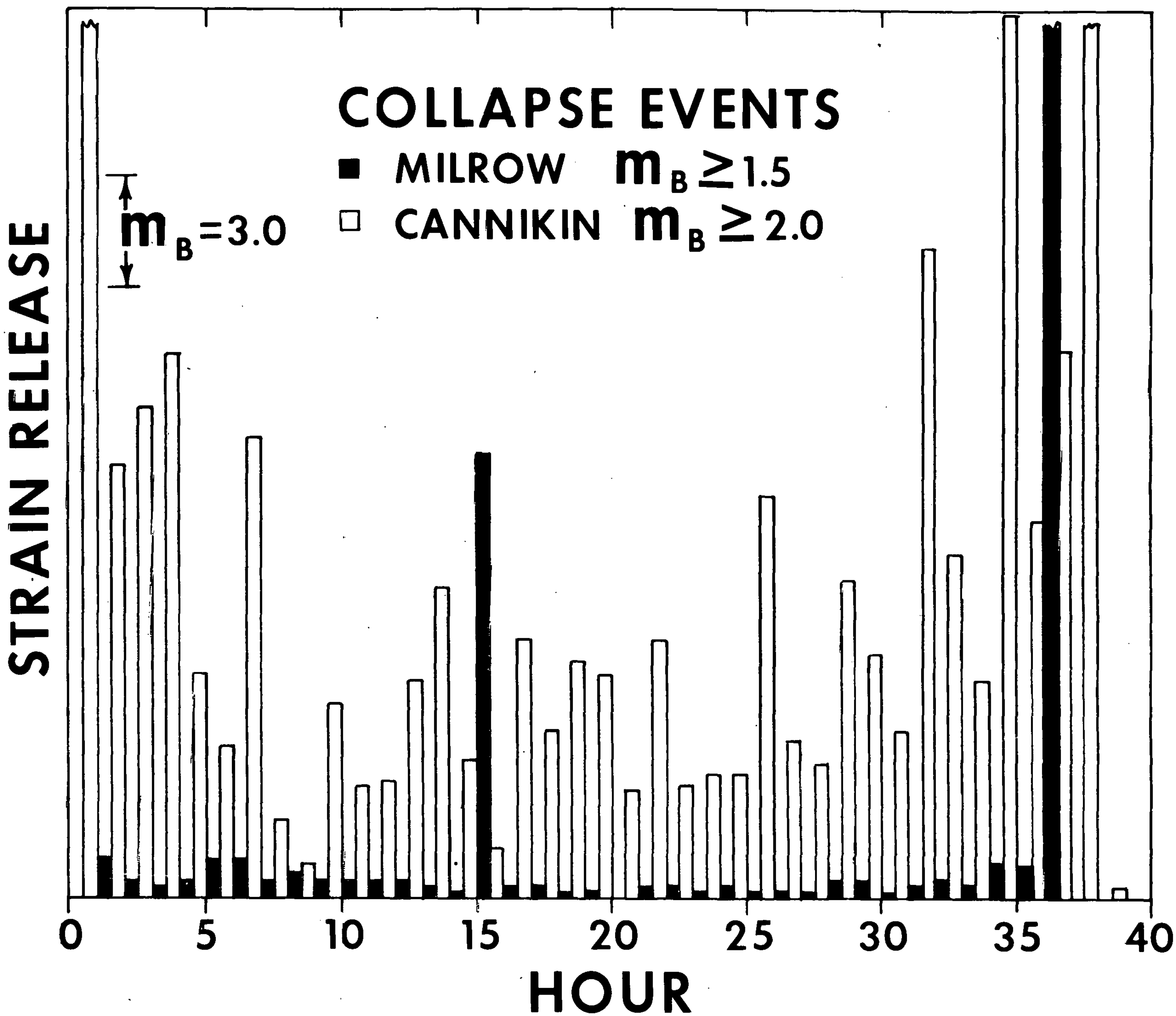
COLLAPSE EVENTS
MILROW $m_B \geq 1.5$
CANNIKIN $m_B \geq 2.0$
$m_B = 3.0$
STRAIN RELEASE
0
5
10
15
20
25
30
35
40
HOUR

Figure 5

effectively terminated within minutes of the cavity collapse. All these characteristics are also readily evident in Figure 1.

The radiation pattern from CANNIKIN collapses, which includes both upgoing and downgoing rays, suggests a mechanism other than simple impact of material at the bottom of the cavity. In Figure 6 representative first motions from the NOAA stations and from 6 Sandia geophones are plotted on the lower hemisphere of an equal-area stereographic projection. Focal angles were computed for a depth of 1.43 km (300 m above the CANNIKIN working point) using a detailed crustal model. Very few dilatations were observed on this network from these events. Assumption of a double-couple source mechanism defines the two planes shown, which are limiting cases. Further study will be necessary to determine a more realistic mechanism for these phenomenon.

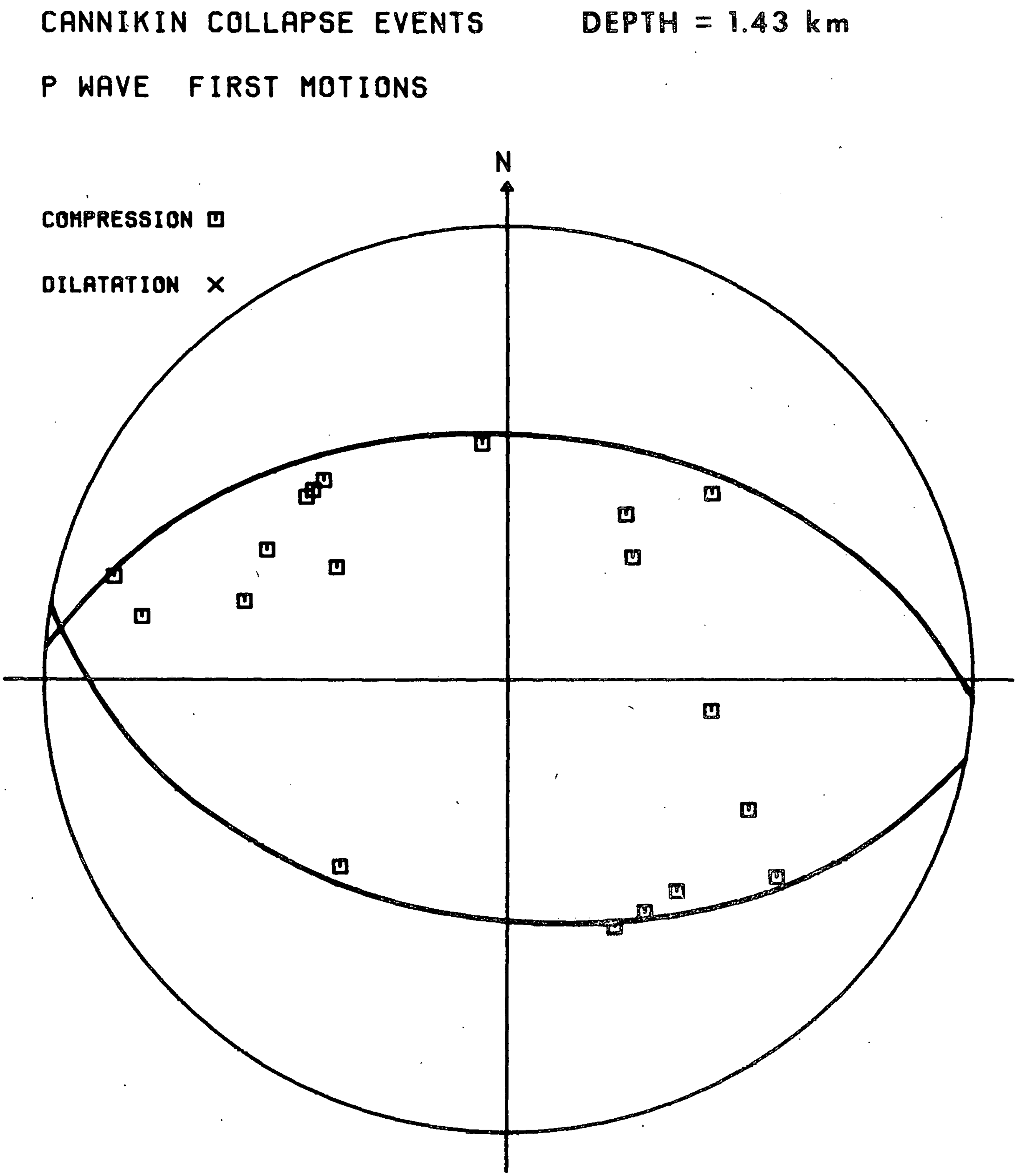
CANNIKIN COLLAPSE EVENTS
DEPTH = 1.43 km
P WAVE FIRST MOTIONS
N
COMPRESSION
DILATATION

Figure 6

EXPLOSION-STIMULATED TECTONIC ACTIVITY

One of the most carefully studied seismic effects of high-yield underground nuclear explosions is earthquake activity stimulated in the upper crust of the test area. This activity generally occurs sporadically for several weeks following the explosion and appears to be largely controlled by regional geologic and tectonic factors. Amchitka was similar to Nevada in these aspects with the exception that Amchitka experienced generally lower-level and more localized seismic activity. Some reasonable arguments for this difference will be discussed later in this report.

Because it is short-term and localized in zones of little or no previous seismicity, explosion-stimulated tectonic activity is usually separable from natural seismicity and other effects. A total of 12 of these tectonic events were detected following MILROW, 10 within 41 days of detonation. For CANNIKIN 22 tectonic events were identified, all but one occurring within 23 days of detonation. Since some of these events were relatively large and it is unlikely that any would go undetected by the seismic network down to at least magnitude 2.0, it appears that normal recurrence rates do not apply to explosion-generated tectonic activity on Amchitka. In Figure 7 are plotted all the tectonic events which could be reliably located using a detailed crustal model of the Island. Three types of events can be identified: post-collapse events near the explosion cavity which had high-frequency signatures; events near the Rifle Range Fault; and events which could not be correlated with any known faults.

Six explosion-stimulated tectonic events occurred very close to the explosion cavity but below it at depths of 3 to 8 km. The first did not occur until more than 7 days after detonation and was the largest observed (magnitude 3.5). The last occurred nearly 3 months after CANNIKIN. In Figure 8 is shown a preliminary composite focal mechanism for these events on the lower hemisphere of the focal sphere. The mechanism is not clearly related to Island tectonics, but may reflect localized geologic changes produced by the explosion. A more precise definition of this near-cavity explosion-related tectonic activity will be the subject of further study.

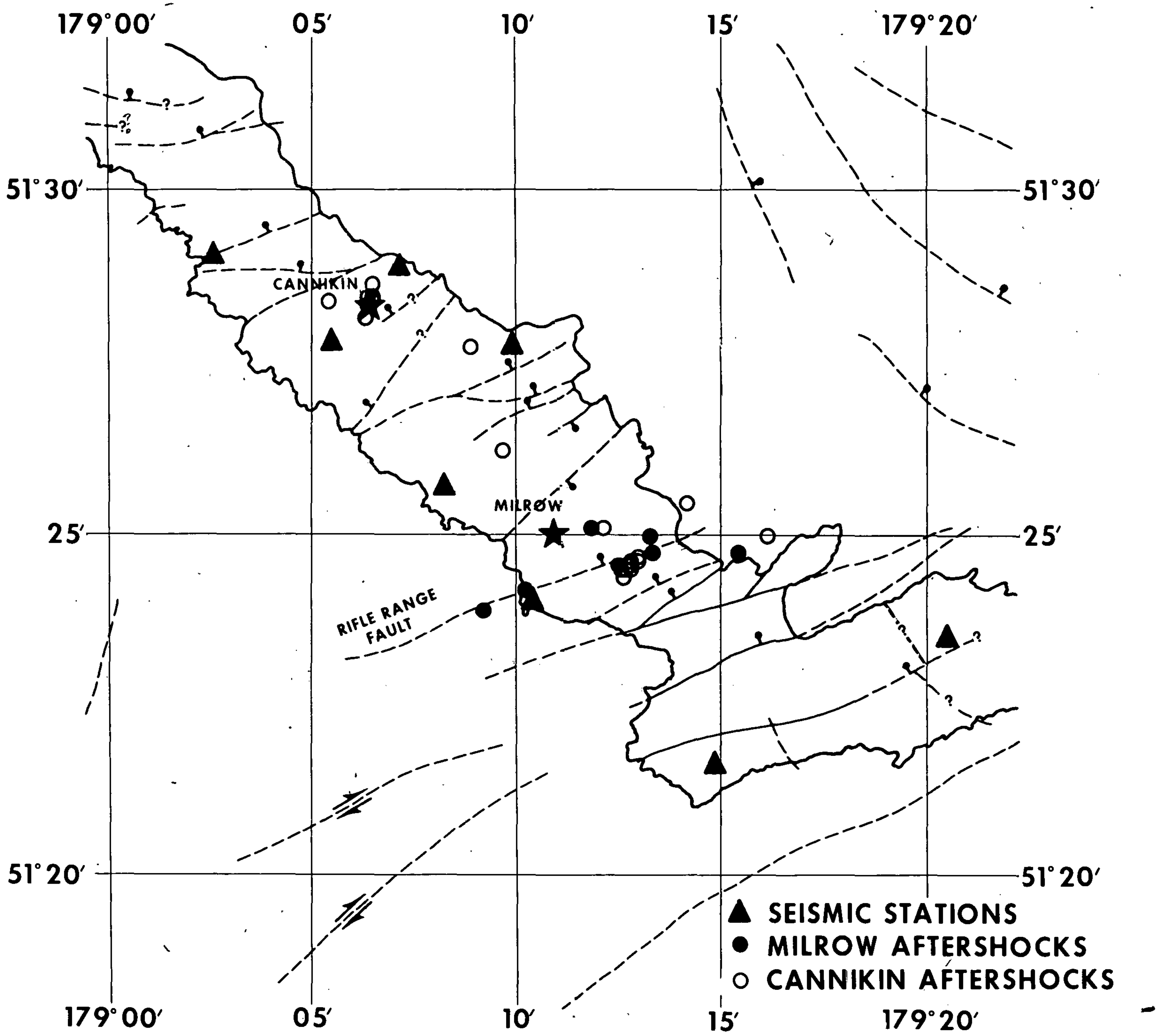
179°00′
05′
10′
15′
179°20′
51°30′
25′
51°20′
CANNIKIN
MILROW
RIFLE RANGE FAULT
SEISMIC STATIONS
MILROW AFTERSHOCKS
CANNIKIN AFTERSHOCKS

Figure 7

CANNIKIN TECTONIC EVENTS - CAVITY REGION

P WAVE FIRST MOTIONS

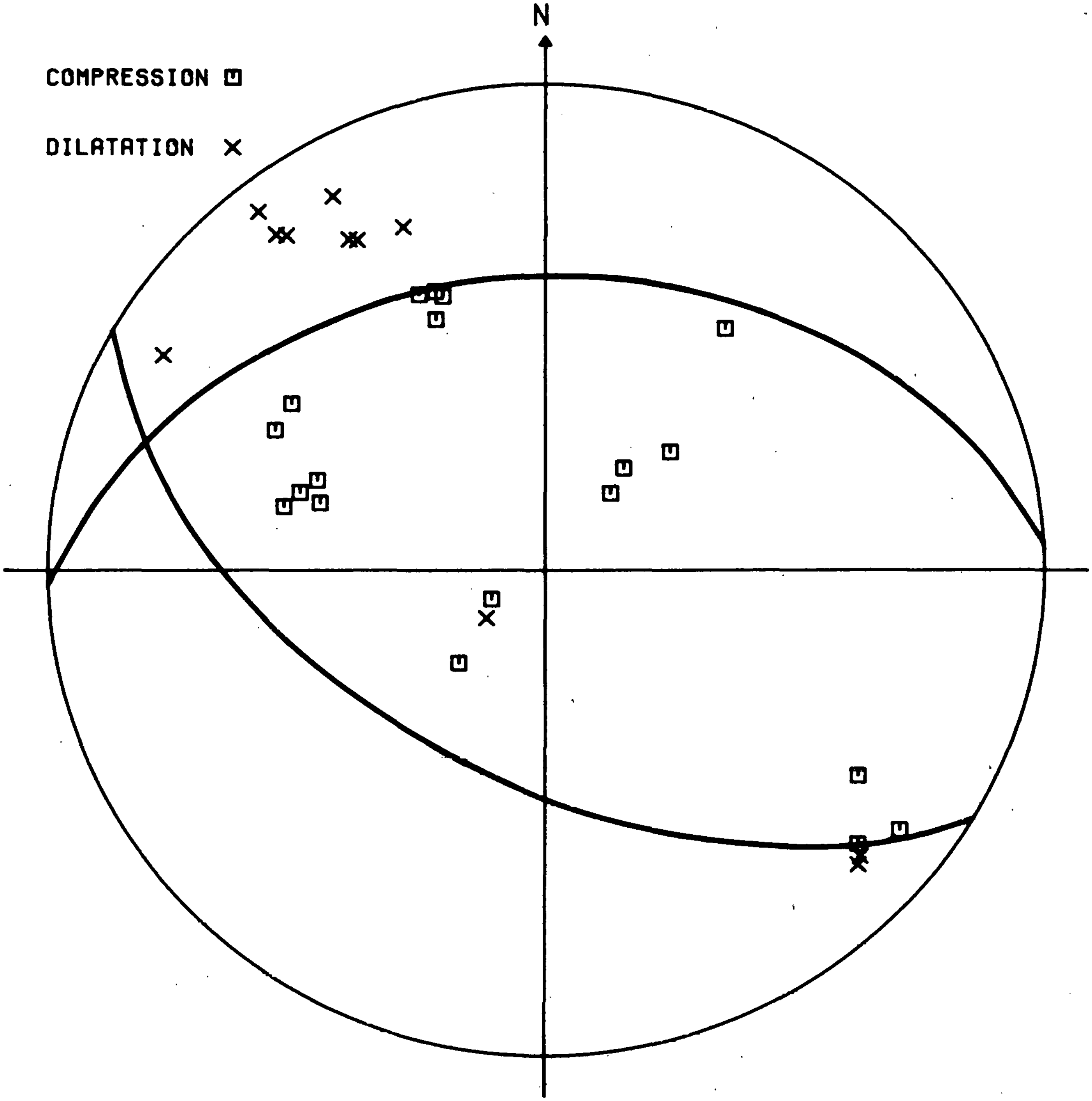

Figure 8

Tectonic activity occurring near the surface trace of the Rifle Range Fault followed both MILROW and CANNIKIN and seems clearly related to motion along the fault. The first of these events occurred about 6 hours after CANNIKIN. The largest was less than magnitude 3. Focal depths are estimated at between 1 and 2 km. Figure 9 shows a composite focal mechanism for these events. Right-lateral motion along a northeast striking fault plane is in the same sense as apparent historical displacements along the Rifle Range Fault. In 1970 and 1971, before CANNIKIN, only two events were detected along this fault. These events occurred in September and November, 1970, along the southwestern extension of the fault and are shown in Figure 7 as residual effects of MILROW. The observed first motions are consistent with the focal mechanism shown.

Finally, several events followed MILROW and CANNIKIN which were well located but not clearly related to known faults, possibly representing new fault creation. It is not clear at this time how these scattered events can be interpreted in context with other effects.

CANNIKIN TECTONIC EVENTS - RIFLE RANGE FAULT

P WAVE FIRST MOTIONS

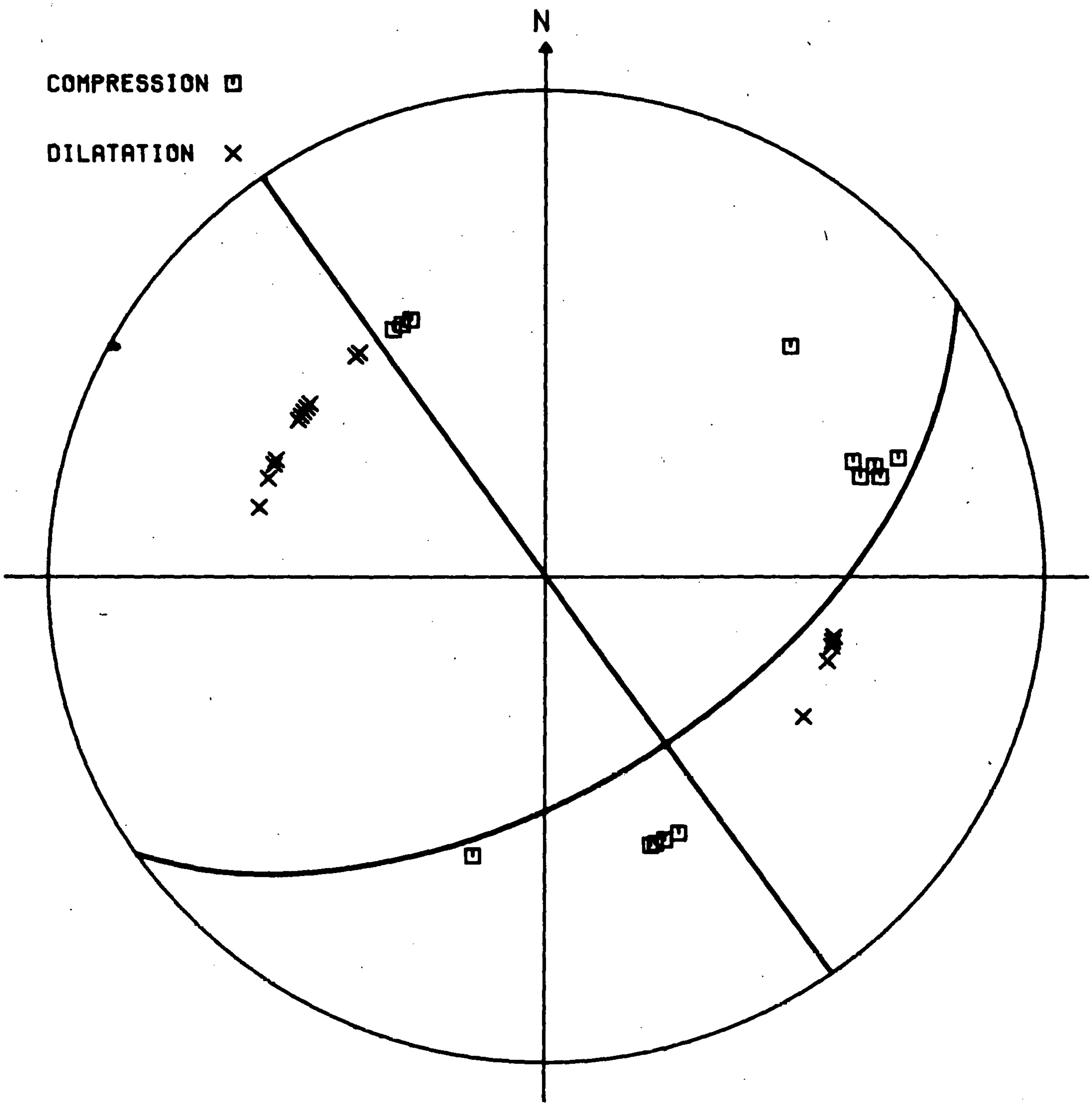

Figure 9

NATURAL SEISMICITY

A large part of the NOAA program is devoted to monitoring extremely low-level seismic activity in the Amchitka Island region in order to accurately describe the natural patterns observable on a larger scale over a longer period of time, and to document any effects from either MILROW or CANNIKIN. A basic principle in this study is to establish a uniform detection capability by the network at some minimum level over some well-described volume, so as to determine as accurately as possible the seismicity within that volume.

In Figures 10 and 11 are plotted in plan view and section the preliminary locations of earthquakes of magnitude 3.0 or greater near Amchitka Island occurring during the three-year period 1969-1971 (events before February 1970 or outside the bounds 178°E and 179.5°W are PDE determinations only). The interesting details of this seismicity will be the subject of a more extensive paper now in preparation. For purposes of this report, however, we note the considerable number of low-level earthquakes occurring primarily along a zone 20 to 60 km beneath Amchitka Island. In fact, a circle of about 55 km in radius from MILROW ground zero, as

AMCHITKA SEISMICITY 1969-1971

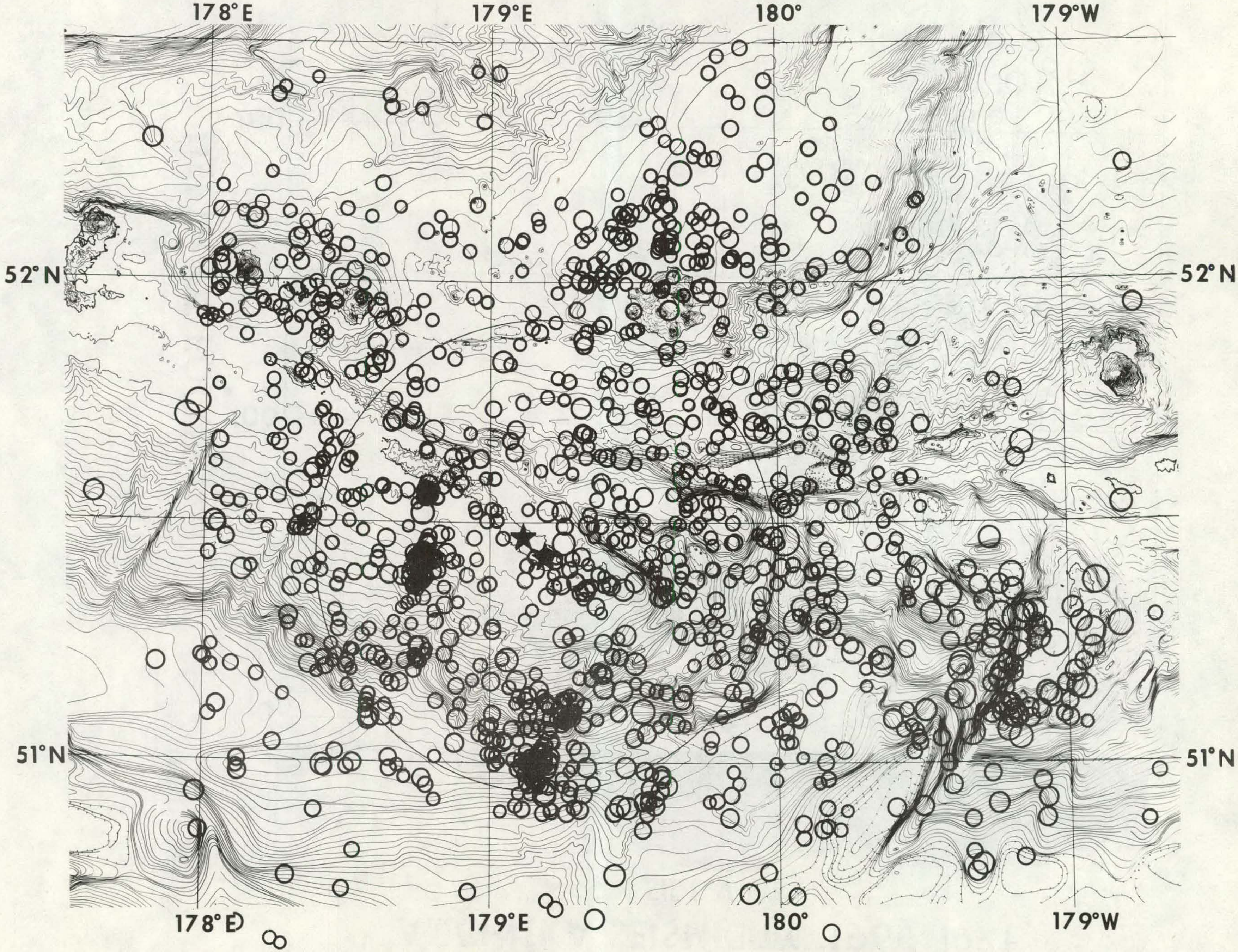

Figure 10

AMCHITKA SEISMICITY 1969-1971

SIDE VIEW

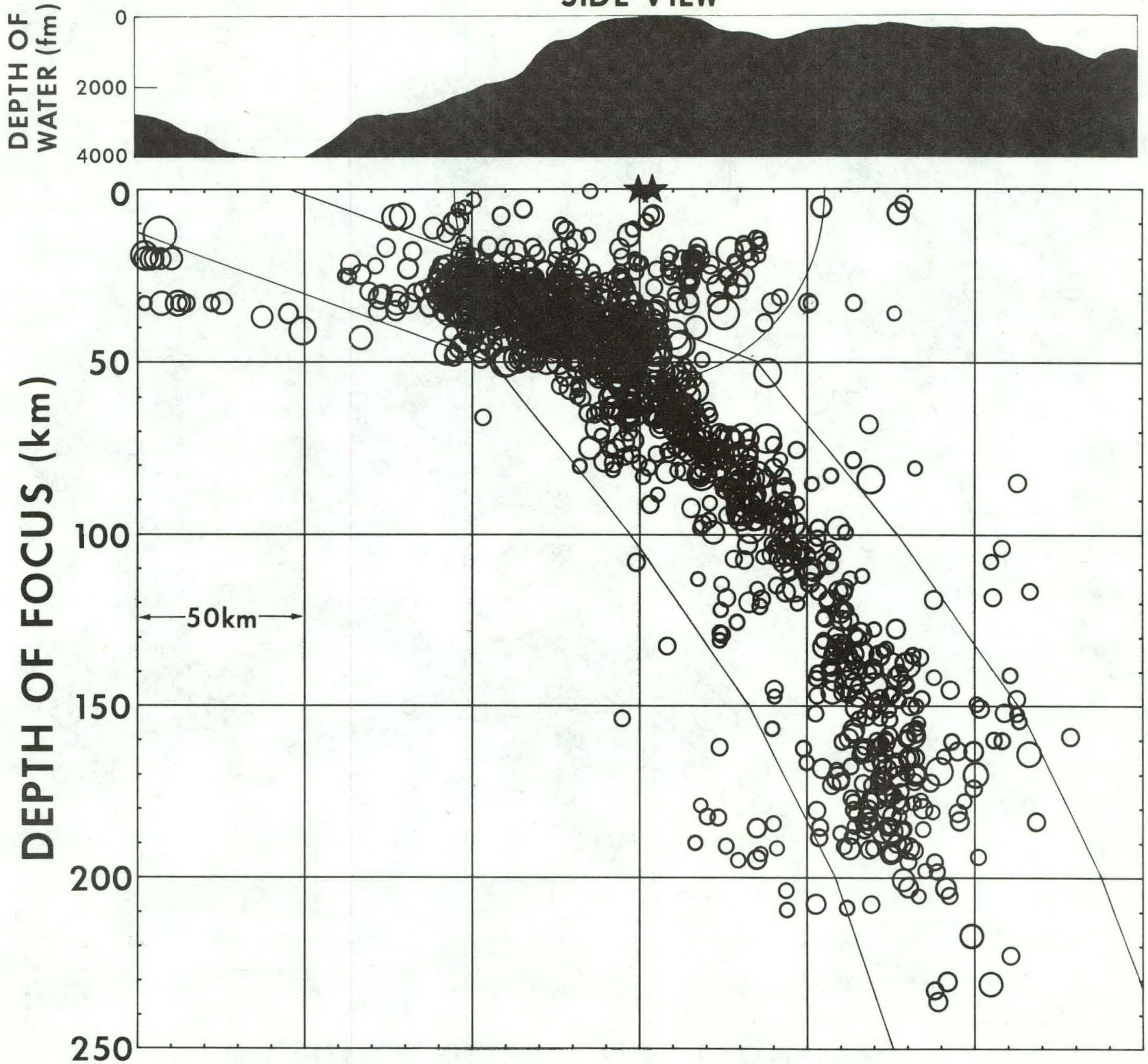

Figure 11

shown, conveniently encircles most of this activity and also describes a volume within which the seismicity can be uniformly monitored. In Figure 12 is plotted the incremental frequency of all events detected within this volume for a 23-month period. The maximum likelihood estimate of the slope of these data is-1.0 for a total detection capability of magnitude 3.0 or above. From the plot it appears that the data fit a log normal distribution as indicated, at least to magnitude 3.0.

On the basis of this network detection capability, we have plotted in Figure 13 the cumulative daily strain release and cumulative daily number of events of magnitude 3.0 or above as representative of the seismicity within the volume monitored. It is clearly evident that CANNIKIN had no apparent effect on the natural seismicity beneath the Island, at least to this level of detection. Careful review of smaller events before and after CANNIKIN, some of which may have gone undetected, and the natural seismicity before and after MILROW gave no indication that the occurrence rate and spatial distribution were different from normal patterns.

In an alternative view, the data in Figures 10 and 11 have been plotted as a function of time of occurrence

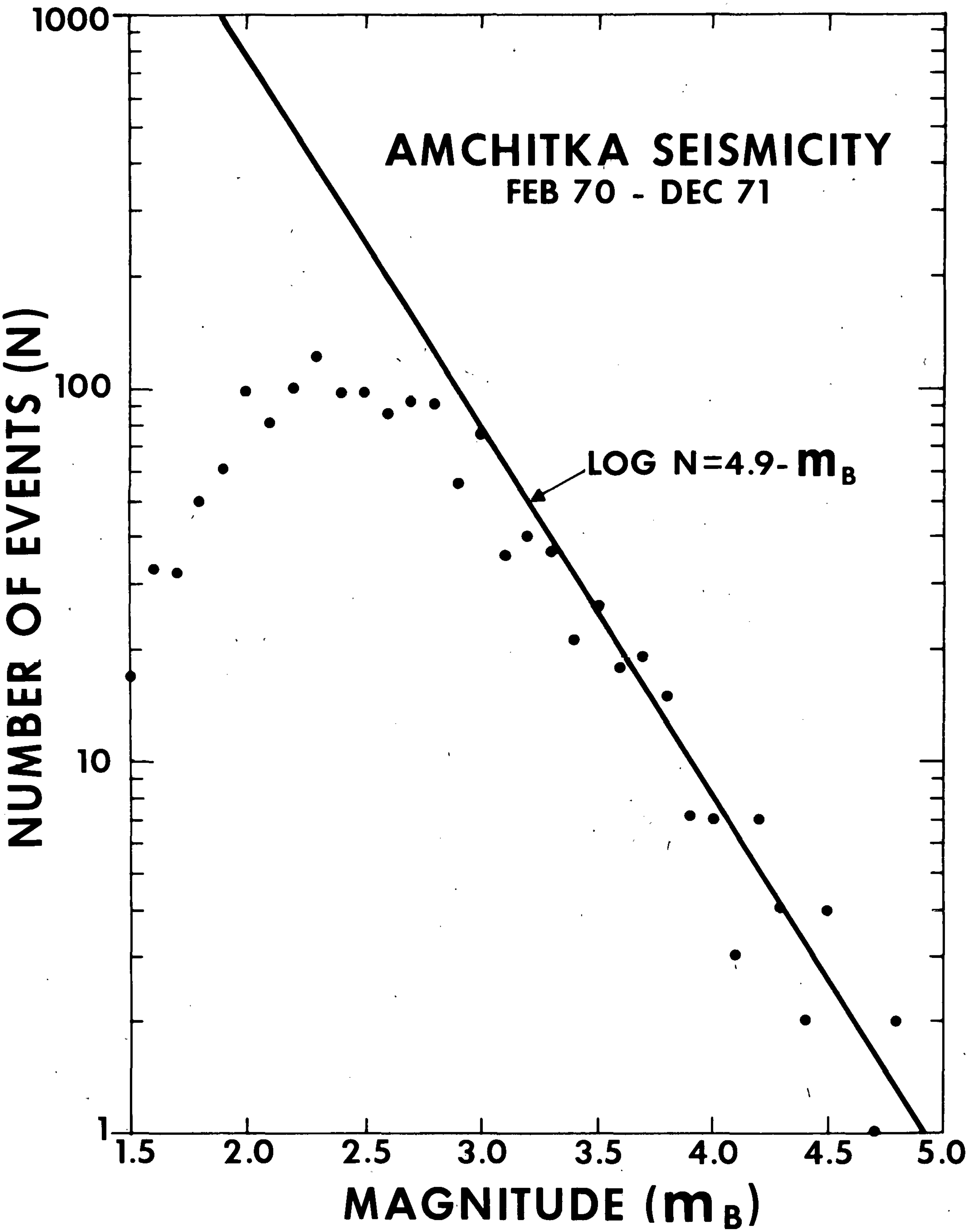
AMCHITKA SEISMICITY
FEB 70 - DEC 71
LOG N=4.9- mB
NUMBER OF EVENTS (N)
1000
100
10
1
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
MAGNITUDE (mB)

Figure 12

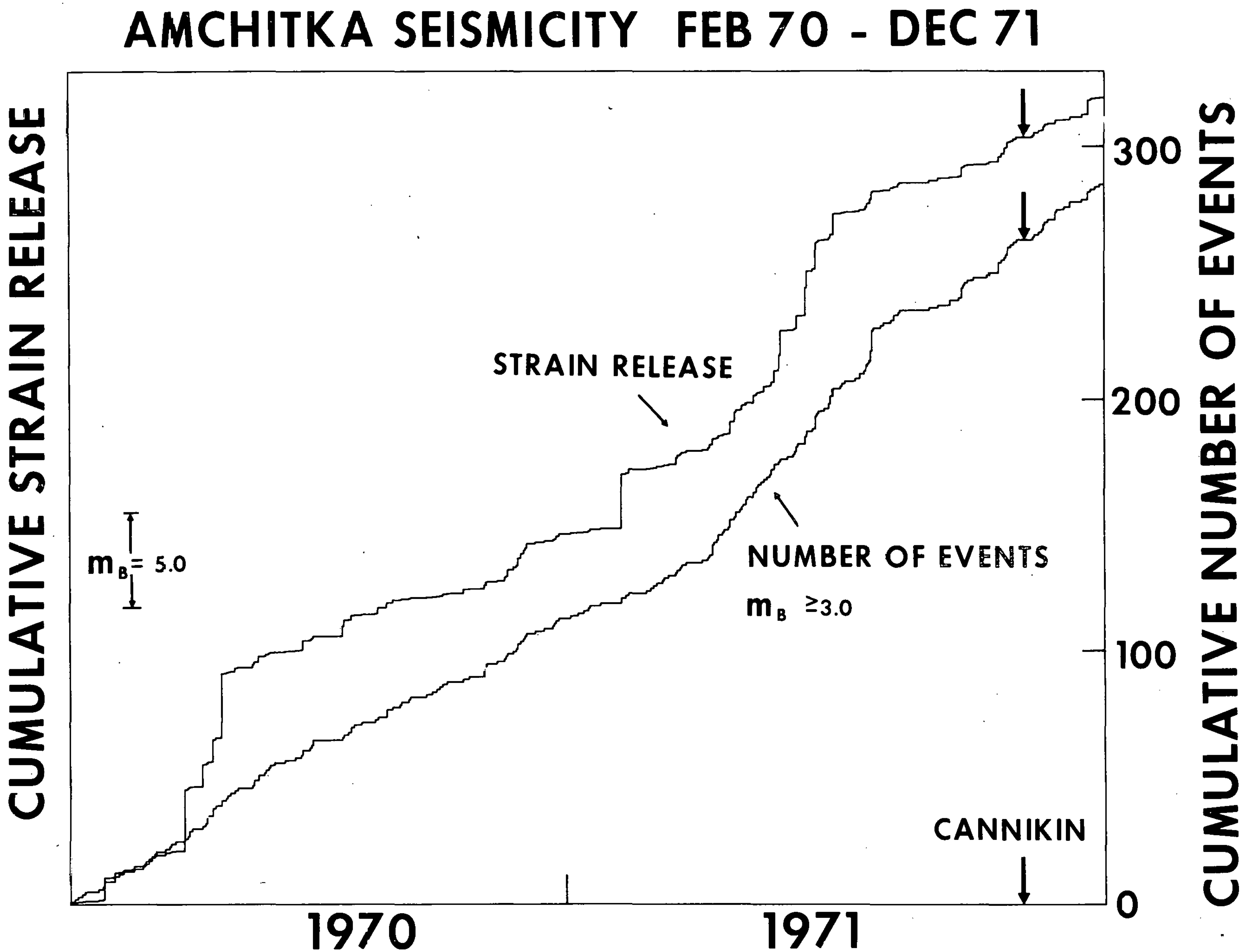
AMCHITKA SEISMICITY FEB 70 - DEC 71
CUMULATIVE STRAIN RELEASE
CUMULATIVE NUMBER OF EVENTS
STRAIN RELEASE
NUMBER OF EVENTS
$m_B \geq 3.0$
$m_B = 5.0$
CANNIKIN
300
200
100
0
1970
1971

Figure 13

and distance along the arc for focal depths of 0-70 km. Again, CANNIKIN, indicated by the star, appears not to have interacted with the natural seismicity beneath the Island.

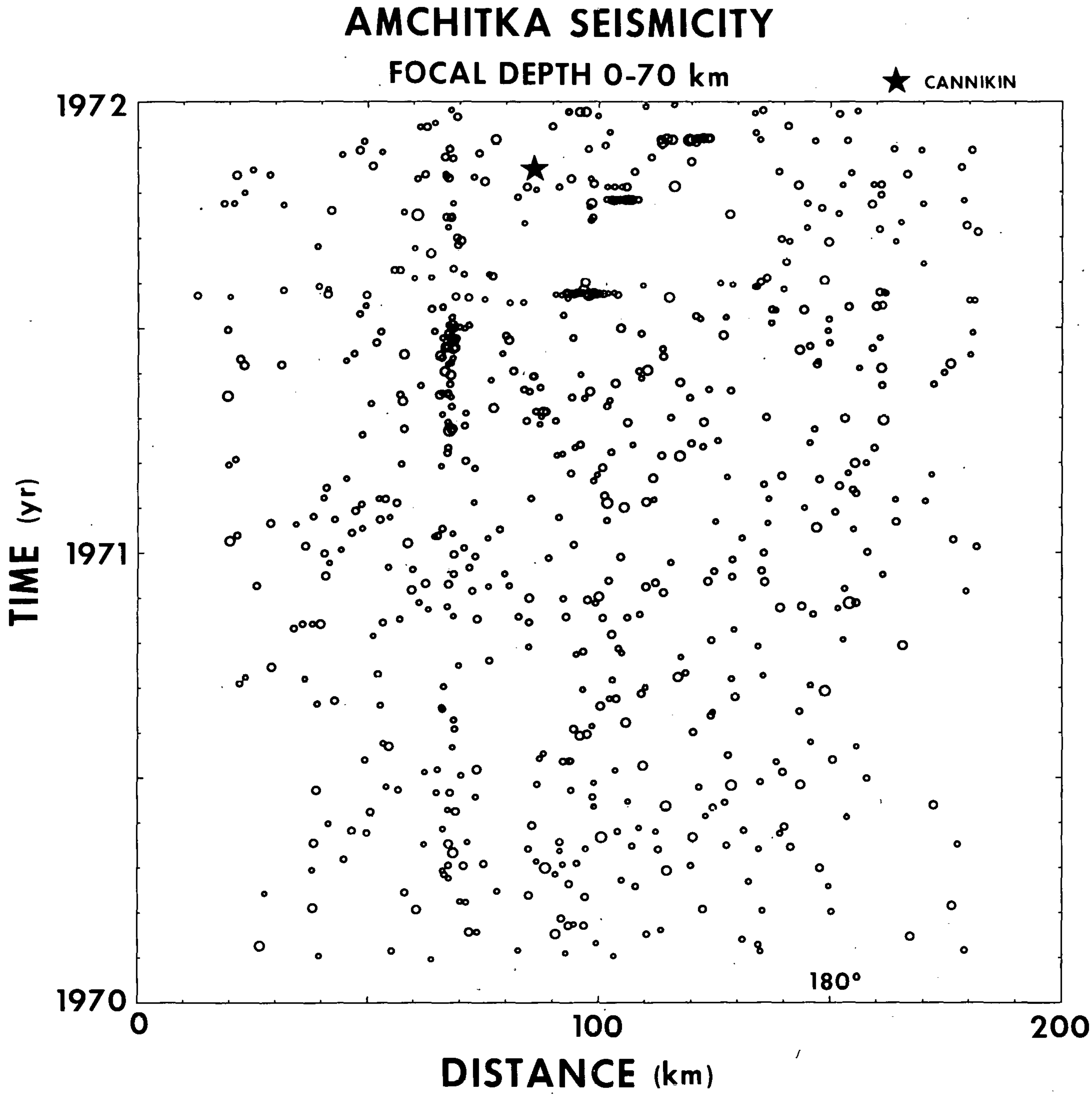
AMCHITKA SEISMICITY
FOCAL DEPTH 0-70 km
CANNIKIN
1972
1971
1970
TIME (yr)
0
100
200
180°
DISTANCE (km)

Figure 14

DISCUSSION

Explosion-produced seismic effects are clearly separable into those occurring near the explosion cavity and related to chimney development and those somehow related to changes in the state of stress and/or strength of the crust nearby. The number and size of events related to the cavity deterioration appear to scale, not unexpectedly, as the yield of the device, subject to local geologic conditions from region to region. Because this represents such a localized and short-term phenomenon, it does not constitute a reasonable hazard.

A key factor in determining the extent of explosion-stimulated tectonic activity appears to be the state of stress of the crust in the test area. Directly and indirectly it can be shown that the upper crust of Amchitka Island is at a relatively low level of ambient tectonic stress. Although Amchitka lies above one of the world's most active seismic zones practically no natural earthquake activity occurs on the Island proper (see Figure 11). Marine terrace studies (Carr et al, 1971) indicate that the upper crust and major faults on Amchitka have been relatively stable during recent geologic time. Finally, in situ studies of stress in shallow drill holes suggest that a relatively low level of stress exists in the surface rocks, even in areas near faults.

The mechanism by which the explosion interacts with the ambient tectonic stress is not clearly understood, however. One view is that the explosion-generated elastic body waves interact with hetereogenieties in the vicinity of the explosion to produce a field of small dislocation loops (Kisslinger and Cherry, 1970). The continued action of the regional stress field on these dislocations then produces tectonic activity, the extent depending on the level of regional stress. Another view has it that changes in fluid pore pressure result in changes in strength of the surrounding rock which subsequently fail under the action of the regional stress field (Healy et al, 1970). In general, hypocenters for the tectonic events are located where changes in fluid pore pressure would be expected to have the greatest effect. An independent line of reasoning suggests the possibility of large nearby natural earthquakes triggering tectonic activity on Island faults. Since 1969 there has been no earthquake large enough or close enough to test this hypothesis.

The high level of natural seismicity 20-60 km beneath the Island and the apparent low level of stress in the rocks of Amchitka suggest that these zones are effectively seismically decoupled. Although it is yet to be proven that explosions produce anything but localized effects, the seismic decoupling of Amchitka from the zone of subduction below, which is well supported by observational data, is one of the most important considerations in evaluating the potential for the triggering of a major earthquake.

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