REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-02-

0135

Public reporting burden for this collection of information is estimated to average 1 hour per response, ir
and maintaining the data needed, and completing and reviewing the collection of information. Senc
information, including suggestions for reducing this burden, to Washington Headquarters Services, Dire
1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Pr

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1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** March 2002	**3. REPORT TYPE AND DATES COVERED** Invention 7/15/96 – 7/14/01

4. TITLE AND SUBTITLE

Detection, Location, and Characterization of Regional Events
Using a Small Broadband Array

5. FUNDING NUMBERS

F49620-96-1-0373

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research
801 North Randolph Street
Arlington, VA 22203-1977

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

Unlimited

12b. DISTRIBUTION CODE

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFOSR)
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13. ABSTRACT *(Maximum 200 words)*

A seismic array combining short period and broadband instruments is being installed in the US Pacific Northwest at the location of the former VELA array BMO (Blue Mountains Observatory, Oregon). No inventions were developed in the course of the work for this project.

20020417 263

14. SUBJECT TERMS			**15. NUMBER OF PAGES** 1
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassifed	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** Unlimited

Standard Form 298 (Rev. 2-89) (EG)
Prescribed by ANSI Std. 239.18

DETECTION, LOCATION, AND IDENTIFICATION OF REGIONAL SEISMIC EVENTS USING A SMALL BROADBAND ARRAY

FINAL REPORT

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CONTRACT NUMBER F49620-96-1-0373
Sponsored by Air Force Office of Scientific Research

March 2002

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Introduction

This report covers a project to open a research seismic array in the United States Pacific Northwest, and to study strategies for locating and characterizing recorded events at regional distances as earthquakes or explosions. The Pacific Northwest is an interesting region in which to develop and calibrate methodology, due to the widespread crustal seismicity and the good hypocentral control provided by regional seismograph networks established for earthquake hazards studies. An early (1962 – 1975) array was operated at Blue Mountains Observatory in northeastern Oregon, and the new research array is being established there because of the central location, low ground noise, availability of vaults, and existing information on recording characteristics and site geology.

Extremely disappointing performance in supplying working digitizers by the chosen manufacturer, Guralp Systems Limited (US representative, Digital Technology Associates), has led to a cascading series of problems in array installation that are not as yet fully resolved. As a consequence, the research program has seriously lagged. Efforts continue to obtain and install equipment that performs according to appropriate specifications, and implement the full research program.

Purpose of project

The purpose of this project is to use a wide dynamic range digital array of broadband and short period seismographs to explore how accurately regional events can be located with a single array-type station. Such research has ramifications for monitoring of explosions that may be related to weapons development. It also has implications for the monitoring of seismicity for research and geologic hazard studies.

The identification and classification of explosions has been of interest to the monitoring of weapons development for many years. Initially, research was directed at teleseismic means of identification and location as a result of the large magnitude of tests common in the 1950's through 1980's. Many of these tests had magnitudes in excess of 4.5 and thus could be detected essentially globally, if the seismograph stations were sufficiently sensitive. The community of weapons developers was also restricted and their test sites and habits generally known, making it possible to target certain regions for attention.

Beginning in the late 1970's and continuing through the present, the situation changed due to several factors. First, weapons developers concentrated more on trigger technology, which requires smaller yield tests than the main weapons. Second, developers studied the masking of signals by decoupling and other means, which reduced the apparent magnitude (and detectability) of the resulting signals. Third, proliferation of weapons technology resulted in weapons programs being initiated by several additional countries spread over a much larger area of the globe than formerly was the case. Fourth, the breakup of the former Soviet Union, the signing of arms reduction and testing accords, and the decommissioning of significant portions of the US and USSR arms stockpiles reduced the number of tests actually being carried out.

This altered situation presents several challenges to monitoring potential weapons development explosions. First, a much larger area of the globe must be monitored for tests. Second, the small magnitude of tests requires that seismograph monitoring stations be placed much closer to the source to detect the signals. Third, the signals at these stations will be severely affected by local and regional geology, making their interpretation more difficult. Fourth, economy and international politics dictates that there cannot be enough seismograph stations deployed in the right places to monitor the globe or even those countries suspected of weapons development at what would normally be considered adequate density.

These factors have led to changes in the focus of seismological research. Much effort has been spent upon better characterization of regional geology, understanding the effects of geology on seismograms at regional distances, and searching for means of quickly and routinely classifying recorded events as earthquakes, blasts of peaceful intent, or potential weapons tests. While much progress has been made, there is still a great deal more work required to develop efficient procedures. The intent of this study is to contribute to this research objective.

Event location is obviously an important factor in identification as a potential weapons test. Dense local seismograph networks can usually locate an event's epicenter within about 0.5 km and estimate the focal depth of a shallow event within 2 km. While special studies are capable of significantly greater relative location precision, the numbers just quoted may serve as benchmarks for the best locations that can be routinely achieved under optimal conditions.

If an event can be proven to be at a depth greater than local mining or well penetration, it must be an earthquake. This is true whether the event has been located or not, making depth a potentially rapid test for sorting events recorded even at only one station. At teleseismic distances, the phases *pP* and *sP* can allow accurate depth determinations from a single station. Unfortunately, at regional distances this level of precision is almost impossible to presently achieve even with networks of stations, owing to the difficulty of identifying depth-dependent phases on regional seismograms.

The location of an event remains a good indicator of whether it may be of interest as a potential weapons test, although this test lacks the desired level of specificity. This is in part due to the comparatively large epicentral uncertainties in events in areas that are not covered by local networks. Worldwide, absolute epicentral uncertainties of 10 km are common and are larger for smaller magnitude events. In areas that are poorly monitored, including countries that do not allow open seismic data availability, uncertainties on small events recorded at a minimal number of stations may be quite large. Yet, these events may still be of importance as potential weapons tests.

Seismic array stations have greater capabilities than single stations. In addition to their well-known ability to somewhat increase detection thresholds, they are capable of both back-azimuth and slowness determination. If some instruments suitable for recording *S*-waves are included, the array station is uniquely capable of locating events in all distance ranges. Its stacking and slowness capabilities can also be helpful in extracting coherent regional phase arrivals from seismograms that exhibit a great deal of scattered energy, as is common on regional seismograms in geologically complex areas. These later phases, if they can be interpreted, may contain information that allows a focal depth interval to be assigned.

Single-array locations are plagued by lateral refraction, however. This phenomenon has been observed to introduce errors of as much as 15° in back azimuth at epicentral distances of 500-1000 km (E. Herrin, personal communications discussing capabilities of TXAR, 1995), implying huge errors in the computed epicenters. If ground truth is available on the actual location, this effect can sometimes be seen to be systematic over small distance ranges. However, it is often the case with clandestine weapons development programs that no ground truth data are available. Furthermore, it is not known where the major portion of the lateral refraction error is introduced. It could be in the source region, the receiver region, along the path, or (most likely) a combination of all three. If at least a large portion of it is in the region of the receiver, its effects might be ameliorated by the choice of monitoring station location.

One question that might be asked is how stable the amount of lateral refraction is with distance. In other words, is there a scale length at which such errors can be considered random? If so, there would be two consequences for monitoring strategies. First, it would suggest the minimum diameter of a network of stations whose location results derived from back-azimuth estimation would be likely to have reduced systematic bias. Second, it would suggest preferred geometries of such a network, which may be different from what we customarily assume because they would be designed with the specific intention of reducing back-azimuth errors.

The ultimate objective of this study was – and remains – an examination of lateral refraction. Rather than deal with events occurring in areas where ground truth on hypocentral locations is unavailable, the US Pacific Northwest was chosen. The Pacific Northwest is an area of complicated regional structure that is well-monitored by regional seismograph networks capable of determining accurate hypocenters. The Pacific Northwest has large numbers of crustal earthquakes distributed throughout the depth range 5-15 km, with shallower and deeper events occurring in significant numbers in some areas. It also has a moderate amount of blasting activity and some rockbursts. The region is divided into at least 8 geological provinces, so event-receiver paths traversing more than one province are common. If the area was not well-monitored by local seismograph networks, these would be almost worst-case conditions for attempting to monitor events at regional distances. The effect of the large numbers of stations is to calibrate the region for source studies, eliminating source location errors as a possible source of variance or bias in the studies to be undertaken. Because of the "worst-case" situation, methodology for locating regional events derived in the Pacific Northwest could have applicability globally.

We have chosen to perform the studies with an array so that we have more confidence in the signals being recorded than is possible with a single 3-component station, or even a few of them. While 3-component stations can determine back-azimuth from the polarization of their *P* waves, the added information an array can give on slowness is critical in identifying a particular wave.

An analog array known as Blue Mountains Observatory (BMO) was operated in the Pacific Northwest from 1962 to 1975. The site is located near the Oregon-Idaho border (Figure 1), and as will be seen is positioned so as to record earthquakes from many different directions in a variety of geologic provinces. The vaults were buried at the time the array ceased operation and remain in relatively good condition. The low ground noise conditions which led to the site originally being chosen for an array remain unchanged, and landowner relations are good. There is relatively little major topography in the immediate area of the old array, and access is reasonably good. It was therefore felt that use of BMO as the site for the project made practical sense.

Geological Provinces

The Pacific Northwest, as it will be referred to here, consists of the traditional states of Washington, Oregon, and Idaho, augmented by western Montana and the northernmost portions of the states of California, Nevada, and Utah. The region is rich in geological provinces with varied histories and morphologies (see Figure 2). Much of the post-

Figure 1. General location map of Blue Mountains Observatory (BMO).

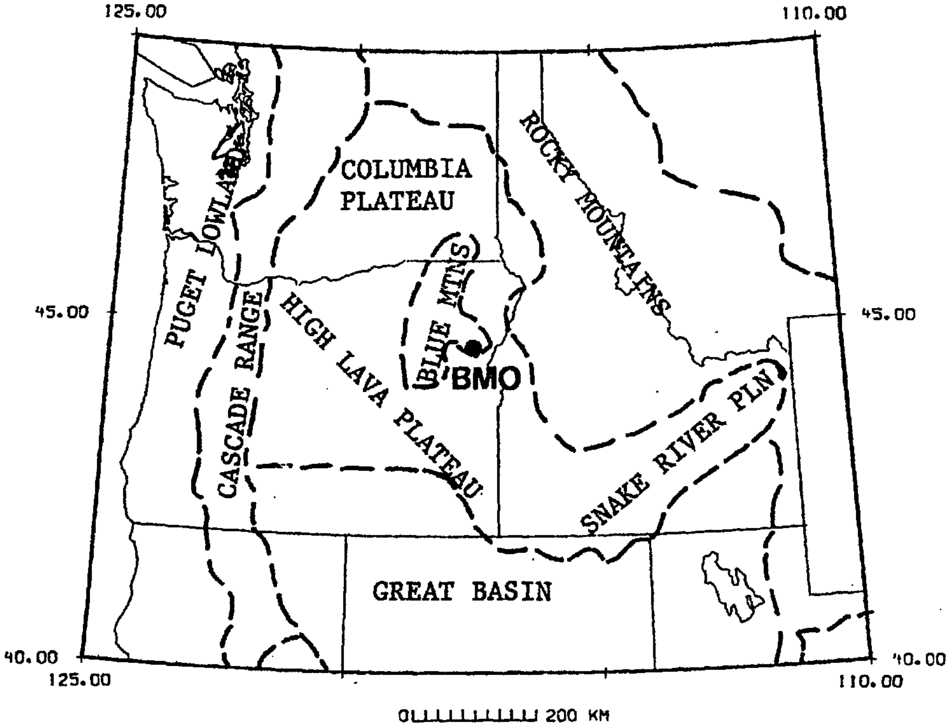

Figure 2. Geologic provinces in the Pacific Northwest.

Eocene geological history has been dominated by repeated "dockings" of accreted terrains against the North American craton, the subduction of the Farallon Plate and its remnants beneath North America, and the development and expansion of the Basin and Range. This history can be expected to lead to wide variation in geology and crustal structure throughout the Pacific Northwest. These variations should in turn lead to complex transmission and scattering of seismic waves along most regional paths.

Probably the largest province in the area is the Great Basin, which occupies much of the southern border strip (California, Nevada, and Utah) and parts of Oregon and Idaho. The Great Basin is deforming under the generally extensional stresses that characterize the Basin and Range stress province. It is characterized by sub-parallel ranges of fault-bounded mountains up to a few hundred kilometers long, separated by wide valleys. Seismicity in this portion of the Great Basin ranges from generally low in southern Oregon to high in Utah and southeastern Idaho.

Northern Oregon east of the Cascades is mostly divided between the High Lava Plateau and the Blue Mountain Province. While these areas do not have the characteristic Basin and Range topography and probably also differ in structure, they are currently under an extensional stress regime that is continuous with that in the Basin and Range. Most of the geological evidence of accreted terrrains is found in the Blue Mountains Province near the Oregon-Idaho border. This area, which includes the Blue Mountains Observatory location, has extremely complex surface geology due to the terrains. While the depth to which the "slivers" of accreted terrains extend and their degree of assimilation by the North American Plate are unknown, it is likely that major variations extend to at least 10 km below the surface. There is some anecdotal evidence that major velocity variations may exist at depths up to 200 km beneath the northern Blue Mountains. Seismicity is fairly low in most of the High Lava Plateau, except in the area (in the vicinity of Blue Mountains Observatory) that is on the edge of the Blue Mountain Province. Few earthquakes are known to have occurred within the Blue Mountains.

The Snake River Plain lies to the southeast of the High Lava Plateau. The physiographic province is divided into two structural provinces. The Western Snake River Plain is a fault-bounded graben system that formed in a similar manner to the valleys in the Great Basin. The Eastern Snake River Plain formed as the result of passage of the North American Plate over the Yellowstone Hot Spot. It is not fault-bounded and its origin is probably more closely related to thermal changes in the crust than to more ordinary block faulting. There is very little seismicity in either division of the Snake River Plain.

The Rocky Mountains province extends along the eastern part of the Pacific Northwest. This is a region of generally parallel mountain ranges somewhat similar to those of the Great Basin, but for the most part longer and more continuous. Most of the Rocky Mountains province in this region is an area of moderate to intense seismicity. The seismicity is generally occurring under the influence of the Basin and Range extensional stress field.

The Columbia Plateau comprises most of Washington east of the Cascades, and has an indistinct physiographic boundary with the High Lava Plateau. The Columbia Plateau is a large basalt province that was the scene of major volcanism in the Miocene. Refraction surveys indicate the existence of a significant structural low in the southwestern part of the Columbia Plateau. The Columbia Plateau is presently under a compressional stress regime that is interpreted as being due to the interaction of the North American and Pacific plates. In this regard it is clearly differentiated from extensional stress domains to the south and east. Columbia Plateau seismicity is dominated by very shallow earthquake swarms in the Columbia River basalts. Deeper earthquakes occur, including some at depths greater than 20 km.

The Cascade Range is a long, narrow province extending from southern Canada into northern California. It contains numerous stratovolcanoes. The stress regime of the Cascades probably differs from north to south. The northern portion appears to be under the influence of the same compressive stress field as exists in the Columbia Plateau, while the southern portion appears to be under the influence of subduction tectonics due to the interaction of the Juan de Fuca and North American plates. The northern portion of the range, in the state of Washington, is much more seismically active than the southern part.

The Puget Sound Lowland is a long, narrow province that parallels the Cascade Province for much of its length and extends well into Oregon. It is a structural trough that has largely been filled by glacial sediments. Gravity has shown that deep basins exist under northern Puget Sound and near Portland, Oregon. The stress field appears to be dominated by the interaction of the Juan de Fuca and North American plates. The Puget Lowland in Washington is host to numerous earthquakes at a variety of focal depths.

Regional Seismicity

Seismicity in the Pacific Northwest (Figure 3) is widespread, intense and varied in its causes. Shallow earthquakes (depth less than 2-3 km) related to volcanic systems occur at Mt. St. Helens, Mt. Rainier, and Mt. Hood, and may have magnitudes as large as 2.5 – 3.5 (some events prior to the 1980 Mt. St. Helens eruption had magnitudes exceeding 5). Very shallow tectonic earthquakes (depth less than 4 km) occur in the central Columbia Plateau, near the Canadian border, and in scattered locations in the vicinity of the eastern shore of Puget Sound (Figure 4). Some of these events have exceeded magnitude 4. Rockbursts having magnitudes between 2.5 and 3.5 occur in northern Idaho near the Montana border. While in-mine sensors routinely locate these events at depths of about 2 to 3 km, regional network locations are typically deeper, probably as a result of poorer depth control. As a result, Figure 4 shows an under-representation of these events.

Upper-crustal earthquakes at shallow depths (4 - 20 km) dominate most of the Pacific Northwest (Figure 5). In most areas, including the Washington Cascades, Idaho, Montana, Wyoming, northern Utah, and northeastern Oregon, focal depths of crustal events are usually between 5 and 15 km. Figure 5 shows a cluster of events in northern Idaho near the Montana border that are actually shallower (depth 2 – 3 km) rockbursts, as discussed in the preceding paragraph. Deeper crustal events are known in three areas (see Figure 6). In northern Puget Sound depths between 15 and 30 km are common. In northwestern Oregon, a similar but more spatially restricted population of relatively deep

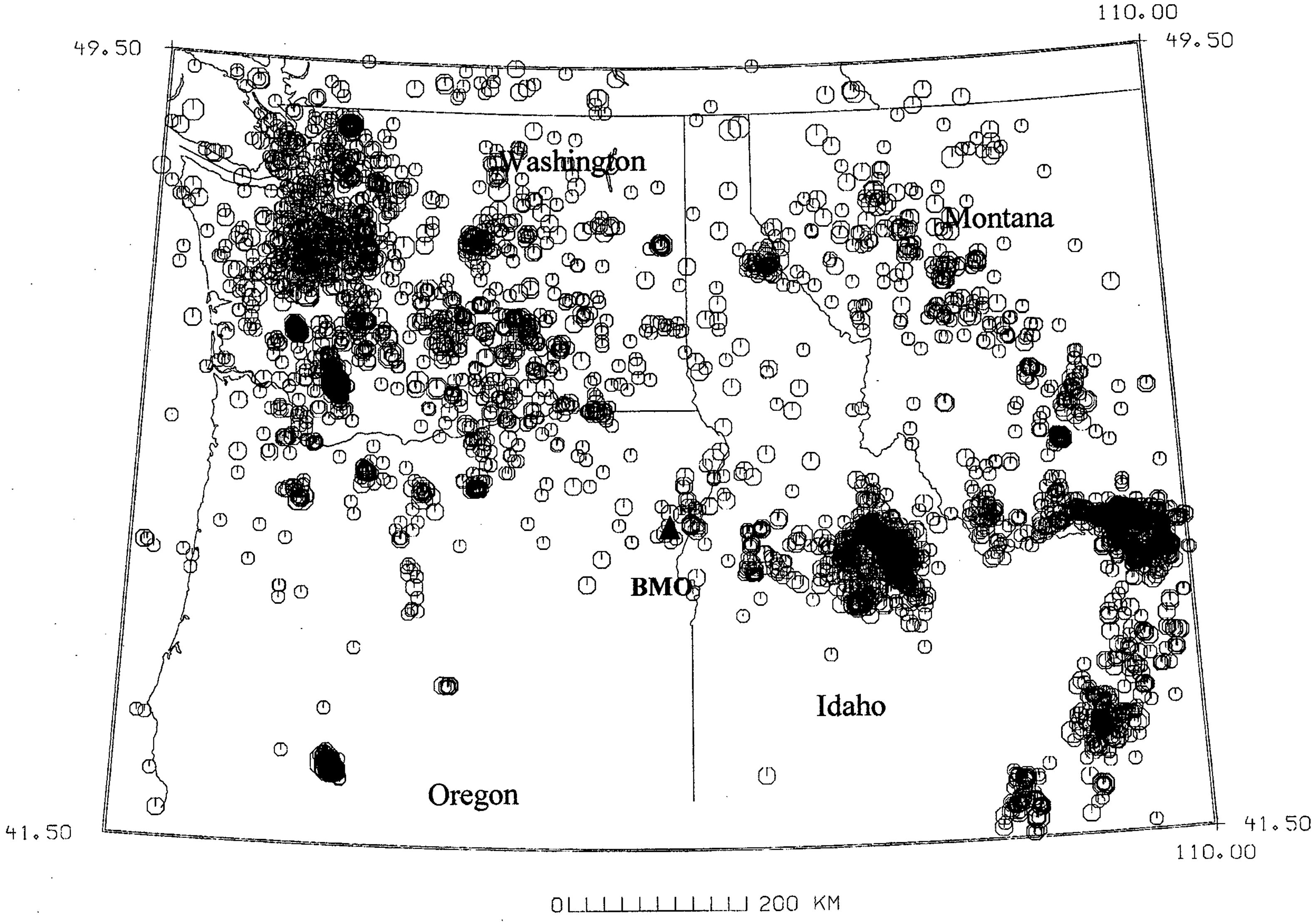

Figure 3. BMO region events (earthquakes and explosions) having a magnitude of 2.5 or greater.

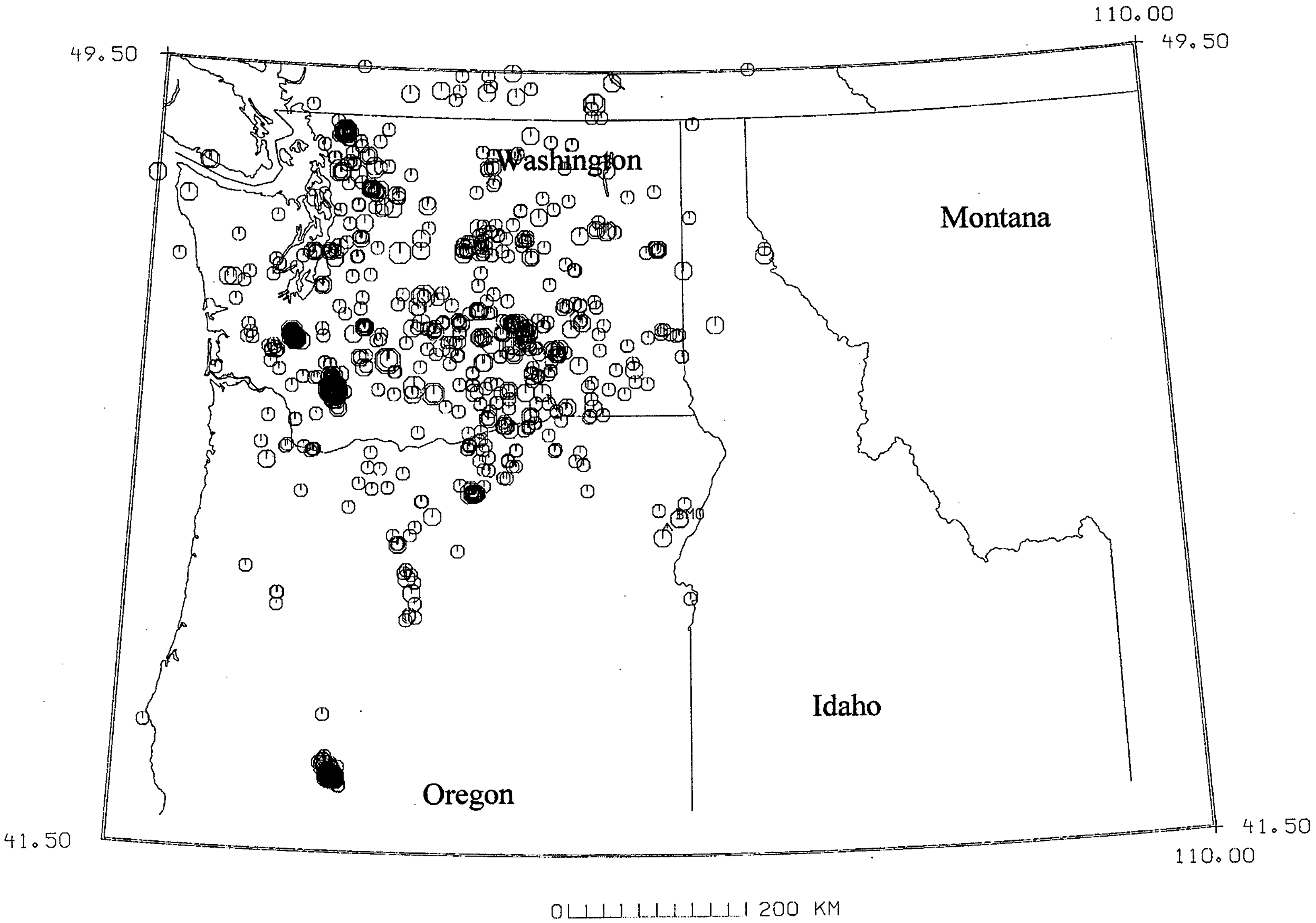

Figure 4. BMO region events (earthquakes and explosions) having a magnitude of 2.5 or greater and a depth of 0 – 4 km.

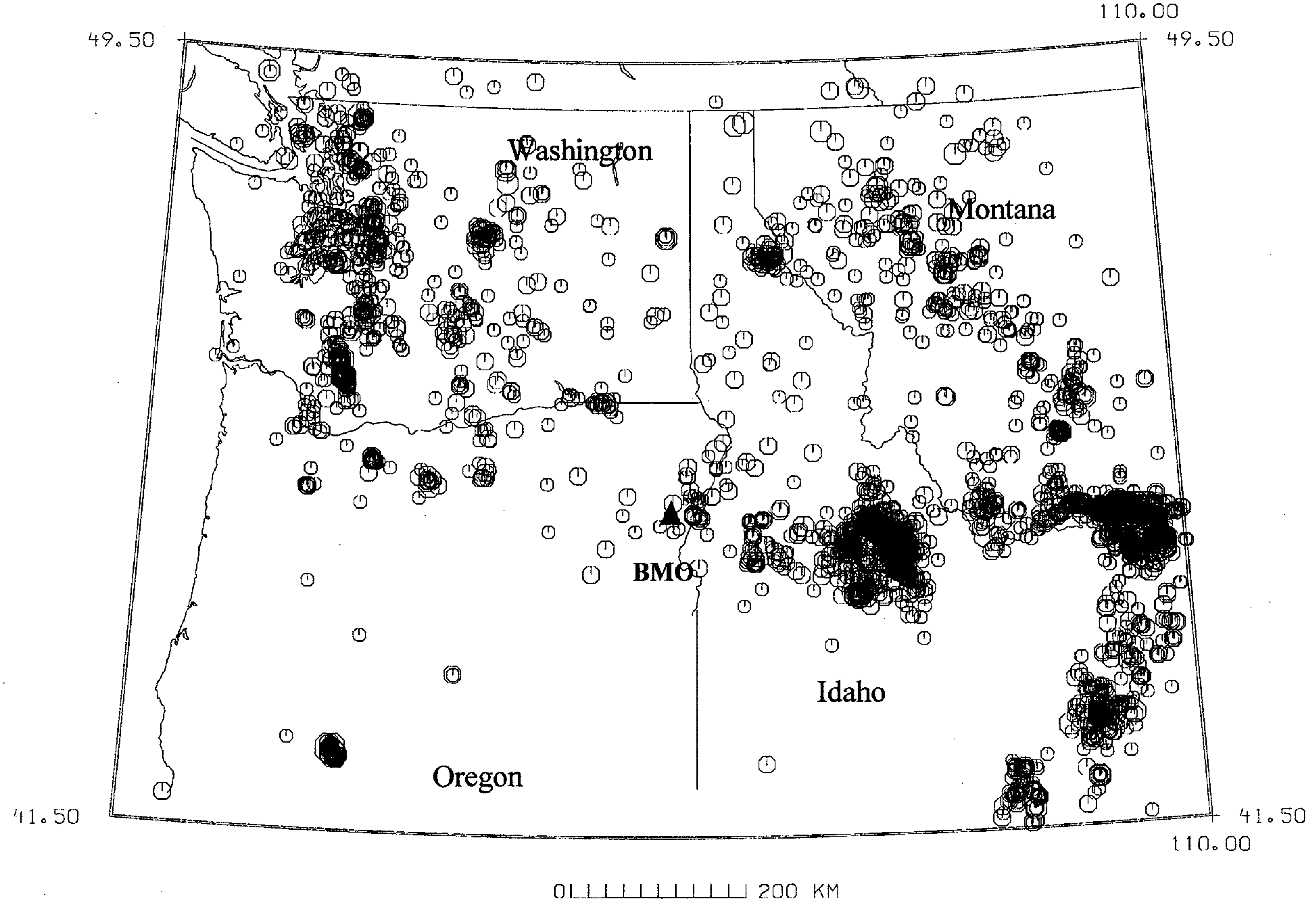

Figure 5. BMO region earthquakes having a magnitude of 2.5 or greater and a depth of 4 – 20 km.

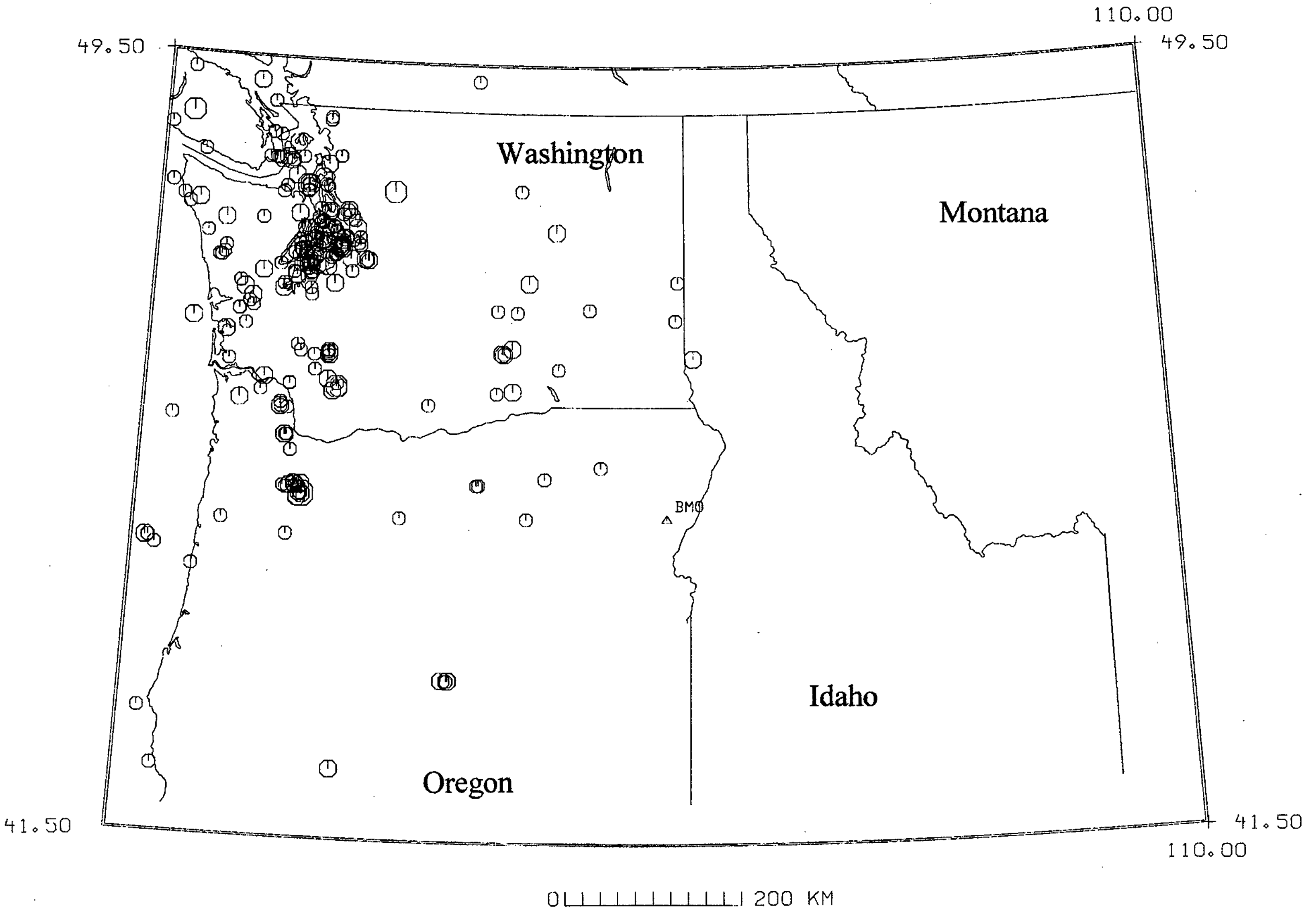

Figure 6. BMO region earthquakes having a magnitude of 2.5 or greater and a depth of 20 – 40 km.

events occurs. In both areas numerous events with magnitudes exceeding 2.5 are known. Crustal events with depths in the more typical range of 5 – 15 km occur in both places as well. In the central Columbia Plateau, events having depths between 15 and 25 km are known, but in this area most crustal seismicity occurs at depths of less than 4 km.

Most earthquakes at depths greater than about 40 km are related to the Juan de Fuca Plate's subduction beneath Washington and Oregon. They generally occur beneath Puget Sound (Figure 7). While depths as great as about 120 km have occurred, few events deeper than about 70 km are known and most of these are quite small. Earthquakes at depths of 30 – 70 km are frequent and several have had magnitudes greater than 3.

In a typical year, 100 - 150 earthquakes having magnitude 2.5 or greater occur in the Pacific Northwest. Most of the provinces mentioned have significant seismicity on at least a local basis. The Blue Mountains, the Snake River Plain, the High Lava Plateau, and the Oregon portion of the Basin and Range are provinces which have comparatively little seismicity in any given year. Areas of very high seismicity typically include the northern Puget Lowland, the western Cascades, the Columbia Plateau, and the Rocky Mountains in central Idaho, western Montana, and northern Utah.

Blue Mountains Observatory Array

The Blue Mountains Observatory array (BMO) was originally installed in 1962 under Project VELA-Uniform. It was one of 5 VELA arrays in the United States (UBO, CPO, TFO, and WMO being the others). Its site was selected to be on an albite granite pluton (Figure 8), in line with then-current thinking that granite outcrops offered the lowest levels of background noise as well as fairly simple transmitted signals. Anecdotally, BMO had the lowest level of ground noise of the VELA arrays, although UBO apparently detected more teleseisms.

The array site is located in a remote area of northeastern Oregon (see Figure 1). The population density is low and the chief occupations are ranching, mining, and logging. The observatory site is located in rolling hills of low to moderate relief on a plateau

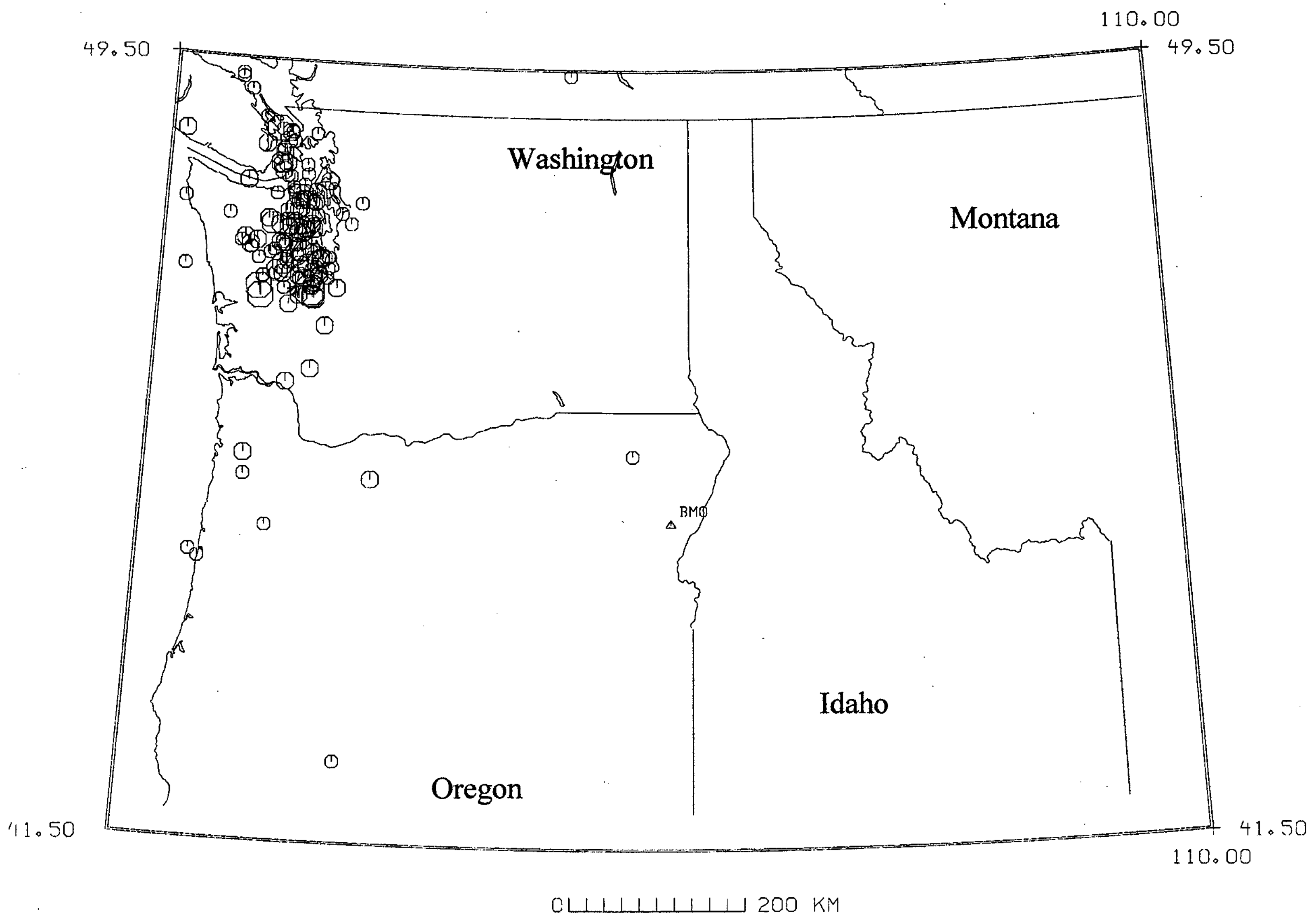

Figure 7. BMO region earthquakes having a magnitude of 2.5 or greater and a depth of 40 – 120 km.

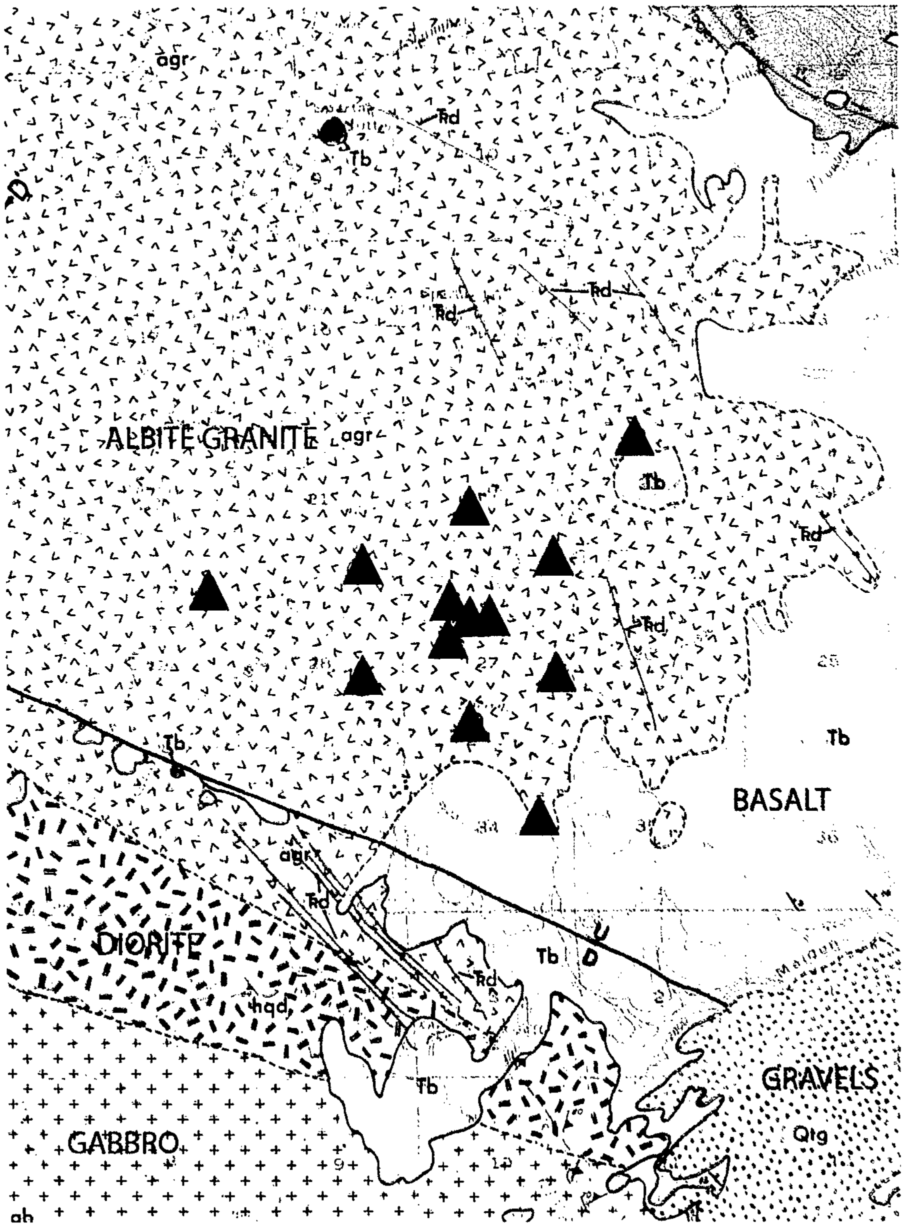

Figure 8. Surface geology in the immediate vicinity of Blue Mountains Observatory. Station sites are shown as triangles. Where basalts are shown as surface outcrops, they overlie the albite granite pluton; they are quite thin near the mapped contact.

above the Powder River. The climate is arid. Vegetation in the area of the observatory is currently mainly grass or sagebrush, although some timber occurs in ravines where there is a little more water. There are occasional rock outcrops, although in most areas near the observatory the bedrock is mantled by 0.5 - 1 m of weathered rock and soil.

The entire observatory site is in private hands, with two different landowners. Both have been extremely cooperative with Boise State University's project to operate instruments at BMO. The land utilization is entirely cattle ranching. Cattle actually are the source of most ground noise recorded. We are experimenting with drift fences to influence the cattle to take paths farther from the seismometers, but one of the conditions of our use of the land is that we not interfere with the use of the land for grazing. Our elimination of sagebrush in some areas to reduce wind noise has actually improved the land, but unfortunately cattle are often drawn to those areas because more grass tends to grow after the sagebrush is eliminated.

All of the VELA arrays had different array geometries, since one of their purposes was to test the efficiency of various array designs. By current thinking, most of the designs were inefficient. All consisted of seismometers with inter-sensor distances of 1.0 km, leading to strong spikes in the array response with respect to frequency. BMO's design consisted of ten sites in an equilateral triangle configuration (Figure 9). In practice, terrain and access difficulties required some minor departures (all less than 300 m) from the ideal design. Nine sites operated single short-period vertical component seismometers. At one site (Z3), unfortunately not the array center, 3-component sets of short-period, intermediate period, broad-band, and long-period seismometers were installed. A separate vault was excavated for each sensor, with pits placed in a rectangular configuration with inter-pit spacing of 50 ft. The vault housing the short-period vertical seismometer was the one whose geographical coordinates were used for reporting BMO arrival times.

Seismometer pits at BMO were excavated to bedrock with a backhoe. The crumbly nature of weathered granite allows relatively easy excavation to hard material, although it

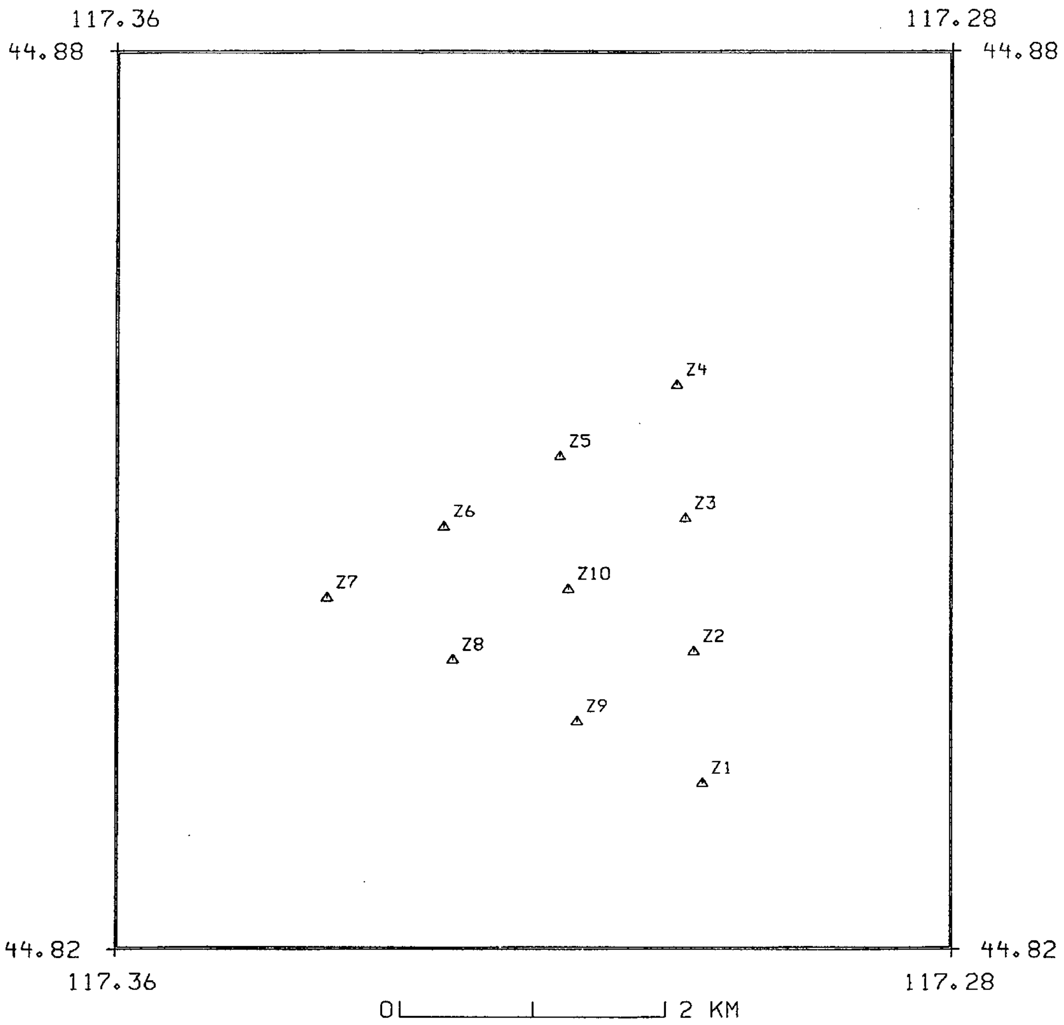

Figure 9. Original (1963) array configuration. All sites were short period vertical installations. Z3 had 3-component sets of short period, intermediate period, broadband, and long period seismometers. It was the array reference point for arrival times and the geographic location that is listed for BMO in seismograph station location catalogs.

is no longer possible to verify just how far the backhoe operator dug in each case. After the hole was completed, a concrete pad was poured and a 4-ft diameter, 4-ft high metal drum was placed in the wet concrete to serve as a vault to house the sensor. After sensor installation, the vaults were covered with 1-3 ft of earth, allowing good thermal insulation as well as some decoupling of wind noise and animal-generated noise.

All short-period vertical sites originally utilized Johnson-Matheson seismometers with 1.25 s natural frequency. The short-period horizontals were Benioffs with natural periods of 1.0 s. The intermediate-period and broadband seismometers were apparently Melton instruments with periods of 2.64 s and varying damping and galvanometer periods, and the long-periods the Geotech Corporation version of the Press-Ewing seismometer. Phototube amplifiers with internal galvanometers were used to shape the response. Incredibly, power to the vaults and return paths for signals were hardwired to the main observatory building over distances as great as about 3 - 4 km along the cable path. It would be expected that lightning and ground loops would be serious problems. However, while lightning was a nuisance it was never a crippling problem, and the recorded data show little evidence of electronic artifacts.

Recording was done at an observatory building, which was located between two of the sites (Z3 and Z4). At the building, there was also a 3-component set of short-period Benioff seismometers installed on isolated piers. These seismometers did not use phototube amplifiers and served as low-gain instruments. Recording was done on 16 mm film by Develocorders, as well as on slow-speed 1-inch magnetic tape. The Boise State University library archives the original film records for BMO (and also UBO). Although a major rescue and replay effort was made for the magnetic tapes about 1994, with archiving at Pennsylvania State University, those tapes reportedly have been discarded and the data were never played back and digitized as planned. The film records have fairly low dynamic range, and since they were multichannel any significant event causes the traces from different sensors to tangle in a practically unrecoverable manner. This problem is much worse for high frequencies than low frequencies.

The designs of the early VELA arrays were quickly realized to be inefficient and their operation was transferred to the U. S. Coast and Geodetic Survey starting in 1966. BMO was the first to be turned over, on 1 January 1966. The Coast and Geodetic Survey's seismology operation was transferred a number of times and finally rested under the U. S. Geological Survey about 1973. During this time period, locations of the short period seismometers Z1 and Z8 were changed slightly, and a borehole seismometer was installed near Z4. This borehole has been variously reported as being 20 ft or 160 ft in depth. Six additional vaults were occupied to make the observatory plan more symmetric. We have not been able to find records of the seismometer locations that augmented the array, nor have we been able to find the sites in the field.

The USGS closed down local operation of BMO in 1975 because of the high expense of keeping local personnel employed to operate and service the single observatory. Some channels were telemetered to Golden, Colorado for recording for about a year, but even this proved too expensive for the USGS and operation of BMO was terminated in 1976. The seismometers were removed and the whereabouts of most of them is now unknown, although Boise State has one of the original Johnson-Matheson short-period vertical seismometers and some of the phototube amplifiers.

The observatory building was removed in 1976 or 1977, but the concrete pad and piers are still in place today. They were utilized briefly in 1984 during a study of a nearby earthquake sequence. In 1991, Boise State University reoccupied the old array reference point (Z3) with a 3-component station. The data were telemetered to Boise State via radio and microwave circuits, and recorded on an event-triggered IASPEI computer system with 12-bit resolution. This recording continued until late 2001, and confirmed that BMO remains a high-sensitivity recording location.

Geology of Blue Mountains Observatory

The regional geology of BMO is complex. The observatory is located in an area of accreted terrains, and it is believed that much of the observatory region was once an island arc system. The observatory itself sits upon a sizeable outcrop of albite granite.

Outcrops of basalt are situated close to observatory elements on the south (see Figure 8). Cinder cones have penetrated the granite near the observatory. Based on a gravity study, the observatory appears to be situated on a laccolith, with the thickness of the granite being variable but rarely greater than about 2 km.

The granite readily weathers to grus and rock outcrops are fairly uncommon and non-extensive. In most places the grus is a half meter or more thick, with weathered bedrock below. The thickness of the weathered part of the bedrock is unknown, but in most places where it has been dug into it is only a matter of 20 – 40 cm before very hard rock is encountered.

This geology likely has some interesting consequences for seismic wave propagation. The looseness of the grus at the surface implies a very low velocity there, and the relatively abrupt transition to hard rock 1-2 m below the surface indicates a strong velocity contrast and near-surface gradient. This velocity contrast may keep some surface noise sources, such as wind, to a low level by confining their vibrational disturbance to the low velocity near-surface zone. However, disturbances which penetrate the surface low velocity zone are unlikely to be significantly further attenuated due to the competent rock then encountered. No comparison records are available to contrast the noise levels in the borehole at Z4 with those encountered at the surface vault, but anecdotally they seemed significantly lower. Given the conditions and the observations we have made of how far from Z3 footsteps can be recorded, it seems unusual that a significant improvement could be made.

Design Concept

The design concept for the current permanent installation of BMO is a 10-element short period vertical array supported by a 4-element broadband three-component array sharing the same center point (Figure 10). Three portable, on-site recording broadband instruments can be used for limited periods of times as an additional array "ring" of configurable size. The idea of a broadband array superimposed upon a short period array is intended to allow some synergy between the two frequency bands while maximizing

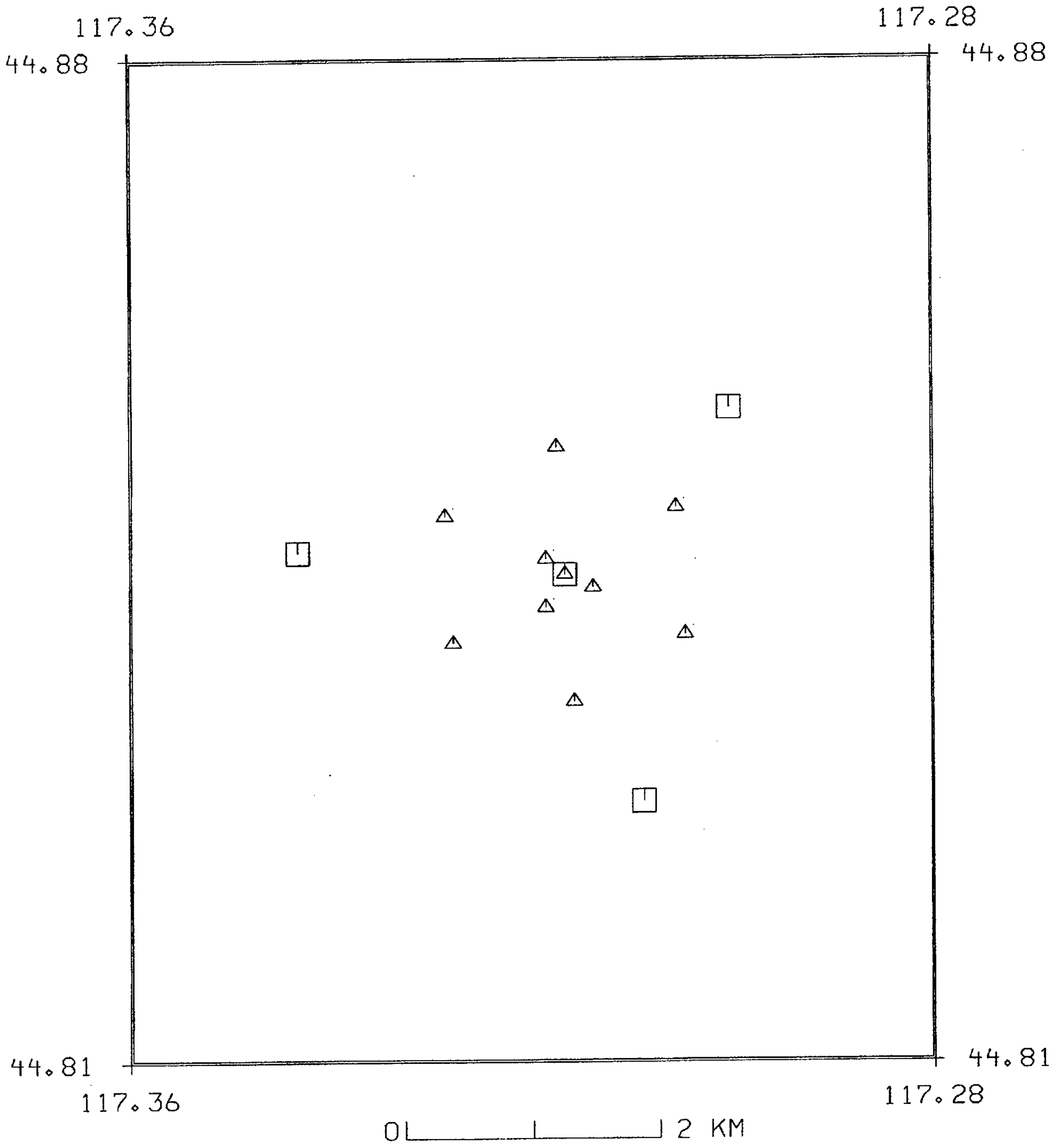

Figure 10. Array configuration being installed. All sites shown by triangles have short period vertical S-13 seismometers. Sites shown by squares have 3-component broadband seismometers. The central site has a Guralp CMG-3T-NSN instrument, while the three outer sites have Guralp CMG-3-ESP instruments.

cost-effectiveness by duplicating only the center element. Data are to be digitized on-site with a sampling rate of 100 Hz and a resolution of 24 bits. Timing is to be synchronized within 2 milliseconds for all channels. The data are to be sent in near-real time or real time to Boise State University for archiving and processing.

Fixed Array

The permanent array design uses the NORSAR concentric ring concept

$$r = n\, d_{min}, \quad n = 0, 1, 2, 4, 8, \ldots$$

where r is the radius of the ring and distance from the center point, n is the ring number, and d_{min} is the distance to the first ring.

The short period elements are arranged with d_{min} = 250 m and n = 0, 1, and 4. The broadband elements are arranged with d_{min} = 2000 m and n = 0, 1. In this manner the broadband outer ring (n = 1) places instruments that act as a partially-populated short period (n = 8) ring. Since the broadband instruments have response adequate response at short periods, they extend the frequency response of the short period array and allow more accurate slowness calculations. Cost-effectiveness is achieved since the more expensive broadband seismometers are not used at sites where their better response at low frequencies is not needed.

The design incorporates added boundary conditions of budget, research objective, and use of the existing BMO vaults where possible. It was decided that the array should be symmetrical about the center point (Z10); this is a necessary condition for optimum utilization of existing vaults. A symmetric hexagonal 1-km aperture array of 7 elements can be constructed around Z10 using existing vaults. This minimal array design has a symmetric response but is fairly sharply peaked in frequency. A better range of short wavelengths can be sampled by including a 3-element "ring" (equilateral triangle) of instruments at a range of 250 m from the center point. Having such close elements will also allow a detailed look at the spatial coherency of high-frequency regional phases.

Since the old array did not have vaults at this range from Z10, entirely new sites were selected.

The NORSAR concept calls for a short period ring at a distance of 500 m from the array center. The budget has not been adequate for this ring, nor is it considered absolutely necessary in light of the research objectives. Since it was desired to examine spatial coherency over a wide variety of wavelengths rather than having the optimal array response, it was considered more important to extend the response to short distances.

The broadband instruments are used for correlation of lower frequency signals than the short period seismometers, and consequently it is thought that they do not need to be so densely represented. Therefore, the array is designed with a broadband instrument at the center point, and another equilateral triangle of broadband instruments at a range of 2 km. This gives a minimally responsive, symmetric broadband array. The broadband instruments, however, extend the response of the short period array at high frequencies.

While the array design configuration is not as powerful as many others, it fulfills the research objectives of having an economical, moderately wide-band array that is large enough to obtain reasonable slowness estimates. It is certainly a much better configuration than the old VELA array.

Portable Ring

When installed centered upon the permanent array center point, the 3-element portable ring allows a degree of flexibility to be introduced for special studies, making the array to some extent focusable or tunable. It is commonly found in network and array studies after some recording time has elapsed that the initial array design was in some manner deficient for studying some interesting problem that has become apparent. In the present case, since it is not known *a priori* what kinds of scale length changes in lateral refraction occur over, it is important to have the flexibility to study the phenomenon at a variety of scales. The portable instruments record on-site with GPS timing and 1 Gb hard drives. Consequently, they are comparatively labor-intensive since it is necessary to visit the sites in order to download the data. When used in triggered mode the disk capacity is adequate for several months of recording; continuous recording is limited to a few weeks.

Search for Vaults

At the beginning of the project the only vaults that had been found were the three short period vaults at Z3. After the observatory was closed, the areas of the vaults had been restored to grade by backfilling. Large regions of the observatory had subsequently been disced to destroy sagebrush and encourage grass growth. By the 1990s little or no evidence of the vaults' locations remained (see Figure 11). Because of the usefulness of these vaults and the high cost of replicating them, an effort was made to find and excavate those that might potentially be of use to this project.

At the time of the original survey of the site in 1962, rebar rods had been driven at the nominal locations where vaults were to be located. As previously noted, however, the vault construction did not follow these markers slavishly and instead used them only as general guides. However, where they still existed, these markers provided good starting points for more intensive searches.

At the time the vaults at Z3 were excavated around 1990, it was found that the vaults were associated with very sharp magnetic anomalies of a few hundred gammas. The anomalies, however, were quite limited in their areal extent and the existence of a vault could usually only be suspected if one was within about 4 m of it. The rebar rods and other surface evidence were sufficient to get us close enough to make magnetometer grid searches that located several of the vaults, but not all.

Since some of the vaults were not found in the expected areas, aerial photographs taken by various agencies were examined. While the coverage was not as good as had been hoped, imagery from 1969 showed disturbed earth at most of the vaults in a lighter color. Correlation of features such as trees, bushes, and rock outcrops found on these photos with those still existing today allowed successful triangulation to most of the "missing" sites that remained. Two remaining vaults whose locations could not be discerned on the

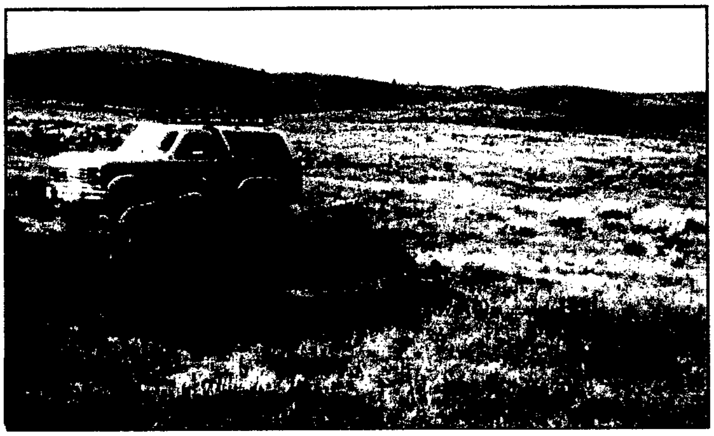

Figure 11. View of the rolling topography and overall lack of tall vegetation that characterizes the Blue Mountains Observatory area. This view looks in a generally northern direction toward Hill 4088 and the array center, from a point near Z9.

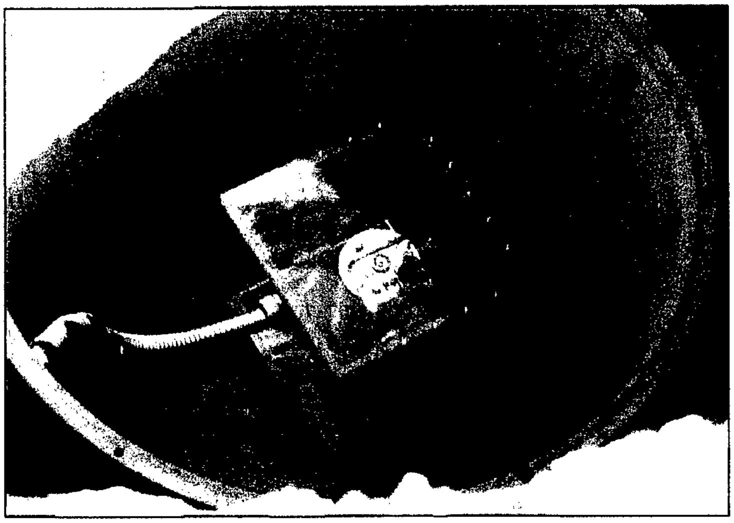

Figure 12. Photo of the original short period vertical tank vault at Z3, showing present S13 seismometer installed in a watertight inner vault. Flexible electrical conduit is mainly for protection of cables from gnawing rodents.

aerial photos were finally located by brute-force magnetometer surveying in widening grids from an initial search point.

Excavation of the vaults has shown that most are in good condition, with little evidence of standing water in most (see Figure 12). Flooding had been a problem at some of the Z3 short period vaults we had excavated several years earlier. Most remaining sites are on hillsides; these have better drainage than Z3 due to the topographic gradient.

While many of the sites are on hillsides, the relief is sufficiently low and the view conditions good enough that radio telemetry sites could be installed within about 30 m of most vaults. In general, it was considered desirable to have the antenna masts as far from the vaults as possible while not causing significant RF cable attenuation. The farther from the vaults the masts are located, the less wind noise they should induce.

Telemetry

All elements of the array do not see any one point, so the choice of radio telemetry paths and data collection sites took some work. Furthermore, the Observatory is about 150 km from Boise and some major topographic features lie in the path. Therefore, there were challenges to be faced both with concentrating the data locally (to reduce the number of telemetry links required) and with getting the concentrated data to Boise for recording. Considerable thought and effort has been expended to assure reliable means of transmitting the data at reasonable cost. Fortunately, technology has been evolving over the course of the project and the present scheme for telemetry bears only a vague resemblance to that originally planned. This discussion will be divided into two parts, the local telemetry aspect (data concentration at the Observatory), and the regional telemetry problem. The regional data telemetry plan that has evolved strongly influences the local data concentration plan. However, the local topography will be discussed first since it was an important factor in our original plan. Vestiges of this plan remain since it was the basis for ordering equipment originally.

Figure 13 is a topographic map section showing the Observatory area and the sites

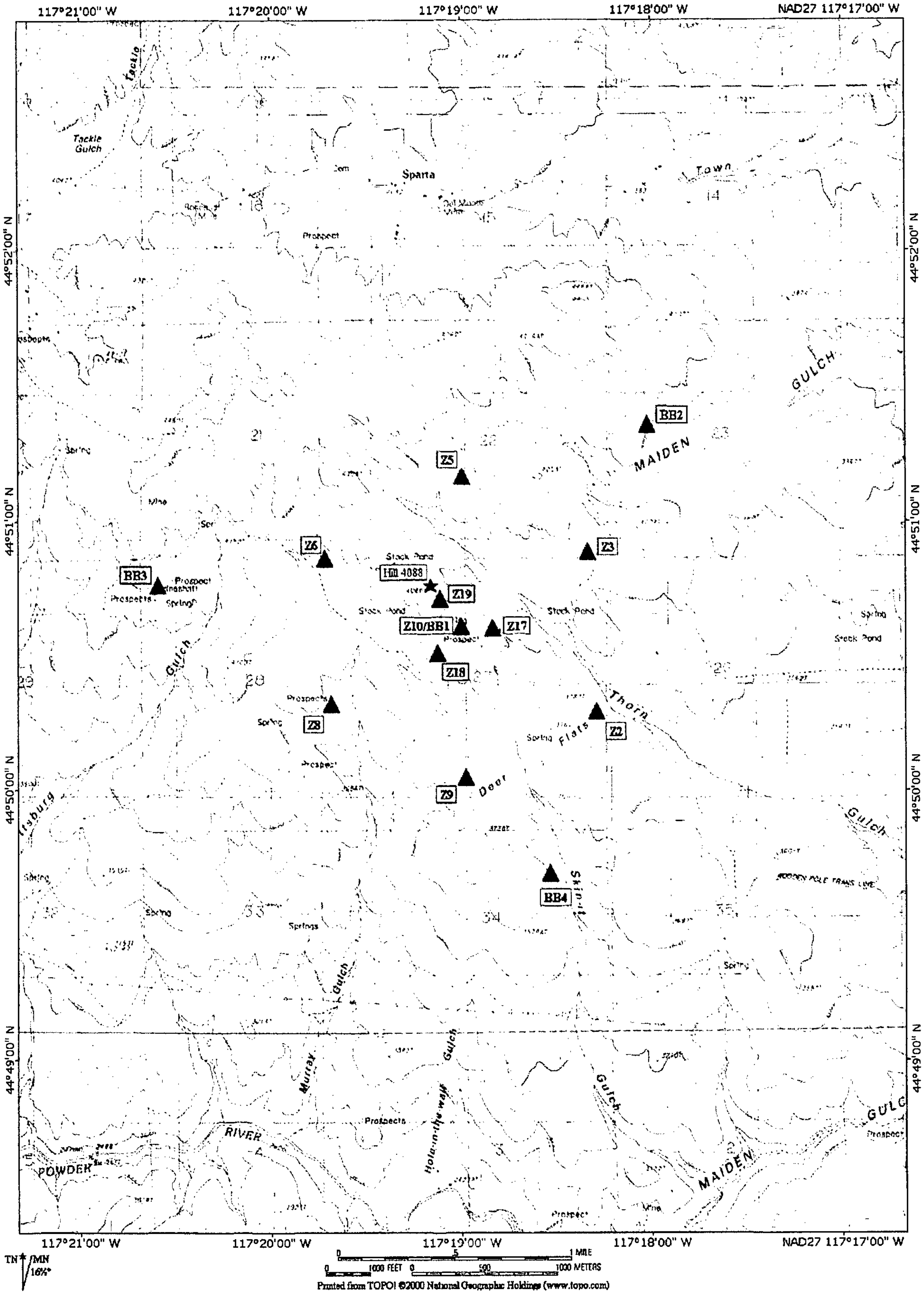

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Figure 13. Topographic map section showing Blue Mountains Observatory.

selected for the new array. The terrain generally slopes toward the south from a high just south of the community of Sparta in the north part of the map. It must be remembered that the original array was laid out without any regard to radio telemetry paths since all elements were hardwired via landlines. Our plan from the beginning was to use digital FM radios in the 216-220 MHz band. It was decided to use simplex (one-way) data communications because of the added bandwidth requirements of two-way communications. The available bandwidth in our licenses is 5 KHz, which limited communications speeds to 9600 baud. A single component digitized at 100 Hz with 24 bit resolution without compression produces outgoing data at 2400 Baud. Allowing some free bandwidth as a result of data compression, this means that about four components can be concentrated onto a single radio link. A digital time-division multiplexer is required for the concentration; this component is referred to in this report as a combiner-repeater module, or CRM. The number of incoming data streams is appended to the designation. As an example, a CRM capable of combining 4 channels will be referred to as a CRM-4. The central site, Z10, acts as its own CRM since it has a 4-component digitizer for the 3 broadband and 1 short period channels.

The insertion of CRM-4s into the telemetry plan relaxes the line-of-sight requirements in part. However, another practical issue is timing synchronization at all the array elements. Since it was necessary to rely on solar power with battery backup, one design objective was to keep power consumption at each element to a minimum. Although a GPS receiver at each element will assure good synchronization, this is an expensive option in terms of both power consumption and equipment cost. Instead, the selected BMO design called for the timing at all elements to be synchronized from a central timing source. Practically, this meant that there must be a site transmitting time that all sites could receive, and that there must be a digital receiver at each array element.

Regional Data Transmission

Figure 14 shows a block diagram of the three principal plans that were developed for data concentration, transmission, and timing synchronization. Originally it was planned to have a GPS receiver at Boise and transmit time and error correction back to BMO over a

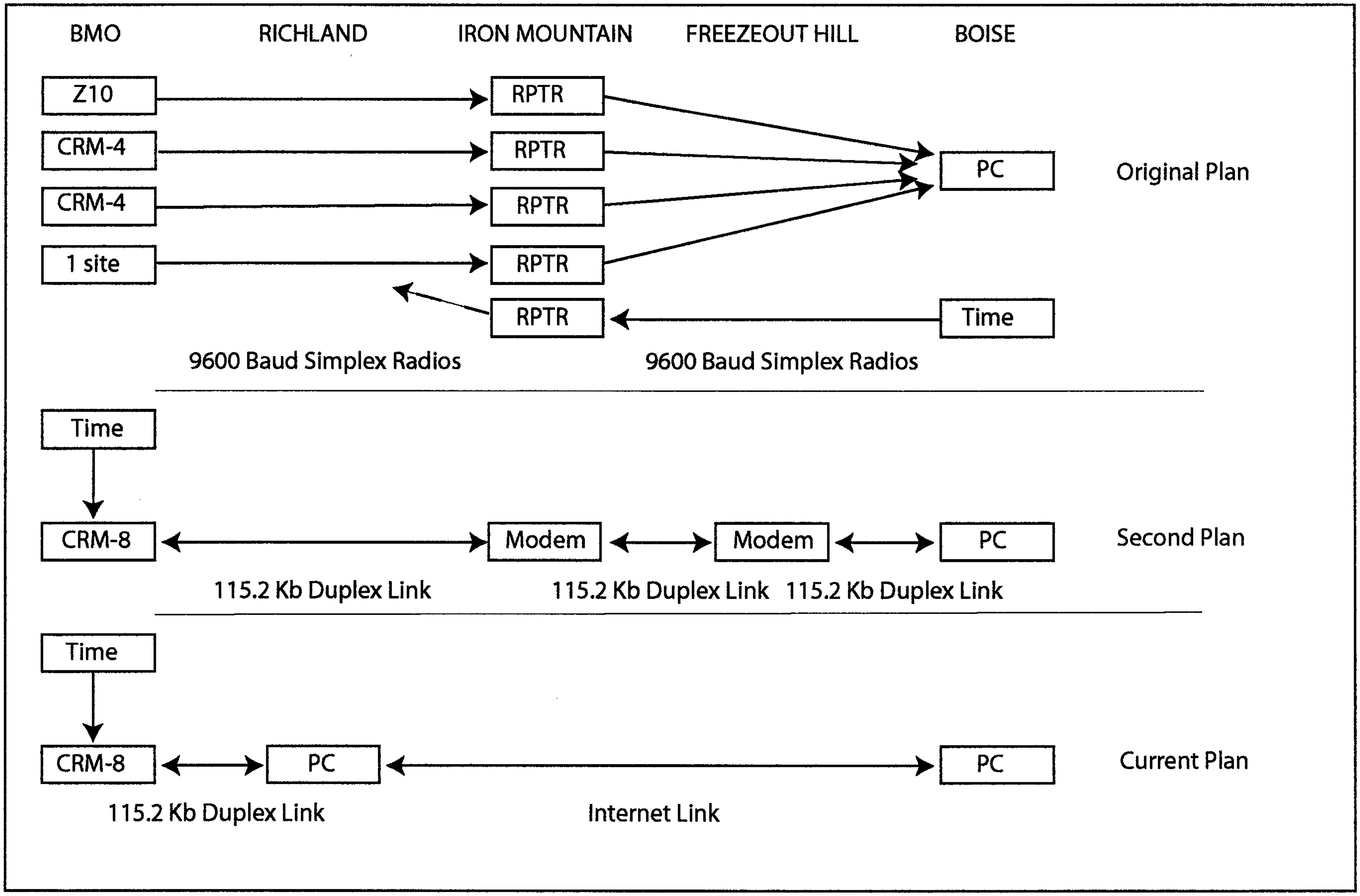

Figure 14. Plans for BMO data collection, wide-area telemetry, and timing. These plans have evolved over time to increase reliability and utilize new data communication technology.

series of repeated radio links. One of the repeat sites was a mountaintop (Iron Mountain) about 60 km ESE of the Observatory. All array elements see Iron Mountain. It was planned to have five 9600 baud simplex radio repeaters at Iron Mountain, one for time and error correction going to BMO from Boise and four for data transmission to Boise. The four transmitter sites at BMO would be Z10, two CRM-4s, and an additional single component site. The total of 13 components matched the original array plan, which did not include the three additional broadband elements later added.

Radio signal and solar insolation tests after the original array equipment had been acquired showed some problems with this original plan. First, radio signal attenuation on the Iron Mountain-Boise link fluctuated over a wide range, requiring higher transmission power at Iron Mountain (and hence higher power consumption) than had been planned. Second, solar power generation at Iron Mountain was much lower than had been anticipated in the months of December and January. Both factors pointed to a need for significantly greater numbers of solar panels and batteries at Iron Mountain, which does not have line AC and which already required a large number of panels and batteries.

At about this time, affordable low power digital modems in the unlicensed 900 MHz frequency band were becoming available. These modems were capable of bi-directional communication at one-way speeds of up to 52.6 K baud. The uncompressed 100 Hz, 24 bit data rate for the original 13 components is 31.2 K baud, and adding the nine broadband components would bring this to 52.8 K baud. Allowing even 20% data compression would allow for added communication overhead. Therefore, a great deal of hardware at Iron Mountain could be replaced by a single modem. To improve the radio link reliability, another repeater modem was planned for an intermediate point between Iron Mountain and Boise, Freezeout Hill.

Following this idea further, it now made sense to concentrate all the data onto a single link from BMO to Iron Mountain. Although farther from Boise, BMO is more accessible than Iron Mountain during the winter due to its lower elevation. It also made sense to place the source of timing synchronization at the array, rather than sending it through several modems and CRMs, each of which adds a wait state and slightly degrades timing accuracy. Accordingly, a central timing transmission site was sought, and a CRM with enough channels to combine all the BMO data sources onto a single link (a CRM-8) was purchased.

A prominent, accessible hilltop near the center of the array (Hill 4088; see Figure 13) was found that had line-of-sight to most elements and Iron Mountain. Those elements that are not line-of-sight are sufficiently close that reliable communication should be possible with sufficiently high-power links and use of directional antennas. Hill 4088 has the additional advantage of being close enough to the center of the array that a CRM-4 could be hardwired into it over an RS-232 link, thus eliminating the need for one radio link.

The selection of Hill 4088 as a central data node and the acquisition of the necessary equipment completed the second principal version of the regional telemetry plan. The local telemetry of the array elements was planned on this basis. A third revision of the regional telemetry plan, that currently being employed, does not require any changes in the local telemetry. This third plan recognizes that the widespread availability of Internet access opens up a means of avoiding the Iron Mountain and Freezeout Hill repeaters altogether, increasing overall reliability. It comes at the cost of requiring an additional PC near BMO at a point near Richland, Oregon, where Internet access is available. The U. S. Geological Survey's Earthworm project is designed for multipoint, multi-access Internet-based data transmission and appears to be a good choice for this plan. It has the added advantage of allowing near-real time, hands-off data access to other interested scientists once the Earthworm system is installed.

Local Data Telemetry

The primary factors in the local data telemetry scheme are the selection of a central data concentration point and the local topography. Once Hill 4088 had been selected as a concentration point, the choice of local telemetry routes was reasonably clear. A CRM-4 at Z9 collects data from Z3, Z6, Z8, and Z9. An identical unit at Z19 collects data from Z2, Z17, Z18, and Z19. Z9 radios its data to Hill 4088, while Z19 is close enough to Hill

4088 that it is hardwired via an RS-232 cable. Z10, which is also BB1, radios the four components from its digitizer to Hill 4088. Z5 and BB2, BB3, and BB4 all radio their data to Hill 4088 via individual links. This uses 7 of the 8 ports on the Hill 4088 CRM-8; the 8th is used to transmit time and error correction signals to all sites via a single radio transmitter.

Array Element Components

The station design has evolved with time. Although our specifications for the digitizers called for an extremely wide operating temperature range and lightning protection, the units received were deficient on both counts. Our original idea had been to put the digitizer, all telemetry components and batteries in a surface box. The plan itself was unrealistic, since virtually no relatively low-cost digitizer could handle the temperature extremes (-25 F to +150 F) that could be expected inside a surface box at the Observatory. Additionally, very low temperatures lead to less efficient battery utilization. Since it was being realized that battery capacity was going to have to be higher than originally planned due to low solar insolation in the winter months, it was realized that a subsurface battery vault was going to be necessary at each site anyway. From there, it was a short step to deciding to place the digitizer and telemetry components inside the same vault as the batteries. The lightning protection requirements had not been fully specified in the original order, and while the digitizers came with the input data lines surge-protected, a more comprehensive system was needed for reliability. BMO is subject to relatively frequent lightning strikes, with the analog station at Z3 having been hit twice in ten years by proximity strikes. While this is not a terrible rate, to reduce array downtime and potentially high repair costs on expensive equipment it seemed worthwhile to protect all cables.

Since it had been decided to bury much of the instrumentation, it is effective in terms of saving maintenance time to have a set of test points at the surface at each site. Reducing the cable clutter in each instrument vault suggested a junction box there. These ideas led to the concept of having two breakout boxes at each array element. A surface breakout box would provide accessible test points and the primary surge protection. A digital breakout box in the instrument vault would handle cable routing and some component placement, as well as providing additional lightning protection. Figure 15 shows the block diagram of a station under this concept.

The breakout boxes were custom-fabricated by VLF Designs of Memphis, Tennessee. Both digital and surface breakout boxes differ according to the complexity of the individual element for which they are intended. CRM sites tend to be the most complex due to the large number of components and cables that must be protected. The simplest versions of the breakout boxes, intended for short period vertical sites, are shown in Figure 16. Figures 17 and 18 show the block diagrams for these breakout boxes. Use of the breakout boxes with their milspec connectors improves the reliability over stations that use terminal strips. At each surface breakout box, it is possible to assess the station state-of-health because power connectors are present and the digitizer can be communicated with using a portable PC with a serial port. Access to seismometer calibration coils is also provided.

Figure 19 shows a generalized cross section of a typical station. The seismometer is placed inside a tank vault, within a waterproof "inner vault" for environmental protection. The seismometer signal travels a few feet to a buried instrument vault that is placed close to the tank vault. The digitizer, digital breakout box, batteries and solar panel regulator are located in this vault. RF cables go to antenna masts that are generally placed 25+ meters from the instrument vault. One mast has a receiver antenna and one a transmit antenna, and both have solar panels mounted on them. Another cable carries the test points to the surface breakout box, which is located in a plastic box on the ground surface above the digital breakout box. Not shown in Figure 19 are the solar panel cabling routes; these go from the masts to the surface breakout box and then down to the buried instrument vault.

While all array elements follow this general plan, the size of the buried instrument vault is greater at some sites that are either more complex (CRM sites) or have higher power requirements. Hill 4088 does not have a seismometer but is the most complicated and

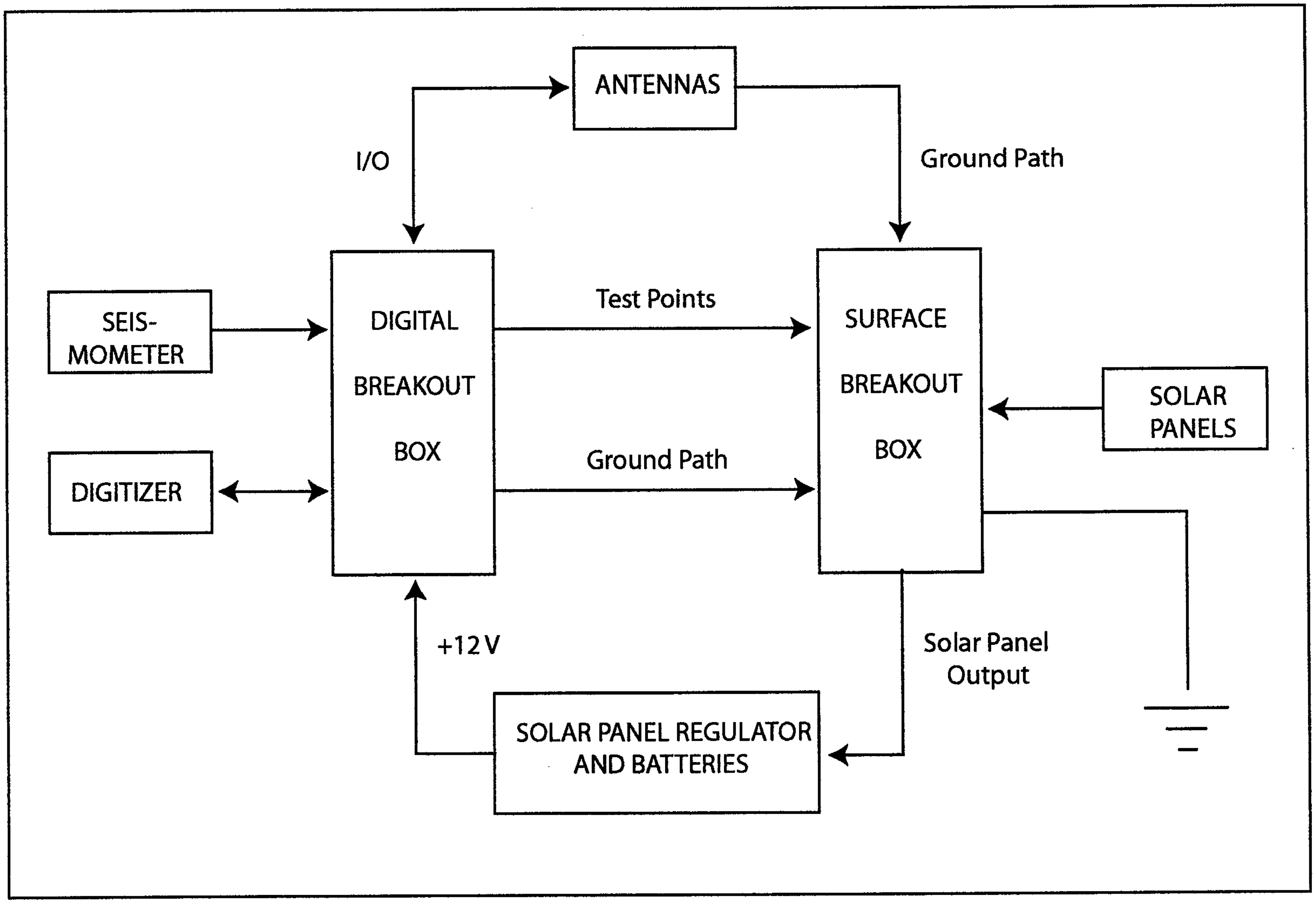

Figure 15. Generalized block diagram for a BMO array element.

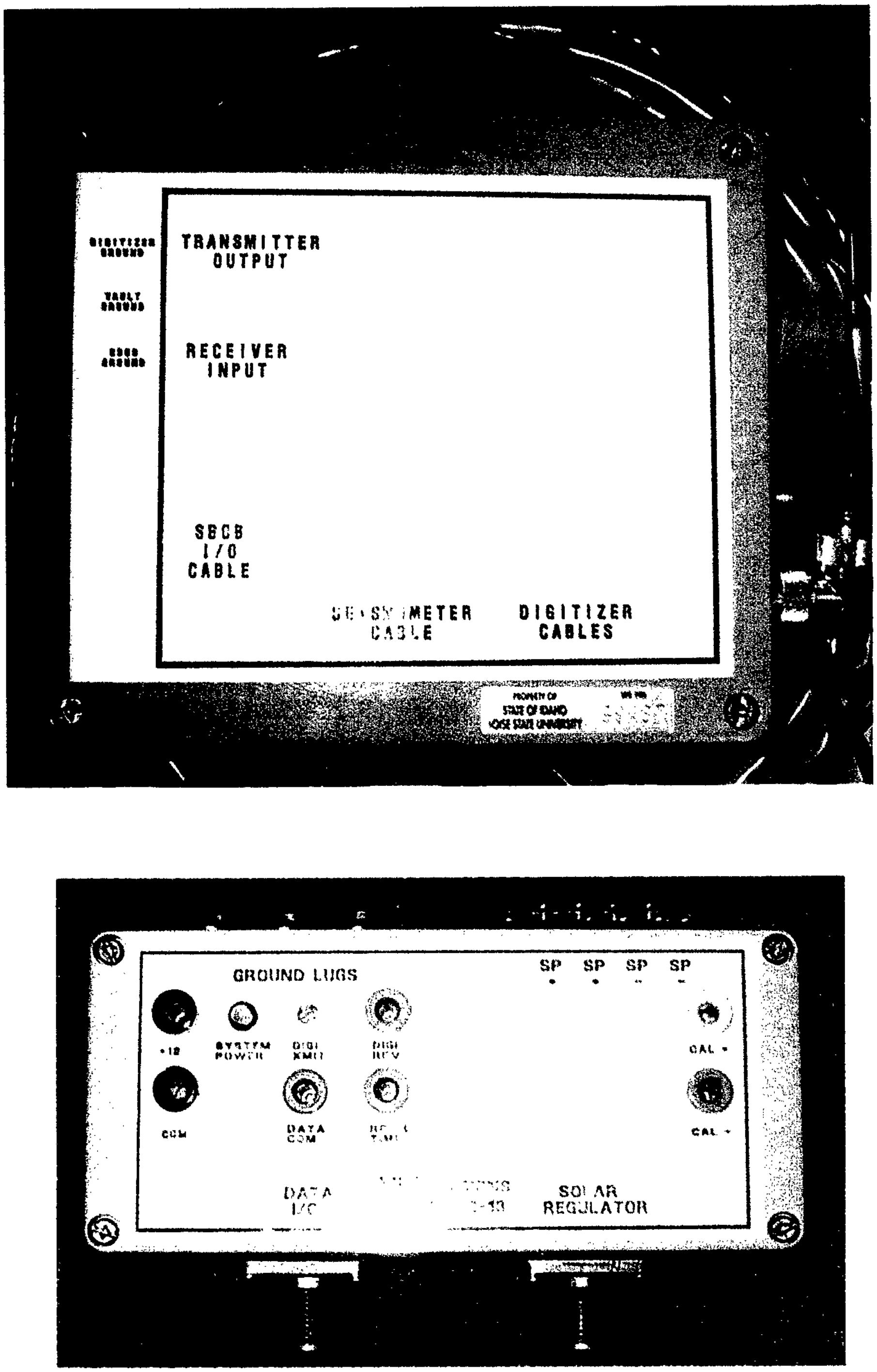

Figure 16. Photos of breakout boxes built for this project. The Digital Breakout Box (top) is buried with the batteries in a vault adjacent to the seismometer vault. The Surface Breakout Box (bottom) is placed in a hard fiberglass box at the ground surface.

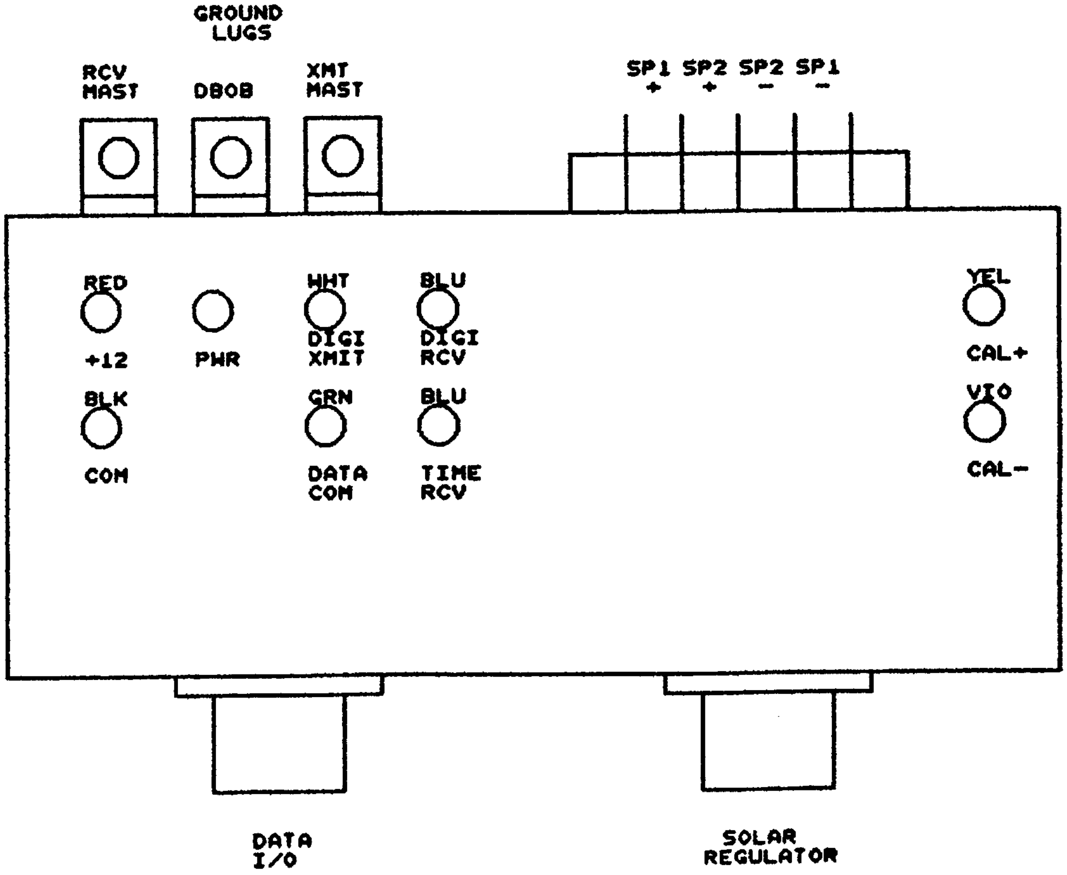

Figure 17. Generalized block diagram for a Surface Breakout Box.

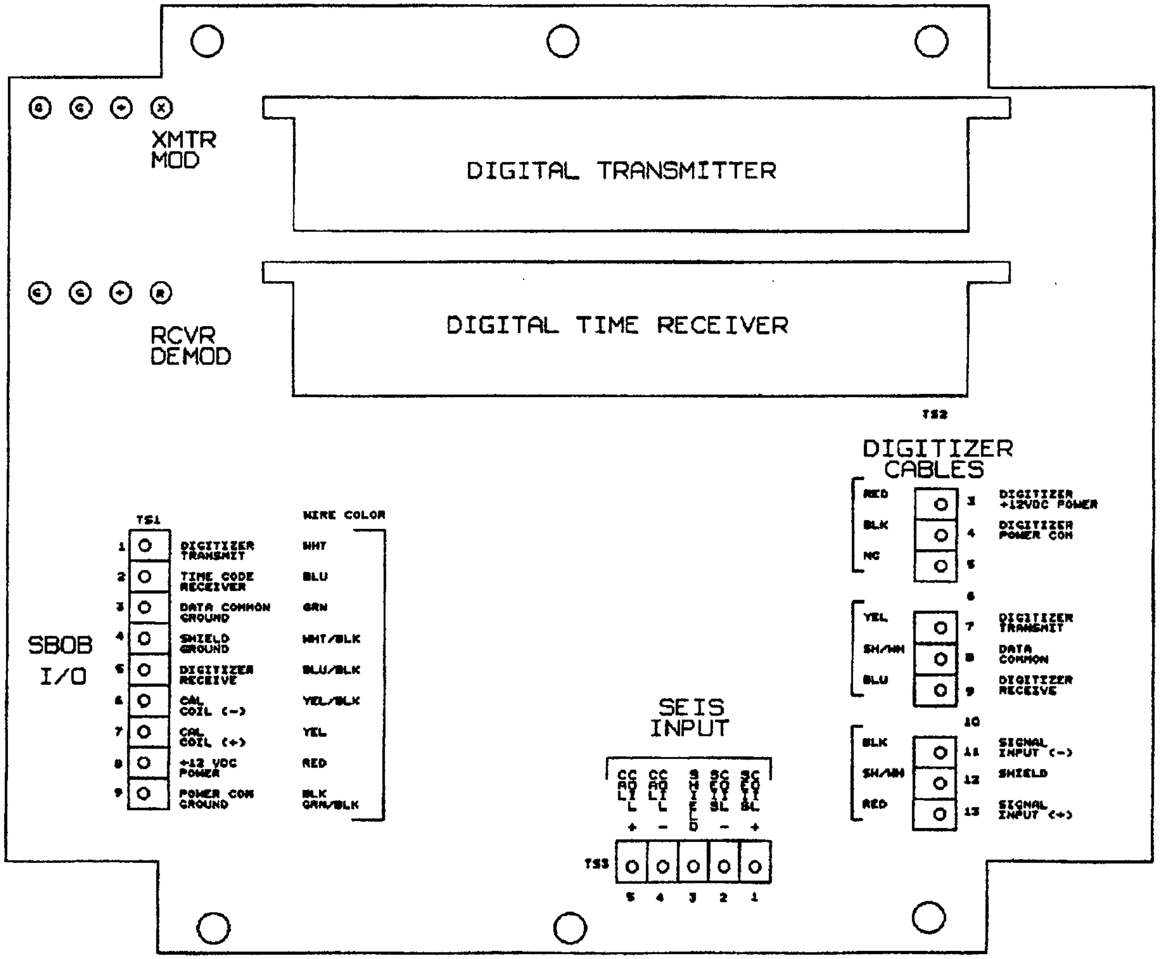

Figure 18. Generalized block diagram for a Digital Breakout Box.

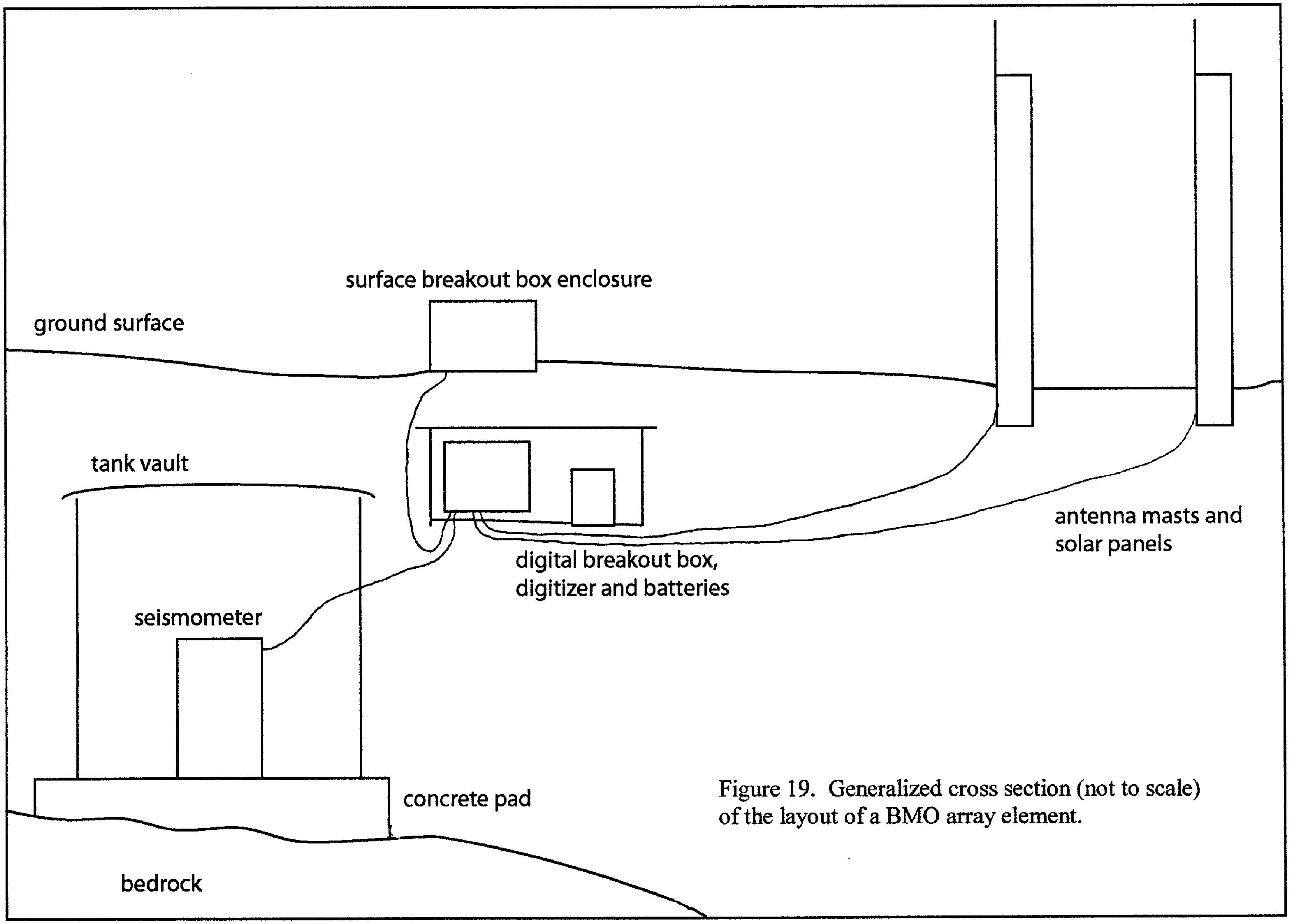

Figure 19. Generalized cross section (not to scale) of the layout of a BMO array element.

power-hungry site due to all the telemetry links it has.

Figure 20 summarizes the local data collection scheme and shows which seismic signals go where. Hill 4088 broadcasts time and error correction to all sites. Time is derived from a local GPS receiver, while the error correction is derived from the first PC the data encounter. Under the current plan, that would be a PC running Earthworm at Richland, Oregon.

Instrumentation

All components are digitized on site with 24-bit resolution and the data streams telemetered via digital RF links to a recording site. Timing derived from a GPS receiver synchronizes data streams at the digitizers. Three portable broad-band seismographs are used to augment the array for special studies.

Seismometers

Two main types of seismometer are used. The short period sites utilize Geotech S-13 short period seismometers, adjusted to natural frequencies of 0.8 Hz and damped at 0.7 critical. These seismometers were chosen because of their long term stability and reliability. GS-13 seismometers would perhaps have been more desirable due to the low level of ground noise prevailing at BMO, but are much more expensive. Furthermore, the purpose of the array is not detection for its own sake but rather study and analysis of signals that are adequately recorded.

The broadband sites utilize Guralp seismometers of three different models. The center array point, Z10, has a CM3T-NSN instrument. This has the widest frequency response, going lower than 0.02 Hz. It is not known how stable the instrument will be at lower frequencies, since these can be strongly dependent on site conditions. The permanent array broadband "ring" utilizes CMG3T-ESP seismometers. These instruments do not have the low frequency response of the CMG3T-NSN instrument, going out only to about 0.1Hz. For most regional events, this should be adequate. Furthermore, unless a vault is carefully prepared it is often difficult to keep the instrument stable at frequencies less

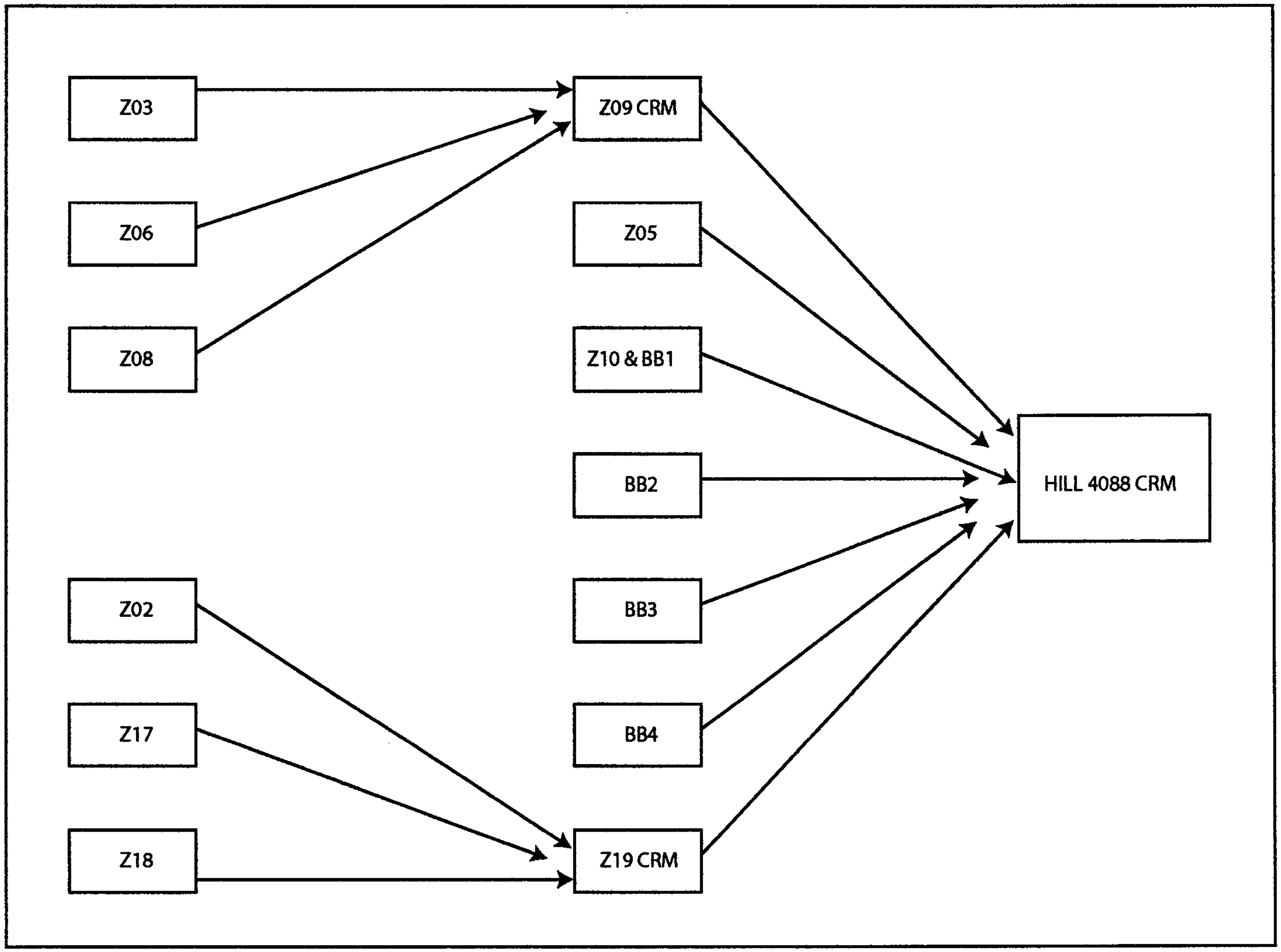

Figure 20. Local BMO data collection block diagram.

than 0.1 Hz. Considering the significant price difference between the standard 3T and the ESP instrument, the ESP seemed like the better choice.

The portable sites use CMG-40T instruments, which were designed for portable use and have a higher intrinsic noise level than the 3T or the ESP instruments. Portable sites do not have well-constructed vaults and are generally not as stable as the permanent sites. Again, the 40T instrument is significantly less expensive than either of the other two broadband instruments, so would seem to be a reasonable compromise given the operating conditions and study objectives.

Digitizers

The project purchased two models of Guralp digitizers for the permanent sites and one model of Reftek digitizers for the portable sites. The Guralp digitizers come in stand-alone configurations using one or four components (DM24/1 and DM24/4) and in an internally mounted configuration inside the CMG3T-ESP seismometer housing. The Reftek 72A-07 digitizers are that company's standard portable configuration used in the IRIS/Pascal program. All digitizers were specified to be low power 24-bit models capable of sampling at 100 Hz. In practice, all can digitize at a wide range of selectable data rates.

The stand-alone Guralp digitizers have proven to be the Achilles' heel of this project. Unfortunately, they have never worked properly, even though they have been returned to the manufacturer several times. A variety of causes seems to be responsible, which ultimately suggests the cause is poor design and engineering. When they work, the data look good and the software provided to control them seems quite good. However, it is difficult to find units that will work on the lab bench for as long as 24 hours. After expending literally thousands of hours on tests and attempts to isolate particular components that were bad, the author of this report concluded that it was impossible to make more than 3 or 4 of the ten standalones work reliably. This view was echoed by a seismological instrument consultant whom we hired to troubleshoot the standalone units.

There are three modes of failure of the Guralp DM24 digitizers. One is a complete hang. The second is dropped data blocks of varying length. The third is high-amplitude, high frequency hash being output continuously. The failure mode does not seem to be tied to a particular unit, with most of them having failed in at least two ways at some point during testing.

The internal digitizers in the CMG3T-ESP units appear better. Extensive testing showed these units were not as quiet as the DM24 standalone units, probably because of our anti-causal front end filter requirement for the standalone units. Dropped data blocks occurred in tests, including some that were quite lengthy. This may have been related to a power saving mode in the test computer upon which the data were being directly recorded; better results have been obtained in tests of up to several days' duration since the power-saving mode was switched off. Figure 21 shows one of several local earthquakes recorded during the tests. Overall this is a nice recording and allows at least some hope for future results.

Unfortunately, other tests with the CMG3T-ESP units purchased showed they were not capable of internal triggering, as advertised. This capability is important because it is useful to have detected events digitized at higher sample rates than background noise; trying to put all data through the communications pipeline at high sample rates uses a great deal of bandwidth. The manufacturer's representative suggested this problem was unique to the three Boise State instruments. It is intended to return the units for an upgrade.

We have had less experience with the Reftek units, since testing and troubleshooting the Guralp digitizers has occupied far more time than was available. Huddle tests with the CMG-40T seismometers and the Reftek digitizers have been good, other than for the widely known tendency for the Guralps to track poorly in frequency bands outside their advertised bandwidth.

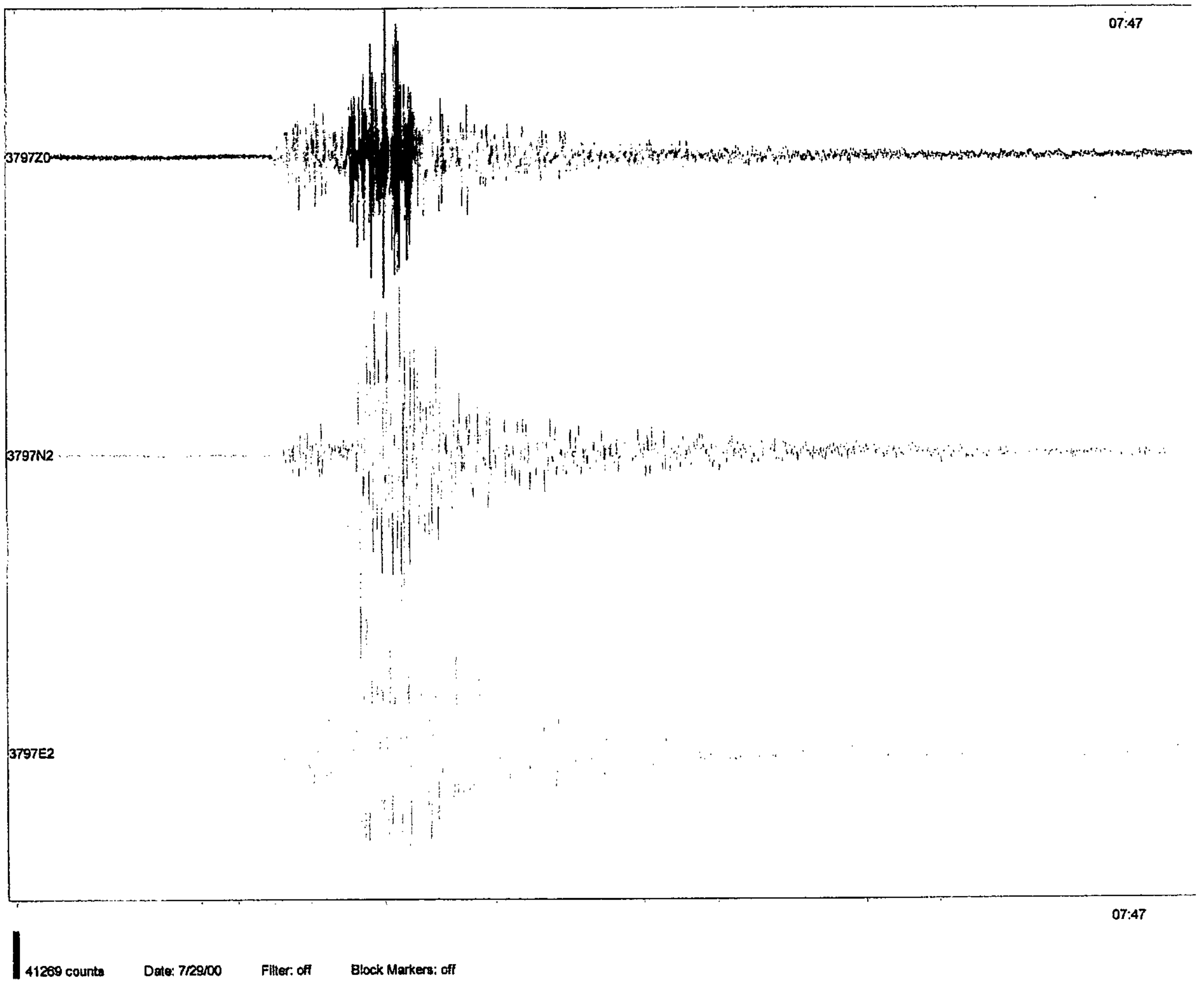

Figure 21. Local earthquake (magnitude about 2) recorded during test of Guralp CMG-3-ESP broadband seismometer. The time axis is about 32 seconds in length. The vertical component is at the top, followed by the north-south and east-west components. The bar at the lower left of the figure represents an amplitude of 41,269 digital counts.

Problems Encountered

A great many problems have unfortunately been encountered in the course of this project. The most serious by far is the failure of Digital Technology Associates and Guralp Systems Limited to provide standalone digitizers for the short period array and center element that function for more than a few days. The delays that this failure has induced in the project, the loss of about two thousand hours of Principal Investigator time in testing and troubleshooting the digitizers, and the downstream effects the delays have caused on this and other projects have been frustrating in the extreme. It is difficult to believe that these companies remain in business with this unbelievably bad level of performance.

Throughout this project, our assumption was that the Guralp digitizers would work at some point and therefore the project could be pursued as originally planned. In retrospect, the best decision would have been to write off the Guralp standalone digitizers as worthless and unrepairable early in the project. Since prices on digitizers built by other vendors have been falling, it is likely that parts of the budget could have been changed to allow purchase of these. However, we were reluctant to sacrifice so much expense and also worried about the added power requirements of other vendors' digitizers, since power was becoming a serious concern. Consequently, we remained focused upon trying to get the Guralp standalone digitizers to work. Since the Guralp CMG3-ESP packages and Refteks do work, we should have pursued the portions of the project utilizing these. That still would have left us deprived of the central array broadband element, and certainly would have involved giving up completely on the portions of the studies using the short period array, since so much time had been lost on the testing that there was not enough to complete the array and do the broadband studies.

The delays had serious side effects. Since the Principal Investigator has an entirely soft money position, the overruns in time on the BMO project impeded progress on other projects. Furthermore, since new projects using BMO data could not be proposed to funding agencies without a working array, the PI was forced to seek a number of smaller, more time-intensive projects to remain at Boise State. This scattering of effort eventually created a severe overwork situation, with resultant delays in completing work on most projects. In addition, personnel and students who were hired to work on BMO data at best worked upon testing and installation problems.

The long delays resulted in equipment going obsolete or failing. Computers, monitors, hard drives, and laser printers purchased for the project or else supplied by other projects eventually failed and needed to be replaced. The field vehicle owned by the seismic program, a 1986 Bronco, developed an undiagnosed problem in 1999 that made it impossible to use the vehicle safely for long trips. Although the original budget had called for lease of a vehicle, when we attempted this we ran into major obstructions created by the Boise State purchasing department. After an excessive amount of time had been wasted upon attempting to satisfy its requirements, it was felt necessary to divert the funds provided for the lease into instrumentation, as will be explained below.

We had originally arranged with Lawrence Livermore for long term loan of most of the S13 seismometers needed for the short period array. In 1998, we were informed that this loan was unlikely to ever happen. Therefore, funds were diverted from the vehicle lease category so that 7 S13 seismometers could be purchased.

Some other problems encountered during the project were two fires on our telemetry receive site (set by incompetent roofing workers) which resulted in smoke damage, two major hacker attacks on project computers, and the largely unrecoverable crash of a multi-CPU disk mirroring system on which most work for 1999 and 2000 was stored.

The PI realizes at this point that although the array concept and implementation plan was reasonable, it was not robust enough to handle major delays and increases in effort required by the circumstances that developed. Most of the additional effort required had to come from the PI, and the level required was injurious to a delicate balance of effort spread among several projects. In other words, it is likely that things could have been accomplished in a reasonable time interval had there not been the delay in getting working digitizers, or had it been realized early in the project that the Guralp standalone digitizers were a waste of time. The lack of a contingency plan was regrettable.

Status of Project

Despite the many difficulties encountered, the PI still desires to complete the array and do the research. A strategy of obtaining some funding directly from Boise State is being pursued and is looking like it may succeed. The PI is also winding up most of his other projects that have been going on simultaneously. He will be looking to submit an equipment proposal to NSF later this year for new digitizers, if efforts to get Guralp to completely replace the standalone digitizers with working current models fail. Although major setbacks have been experienced, it is still believed that the scientific value of the results of a BMO installation remains high and continued effort is therefore worthwhile.

Conclusions

A research seismic array is being installed at Blue Mountains Observatory in northeastern Oregon. This array will take advantage of widespread seismicity and the accurate locations determined by local monitoring networks to study the accuracy of source location at regional distances over geologically complex paths. Performance of the research has been delayed due to problems in obtaining usable digitizers. However, results from the array will likely provide important clues for strategies to maximize location accuracy in the presence of complicated geology.