PNNL-11557-19

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Annual Hanford Seismic Report for Fiscal Year 2001

PNNL Seismic Monitoring Team

November 2001

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
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Printed in the United States of America

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Pacific Northwest National Laboratory Seismic Monitoring Team

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

Hanford Seismic Monitoring provides an uninterrupted collection of high-quality raw and processed seismic data from the Hanford Seismic Network for the U.S. Department of Energy and its contractors. Hanford Seismic Monitoring also locates and identifies sources of seismic activity and monitors changes in the historical pattern of seismic activity at the Hanford Site. The data are compiled, archived, and published for use by the Hanford Site for waste management, Natural Phenomena Hazards assessments, and engineering design and construction. In addition, the seismic monitoring organization works with the Hanford Site Emergency Services Organization to provide assistance in the event of a significant earthquake on the Hanford Site.

The Hanford Seismic Network and the Eastern Washington Regional Network consist of 41 individual sensor sites and 15 radio relay sites maintained by the Hanford Seismic Monitoring staff.

For the Hanford Seismic Network, there were 1,706 triggers during fiscal year 2001. Of these triggers, 691 were earthquakes.

Ninety-eight earthquakes were located in the Hanford Seismic Network area. Twenty-eight occurred in the Columbia River basalt, 55 were earthquakes in the pre-basalt sediments, and 15 were earthquakes in the crystalline basement. Geographically, 79 earthquakes occurred in swarm areas, 5 earthquakes were associated with major structures, and 14 were random events.

The February 28, 2001 Nisqually earthquake triggered the Hanford Strong Motion Accelerometers during the second quarter of fiscal year 2001. There were no other earthquake triggers during the fiscal year.

Acronyms

BWIP	Basalt Waste Isolation Project
CRBG	Columbia River Basalt Group
DMIN	closest distance from the epicenter to a station
DOE	U.S. Department of Energy
ETNA	strong motion accelerometer manufactured by Kinemetrics
EWRN	Eastern Washington Regional Network
FY	fiscal year
GAP	largest gap in event-station azimuth distribution
GPS	Global Positioning System
HSN	Hanford Seismic Network
M_c	Coda Length Magnitude
M_L	Local Magnitude
M_w	Moment Magnitude
NP	number of p-wave and s-wave phases
NS	number of stations
PNNL	Pacific Northwest National Laboratory
RAW	Rattlesnake Mountain-Wallula Alignment
RMS	root-mean-square residual
SMA	strong motion accelerometer
USGS	United States Geological Survey
UTC	Universal Time, Coordinated
UW	University of Washington
WG4	Wallula Gap 4 site
WHC	Westinghouse Hanford Company
YPT	Yellepit site

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1.0 Introduction

This report is the annual Hanford seismic activity report for fiscal year (FY) 2001. The report includes earthquake activity that occurred on the Hanford Site and vicinity that occurred between October 1, 2000 and September 30, 2001 and our geologic interpretation of the sources of the earthquakes.

1.1 Mission

The principal mission of Hanford Seismic Monitoring at the Hanford Site is to insure compliance with DOE Order 420.1, "Facility Safety and DOE Order G 420.1-1," Section 4.7, "Emergency Preparedness and Emergency Communications." DOE Order 420.1 establishes facility safety requirements related to nuclear safety design, criticality safety, fire protection, and natural phenomena hazards mitigation. For seismic monitoring, this order states:

> 4.4.5 Natural Phenomena Detection.
> *Facilities or sites with hazardous materials shall have instrumentation or other means to detect and record the occurrence and severity of seismic events.*

The Seismic Monitoring Project supports Hanford Site emergency services organizations in complying with DOE Order G 420.1-1, Section 4.7, "Emergency Preparedness and Emergency Communications," by providing assistance in the event of an earthquake on the Hanford Site.

In addition, seismic monitoring provides an uninterrupted collection of high-quality raw seismic data from the Hanford Seismic Network (HSN) located on and around the Hanford Site, and provides interpretations of seismic events from the Hanford Site and vicinity. Hanford Seismic Monitoring locates and identifies sources of seismic activity, monitors changes in the historical pattern of seismic activity at the Hanford Site, and builds a "local" earthquake database (processed data) that is permanently archived. The focus of this report is the precise location of earthquakes proximal to or on the Hanford Site, specifically between 46 degrees and 47 degrees north latitude and between 119 degrees and 120 degrees west longitude. Data from the Eastern Washington Regional Network (EWRN) and other seismic networks in the northwest provide the Seismic Monitoring Project with necessary regional input for the seismic hazards analysis at the Hanford Site. These seismic data are used to support Hanford Site contractors for waste management activities, Natural Phenomena Hazards assessments, and engineering design and construction.

1.2 History of Seismic Monitoring at Hanford

Seismic monitoring at the Hanford Site was established in 1969 by the United States Geological Survey (USGS) under a contract with the U.S. Atomic Energy Commission. In 1975, the University of Washington (UW) assumed responsibility for the network and subsequently expanded it. In 1979, the Basalt Waste Isolation Project (BWIP) became responsible for collecting seismic data for the Hanford Site as part of site characterization activities. Rockwell Hanford Operations, followed by Westinghouse Hanford

Company (WHC), operated the local network and were the contract technical advisors for the EWRN operated and maintained by UW. Funding ended for BWIP in December 1988. Seismic monitoring and responsibility for the UW contract were then transferred to WHC's Environmental Division. Maintenance responsibilities for the EWRN were also assigned to WHC who made major upgrades to EWRN sites.

Effective October 1, 1996, seismic monitoring was transferred to the Pacific Northwest National Laboratory (PNNL).[1] Seismic monitoring is part of PNNL's Applied Geology and Geochemistry Group, Environmental Technology Division.

The Hanford Strong Motion Accelerometer (SMA) network was constructed during 1997 and came on line in May 1997. It operated continuously until September 30, 1997 when it was mothballed due to lack of funding. Funding was restored on October 1, 1998 by joint agreement between the U.S. Department of Energy (DOE) and PNNL. Operation of the free-field sites resumed on November 20, 1999 and has operated continuously since that time.

1.3 Documentation and Reports

The Seismic Monitoring Project issues quarterly reports of local activity, an annual catalog of earthquake activity on and near the Hanford Site, and special-interest bulletins on local seismic events. The annual catalog includes the fourth quarter report for the fiscal year. Hanford Seismic Monitoring also provides information and special reports to other functions as requested. Earthquake information provided in these reports is subject to revisions if new data become available. In addition, an archive of all seismic data from the HSN is maintained by PNNL.

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[1] Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy.

2.0 Network Operations

2.1 Seismometer Sites

The seismic monitoring network consists of two designs of equipment and sites: seismometer sites and strong motion accelerometer (SMA) sites. Seismometer sites are designed to locate earthquakes and determine their magnitude and hypocenter location. SMA sites are designed to measure ground motion.

The HSN and the EWRN consist of 41 sensor sites. Most sites are in remote locations and require solar panels and batteries for power. The HSN uses 21 sites (Table 2.1 and Figure 2.1) and the EWRN uses 36 sites (Table 2.2 and Figure 2.2); both networks share 16 sites. The networks have 45 combined data channels because Gable Butte and Frenchman Hills East are three-component sites, each consisting of one vertical, one north-south horizontal, and one east-west horizontal data channel. Both networks use 15 additional telemetry relay sites. Data from all sites or relays are transmitted to the Sigma V building, Richland, Washington.

2.1.1 Station Maintenance

The HSN's maintenance records for the seismic sensor and relay sites are filed in the Hanford Seismic Monitoring office, Sigma V Building, Richland Washington.

2.1.2 Data Acquisition

The signals from the seismometer sites are monitored for changes in signal amplitude that are expected from earthquakes. The seismic network is subdivided into spatial groupings of stations that are monitored for nearly simultaneous amplitude changes, resulting in triggering a permanent recording of the events. The groupings and associated weighting schemes are designed to allow very small seismic events to be recorded and to minimize false triggers. Events are classified as locals (south-central Washington near the Hanford Site), regionals (Western U.S. and Canada), and teleseisms (from farther distances around the world). Local and regional events are usually earthquakes, but quarry and mining explosions are also recorded. Quarry and mining explosions can usually be identified from wave characteristics, time of day, and through confirmation with local government agencies and industries. Frequently, military exercises at the U.S. Army's Yakima Training Center produce a series of acoustic shocks that unavoidably trigger the recording system. Sonic booms and thunder also produce acoustic signals that trigger the recording system.

A PC-based system adapted from a USGS program and the UW system was implemented at Hanford during FY 1999. One new system has been in continuous operation since January 6, 1999. A second, backup PC system was installed in mid-March 1999, and both new systems have been running in parallel since that time. Although the two new systems are practically identical, there is enough granularity in the

Table 2.1. Seismic Stations in the Hanford Seismic Network

The first column is the three-letter seismic station designator. The latitude and longitude, elevation above sea level in meters, and the full station name follow this. The locations of the stations are all in Washington; locations were derived from a Global Positioning System (GPS).

Station	Latitude Deg.Min.N	Longitude Deg.Min.W	Elevation (m)	Station Name
BEN	46N31.13	119W43.02	340	Benson Ranch
BRV	46N49.12	119W59.47	920	Black Rock Valley
BVW	46N48.66	119W52.99	670	Beverly
CRF	46N49.50	119W23.22	189	Corfu
ET3	46N34.64	118W56.25	286	Eltopia Three
*FHE	46N57.11	119W29.82	455	Frenchman Hills East
*GBB	46N36.49	119W37.62	177	Gable Butte
GBL	46N35.92	119W27.58	330	Gable Mountain
H2O	46N23.75	119W25.38	158	Water
LOC	46N43.02	119W25.85	210	Locke Island
MDW	46N36.79	119W45.66	330	Midway
MJ2	46N33.45	119W21.54	146	May Junction Two
OT3	46N40.14	119W13.98	322	Othello Three
PRO	46N12.73	119W41.15	550	Prosser
RED	46N17.92	119W26.30	366	Red Mountain
RSW	46N23.67	119W35.48	1,045	Rattlesnake Mountain
SNI	46N27.85	119W39.60	312	Snively Ranch
WA2	46N45.32	119W33.94	244	Wahluke Slope
WIW	46N25.76	119W17.26	128	Wooded Island
WRD	46N58.20	119W08.69	375	Warden
YPT	46N02.93	118W57.73	325	Yellepit

* Three-component station.

trigger timing that they sometimes record exclusive events. In nearly all cases, these exclusive triggers are "false" triggers, not earthquakes or quarry blasts (i.e., from acoustic sources). The remainders are from barely detectable, small signals from regional and teleseismic earthquakes.

The types and numbers of triggers recorded in the second and third quarters of FY 2001 by the seismic acquisition system are summarized in Table 2.3.

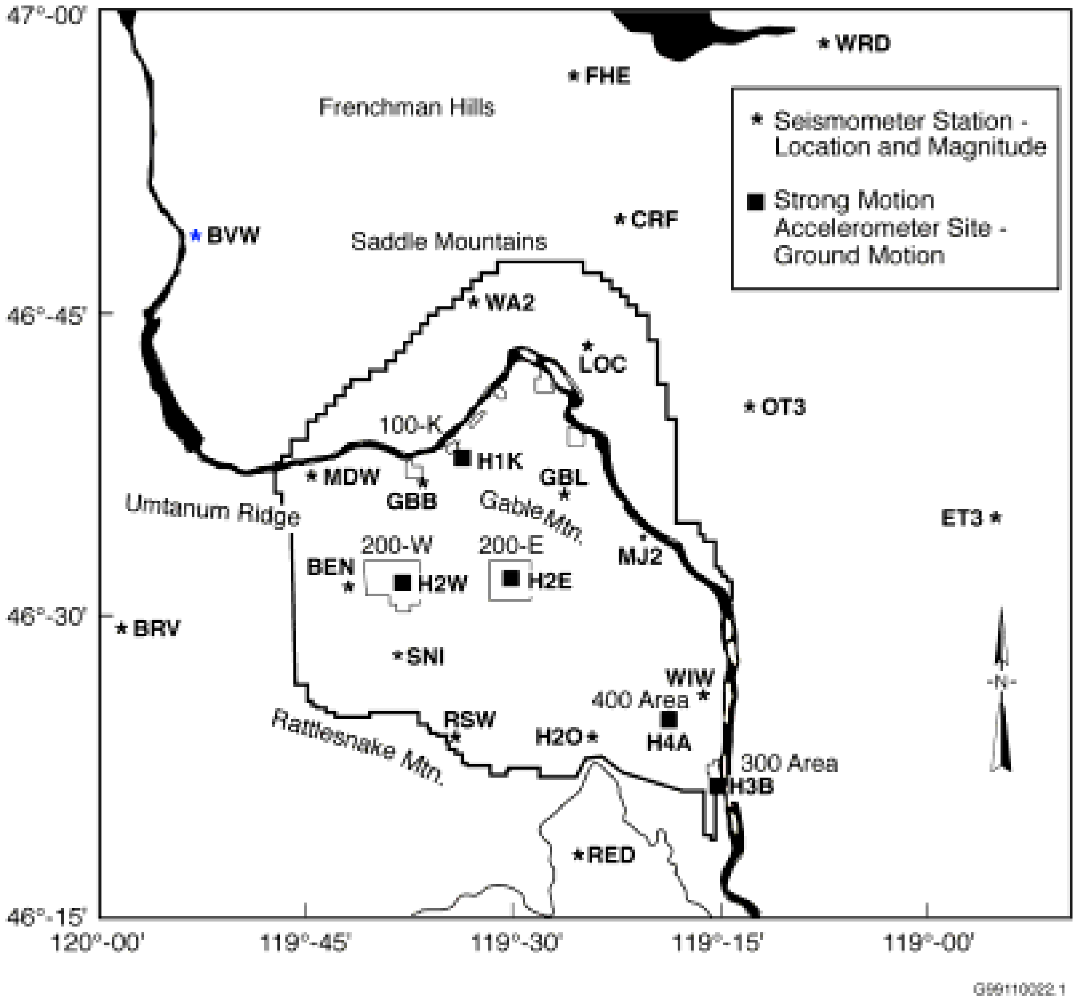

Figure 2.1. Locations of Seismograph Stations and Strong Motion Accelerometer Sites in the Hanford Seismic Network (see Table 2.1 for description of locations). Locations for Prosser (PRO) and Yellepit (YPT) are not shown. See Figure 2.2 for the locations of those sites.

2.2 Strong Motion Accelerometer Sites

2.2.1 Location

The Hanford SMA network consists of five free-field SMA sites (see Figure 2.1) (Table 2.4). There is one free-field SMA located in each of the 200 Separations Areas, one adjacent to the K Basins in the 100-K Area, one adjacent to the 400 Area where the Fast Flux Test Reactor is located, and one at the south end of the 300 Area.

The instrumentation locations were chosen based on two criteria (Moore and Reidel 1996): 1) instruments should be located in areas having the highest densities of people and 2) instruments should be

Table 2.2. Seismic Stations in the Eastern Washington Regional Network

The first column is the three-letter seismic station designator. The latitude and longitude, elevation above sea level in meters, and the full station name follow this. The locations of the stations are all in Washington unless otherwise indicated; locations were determined from a Global Positioning System (GPS).

Station	Latitude Deg.Min.N.	Longitude Deg.Min.W.	Elevation (m)	Station Name
BRV	46N29.12	119W59.47	920	Black Rock Valley
BVW	46N48.66	119W52.99	670	Beverly
CBS	47N48.26	120W02.50	1,067	Chelan Butte, South
CRF	46N49.50	119W23.22	189	Corfu
DPW	47N52.25	118W12.17	892	Davenport
DY2	47N59.11	119W46.28	890	Dyer Hill Two
ELL	46N54.58	120W33.98	789	Ellensburg
EPH	47N21.38	119W35.76	661	Ephrata
ET3	46N34.64	118W56.25	286	Eltopia Three
ETW	47N36.26	120W19.94	1,477	Entiat
*FHE	46N57.11	119W29.82	455	Frenchman Hills East
*GBL	46N35.92	119W27.58	330	Gable Mountain
LNO	45N52.31	118W17.11	771	Lincton Mountain, Oregon
LOC	46N43.02	119W25.85	210	Locke Island
MDW	46N36.79	119W45.66	330	Midway
MJ2	46N33.45	119W21.54	146	May Junction Two
MOX	46N34.64	120W17.89	501	Moxee City
NAC	46N43.99	120W49.42	728	Naches
NEL	48N04.21	120W20.41	1,500	Nelson Butte
OD2	47N23.26	118W42.58	553	Odessa Two
OT3	46N40.14	119W13.98	322	Othello Three
PAT	45N52.92	119W45.14	262	Paterson
PRO	46N12.73	119W41.15	550	Prosser
RSW	46N23.67	119W35.48	1,045	Rattlesnake Mountain
SAW	47N42.10	119W24.03	701	St. Andrews
TBM	47N10.20	120W35.88	1,006	Table Mountain
TRW	46N17.32	120W32.31	723	Toppenish Ridge
TWW	47N08.29	120W52.10	1,027	Teanaway
VT2	46N58.04	119W58.95	1,270	Vantage Two
WA2	46N45.32	119W33.94	244	Wahluke Slope Two
WAT	47N41.92	119W57.24	821	Waterville
WIW	46N25.76	119W17.26	128	Wooded Island
WRD	46N58.20	119W08.69	375	Warden
YA2	46N31.60	120W31.80	652	Yakima Two
YPT[(a)]	46N02.93	118W57.73	325	Yellepit

* Three-component station.
(a) YPT replaced WG4 in FY 2000.

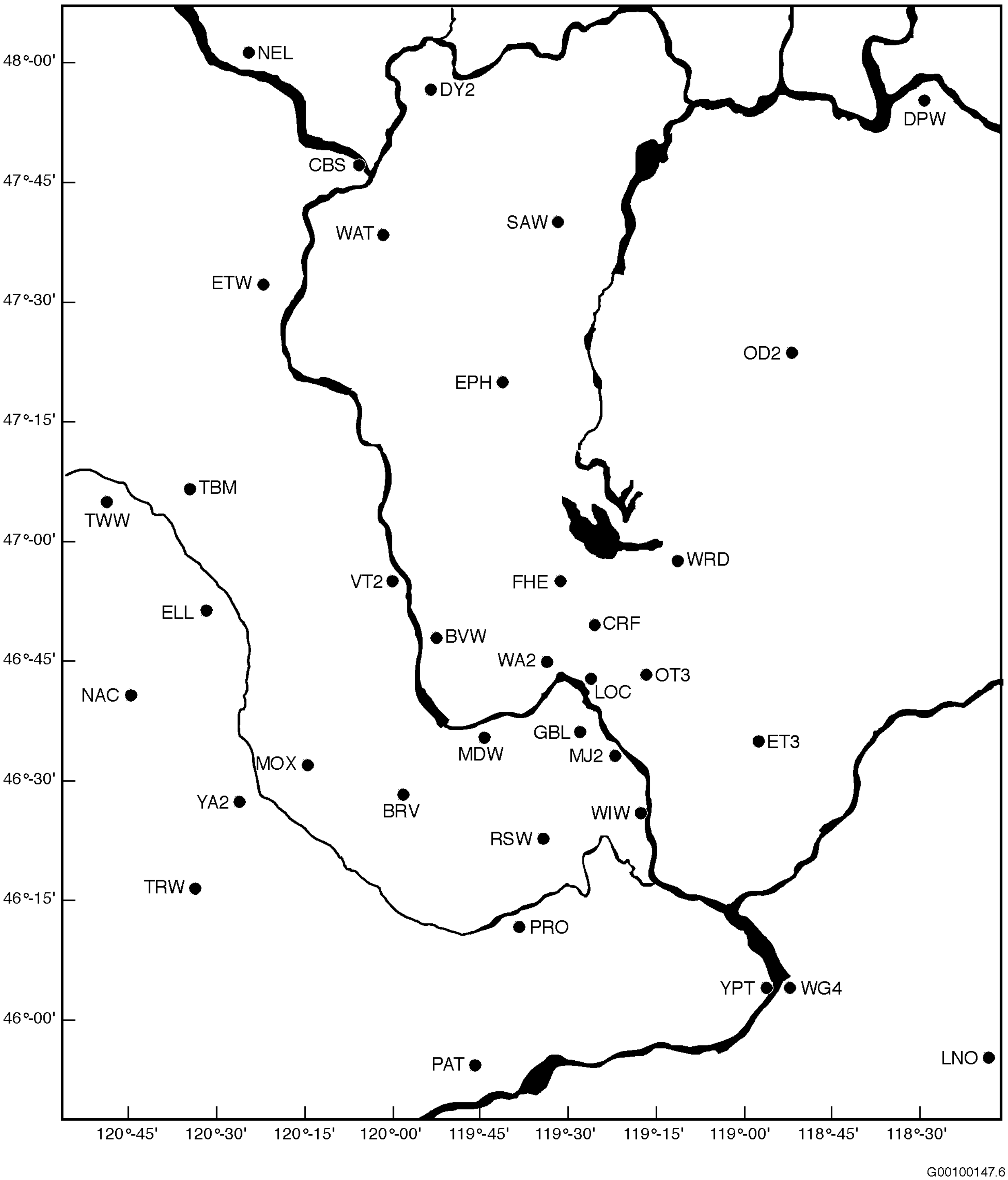

Figure 2.2. Locations of Seismograph Stations in the Eastern Washington Regional Network (see Table 2.2 for location descriptions). YPT replaced site WG4.

Table 2.3. Acquisition System Recorded Triggers

Event Type	First Quarter	Second Quarter	Third Quarter	Fourth Quarter	Total	Description
South-central Washington	61	30	31	23	145	Seismic events in southcentral Washington and northcentral Oregon that triggered the HSN.
Regional	35	41	58	79	213	Seismic events in the Western United States and Canada.
Teleseism	80	82	101	70	333	Seismic events at farther distances from around the world.
Total Earthquake Events	176	153	190	172	691	Total number of earthquake triggers.
Total Triggers on Primary System	477	333	587	309	1,706	Total number of triggers examined. Includes all sources of triggers.
Explosions	2	3	1	1	7	Quarry blasts, typically, within the 46-47 degrees north latitude and 119-120 degrees west longitude.
Local Earthquakes	45	19	18	16	98	Seismic events within the 46-47 degrees north latitude and 119-120 degrees west longitude.

Table 2.4. Free-Field Strong Motion Accelerometer Sites

Site	Site ID	Location	Latitude Longitude Elevation
100-K Area	H1K	South of K Basins outside 100 Area fence lines.	46° 38.51' 119° 35.53' 152 m
200 East Area	H2E	East of B Plant; north of 7th Street and east of Baltimore Avenue.	46° 33.58' 119° 32.00' 210 m
200 West Area	H2W	Northeast of Plutonium Finishing Plant (PFP); north of 19th street and east of Camden Avenue.	46° 33.23' 119° 37.51' 206 m
300 Area	H3A	South end of 300 Area inside fence lines. (NE 1/4, SW 1/4, Sec. 11, T10N, R28E).	46° 21.83' 119° 16.55' 119 m
400 Area	H4A	500 feet from fence line on east side of facility and north of parking area).	46° 26.13' 119° 21.30' 171 m

located in areas having hazardous facilities. Some of the highest concentrations of employees at Hanford are 200 East and West Areas, 100-K Area, the Fast Flux Test Facility (400 Area), and the 300 Areas. The 200 Areas are where all high-level radioactive waste from past processing of fuel rods has been stored in single-shell and double-shell tanks. In addition, the Canister Storage Facility that will hold encapsulated spent fuel rods is in 200 East Area. The 100-K Area contains the K Basins where all spent fuel rods from the N Reactor are stored prior to encapsulation. The Cold Vacuum Drying Facility, located in the 100-K Area, is used to encapsulate spent fuel rods from the K Basins prior to shipment to the Canister Storage Building in 200 East Area.

2.2.2 Site Design

All free-field SMA sites consist of two 30-gallon drums set in the ground such that the base of the drum is about 1 meter below the surface. One drum houses only the SMA; the other drum houses the electronics and communications equipment. A distance of 1 to 2.16 meters (40 to 85 inches) separates the drum containing the electronics and communications equipment from the SMA drum; a sealed conduit connects the two drums.

The SMA instruments are three-component units consisting of one vertical, one north-south horizontal, and one east-west horizontal data channel. The instruments in use are the ETNA™ system (registered trademark of Kinemetrics, Inc.). Instrument specifications are summarized in Table 2.5. In

Table 2.5. Instrument Parameters for the Kinemetrics ETNA System in the Hanford SMA Network

Parameter	Value or Range
Sensor	
Type	Tri-axial Force Balance Accelerometer orthogonally oriented with internal standard
Full-Scale	±2 g[(a)]
Frequency Range	0-50 Hz
Damping	Approximately 70% critical [(a)]
Data Acquisition	
Number of Channels	3
Sample Rate	18-bit resolution @ 200 samples/second
Digital Output	Real-time, RS-232 Output Stream
Seismic Trigger	
Filter	0.1 - 12.5 Hz
Trigger level	0.05% - 0.20% g [(b)]
Alarm (call-out) Threshold	4.00% g
Pre-event Memory	10 sec
Post-event Time	40 sec

(a) Setting is dependent on instrument calibration.
(b) See Section 2.2.4 for discussion of trigger thresholds.

addition to the three-component SMAs, each ETNA SMA unit contains a computer, Global Positioning System (GPS) receiver and a modem (Figure 2.3). These systems are housed in a watertight box.

Two 100 amp-hour batteries that are housed in the equipment and communications drum (see Figure 2.3) power the SMAs. The batteries are charged by four solar panels; a regulator is located between the solar panels and the batteries.

The communication link between the SMAs and the data analysis computer system housed in the Sigma V building is a cellular telephone/modem connection. The built-in modem in the SMA allows the system to use a cellular telephone to call an accelerometer or for the accelerometer to call out in the event it is triggered. The cellular telephone system is in the process of being upgraded to ensure greater reliability. It the event of a cellular telephone failure, the SMAs can be directly accessed at the site using a built-in RS232 cable connection.

The SMAs have an internal GPS receiver used principally to link it to the National Bureau of Standards timing system. The GPS is internally activated approximately every 4 hours and checks the "location of the instrument" and the time. Any differences between the internal clock and the GPS time are recorded and saved by the SMA. Any corrections to the internal timing are made automatically. Typically, the greatest correction recorded is approximately 4 milliseconds.

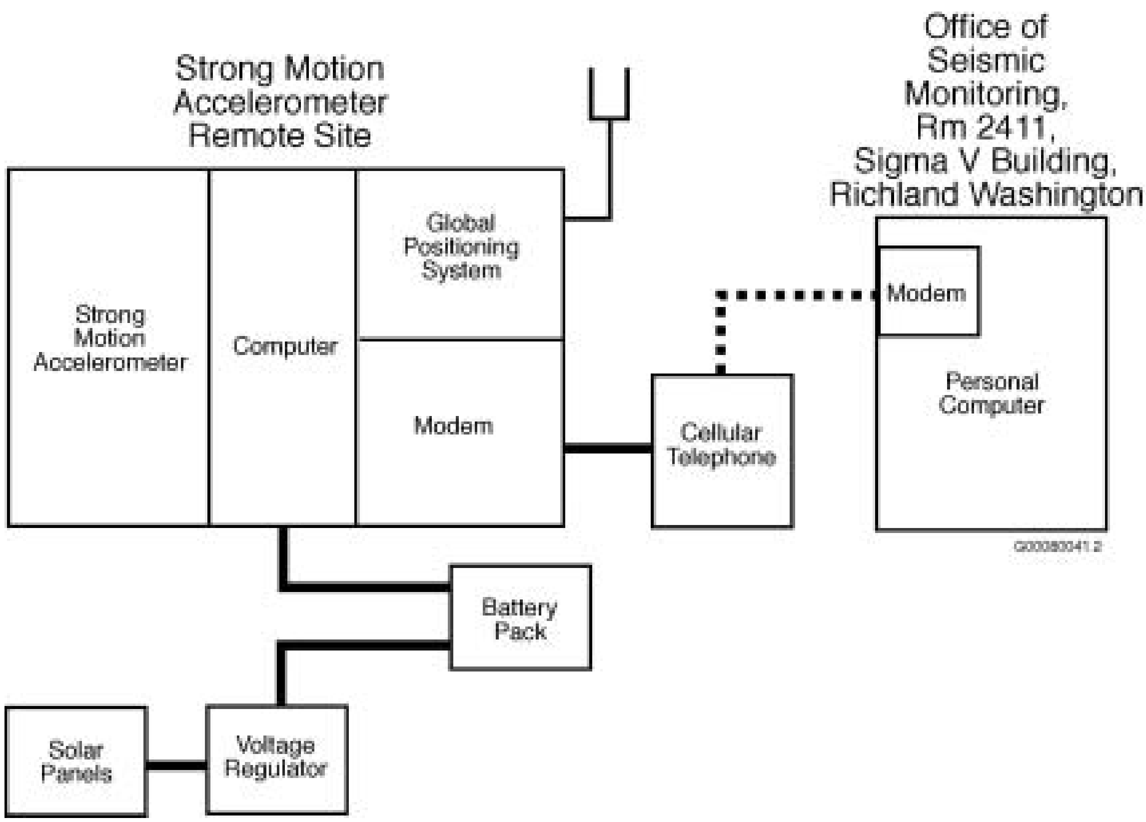

Figure 2.3. Schematic Diagram of a Strong Motion Accelerometer Installation

2.2.3 Strong Motion Accelerometer Operations Center

The combined operations, data recording, data interpretation, and maintenance facility is located in the Sigma V building and is operated by the PNNL Seismic Monitoring Team.

2.2.4 Strong Motion Operational Characteristics

The signals from the three-accelerometer channels at each site are digitized with a 24-bit digitizer and temporarily stored in a memory buffer. The sampling rate of the digitizer is set to 200 samples/second. The three channels are monitored for signals that equal or exceed a programmable trigger threshold. When one accelerometer channel is triggered, the other channels automatically record. The nominal threshold used is 0.05% of the full-scale range of 2.0 g (g is the acceleration of gravity, 9.8 m/s^2 or 32 ft/s^2) or 0.001 g. Threshold trigger levels are being adjusted to trigger infrequently on the noise sources (e.g., vehicles, sonic booms) near each site. This will provide ground motion data for smaller, non-damaging earthquakes that can be useful in estimating the ground motion expected from larger earthquakes, and to confirm correct operation of the instruments by analyzing the smaller-amplitude triggers. The recorders store information for 10 seconds before the trigger threshold is exceeded and for 40 seconds after the trigger ceases to be exceeded.

3.0 Magnitude, Velocity Models, and Quality Factors

3.1 Coda Length Magnitude

Coda-length magnitude (M_c), an estimate of local magnitude (M_L) (Richter 1958), is calculated using the coda-length/magnitude relationship determined for Washington State by Crosson (1972).

3.2 Velocity Model

The program XPED uses the velocities and layer depths given in Table 3.1. XPED was developed at UW and the velocity model used in XPED is based on Rohay et al. (1985). XPED is an interactive earthquake seismogram display program used to analyze seismic events.

3.3 Quality Factors (Q)

XPED assigns a two-letter **Quality factor** (Table 3.2) that indicates the general reliability of the solution (**A** is best quality, **D** is worst). Similar quality factors are used by the USGS for events located with the computer program HYPO71. The first letter of the quality code is a measure of the hypocenter quality based primarily on travel time residuals. For example: Quality **A** requires a root-mean-square residual (**RMS**) less than 0.15 seconds while a **RMS** of 0.5 seconds or more is **D** quality (other estimates of the location uncertainty also affect this quality parameter). The second letter of the quality code is related to the spatial distribution of stations that contribute to the event's location, including the number of stations (**NS**), the number of p-wave and s-wave phases (**NP**), the largest gap in event-station azimuth distribution (**GAP**), and the closest distance from the epicenter to a station (**DMIN**). Quality **A** requires a solution with **NP** >8, **GAP** <90°, and **DMIN** <5 km (or the hypocenter depth if it is greater than 5 km). If **NP** ≤5, **GAP** >180°, or **DMIN** >50 km, the solution is assigned Quality **D**.

Table 3.1. Seismic Velocities for Columbia Basin Stratigraphy (from Rohay et al. 1985)

Depth to Top of Velocity Layer (km)	Stratigraphy	Velocity (km/sec)
0.0	Saddle Mountains and Wanapum Basalts and intercalated Ellensburg Formation	3.7
0.4	Grande Ronde Basalt and pre-basalt sediments	5.2
8.5	Crystalline Basement, Layer 1	6.1
13.0	Crystalline Basement, Layer 2	6.4
23.0	Sub-basement	7.1
38.0	Mantle	7.9

Table 3.2. Local Earthquake Data, October 1, 2000 to September 30, 2001

Event ID	Type	Date	Time	Latitude	Longitude	Depth	Mag	NS/NP	Gap	DMIN	RMS	Q	Location
00100318002		00/10/03	18:00 51.12	46N14.57	119W35.21	7.95	0.1	8/13	209	8	0.06	AD	14.5 km ENE of Prosser
00100715291	P	00/10/07	15:29 40.95	46N12.49	119W24.45	0.58	1.1	8/11	250	10	0.23	BD	12.2 km SW of Richland
00101712231		00/10/17	12:23 33.49	46N05.45	119W36.73	10.16	0.7	10/13	306	14	0.11	AD	17.7 km SE of Prosser
00102323391		00/10/23	23:39 25.37	46N38.32	119W55.63	0.34	0.7	6/6	126	13	0.26	BC	23.9 km WNW of 200 West
00102415322	P	00/10/24	15:32 46.52	46N14.51	119W27.07	0.05	2.0	14/14	179	6	0.23	BC	13.1 km WSW of Richland
00110200004		00/11/02	00:01 08.12	46N11.69	119W32.50	9.46	0.1	7/10	304	11	0.07	AD	17.5 km E of Prosser
00110200034		00/11/02	00:04 11.15	46N12.24	119W33.04	8.08	0.4	7/13	235	10	0.06	AD	16.8 km E of Prosser
00113010391		00/11/30	10:39 33.21	46N03.44	119W42.36	18.25	0.5	6/8	174	17	0.22	BC	17.3 km SSE of Prosser
00121214131		00/12/12	14:13 37.59	46N13.50	119W36.34	6.33	0.4	8/14	287	6	0.08	AD	12.7 km E of Prosser
00121214132		00/12/12	14:13 52.18	46N12.41	119W36.16	9.11	1.6	18/21	146	6	0.07	AC	12.8 km E of Prosser
00121214133		00/12/12	14:14 07.58	46N12.90	119W36.29	8.09	1.6	12/16	142	6	0.09	AC	12.6 km E of Prosser
00121214145		00/12/12	14:15 37.84	46N12.64	119W35.80	8.34	0.9	14/16	87	6	0.08	AA	13.2 km E of Prosser
00121214402		00/12/12	14:40 48.23	46N12.38	119W35.90	10.65	1.7	20/37	82	6	0.15	AA	13.1 km E of Prosser
00121214434		00/12/12	14:44 07.62	46N12.43	119W35.83	8.30	0.2	8/9	224	6	0.05	AD	13.2 km E of Prosser
00121214443		00/12/12	14:45 00.94	46N12.51	119W36.24	8.97	0.3	8/12	221	6	0.07	AD	12.7 km E of Prosser
00121214445		00/12/12	14:45 25.69	46N12.19	119W36.10	9.00	-0.2	3/9	311	6	0.06	AD	12.9 km E of Prosser
00121214473		00/12/12	14:48 03.51	46N12.50	119W35.69	9.87	2.1	28/42	88	7	0.13	AA	13.4 km E of Prosser
00121214482		00/12/12	14:48 51.19	46N12.64	119W36.63	9.60	-0.1	5/8	218	5	0.08	AD	12.2 km E of Prosser
00121214572		00/12/12	14:57 44.72	46N12.15	119W36.45	10.29	0.7	13/19	170	6	0.14	AC	12.4 km E of Prosser
00121215374		00/12/12	15:38 09.10	46N12.29	119W35.85	8.30	0.3	8/13	227	6	0.06	AD	13.2 km E of Prosser
00121217430		00/12/12	17:43 26.52	46N12.33	119W35.88	9.18	0.3	10/16	226	6	0.08	AD	13.1 km E of Prosser
00121219402		00/12/12	19:40 53.13	46N12.28	119W35.69	9.71	2.1	32/46	82	7	0.20	BA	13.4 km E of Prosser
00121220081		00/12/12	20:08 31.77	46N11.86	119W36.38	9.79	0.1	6/13	235	6	0.08	AD	12.5 km E of Prosser
00121220453		00/12/12	20:46 10.56	46N12.87	119W35.90	7.88	0.4	11/11	214	6	0.11	AD	13.1 km E of Prosser
00121220455		00/12/12	20:46 48.79	46N12.17	119W36.19	8.95	-0.2	6/10	229	6	0.07	AD	12.7 km E of Prosser
00121223352		00/12/12	23:35 44.80	46N12.85	119W36.00	7.80	0.5	10/19	214	6	0.12	AD	13.0 km E of Prosser

Table 3.2. (contd)

Event ID	Type	Date	Time	Latitude	Longitude	Depth	Mag	NS/NP	Gap	DMIN	RMS	Q	Location
00121303480		00/12/13	03:48 28.41	46N12.90	119W36.06	7.82	0.7	13/18	87	6	0.09	AA	12.9 km E of Prosser
00121308024		00/12/13	08:03 13.37	46N12.20	119W36.09	9.76	1.3	23/27	88	6	0.18	BA	12.9 km E of Prosser
00121308222		00/12/13	08:22 51.10	46N13.19	119W36.38	7.61	0.2	8/12	206	6	0.03	AD	12.6 km E of Prosser
00121308245		00/12/13	08:25 15.58	46N12.17	119W35.86	8.38	0.4	8/11	229	6	0.03	AD	13.2 km E of Prosser
00121308274		00/12/13	08:28 03.67	46N12.88	119W36.30	7.75	0.3	8/11	213	6	0.06	AD	12.6 km E of Prosser
00121309042		00/12/13	09:04 51.59	46N13.15	119W36.13	7.62	0.5	8/10	208	6	0.03	AD	12.9 km E of Prosser
00121309085		00/12/13	09:09 18.87	46N12.79	119W36.24	7.87	0.3	8/11	215	6	0.04	AD	12.7 km E of Prosser
00121310091		00/12/13	10:09 39.10	46N12.35	119W36.06	9.53	2.0	29/34	82	6	0.09	AA	12.9 km E of Prosser
00121311474		00/12/13	11:48 06.63	46N12.70	119W35.84	7.88	0.8	13/21	87	6	0.11	AA	13.2 km E of Prosser
00121311545		00/12/13	11:55 12.80	46N12.52	119W36.17	7.86	0.2	7/10	221	6	0.07	AD	12.8 km E of Prosser
00121312105		00/12/13	12:11 16.32	46N11.95	119W36.16	9.99	1.5	22/28	88	6	0.19	BA	12.8 km E of Prosser
00121314060		00/12/13	14:06 32.47	46N12.28	119W36.14	10.02	1.9	29/37	82	6	0.14	AA	12.8 km E of Prosser
00121401252		00/12/14	01:25 52.01	46N12.69	119W36.05	8.30	1.6	20/24	144	6	0.07	AC	12.9 km E of Prosser
00121401514		00/12/14	01:52 06.38	46N12.54	119W35.92	8.76	0.4	10/19	163	6	0.14	AC	13.1 km E of Prosser
00121402173		00/12/14	02:18 02.68	46N12.39	119W35.96	9.16	1.2	15/21	83	6	0.06	AA	13.0 km E of Prosser
00121407280		00/12/14	07:28 30.62	46N12.18	119W36.06	10.25	0.7	9/17	169	6	0.08	AC	12.9 km E of Prosser
00121422571		00/12/14	22:57 43.12	46N11.22	119W36.06	11.11	1.9	24/29	146	7	0.13	AC	13.1 km E of Prosser
00121817443		00/12/18	17:44 55.87	46N12.72	119W36.26	7.93	0.2	9/11	217	6	0.05	AD	12.7 km E of Prosser
00121819191		00/12/18	19:19 34.56	46N12.98	119W36.37	8.08	0.3	6/7	290	6	0.04	AD	12.5 km E of Prosser
00121820064		00/12/18	20:07 05.01	46N12.80	119W36.00	8.15	0.9	16/21	144	6	0.14	AC	13.0 km E of Prosser
00123013033		00/12/30	13:04 02.21	46N12.41	119W36.88	6.83	0.4	8/11	292	5	0.07	AD	11.8 km E of Prosser
01010601414		01/01/06	01:41 57.01	46N07.29	119W48.36	23.63	0.6	15/18	135	13	0.05	AB	10.0 km SSW of Prosser
01010906351		01/01/09	06:35 42.66	46N11.26	119W35.84	11.57	1.2	15/16	209	7	0.09	AD	13.4 km E of Prosser
01010907460		01/01/09	07:46 25.53	46N13.03	119W36.10	7.87	1.1	11/11	210	6	0.07	AD	12.9 km E of Prosser
01010908553		01/01/09	08:55 55.15	46N12.03	119W36.12	9.89	1.5	20/24	172	6	0.08	AC	12.8 km E of Prosser
01010912560		01/01/09	12:56 27.53	46N13.22	119W36.12	7.59	1.2	10/10	206	6	0.08	AD	12.9 km E of Prosser

Table 3.2. (cont)

Event ID	Type	Date	Time	Latitude	Longitude	Depth	Mag	NS/NP	Gap	DMIN	RMS	Q	Location
01010914153		01/01/09	14:15 51.24	46N02.64	119W39.76	4.47	0.5	9/10	169	18	0.14	BC	19.9 km SSE of Prosser
01010917130		01/01/09	17:13 31.19	46N13.27	119W36.08	7.06	1.0	8/8	205	6	0.08	AD	13.0 km E of Prosser
01011814003		01/01/18	14:00 50.09	46N18.49	119W32.50	13.74	-0.2	6/9	231	8	0.06	AD	19.5 km W of Richland
01011904380		01/01/19	04:38 23.72	46N03.82	119W50.47	0.02	1.8	22/31	98	20	0.24	BC	16.9 km SSW of Prosser
01012014191		01/01/20	14:19 37.28	46N27.57	119W43.05	16.46	-0.1	9/15	219	6	0.08	AD	12.5 km SSW of 200 West
01012305560		01/01/23	05:56 29.43	46N50.62	119W44.28	4.15	1.3	19/21	67	11	0.13	AC	22.6 km SE of Vantage
01012623262	X	01/01/26	23:27 27.99	46N07.19	119W01.32	0.03	2.3	17/18	151	9	0.14	AC	12.1 SE of Kennewick
01013023232		01/01/30	23:24 23.03	46N25.31	119W17.41	0.02	-0.6	5/9	240	0	0.24	BD	5.4 km ESE of 400 Area
01020721394	P	01/02/07	21:40 00.53	46N07.89	119W00.36	0.03	0.0	11/11	111	9	0.12	AB	12.1 km SE of Kennewick
01021317251		01/02/13	17:25 43.69	46N26.65	119W38.14	16.58	-0.1	10/14	131	2	0.07	AB	12.7 km S of 200 West
01022122262		01/02/21	22:26 52.15	46N44.24	119W25.53	0.03	0.2	7/11	100	2	0.08	AB	16.9 km NE of 100-K Area
01030410244		01/03/04	10:25 05.66	46N44.21	119W25.91	0.03	0.6	12/20	126	2	0.14	AB	16.5 km NE of 100-K Area
01030812391		01/03/08	12:39 32.81	46N18.57	119W40.55	0.45	0.2	11/14	165	10	0.15	AC	13.4 km NNE of Prosser
01031218263	P	01/03/12	18:26 46.40	46N03.96	119W27.50	0.70	0.0	4/6	340	25	0.04	AD	27.4 km SSW of Richland
01031300300		01/03/13	00:30 22.30	46N32.20	119W47.04	23.22	0.2	10/13	121	5	0.09	AB	11.5 km WSW of 200 West
01031303011		01/03/13	03:01 37.70	46N13.09	119W36.19	7.31	0.0	7/9	289	6	0.05	AD	12.8 E of Prosser
01031616463		01/03/16	16:46 55.75	46N05.48	119W54.39	0.03	1.8	22/25	73	21	0.16	BC	16.7 km SW of Prosser
01040322051		01/04/03	22:05 42.87	46N44.74	119W24.86	0.04	1.1	12/13	155	3	0.10	AC	18.1 km NE of 100-K Area
01040505114		01/04/05	05:12 11.17	46N53.18	119W37.36	15.39	0.7	23/30	57	12	0.12	AA	27.3 km N of 100-K Area
01040714464		01/04/07	14:47 09.99	46N23.02	119W14.74	2.53	-0.3	5/10	269	6	0.15	BD	3.8 km NE of 300 Area
01041505571		01/04/15	05:57 43.18	46N44.69	119W25.33	0.02	0.4	9/12	204	3	0.16	BD	17.6 km NE of 100-K Area
01041520213		01/04/15	20:21 58.66	46N44.27	119W25.22	0.02	0.1	8/9	103	2	0.09	AB	17.2 km NE of 100-K Area
01042504163		01/04/25	04:16 54.65	46N24.18	119W45.81	14.36	0.2	9/16	245	10	0.08	AD	19.8 km SSW of 200 West
01042808094		01/04/28	08:10 13.40	46N44.67	119W25.45	0.05	0.8	18/25	76	3	0.15	AA	17.5 km NE of 100-K Area
01043003472		01/04/30	03:47 49.12	46N35.83	119W46.64	16.79	0.5	22/29	80	2	0.14	AA	11.5 km WNW of 200 West
01050308484		01/05/03	08:49 06.79	46N44.54	119W24.45	0.03	1.0	8/9	160	3	0.10	AC	18.3 km NE of 100-K Area

Table 3.2. (contd)

Event ID	Type	Date	Time	Latitude	Longitude	Depth	Mag	NS/NP	Gap	DMIN	RMS	Q	Location
01050411191		01/05/04	11:19 31.90	46N44.79	119W24.91	0.03	0.7	5/6	154	3	0.16	BD	18.1 km NE of 100-K Area
01050417073	P	01/05/04	17:07 55.35	46N01.26	119W34.58	0.46	1.5	7/8	252	22	0.12	AD	25.5 km SE of Prosser
01050904325		01/05/09	04:33 15.79	46N44.09	119W25.53	0.03	0.8	4/6	194	2	0.16	BD	16.7 km NE of 100-K Area
01060311513		01/06/03	11:51 58.55	46N43.43	119W18.33	13.65	1.6	21/30	88	8	0.15	AA	15.6 km SW of Othello
01060712452		01/06/07	12:45 42.64	46N57.76	119W31.39	19.99	2.3	33/38	48	2	0.12	AA	25.8 km SW of Moses Lake
01060815053		01/06/08	15:06 03.62	46N36.31	119W40.29	0.02	1.8	23/26	47	3	0.14	AA	5.8 km NNW of 200 West
01060904195		01/06/09	04:20 19.36	46N36.52	119W40.24	0.03	0.0	8/16	175	3	0.17	BC	6.2 km NNW of 200 West
01061203283		01/06/12	03:29 01.34	46N43.46	119W37.68	12.08	0.2	8/12	194	5	0.03	AD	9.5 km NNW of 100-K Area
01062416473		01/06/24	16:47 54.72	46N21.33	119W31.10	4.22	0.1	6/9	171	7	0.05	AC	15.2 km SW of 400 Area
01062503425		01/06/25	03:43 14.17	46N37.75	119W39.42	3.24	-0.6	4/6	238	3	0.08	AD	4.8 km WSW of 100-K Area
01070500450		01/07/05	00:45:30.05	46N40.46	119W33.73	3.22	-0.3	7/08	112	8	0.16	BB	4.5 km NE of 100-K Area
01071306101		01/07/13	06:10:37.25	46N42.20	119W28.08	4.63	0.1	9/14	90	3	0.09	AA	12.0 km NE of 100-K Area
01071306161		01/07/13	06:16:37.62	46N42.44	119W27.86	4.83	-0.4	4/07	126	2	0.10	AD	12.5 km NE of 100-K Area
01071306225		01/07/13	06:23:19.36	46N42.68	119W27.98	5.60	-0.1	6/09	134	2	0.10	AC	12.6 km NE of 100-K Area
01071802144		01/07/18	02:15:06.33	46N44.66	119W25.23	0.03	1.1	5/08	151	3	0.13	AD	17.7 km NE of 100-K Area
01071905204		01/07/19	05:21:05.09	46N25.13	119W16.98	1.24	0.6	5/06	273	1	0.10	AD	6.0 km ESE of 400 Area
01072222283		01/07/22	22:28:58.87	46N03.89	119W50.69	0.04	1.8	27/28	60	20	0.22	BC	16.9 km SSW of Prosser
01072910513		01/07/29	10:51:57.90	46N19.30	119W35.79	11.95	0.0	7/11	234	8	0.18	BD	18.4 km NE of Prosser
01080501072		01/08/05	01:07:39.01	46N08.77	119W02.97	7.37	0.7	11/12	130	12	0.18	BB	8.5 km SE of Kennewick
01082000290		01/08/20	00:29:30.60	46N29.80	119W44.91	8.78	-0.2	8/12	222	3	0.12	AD	10.9 km SW of 200 West
01082000493		01/08/20	00:50:01.86	46N29.98	119W44.61	9.08	-1.1	5/08	218	2	0.17	BD	10.4 km SW of 200 West
01082000512		01/08/20	00:51:51.16	46N29.73	119W44.26	8.69	-0.3	7/11	217	3	0.11	AD	10.3 km SW of 200 West
01082000515		01/08/20	00:52:16.70	46N29.83	119W44.73	8.41	-0.8	4/07	312	3	0.04	AD	10.7 km SW of 200 West
01082000580		01/08/20	00:58:35.11	46N29.86	119W43.74	7.21	0.4	10/14	211	2	0.10	AD	9.7 km SW of 200 West
01082001075		01/08/20	01:08:16.80	46N29.82	119W44.45	8.31	-0.7	5/08	227	3	0.06	AD	10.4 km SW of 200 West
01082522295	P	01/08/25	22:30:11.09	46N48.52	119W14.13	34.77	-0.1	4/04	321	25	0.01	AD	5.6 km WSW of Othello
01090810244		01/09/08	10:25:09.36	46N19.44	119W33.03	17.22	0.2	11/21	111	7	0.07	AB	19.3 km SW of 400 Area

Explanation of Table 3.2

EVENT ID: The Earthworm Recording System creates the identification number. XPED uses the year, month, day and time to create a unique number for each event.

TYPE: P is Probable Blast; X is Confirmed Blast; F is Felt Earthquake; H is hand picked from helicorder; S is surficial event (rockslide, avalanche) and not a explosion or tectonic earthquake; blank is local earthquake**.**

DATE: The year and day of the year in Universal Time Coordinated (UTC). UTC is used throughout this report unless otherwise indicated.

TIME: The origin time of the earthquake given in UTC. To covert UTC to Pacific Standard Time, subtract eight hours; to Pacific Daylight Time, subtract seven hours.

LATITUDE: North latitude, in degrees and minutes, of the earthquake epicenter.

LONGITUDE: West longitude, in degrees and minutes, of the earthquake epicenter.

DEPTH: The depth of the earthquake in kilometers (km).

MAG: The magnitude is expressed as Coda-Length magnitude M_c, an estimate of local magnitude M_L (Richter 1958). If magnitude is blank no determination could be made.

NS/NP: Number of stations/number of phases used in the solutions.

GAP: Azimuthal gap. The largest angle (relative to the epicenter) containing no stations.

DMIN: The distance from the earthquake epicenter to the closest station

RMS: The root-mean-square residual (observed arrival times minus the predicted arrival times) at all stations used to locate the earthquake. It is only useful as a measure of quality of the solution when five or more well-distributed stations are used in the solution. Good solutions are normally characterized by RMS values of less than about 0.3 seconds.

Q: The Quality Factors indicate the general reliability of the solution/location (**A** is best quality, **D** is worst). See Section 3.3 of this report: Quality Factors.

4.0 Geology and Tectonic Analysis

The Hanford Site lies within the Columbia Basin, which is an intermontane basin between the Cascade Range and the Rocky Mountains that is filled with Cenozoic volcanic rocks and sediments. This basin forms the northern part of the Columbia Plateau physiographic province (Fenneman 1931) and the Columbia River flood-basalt province (Reidel and Hooper 1989). In the central and western parts of the Columbia Basin, the Columbia River Basalt Group (CRBG) overlies Tertiary continental sedimentary rocks and is overlain by late Tertiary and Quaternary fluvial and glaciofluvial deposits (Campbell 1989; Reidel et al. 1989, 1994; DOE 1988). In the eastern part, a thin (<100 m) sedimentary unit separates the basalt and underling crystalline basement and a thin (<10 m) veneer of eolian sediments overlies the basalt (Reidel et al. 1989, 1994).

The Columbia Basin has two structural subdivisions or subprovinces: the Yakima Fold Belt and the Palouse Slope. The Yakima Fold Belt includes the western and central parts of the Columbia Basin and is a series of anticlinal ridges and synclinal valleys with major thrust faults along the northern flanks (Figure 4.1) (Reidel and Fecht 1994a, 1994b). The Palouse Slope is the eastern part of the basin and is less deformed than the Yakima Fold Belt with only a few faults and low amplitude, long wavelength folds on an otherwise gently westward dipping paleoslope. Figure 4.2 shows north-south and east-west cross sections through the Columbia Basin based on surface mapping (Reidel and Fecht 1994a, 1994b), deep boreholes (Reidel et al. 1994), geophysical data (Rohay et al. 1985; DOE 1988), and magnetotelluric data obtained as part of BWIP (DOE 1988).

4.1 Earthquake Stratigraphy

Studies of seismicity at the Hanford Site have shown that the seismic activity is related to crustal stratigraphy (layers of rock types) (Rohay et al. 1985; DOE 1988). The main geologic units important to earthquakes at Hanford and the surrounding area are:

- The Miocene Columbia River Basalt Group (CRBG)
- Pre-basalt sediments of Paleocene, Eocene, and Oligocene age
- The crystalline basement consisting of 2 layers composed of Precambrian and Paleozoic craton and Mesozoic accreted terranes.

4.2 Geologic Structure Beneath the Monitored Area

Between the late 1950s and the early 1980s, deep boreholes were drilled for hydrocarbon exploration in the Columbia Basin. These boreholes provided accurate measurements of the physical properties of the CRBG and the pre-basalt sediments (Reidel et al. 1989, 1994), but the thickness of the pre-basalt sediments and nature of the crystalline basement are still poorly understood. The difference between the thicknesses listed in Table 4.1 and the thicknesses of the crustal layers in the velocity model in Table 3.1 reflect data specific to UW's crustal velocity model for eastern Washington. Table 4.1 is derived from

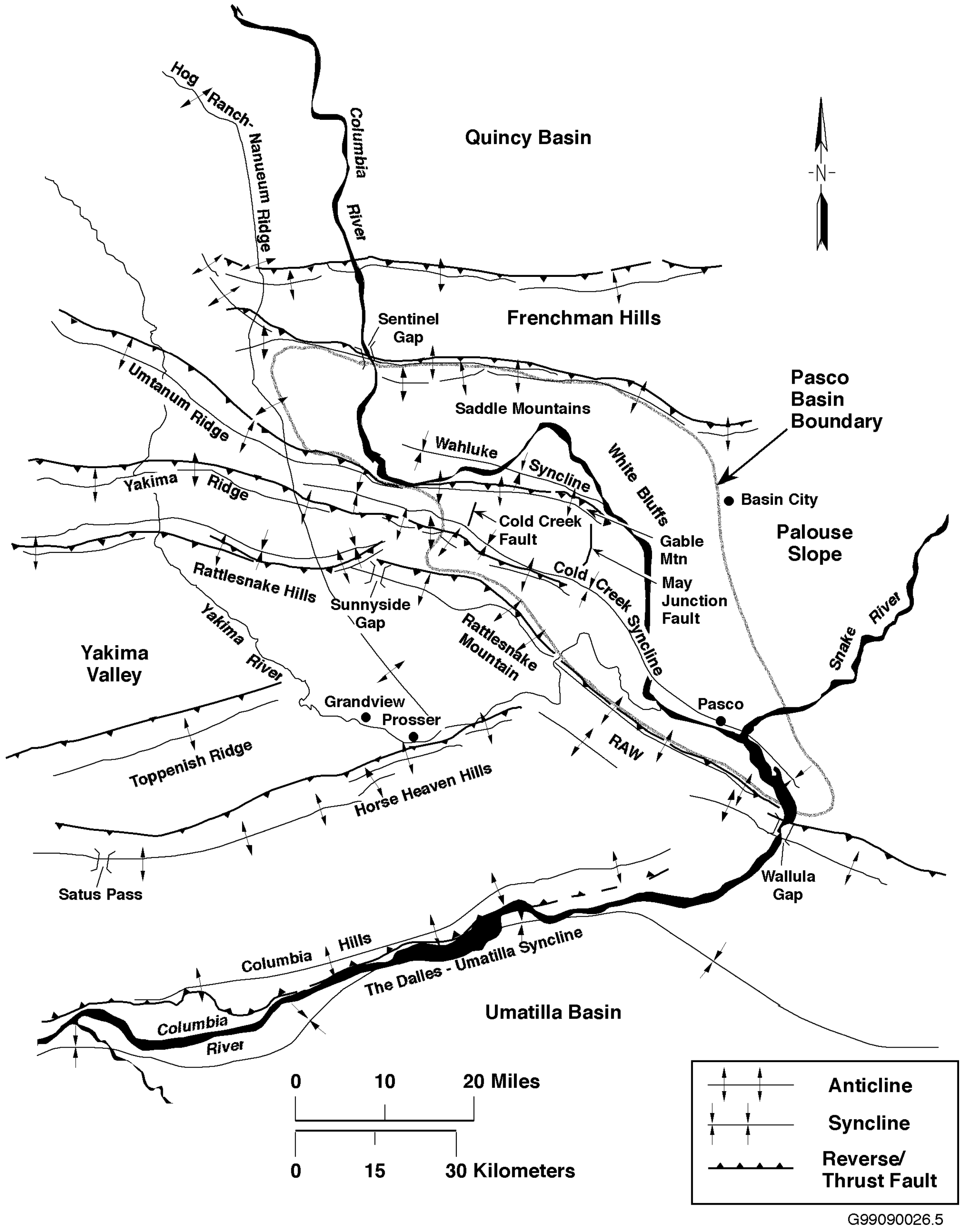

Figure 4.1. Structural and Tectonic Map of Columbia Basin Showing Major Seismic Source Structures

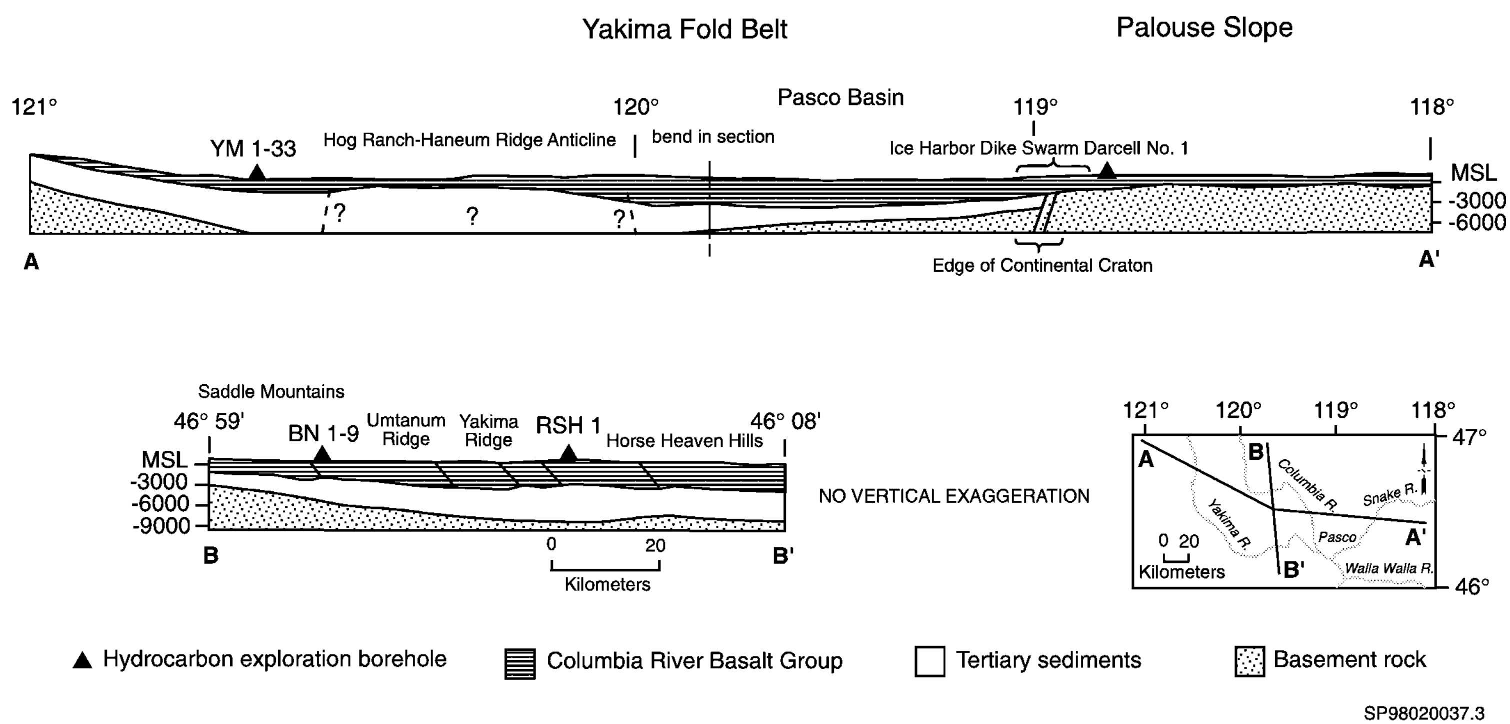

Figure 4.2. Geologic Cross Sections Through the Columbia Basin (Reidel et al. 1994)

Table 4.1. Thicknesses of Stratigraphic Units in the Monitoring Area

Stratigraphy	North	South	East	West
Columbia River Basalt Group (includes suprabasalt sediments)	3.0 km	4.5 km	2.2 km	4.2 km
Pre-basalt Sediments	3.0 km	>4.5 km	0	>6.0 km

Figure 4.2 and was developed for the geologic interpretation in this report. The thicknesses of these units are variable across the monitored area. Table 4.1 summarizes the approximate thickness at the borders of the monitored area.

The thickness of the basalt and the pre-basalt sediments varies as a result of different tectonic environments. The western edge of the North American craton (late Precambrian/Paleozoic continental margin and Precambrian craton) is located in the eastern portion of the monitored area. The stratigraphy on the craton consists of CRBG overlying crystalline basement; the crystalline basement is continental crustal rock that underlies much of the western North America. The stratigraphy west of the craton consists of 4 to 5 km of CRBG overlying greater than 6 km of pre-basalt sediments. This in turn overlies accreted terranes of Mesozoic age. The area west of the craton was subsiding during the Eocene and Oligocene, accumulating great thickness of pre-CRBG sediments. Continued subsidence in this area during the Miocene resulted in thicker CRBG compared to that on the craton. Subsidence continues today but at a greatly reduced rate (Reidel et al. 1994).

4.3 Depth of Earthquakes

Since records have been kept, most of the earthquakes at the Hanford Site have originated in the CRBG layer. The crystalline basement has had the next greatest amount of earthquakes followed by the pre-basalt sediments. The stratigraphic units for local earthquakes recorded during FY 2001 are listed in Table 4.2. Note that the majority of seismic activity in FY2001 was in the pre-basalt sediments and not in the CRBG.

Table 4.2. Number of Local Earthquakes Occurring in Stratigraphic Units

Unit	First Quarter	Second Quarter	Third Quarter	Fourth Quarter	FY 2001
Basalt	1	8	12	7	28 (29%)
Pre-basalt Sediments	43	5	0	7	55 (56%)
Crystalline Basement	1	6	6	2	15 (15%)
Total	45	19	18	16	98

4.4 Tectonic Pattern

Studies have concluded that earthquakes can occur in the following six different tectonic environments (earthquake sources) at the Hanford Site (Geomatrix 1996).

- **Reverse/thrust faults**. Reverse/thrust faults in the CRBG associated with major anticlinal ridges such as Rattlesnake Mountain, Yakima Ridge, and Umtanum Ridge could produce some of the largest earthquakes.

- **Secondary faults**. These are associated with the major anticlinal ridges.

- **Swarm areas**. Small geographic areas not known to contain any geologic structures produce clusters of events (swarms), usually in the CRBG in synclinal valleys. These clusters consist of a series of small shocks with no outstanding principal event. Swarms occur over a period of days or months and the events may number into the hundreds and then quit, only to start again at a later date. This differs from the sequence of foreshocks, mainshock, and trailing-off aftershocks that have the same epicenter or are associated with the same fault system. In the past, swarms were thought to occur only in the Columbia River Basalt Group. We now realize that swarm events can occur in all geologic layers but typically a swarm event at a specific time is usually restricted to one layer. There are seven earthquake swarm areas that we recognize in the monitoring area (Figure 4.3) but this list will be updated as new swarm areas develop. The Saddle Mountains Swarm Area, Wooded Island Swarm Area and Coyote Rapids Swarm area are typically active at one time or another during each year. The other earthquake swarm areas are active less frequently.

- **The entire Columbia Basin**. The entire basin, including the Hanford Site, could produce a "floating" earthquake. A floating earthquake is one that, for seismic design purposes, can happen anywhere in a tectonic province and is not associated with any known geologic structure. Seismic Monitoring classifies it as a random event for purposes of seismic design and vibratory ground motion studies.

- **Basement source structures**. Studies (Geomatrix 1996) suggest that major earthquakes can originate in tectonic structures in the crystalline basement. Because little is known about geologic structures in the crystalline basement beneath the Hanford Site, earthquakes cannot be directly tied to a mapped fault. Earthquakes occurring in the crystalline basement without known sources are treated as random events.

- **The Cascadia Subduction Zone**. This source has been postulated to be capable of producing a magnitude 9 earthquake. Because this source is along the western boundary of Washington State and outside the HSN, the Cascadia Subduction Zone is not an earthquake source that is monitored at the Hanford Site, so subduction zone earthquakes are not reported here. Because any earthquake along the Cascadia Subduction zone can have a significant impact on the Hanford Site or can be felt like the February 2001 Nisqually earthquake, UW monitors and reports on this earthquake source for DOE. Ground motion from any moderate or larger Cascadia Subduction Zone earthquake is detected by Hanford SMAs and reported (see Section 5.0).

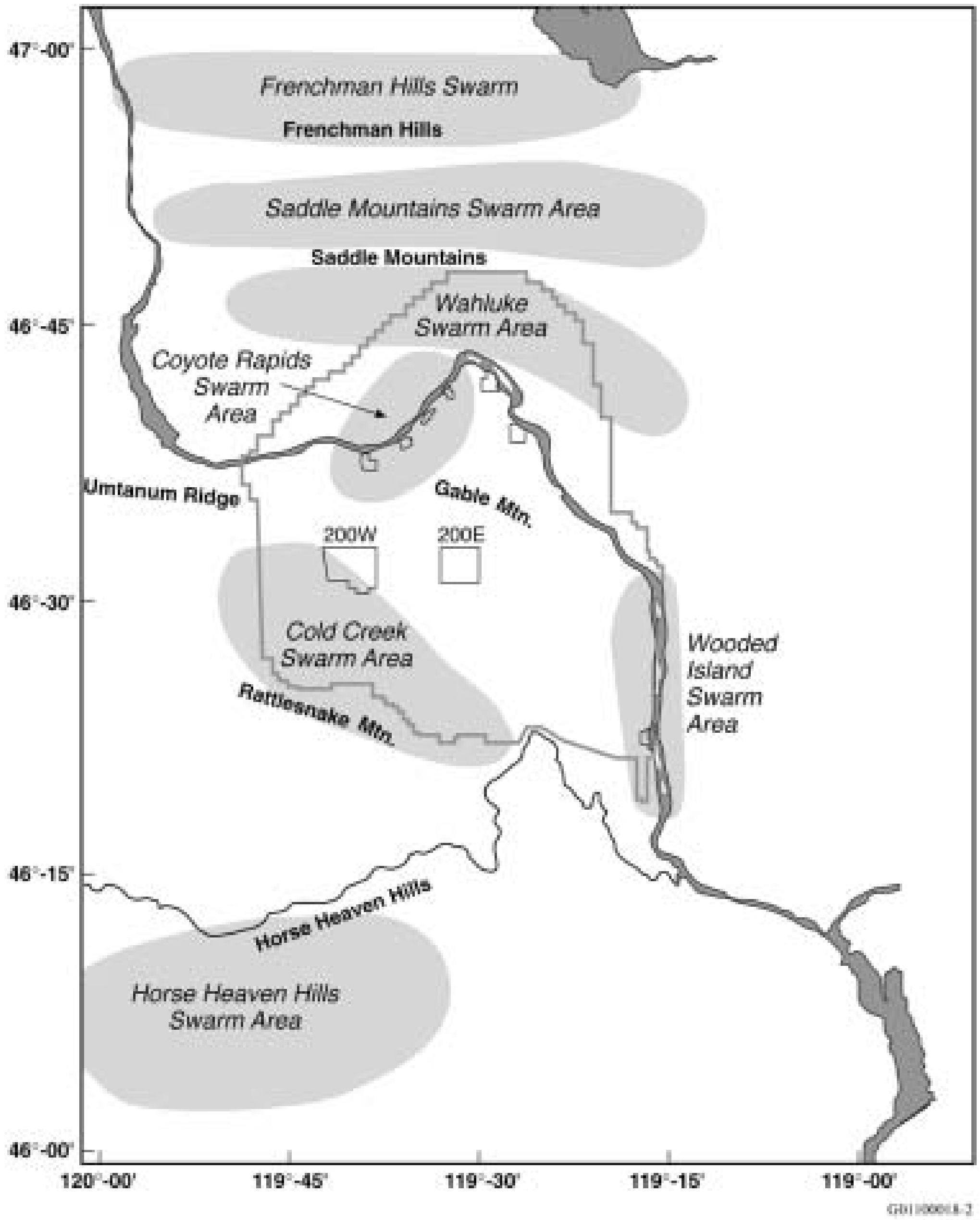

Figure 4.3. Locations of Known Earthquake Swarm Areas in the Hanford Monitoring Network Area

4.5 Tectonic Activity

4.5.1 Annual Summary

Ninety-eight earthquakes occurred in the Hanford monitoring area during FY 2001 (October 1, 2000 through September 2001) (Table 4.3) (Figure 4.4). This section summarizes the earthquake activity for

Table 4.3. Summary of Earthquake Locations

Seismic Sources		First Quarter 10/01- 2/30	Second Quarter 1/01 - 3/31	Third Quarter 4/01 - 6/30	Fourth Quarter 7/01 - 9/30	FY 2001
Geologic Structure		1	0	4	0	5 (5%)
Swarm Areas	Saddle Mountains/ Royal	0	1	0	0	1 (1%)
	Coyote Rapids	0	0	0	1	1 (1%)
	Wooded Island	0	1	1	1	3 (3%)
	Wahluke Slope	0	2	7	4	13 (13%)
	Cold Creek	0	0	0	6	6 (6%)
	Horse Heaven Hills	44	10	0	1	55 (56%)
	Total for swarms	44	14	8	13	79 (81%)
Random Events		0	5	6	3	14 (14%)
Total for all earthquakes		45	19	18	16	98

the year. More detailed descriptions of this activity for each quarter are given in later sections. Details of the SMA data obtained at Hanford from the February Nisqually earthquake is given in Section 5.0.

4.5.1.1 Depth of Earthquakes

During FY 2001, 28% of the earthquakes occurred in the Columbia River Basalt Group, 55% of the earthquakes occurred in the underlying pre-basalt sediments, and 15% of the earthquakes occurred in the crystalline basement. Typically, more earthquakes occur in the basalt but swarm events in the pre-basalt sediments dominated the year.

4.5.1.2 Location of Earthquakes

During FY 2001, 81% of the earthquakes were classified as swarm events. Only 5 % were classified as having some association with major anticlinal ridges and 14% of the earthquakes were classified as random events. We typically classify earthquakes as random if they occur below the Columbia River Basalt Group. Very little is known about geologic structures in the pre-basalt sediments and crystalline basement so we consider any interpretations to speculative at this time. An earthquake also can be classified as a random event if it occurs in the basalt but is not located near any known geologic structure. During FY 2001, all but one random event occurred in the crystalline basement. The other event occurred in the basalt and was not near any known structure.

Of the five earthquakes that occurred on anticlinal ridges, one occurred in the first quarter and four occurred in the third quarter. Four of the earthquakes were centered on Umtanum ridge southwest of 100-K Area. The other earthquake occurred on Rattlesnake Mountain. All events occurred in the CRBG.

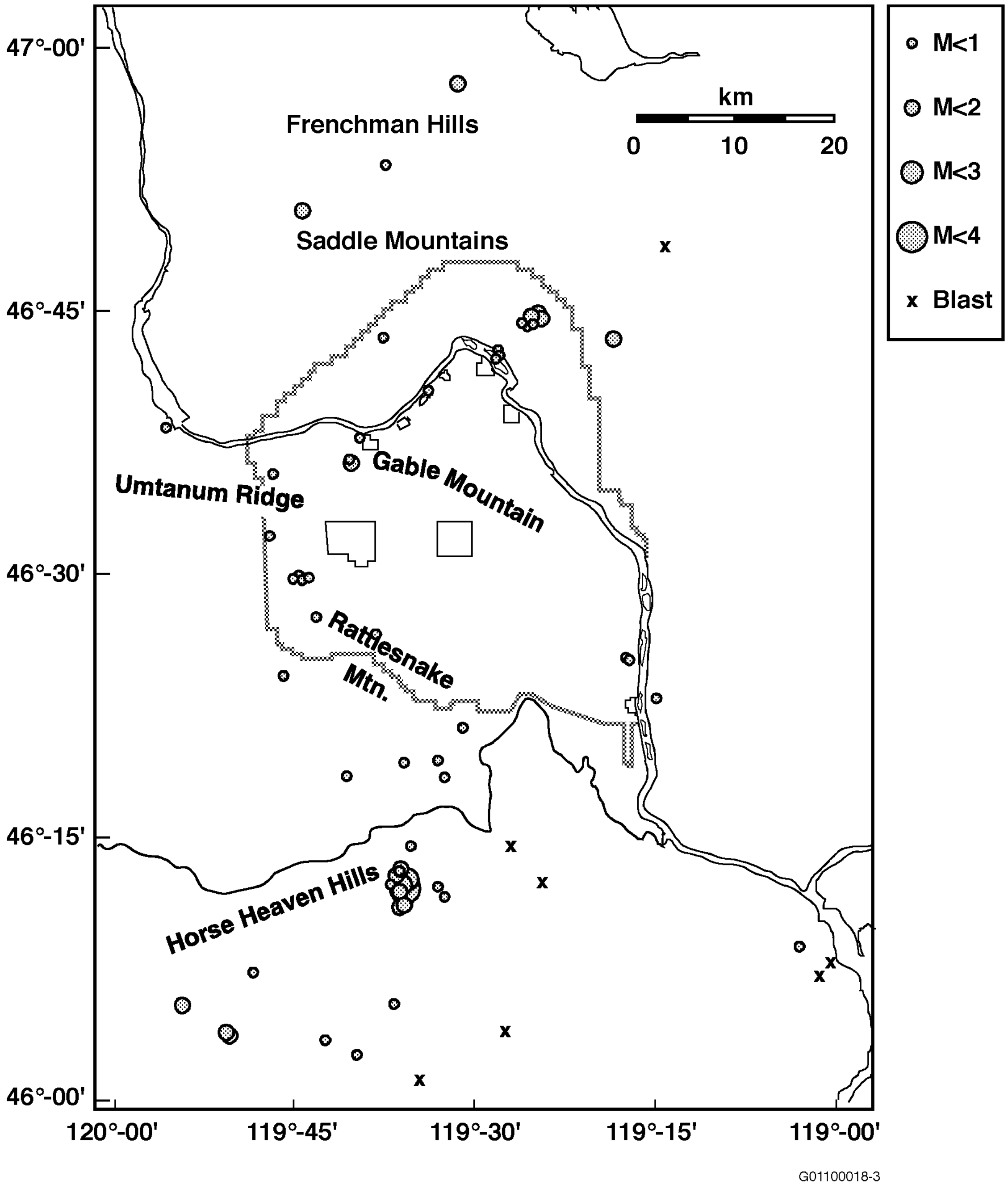

Figure 4.4. All Earthquakes Recorded in the Hanford Monitoring Area between October 1, 2000 and September 30, 2001 (Coda Length Magnitude (M_c) scale is shown at the side of the map)

The Saddle Mountains, Coyote Rapids, Wahluke Slope, Wooded Island, Cold Creek and Horse Heaven Hills swarm areas (see Figure 4.3) were all active at one time or another during FY 2001. The main activity was concentrated in the Wahluke Slope, Cold Creek, and Horse Heaven Hills swarm areas.

During the first quarter, the Horse Heaven Hills was active but this activity continued from the previous year. Activity in the Horse Heaven Hills continued into the second quarter and then, for the most part, ended. Activity then shifted to the Wahluke Slope, which was active through the third and fourth quarters as well. During the fourth quarter, the Cold Creek swarm area was active for a short period of time.

4.5.2 First Quarter of FY 2001

The locations of all earthquakes that occurred between October 1, 2000 and December 31, 2000 are shown on Figure 4.5.

4.5.2.1 Major Anticlinal Ridges

During the first quarter of FY 2001, we interpret one seismic event to have occurred on a major ridge. On October 23rd, a small (0.7 M_c), shallow earthquake occurred along the Umtanum Ridge anticline south of Priest Rapids Dam. This event was shallow and occurred in the CRBG. The location and depth are consistent with this earthquake occurring in the Umtanum Ridge fault zone.

4.5.2.2 Earthquake Swarm Areas

4.5.2.2.1 Horse Heaven Hills Swarm Area

Forty-four earthquakes occurred in swarm areas during the first quarter of FY 2001 and were all in the Horse Heaven Hills (see Figures 4.4 and 4.5). We defined the Horse Heaven Hills as a new swarm area (see Figure 4.3) during FY 2000 because of increased activity south of Prosser, Washington that began during FY 1999. Through the end of the first quarter of FY 2001, 61 earthquakes occurred in this swarm area. This activity continued into the second quarter of FY 2001 (see Section 4.5.3.1.3).

During this quarter, 39 events were clustered in a very small area (see Figure 4.5); three were near the highest concentration (one north and two east) and two were south of the highest concentration. The largest event was 2.1 M_c and ranged down to 0 M_c. All but one of the earthquakes occurred in the pre-basalt sediments at approximately the same depth (7 to 11 km). The southern most event, however, occurred in the crystalline basement (18.3 km).

The time sequence of all earthquakes is shown in Figure 4.6. The first event occurred on October 3rd and was the northern most. The next event was on October 17th, which occurred to the south of the main swarm. This was followed by two events on November 2nd just east of the main swarm. The next earthquake was on November 30th, which was the southern most event.

December 12th marked the beginning of the main activity. Eighteen events occurred on this day followed by 12 events on the 13th and 5 events on the 14th. Four days later on December 18th, three more earthquakes occurred. The last earthquake for this quarter occurred on December 30th.

The earthquake pattern on the three most active days, December 12th, 13th and 14th, occurred in four clusters separated by sporadic earthquakes. For this swarm, we define a cluster of earthquakes in a swarm

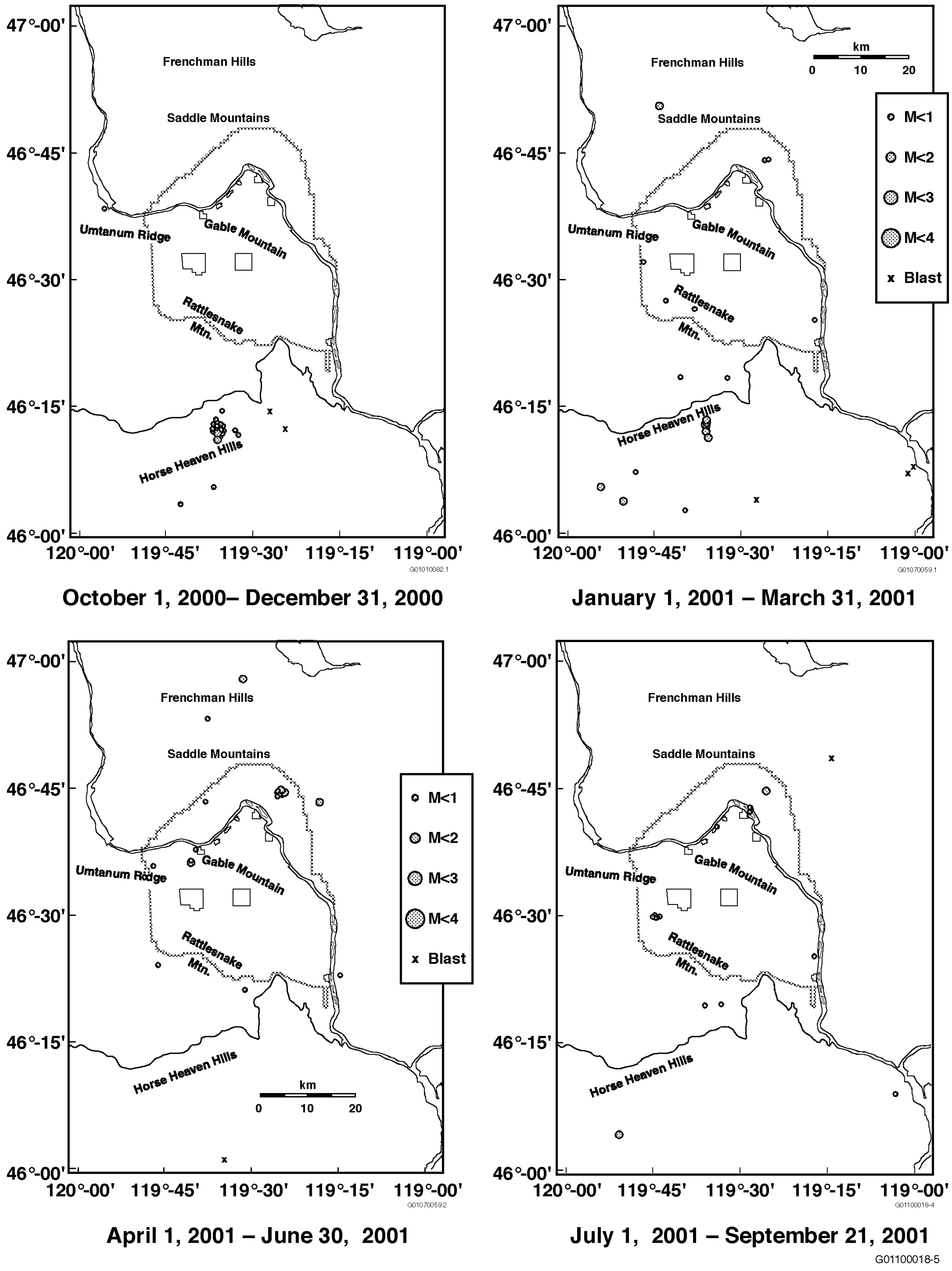

Figure 4.5. Locations of All Events between October 1, 2000 and September 30, 2001 Separated by FY quarter (Coda Length Magnitude (M_c) scale is shown at the side)

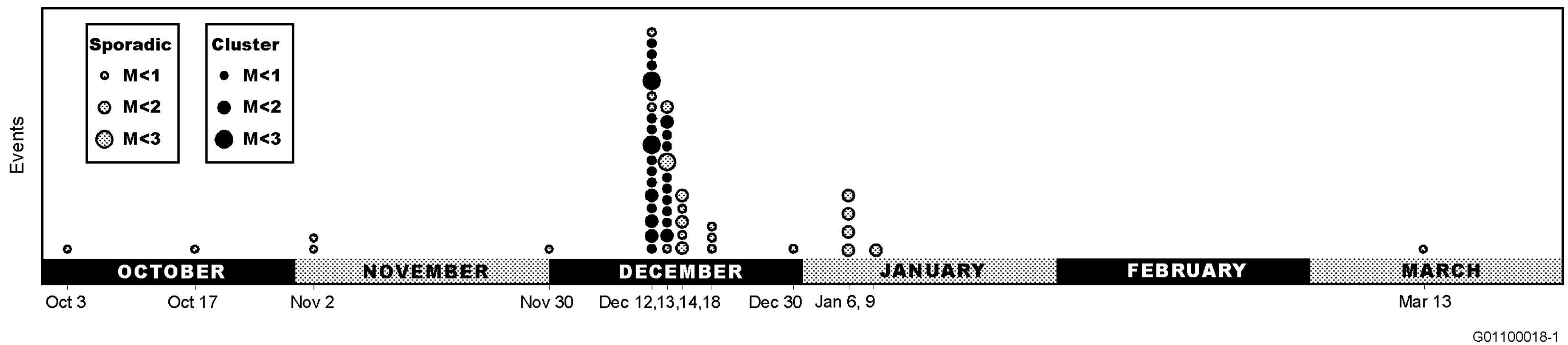

Figure 4.6. Time Sequence for Horse Heaven Hills Earthquake Swarm

as a series of earthquakes occurring closely spaced in time (e.g., within minutes or an hour) relative to individual events that occur sporadically during the swarm. The first cluster included 11 events within 45 minutes of each other (see Figure 4.6). The second cluster started approximately 4.5 hours later and was separated from the first cluster by two events. The second cluster lasted about 1 hour and consisted of four events. The third cluster, consisting of six events, started approximately 7 hours after the second. Two events separated the second and third clusters of earthquakes. The last earthquake cluster, consisting of three earthquakes, occurred approximately 2 hours after the third and was separated from it by 1 earthquake. Six sporadic earthquakes followed the last cluster.

4.5.2.3 Random or Floating Events

During the first quarter of FY 2001, we did not interpret any earthquakes as random or floating events.

4.5.3 Second Quarter of FY 2001

The locations of all mapped earthquakes that occurred between January 1, 2001 and March 31, 2001 are shown on Figure 4.5.

4.5.3.1 Earthquake Swarm Areas

During the second quarter of FY 2001, we interpret 14 seismic events to have occurred in swarm areas (see Figure 4.5). One event occurred in the Saddle Mountains swarm area, two were on the Wahluke Slope, one in Wooded Island, and ten were in the Horse Heaven Hills area.

4.5.3.1.1 Saddle Mountain Swarm Area. One small (1.3 M_c) earthquake occurred on January 23rd in the Saddle Mountain swarm area on the north side of the Saddle Mountains. This event occurred in the CRBG layer (4.2 km).

4.5.3.1.2 Wahluke Slope Swarm Area. Two small (0.2 and 0.6 M_c, respectively), shallow events occurred on February 21st and March 4th. These events occurred on the south side of the Saddle Mountains east of the horn of the Columbia River. This area has been active in the past, most recently in 1999.

4.5.3.1.3 Horse Heaven Hills Swarm Area. Ten events occurred within the Horse Heaven Hills swarm area during this quarter (see Figure 4.5). Magnitudes of these earthquakes ranged from 0 to 1.8 M_c. Four of the earthquakes were spread across the south side of the area and six were clustered together. Three occurred in the basalt (one was 4 km deep and the other two were near surface), three in the crystalline basement (12 to 24 km), and five earthquakes occurred within the pre-basalt sediments.

The activity from the first quarter continued on January 6th with the first (0.6 M_c, 24 km deep) of the four events that were spread around the swarm area. The second event occurred on January 9th (0.5 M_c, 4.5 km deep) followed by one on the 19th (1.8 M_c, near surface) to the southwest of the swarm area. After a brief lull in activity, the last event occurred on March 16th (1.8 M_c, near surface) on the west side of the swarm.

The tight earthquake swarm that became active in the first quarter continued into the second quarter (see Figure 4.6). On January 9th, three events occurred that were approximately an hour apart, followed by two more events later on the same day (see Figure 4.6). The last event occurred on March 13th, and there was no activity there during the third or fourth quarter. The depth of all these swarm events was 7 to 12 km in the pre-basalt sediments.

4.5.3.1.4 Wooded Island Swarm Area. One earthquake occurred in the Wooded Island swarm area near Johnson Island. This event was very small (approximately 0 M_c) and shallow.

4.5.3.2 Random or Floating Events

During the second quarter, five events were classified as random events. Four events occurred in the crystalline basement and one occurred in the CRBG. The fifth event did not occur in a known earthquake swarm area or along known geologic structures, so it has been classified as a floating event.

On January 18th, a small event (M_c <1) occurred on the south flank of Rattlesnake Mountain. This event was in the crystalline basement and was 14 km deep. The next two events (M_c <1) were on January 20th and February 13th and occurred below the Rattlesnake Hills in the crystalline basement (16 to 23 km). On March 8th, a small (M_c 0.2) shallow (1 km deep) earthquake occurred below the south flank of Rattlesnake Mountain. The last event (0.2 M_c) occurred on March 13th and was in the crystalline basement below Yakima Ridge (23 km).

4.5.4 Third Quarter of FY 2001

The locations of all mapped earthquakes that occurred between April 1, 2001 and June 30, 2001 are shown on Figure 4.5.

4.5.4.1 Major Anticlinal Ridges

During the third quarter of FY 2001, we interpret four seismic events to have occurred on major ridges. On June 8th, a small (1.8 M_c) earthquake occurred along the Umtanum Ridge anticline south of Vernita Bridge. This event was shallow (0.02 km) and occurred in the CRBG. On June 9th, a smaller (0.0 M_c), shallow event occurred on Umtanum Ridge anticline at the same locality as the June 8th event. A third small earthquake (<1 M_c) on June 25th occurred about 1 km north of the previous two events and at a greater depth (3 km) in the CRBG. The locations and depths are consistent with this earthquake occurring in the Umtanum Ridge fault zone.

On June 24th, a small (0.1 M_c) earthquake occurred on Rattlesnake Mountain in the CRBG (near surface). This event occurred within 1 km of the Rattlesnake Mountain fault zone. Because of its proximity, we interpret it to be associated with the Rattlesnake Mountain structure.

4.5.4.2 Earthquake Swarm Areas

Eight earthquakes occurred in swarm areas during the third quarter of FY 2001. Of those eight, all but one was in the Wahluke Slope swarm area. The seven events on the Wahluke Slope took place in the same region that was active during the second quarter (see Figures 4.4 and 4.5).

4.5.4.2.1 Wahluke Slope Swarm Area. All seven earthquakes were shallow (near surface) and occurred in the CRBG. These events ranged in magnitude from 0.1 to 1.1 M_c. They occurred between April 3rd and May 9th and appear to be sporadic with only two occurring on the same day.

4.5.4.2.2 Wooded Island Swarm Area. One earthquake occurred on April 7th within the Wooded Island swarm area east of Johnson Island. This event was small ($<1\ M_c$) and was in the CRBG.

4.5.4.3 Random or Floating Events

During the third quarter, six events were classified as random. On April 5th, a small (0.7 M_c) event occurred was just north of the Saddle Mountains. Although this event's location is within the Saddle Mountains, it is considered a random event because it is in the crystalline basement (15 km) where no geologic structure has been identified. The second random event occurred south of Snively Basin where Rattlesnake Mountain and the Rattlesnake Hills intersect. This event was small (0.2 M_c) and 14 km deep. On April 30th, a small earthquake (0.5 M_c) occurred beneath Umtanum Ridge. We do not classify this earthquake as controlled by the Umtanum Ridge structure because it occurs within the crystalline basement (17 km). On June 3rd, a 1.6 M_c earthquake occurred east of the Wahluke Slope swarm area at a depth of 14 km. The next event was on June 7th in the Frenchman Hills and was the largest (2.3 M_c) and deepest (20 km) earthquake of the third quarter. The last random event was on June 12th. It occurred west of the 100-N Area at a depth of 12 km and had a magnitude of 0.2 (M_c).

4.5.5 Fourth Quarter of FY 2001

The locations of all mapped earthquakes that occurred between October 1, 2000 and December 31, 2001 are shown on Figure 4.5.

4.5.5.1 Major Anticlinal Ridges

No earthquakes occurred along major anticlinal structures during the fourth quarter of FY 2001.

4.5.5.2 Earthquake Swarm Areas

A total of 13 earthquakes occurred in known swarm areas during the fourth quarter of FY 2001. Four occurred in the Wahluke swarm area, one in the Coyote Rapids swarm area, six in the Cold creek swarm area, one in the Wooded Island swarm area, and one in the Horse Heaven Hills swarm area (see Figure 4.5).

4.5.5.2.1 Wahluke Swarm Area. Four small earthquakes (approximately M_c 1 or less) occurred in the Wahluke swarm area during the fourth quarter. Three were on July 13th and were within 13 minutes of each other. The fourth occurred on July 18th. All were within the basalt. These earthquakes occurred in the same area that was active during the second and third quarters of FY 2001 (see Figures 4.4 and 4.5).

4.5.5.2.2 Coyote Rapids Swarm Area. One small earthquake (M_c >1) occurred on July 5th in the Coyote Rapids swarm area. This earthquake was in the basalt and near 100-N Area.

4.5.5.2.3 Cold Creek Swarm Area. On August 20th, six earthquakes occurred in the Cold Creek swarm area within 30 minutes of each other. The earthquakes were small (M_c<1) and located in the pre-basalt sediments. All six events were clustered together and located in the Dry Creek drainage near Yakima Ridge.

4.5.5.2.4 Wooded Island Swarm Area. One earthquake occurred in the Wooded Island swarm area on July 19th. The event was small (M_c<1) and originated in the basalt. This event was located near Johnson where an event occurred during the second quarter (see Figure 4.5).

4.5.5.2.5 Horse Heaven Hills Swarm Area. On July 22nd, a small (M_c<1.0) event occurred in the basalt in the Horse Heaven Hills. This event occurred near the location of one of the second quarter swarm events (see Figure 4.5).

4.5.5.3 Random or Floating Events

Three events were classified as random during the fourth quarter. The first random event (M_c<1.0) occurred on July 29th and was in the crystalline basement along the south flank of Rattlesnake Mountain. The second random event (M_c<1.0) occurred on August 5th in the pre-basalt sediments. This event occurred near "The Butte" where the Rattlesnake trend intersects Wallula Gap along the Columbia River.

5.0 Strong Motion Accelerometer Operations

The Hanford SMA network has been in continuous operation since November 20, 1998. The nominal threshold used in the SMA network is 0.001 g in order to provide ground motion for smaller, non-damaging earthquakes that can be useful in estimating the ground motion expected from larger earthquakes, and to confirm correct operation of the instruments by analyzing the smaller-amplitude triggers (see Section 2.2).

5.1 Nisqually Earthquake

At 10:54:32 a.m. (18:54:32.78 UTC) on February 28, 2001, a 6.8 magnitude (M_w) earthquake occurred 57 km southwest of Seattle, Washington. Although this earthquake did not cause any damage on the Hanford Site, people noted windows rattling and, in come cases, water in pools was noted to produce ripples. This earthquake triggered the Hanford SMA network.

The raw data obtained from the Hanford SMAs, Caltech broadband instrument at LIGO, and the USGS broadband instrument (HAWA) on Rattlesnake Mountain are given in Table 5.1. The traces recorded on the Hanford SMA network are shown in Figures 5.1, 5.2, and 5.3. The data in Table 5.1 has been baseline corrected to remove the small DC offset in the center line of the accelerometers and a filter has been introduced to reduce low-frequency noise from the instrument, which does not affect the frequency range of interest. In addition, several of the recorders are not oriented exactly north-south and east-west; the horizontal components have been rotated to represent true north and east directions. The maximum positive and negative peaks are not necessarily equal and may not even occur at the same exact time. Table 5.2 shows the average absolute value of the maximum and minimum peak accelerations.

For the five Hanford SMAs, the highest accelerations were recorded at the 100-K and 200 East locations (northern portion of the Hanford Site, see Figure 2.1) and the overall lowest were recorded at the 400 and 300 Area locations (southern portion of the Hanford Site, see Figure 2.1). The overall lowest accelerations were recorded on a bedrock site (HAWA) in the CRBG, south of 200 West Area on the Hanford Reach National Monument. However, the accelerations at the Caltech LIGO site, which is closest to HAWA and the 400 Area sites, were nearly as high as the northern sites. Both the LIGO site and the 400 Area site are located in unconsolidated, stabilized sand dune deposits that are 11,000 years old.

In summary: Hanford Area locations experienced approximately

- 0.002 to 0.003 g or maximum of 0.3% g vertical peak ground acceleration
- 0.002 to 0.005 g or maximum of 0.5% g horizontal peak ground acceleration

Table 5.1. Hanford Strong Motion Accelerometer Raw Data

Nisqually Earthquake 2001/02/28 18:54			
	Acceleration in % g's		
Site	Vertical	North-South	East-West
100-K Area	+0.290 -0.255	+0.569 -0.530	+0.468 -0.444
200 East Area	+0.264 -0.350	+0.502 -0.442	+0.524 -0.473
200 West Area	+0.261 -0.269	+0.325 -0.411	+0.351 -0.319
400 Area (FFTF)	+0.264 -0.285	+0.272 -0.383	+0.415 -0.277
300 Area	+0.151 -0.198	+0.221 -0.238	+0.183 -0.205
LIGO (Caltech) Episensor Broadband	+0.285 -0.343 +0.280 -0.341	+0.399 -0.446 +0.397 -0.444	+0.487 -0.554 +0.480 -0.552
HAWA (USGS) Episensor Broadband (Base of Rattlesnake Mountain)	+0.131 -0.161 +0.131 -0.163	+0.219 -0.185 +0.175 -0.149	+0.153 -0.160

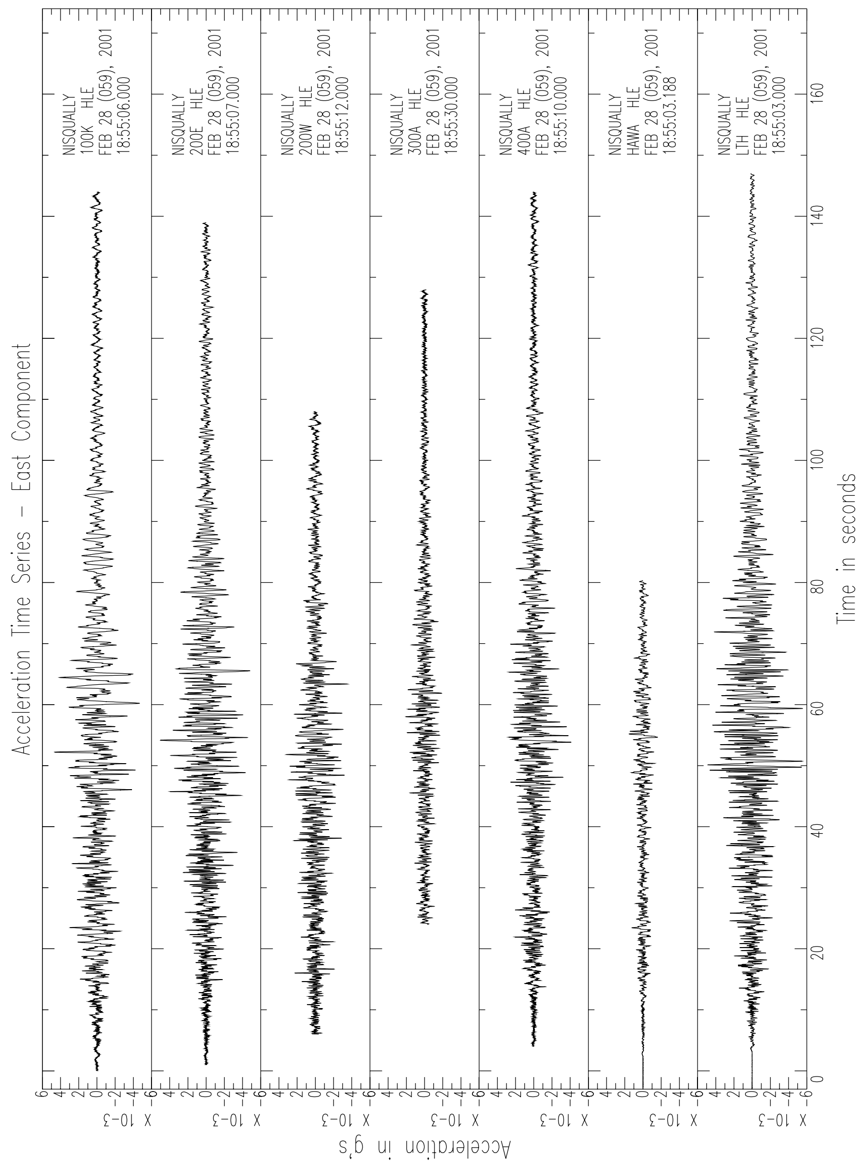

Figure 5.1. East Component of Nisqually Earthquake at Hanford Strong Motion Array. From left to right, the ground motion in g's is plotted against time for the five Hanford SMA at 100K, 200E, 200W, 300A, 400A (FFTF), the USGS site HAWA on ALE, and the Caltech site LTH at LIGO.

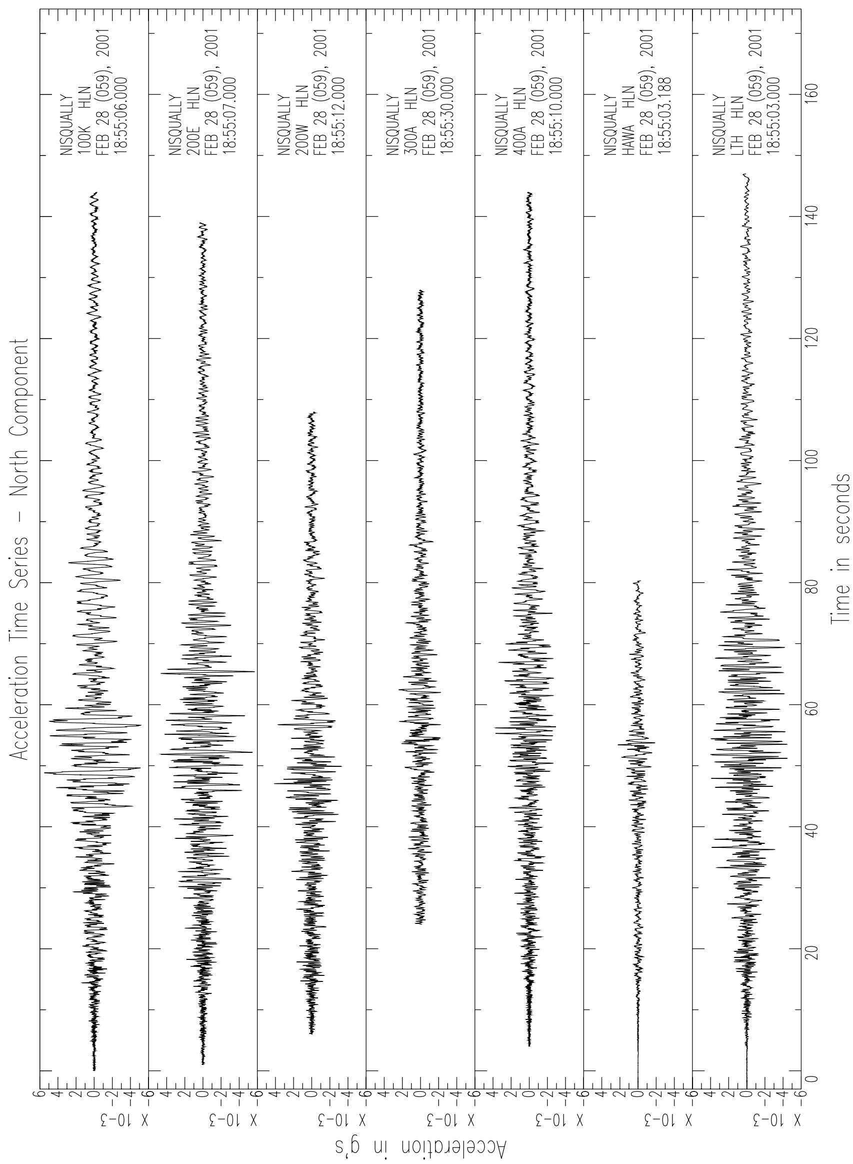

Figure 5.2. North Component of the Nisqually Earthquake at Hanford Strong Motion Array. From left to right, the ground motion in g's is plotted against time for the five Hanford SMA at 100K, 200E, 200W, 300A, 400A (FFTF), the USGS site HAWA on ALE, and the Caltech site LTH at LIGO.

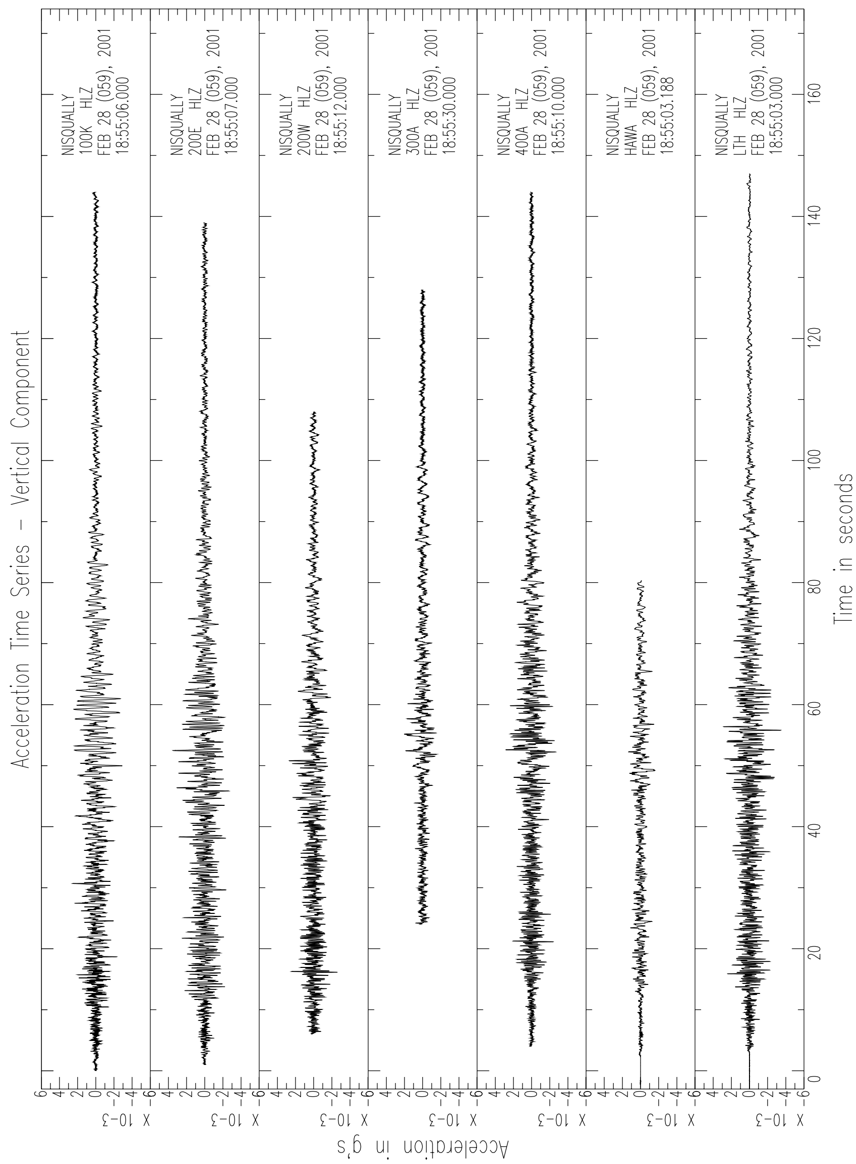

Figure 5.3. Vertical Component of the Nisqually Earthquake at Hanford Strong Motion Array. From left to right, the ground motion in g's is plotted against time for the five Hanford SMA at 100K, 200E, 200W, 300A, 400A (FFTF), the USGS site HAWA on ALE, and the Caltech site LTH at LIGO.

Table 5.2. Hanford Strong Motion Accelerometer Data as 1/2 Peak-to-Peak

Nisqually Earthquake 2001/02/28 18:54			
Site	Acceleration in % g's (1/2 peak-to-peak)		
	Vertical	North-South	East-West
100-K Area	0.272	0.550	0.456
200 East Area	0.307	0.472	0.499
200 West Area	0.265	0.368	0.335
400 Area (FFTF)	0.275	0.328	0.346
300 Area	0.175	0.230	0.194
LIGO (Caltech) Episensor	0.314	0.423	0.521
HAWA (USGS) Episensor	0.146	0.202	0.157

6.0 Capabilities in the Event of a Significant Earthquake

The SMA network was designed to provide ground motion in areas at the Hanford Site that have high densities of people and/or facilities containing hazardous materials in order to insure the Hanford Site is in compliance with DOE Order 420.1, "Facility Safety." The network also allows Hanford Seismic Monitoring to support Hanford Site emergency services organizations in complying with DOE Order G 420.1-1, Section 4.7, "Emergency Preparedness and Emergency Communications," by providing area ground motion data in the event of an earthquake on the Hanford Site. This section summarizes the capabilities of the Seismic Monitoring Team in the event of an earthquake at Hanford.

6.1 Use of the SMA Network in the Event of an Earthquake

Historically, only a few facilities at the Hanford Site had instruments to provide data on peak ground accelerations or any type of ground motion. The present SMA instruments were located so that if an earthquake occurred, ground motion data would be readily available to assess the damage at the 100-K Area, the 200 East and West Areas, the 300 and 400 Area facilities, which have the greatest concentration of people and also contain hazardous materials.

Many facilities at the Hanford Site have undergone various degrees of seismic analysis either during design or during re-qualification. Although the seismic design of a building may be known, when an earthquake is felt, a determination must be made as to the extent of damage before it can be reoccupied and the systems restarted. A felt earthquake may not cause any significant damage to a building but, without adequate characterization of the ground motion, initial determination of the buildings possibility of having damage may be impossible.

In the event of an earthquake such as the Nisqually earthquake, building managers, emergency directors, and engineers can obtain ground motion data recorded by the SMA network from the Seismic Monitoring Team in the Sigma V Building. Normal hours of operation are between 6 a.m. and 4:30 p.m., Monday through Friday. If a SMA is triggered, the Seismic Monitoring Team will download events that were recorded and determine the peak ground accelerations. This information is then passed on to Hanford Emergency services personel where the facility engineers can use the data to determine if the ground motion exceeded, is equal to, or is less than the building design. This, along with assessments from trained engineers, allows the facility manager to make a rapid and cost-effective determination on whether a building is safe to re-occupy or should not be used until it has been inspected in more detail. Buildings that have designs exceeding the recorded ground motion could be put back into service very quickly; buildings with designs that are very close to or less than measured ground motion could be given priority for onsite damage inspections.

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