

Third Quarter Hanford Seismic Report for Fiscal Year 2011 (April-June 2011)

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[Including much material prepared and presented by Alan Rohay and others at
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Notice

This quarterly report of seismic monitoring for public safety and resource protection at the Hanford site in Washington State is a transitional document. This is the first report prepared by the Pacific Northwest Seismic Network (PNSN) at the University of Washington (UW). PNSN are sub-contractors to the Mission Support Alliance (MSA), and these reports are part of the contractual obligations. The PNSN/MSA team is taking over operations of the seismic monitoring network from years of operation by the Pacific Northwest National Laboratory (PNNL). *To maintain continuity with past reports, we have chosen to retain, as closely as possible, the format and content of the report.* Future reports are likely to diverge somewhat from the current model, as the PNSN/MSA team's familiarity with both the network and our clients' needs and wishes evolve. However, this report will use much wording quoted directly from earlier reports (*e.g.*, Rohay *et al.*, 2009a, 2009b, 2010a, 2010b, *etc.*)

Summary

The PNSN/MSA team continues to provide 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. The team is responsible for identifying and locating sources of seismic activity that might affect the Hanford site, monitoring changes in the historical pattern of seismic activity surrounding the Hanford Site, and monitoring ground motion to provide data to constrain studies of earthquake effects on the Hanford site. Seismic 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 team 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 44 individual sensor sites and 15 radio relay sites maintained by the PNSN.

The Hanford Seismic Network recorded 53 local earthquakes during the third quarter of FY 2010. Nineteen earthquakes were located at shallow depths (less than 4 km), fifteen earthquakes at intermediate depths (between 4 and 9 km), most likely in the pre-basalt sediments, and nineteen earthquakes were located at depths greater than 9 km, within the basement. Geographically, 12 earthquakes were located in known swarm areas, 3 earthquakes occurred on or near a geologic structure (Saddle Mountain anticline), and 8 earthquakes were classified as random events.

The largest event (3.3 M_d) was recorded on May 1, 2011 at depth 1.9 km with epicenter located within the Wye Swarm area in the vicinity of Wooded Island, a few miles north of Richland. Wooded Island events recorded this quarter were a continuation of the swarm events observed during the 2009 and 2010 fiscal years and reported in previous reports (Rohay et al. 2009a, 2009b, 2009c, 2010a, and 2010b).

Abbreviations and Acronyms

BWIP Basalt Waste Isolation Project
CRBG Columbia River Basalt Group
DOE U.S. Department of Energy
ETNA strong motion accelerometer manufactured by Kinometrics
EWRSN Eastern Washington Regional Sub-Network
FY fiscal year
GPRS General Packet Radio Service
GPS Global Positioning System
HLSMP Hanford Lifecycle Seismic Monitoring Program
HSN Hanford Site Network
 M_c coda-length magnitude
 M_L local magnitude
PNNL Pacific Northwest National Laboratory
SMA strong motion accelerometer
USGS U.S. Geological Survey
UTC Coordinated Universal Time
UW University of Washington
WHC Westinghouse Hanford Company

1.0 Introduction

This quarterly report documents the locations, magnitudes, and seismic interpretations of earthquakes recorded for the Hanford monitoring region of south-central Washington during the third quarter of fiscal year (FY) 2011 (April 2011 through June 2011). Since April 1st, 2011, seismic monitoring for Public Safety and Resource Protection (PSRP) at the Hanford site has been carried out by the Hanford Lifecycle Seismic Monitoring Program (HLSMP). HLSMP is managed by Mission Support Alliance (MSA) with the monitoring work being performed under a sub-contract to the Pacific Northwest Seismic Network (PNSN).

1.1 Mission

The mission of the HLSMP is to maintain seismic stations, report data from measured events, and provide assistance in the event of an earthquake. This mission supports the U.S. Department of Energy (DOE) and the other Hanford Site contractors in their compliance with DOE Order 420.1B, Chapter IV, Section 3.d “Seismic Detection” and DOE Order G 420.1-1, Section 4.7, “Emergency Preparedness and Emergency Communications.” DOE Order 420.1B requires facilities or sites with hazardous materials to maintain instrumentation or other means to detect and record the occurrence and severity of the seismic event. The HLSMP maintains the seismic network located on and around the Hanford Site. The data collected from the seismic network can be used to support facility or site operations to protect the public, workers, and the environment from the impact of seismic events.

In addition, the HLSMP provides an uninterrupted collection of high-quality raw seismic data from the Hanford Site Network (HSN) and the Eastern Washington Regional Sub-Network (EWRSN) and provides interpretations of seismic events from the Hanford Site and the vicinity. The program locates and identifies sources of seismic activity, monitors changes in the historical pattern of seismic activity, 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 46-47° north latitude and between 119-120° west longitude. Data from the EWRSN and other seismic networks in the Northwest provide the HLSMP 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 Monitoring Seismic Activity at Hanford

Monitoring seismic activity at the Hanford Site was initiated in 1969 by the U.S. 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 EWRSN operated and maintained by UW. Funding ended for BWIP in December 1988; the seismic program (including the UW

contract) was transferred to the WHC Environmental Division. Maintenance responsibilities for the EWRSN also were assigned to WHC, who made major upgrades to EWRSN sites. Effective October 1, 1996, all seismic assessment activities were transferred to the Pacific Northwest National Laboratory (PNNL).

The Hanford SMA network was constructed during 1997, becoming operational in May 1997. It was shut down in FY 1998 due to lack of funding but became operational again in FY 1999 and has operated continuously since that time.

During the third quarter of FY2011, operations of the seismic monitoring network were taken over by HLSMP. As of the writing of this quarterly report the PNSN/MSA team is operating the network, assessing the state of the network and planning long term monitoring strategy.

1.3 Documentation and Reports

The HLSMP issues quarterly reports of local activity, an annual catalog of earthquake activity in southeastern Washington, and special-interest bulletins on local seismic events. This includes information and special reports as requested by DOE and Hanford Site contractors. Earthquake information provided in these reports is subject to revision as new information becomes available. An archive of all seismic data from the HLSMP is maintained by PNSN on computer servers at the UW. PNSN is in the process of documenting the metadata from stations taken over from PNNL so that all data can also be archived at the Incorporated Research Institutions in Seismology (IRIS) seismic data archive in Seattle, with backup copies in IRIS facilities in Socorro, NM, and in Golden, CO.

2.0 Network Operations

2.1 Seismic Stations

The seismic network consists of two types of earthquake sensors—seismometers and strong motion accelerometers (SMAs). Seismometers are very sensitive sensors designed primarily to detect micro earthquakes near Hanford. They record seismograms that are used to determine the magnitudes and locations of seismic events. SMA stations are designed to measure ground motion from larger earthquakes, and are discussed separately in Section 2.2. We further divide the seismic stations supported by MSA into two geographic sub-networks for discussion: the Hanford Site Network (HSN), which are sites located on the Hanford site itself, and the Eastern Washington Regional Sub-Network (EWRSN), which includes sites that surround the Hanford site.

Combined, the HSN and the EWRSN include 49 stations. Most stations reside in remote locations and require solar panels and batteries for power. The HSN includes 16 stations (Table 2.1 and Figure 2.1), and the EWRSN consists of 33 stations (Table 2.2 and Figure 2.2).

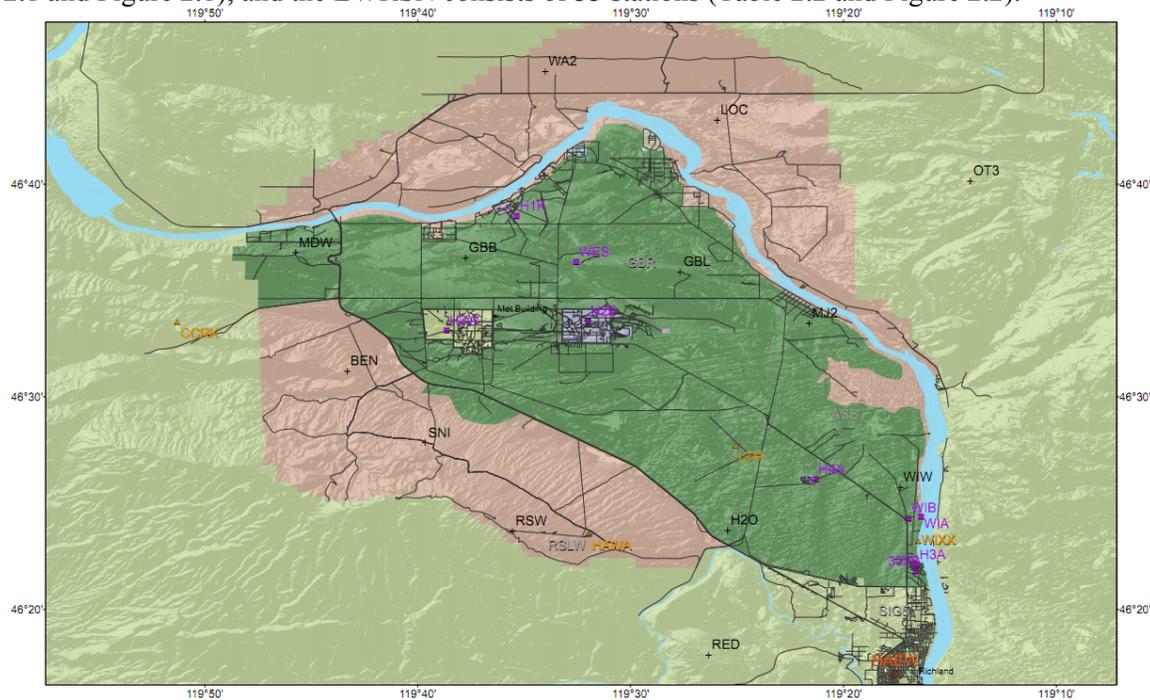


Figure 2.1 SMAs and seismometer stations of the Hanford Seismic Network, on the Hanford site. SMA stations are H1K, H2E, H2W, H3A, and H4A.

The EWRSN is used by the HLSMP for two major reasons. A large earthquake located in the Pacific Northwest outside of Hanford could produce significant ground motion and damage to structures at the Hanford Site. For example, the magnitude 7.0 earthquake that occurred in 1872 near Chelan/Entiat or other earthquakes located in the region (e.g., eastern Cascade mountain range) could have such an effect. The EWRSN would provide valuable information to help determine the impacts of such an event. Additionally, the characterization of seismicity throughout the surrounding areas, as required for the Probabilistic Seismic Hazard Analysis,

supports facility safety assessments at the Hanford Site. Both the HSN and the EWRSN are fully integrated within the Pacific Northwest Seismic Network managed by the University of Washington.

The HSN and EWRSN networks have a total of 69 combined data channels because the 5 three-component seismometer sites (GBB, FHE, CCRK, DDRF, and PHIN), and the 5 SMA sites in the HSN (H1K, H2E, H2W, H3A, and H4A) require two additional data channels per station. The tri-axial stations record motion in the vertical, north-south horizontal, and east-west horizontal directions. Stations CCRK, DDRF, and PHIN were acquired from the National Science Foundations US ARRAY, Transportable Arrays (TA) experiment that are broad-band seismometers with digital telemetry via cellular telephone. GBB and FHE are tri-axial sites with 1-Hz seismometers and analog radio telemetry. The other 39 stations are single vertical component seismometers. Fifteen radio telemetry relay sites are used by both networks to continuously transmit seismogram data to the PNSN in Seattle, Washington, for processing and archiving.

Table 1. Hanford Site Network (HSN) Stations. *Italic font* indicates a 3-channel station, **bold font** indicates a Strong Motion Accelerometer.

Station	Latitude	Longitude	Elevation (m)	Station Name
BEN	46.52	-119.72167	335	Benson Ranch
<i>GBB</i>	<i>46.60814</i>	<i>-119.62898</i>	<i>185</i>	<i>Gable Butte</i>
GBL	46.59819	-119.46097	33	Gable Mountain
<i>H1K</i>	<i>46.64468</i>	<i>-119.59287</i>	<i>152</i>	<i>100 K Area (SMA)</i>
<i>H2E</i>	<i>45.55780</i>	<i>-119.53450</i>	<i>187</i>	<i>200 East Area (SMA)</i>
H2O	46.39555	-119.42411	175	Water Station
<i>H2W</i>	<i>46.5517</i>	<i>-119.64532</i>	<i>129</i>	<i>200 West Area (SMA)</i>
<i>H3A</i>	<i>46.36322</i>	<i>-119.27747</i>	<i>99</i>	<i>300 Area (SMA)</i>
<i>H4A</i>	<i>46.46835</i>	<i>-119.35441</i>	<i>147</i>	<i>400 Area (SMA)</i>
LOC	46.71686	-119.43197	21	Locke Island
MDW	46.61302	-119.76215	33	Midway
MJ2	46.55736	-119.36013	146	May Junction Two
RSW	46.39436	-119.59247	1045	Rattlesnake Mountain
SNI	46.46386	-119.66089	323	Snively Ranch
WA2	46.75519	-119.56681	244	Wahluke Slope
WIW	46.42919	-119.2888	128	Wooded Island

Table 2. Eastern Washington Regional Sub-Network (EWRSN) Stations. *Italic font* indicates a 3-channel station, **bold font** indicates a Strong Motion Accelerometer.

Station	Latitude	Longitude	Elevation (m)	Station Name
BLT	45.915	-120.177	659	Bickleton
BRV	46.48519	-119.992	920	Black Rock Valley
BVW	46.81083	-119.883	670	Beverly
CBS	47.80469	-120.043	1067	Chelan Butte South

<i>CCRK</i>	46.5585	-119.855	561	<i>Cold Creek</i>
CRF	46.82486	-119.388	189	Corfu
<i>DDRF</i>	46.4911	-119.06	233	<i>Didier Farms</i>
DPW	47.87052	-118.204	892	Davenport
DY2	47.98503	-119.773	890	Dyer Hill Two
ELL	46.90951	-120.568	789	Ellensburg
EPH	47.35619	-119.597	661	Ephrata
ET3	46.57719	-118.939	286	Eltopia Three
ETW	47.60418	-120.334	1477	Entiat
<i>FHE</i>	46.95178	-119.498	455	<i>Frenchman Hills East</i>
LNO	45.87169	-118.286	771	Lincton Mountain Oregon
MOX	46.57718	-120.299	501	Moxee City
NAC	46.73301	-120.825	728	Naches
NEL	48.07003	-120.341	1500	Nelson Butte
OD2	47.38754	-118.711	553	Odessa Two
OT3	46.66886	-119.234	322	Othello Three
PAT2	45.88362	-119.75775	262	Paterson Two
<i>PHIN</i>	45.8951	-119.928	227	<i>Phinney Hill</i>
PRO	46.21252	-119.687	553	Prosser
RED	46.29736	-119.43880	330	Red Mountain
SAW	47.70153	-119.402	701	St. Andrews
TBM	47.16985	-120.599	1006	Table Mountain
TRW	46.29207	-120.543	723	Toppenish Ridge
TWW	47.13801	-120.87	1027	Teanaway
VT2	46.96719	-120	385	Vantage Two
WAT	47.69852	-119.955	821	Waterville
WRD	46.96986	-119.146	375	Warden
YA2	46.52652	-120.531	652	Yakima Two
YPT	46.04869	-118.963	325	Yellepit

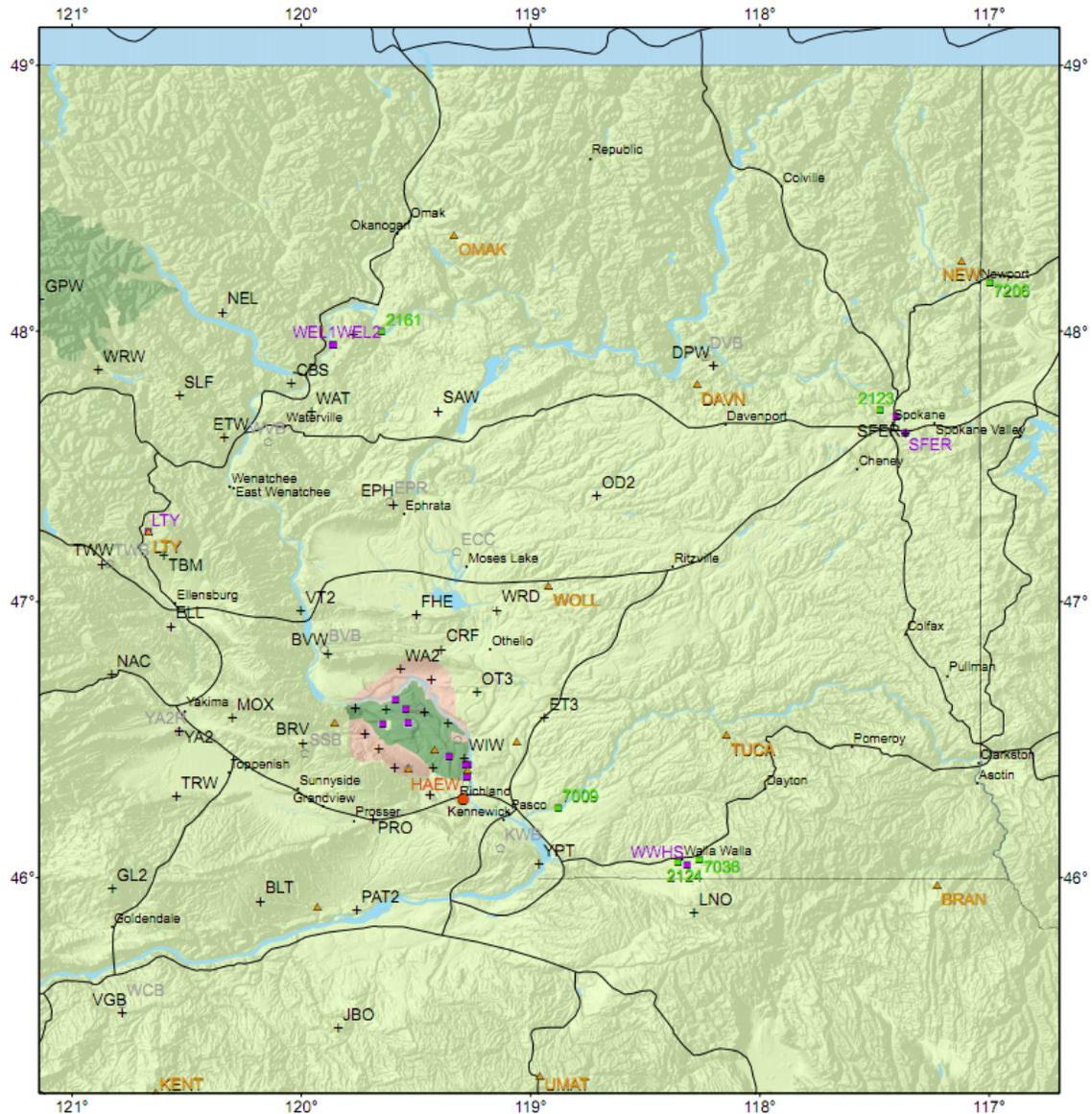


Figure 2.2 Seismic stations of the Eastern Washington Region Sub-Network.

2.1.1 Station Maintenance

During the third quarter of FY 2011 the many of the seismometer stations located on the Hanford Site (Figure 2.1) were visited, surveyed, and some revision carried out to make them more robust and stable. The most significant change was the installation of a remote data acquisition “node” at the RSLW (Lower Rattlesnake) facility on US Fish and Wildlife (USFW) managed land on the Hanford site. The HLSMP installed “GlowWorm”—a small data acquisition system that now receives seismic data from GBB, H2O, and BEN and forwards them to the PNSN facilities at the UW. GlowWorm is also designed to relay data from seismometer stations SNI and RED.

However, antennas at those stations were not able to be “turned” to send to RSLW during this quarter. In the next section we present more general overview of how seismometer data from HSN and EWRSN are used.

2.1.2 Data Acquisition

The signals from the seismometers 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 local (south-central Washington near the Hanford Site), regional (western United States and Canada), and teleseisms (from farther distances around the world). Local and regional events are usually earthquakes, but quarry and mining explosions also are recorded. Quarry and mining explosions usually can be identified from wave characteristics and the time of occurrence and may be confirmed with local government agencies and industries. Frequently, military exercises at the U.S. Army Yakima Training Center produce a series of acoustic shocks that trigger the recording system. Sonic booms and thunder also produce acoustic signals that may trigger the recording system.

The HLSMP uses Earthworm, an automated computer-based software system developed by the USGS and used throughout the region by the Pacific Northwest Seismic Network at the UW, to record triggered events. We currently run Earthworm Version 7.4. Two Earthworm systems run continuously at the PNSN. If one fails, the second one serves as a “backup”. The two systems are located in different buildings on computer servers with redundant power supplies, backed up by different uninterruptible power supplies and a diesel-powered electric generator capable of powering the network for 14 days until refueling is needed. Seismic data from triggered events are collected on a SUN workstation (Sun Microsystems, Santa Clara, California) for assessment by HLSMP staff. This information is evaluated to determine if the event is “false” (for example, due to a sonic boom) or is an earthquake or ground-surface or underground blast. Earthquake events are evaluated to determine epicenter locations, focal depths, and magnitudes (Section 4).

2.2 Strong Motion Accelerometer Stations

2.2.1 Location

The Hanford SMA network consists of five free-field SMA stations (see Figure 2.2; Table 2.3). SMAs are located in the 200 East and 200 West Areas, in the 100-K Area adjacent to the K Basins, in the 400 Area near the former Fast Flux Test Facility, and at the south end of the 300 Area.

The locations of SMA stations were chosen based on two criteria: 1) density of workers and 2) sites of hazardous facilities (Moore and Reidel 1996). The 200 East and 200 West Areas contain single-shell and double-shell tanks in which high-level radioactive wastes from past processing of fuel rods are stored. In addition, the Canister Storage Facility (holding encapsulated spent fuel

rods) and the new Waste Treatment and Immobilization Plant being constructed are both located in the 200 East Area. The 100-K Area contained the K Basins, where spent fuel rods from the N Reactor were stored prior to encapsulation. The now inactive Fast Flux Test Facility is located in the 400 Area.

2.2.2 Station Design

All free-field SMA stations consist of a four-panel solar array and two 30-gallon galvanized drums that contain equipment. Each panel has a maximum 42 watt output. The two drums are set in the ground such that the base of each drum is about 1 m below the ground surface. One drum houses only the SMA; the other drum, which is connected via a sealed conduit to the SMA drum, contains the batteries. During the 3rd quarter of FY2011, data communication from all five stations was revised to be provided by cellular modem. The enclosure serves as a junction box for all cabling that is routed through conduit inside and outside the equipment drums. The antenna for the cell modem is mounted on top of the enclosure. The enclosure permits quick access to check battery conditions and a connection directly to the RS-232 port of the SMA without removing the drum lids. However, with continuous data telemetry via cell modem, most interrogation of the system is accomplished remotely.

The SMA stations are three-component units consisting of vertical, north-south horizontal, and east-west horizontal seismometers manufactured by Kinometrics, Inc., Pasadena, California, and known as the ETNA system. Each ETNA unit contains a digital recorder, a data storage unit, and a Global Positioning System (GPS) receiver (Figure 2.5) with the equipment housed in a watertight box.

The cell modem system provides the Internet address connection to access the system. Stations can be monitored from any computer with appropriate access, and data can be downloaded to a dedicated computer in the Seismic Assessment Laboratory. The data also can be downloaded directly at each site via a built-in cable connection at the enclosure in case of communication failure. The GPS receiver is used principally to access the National Bureau of Standards timing system. The GPS receiver antenna is mounted on the enclosure at the rear of the solar array. The GPS receiver is activated internally approximately every 4 hr and checks the “location of the instrument” and the time. Any differences between the internal clock and the GPS time are recorded by the SMA. Any corrections to the internal timing are made automatically. Typically, the greatest correction recorded is approximately 4 milliseconds (ms).

2.2.3 Strong Motion Accelerometer Operations Center

The combined operations, data recording, data interpretation, and maintenance facility is located in the PNSN offices at the UW in Seattle.

2.2.4 Strong Motion Operational Characteristics

Signals from the three accelerometer channels use an 18-bit digitizer with data temporarily stored in a memory buffer. The digital sampling rate is 200 samples/s. Data are sent continuously in real-time to the PNSN offices at the UW in Seattle. The three channels are monitored for signals that exceed a programmable trigger threshold. When one accelerometer channel is triggered, the other channels automatically record. The nominal threshold used from 1998 to 2006 was 0.1% g (0.05% of the full-scale range of 2.0 g; g is the acceleration of gravity, 9.8 m/s² or 32 ft/s²).

Threshold trigger levels are set to trigger infrequently on noise sources (e.g., vehicles, sonic booms) near each site. In 2006, larger data storage capacities were installed that allowed the trigger thresholds to be reduced to 0.02% g (see Section 6). This permits the recording of ground motion data for smaller, non-damaging earthquakes that can be useful in estimating impacts of larger earthquakes. It also helps confirm the correct operation of the instruments by analyzing the smaller-amplitude triggers.

When one of the accelerometer channels exceeds the trigger threshold, the recorders save information within the data buffers. Data recording begins 10 s before the actual trigger time, continues until the trigger threshold is no longer exceeded, and ends with an additional 40 s of data. The saved files created by a triggered event are stored on memory cards to be retrieved and examined by HLSMP staff.

3.0 Geology and Tectonic Analysis

The Hanford Site lies within the Columbia Basin, an intermontane basin between the Cascade Range and the Rocky Mountains 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 et al. 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, little or no sediment separates the basalt and underlying 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 typically along the northern flanks (Figure 3.1) (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 3.2 shows north-south (B-B') and east-west (A-A') 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).

3.1 Earthquake Stratigraphy

Seismic studies at the Hanford Site have shown that the earthquake activity is related to crustal stratigraphy (large groupings of rock types) (Rohay et al. 1985; DOE 1988). The main geologic units important to earthquakes at the Hanford Site and the surrounding area are

- Miocene Columbia River Basalt Group
- Sub-basalt sediments of Paleocene, Eocene, Oligocene, and Early Miocene age
- Precambrian and Paleozoic cratonic basement
- Mesozoic accreted terranes forming the basement west of the craton margin.

3.2 Geologic Structure Beneath the Monitored Area

Between the late 1950s and the mid 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 sub-basalt sediments and nature of the basement are still poorly understood. Table 3.1, derived from Reidel et al. (1994), was developed for the geologic interpretation in this report. The thicknesses of these units are variable across the monitored area. Table 3.1 summarizes the approximate thickness at the borders of the monitored area.

Table 3.1. Thicknesses of Stratigraphic Units in the Monitoring Area (from Reidel *et al.*, 1994)

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

The thickness of the basalt and the sub-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 (Reidel *et al.*, 1994). The stratigraphy on the craton consists of CRBG overlying basement; the basement is continental crustal rock that underlies much of western North America. The stratigraphy west of the craton consists of 4 to 5 km of CRBG overlying up to 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).

3.3 Tectonic Pattern

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

- **Major Geologic Structures.** 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 faults are typically smaller (1 to 20 km in length) than the main reverse/ thrust faults that occur along the major anticlinal ridges (up to 100 km in length). Secondary faults can be segment boundaries (tear faults) and small faults of any orientation that formed along with the main structure.
- **Swarm Areas.** Small geographic areas not known to contain any geologic structures produce clusters of events (swarms), usually located 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 CRBG. Most swarm areas are in the basalt, but swarm events also appear to occur in all geologic layers. However, typically a swarm event at a specific time is usually restricted to one layer. Seven earthquake swarm areas are recognized in the HSN area, but this list will be updated as new swarm areas develop. The Saddle Mountains, Wooded Island, Wahluke, Coyote Rapids, and Horse Heaven Hills swarm areas are typically active at one time or another during the year (see Figure 5.1 for a map of these swarm areas). The other earthquake swarm areas are active less frequently.

- **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 interpretation 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 basement. Because little is known about geologic structures in the basement beneath the Hanford Site, earthquakes cannot be directly tied to a mapped fault. Earthquakes occurring in the basement without known sources are treated as random events.
- **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 the DOE. Ground motion from any moderate or larger Cascadia subduction zone earthquake is detected by Hanford SMAs and reported (see Section 5).

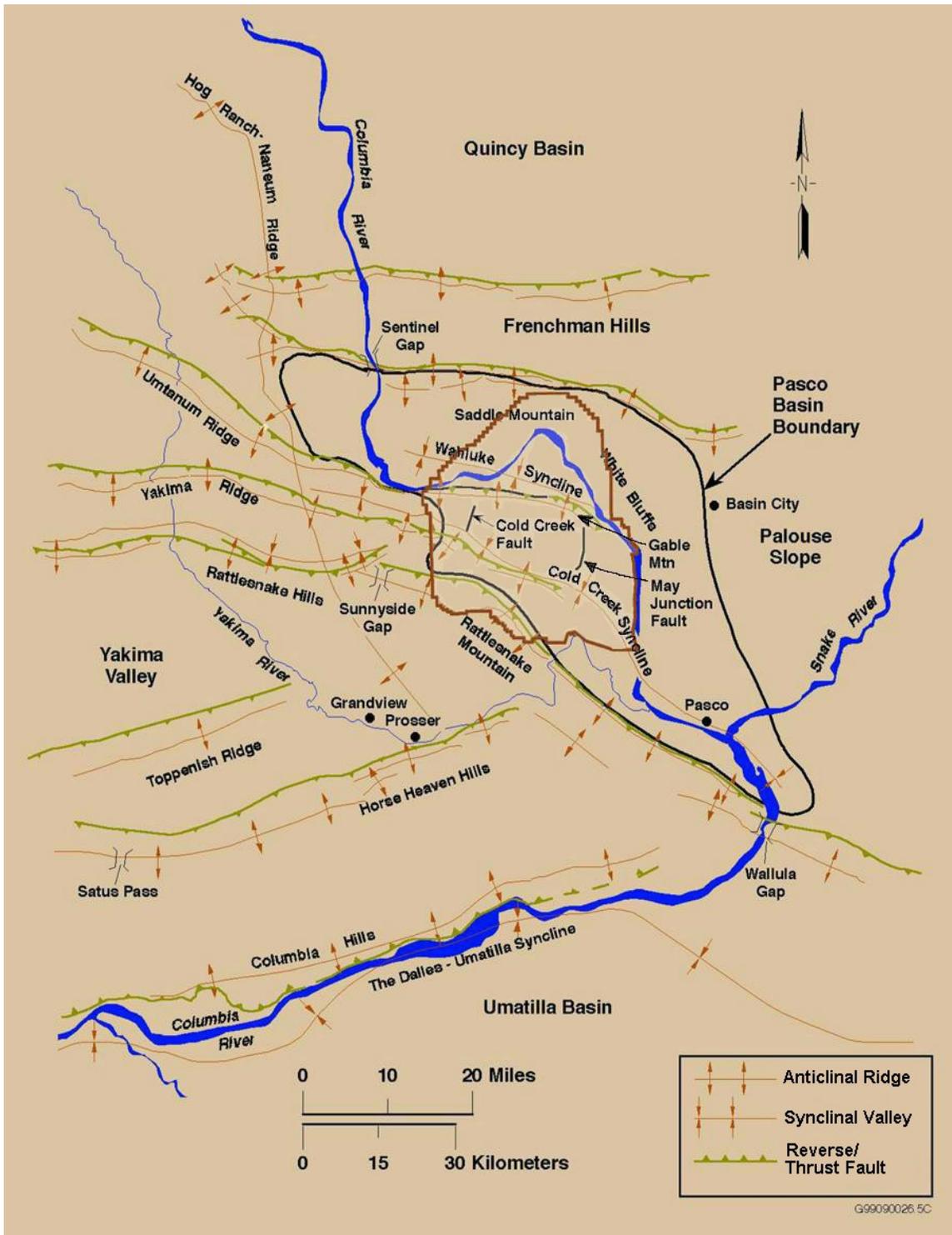


Figure 3.1 Tectonic features of the Hanford site within eastern Washington. (from Rohay et al., 2010b).

4.0 Earthquake Catalog Description

An interactive program called XPED, developed at the University of Washington, is currently used to manually review and revise automatic pick arrival times and signal durations and their uncertainties. Arrival and duration times and uncertainties are used as input to the hypocenter locating routine (called SPONG) within XPED to estimate locations and magnitudes of the seismic events. XPED results for local earthquakes (46-47° north latitude, 119-120° west longitude) are reported in Table 4.1. Other seismic events located in southeastern Washington, the Pacific Northwest, or outside the region also are evaluated, with results stored on the computer system; these results are not reported in this document. These other results sometimes are used as a check to confirm that the HSN is functioning properly (*e.g.*, quality checks on data recording).

4.1 Coda-Length Magnitude

Coda-length magnitude (M_c), an estimate of local magnitude (M_L) (Richter 1958), is calculated using a relationship developed for Washington State by Crosson (1972):

$$M_c = 2.82 \log (D) - 2.46$$

where D is the duration of the observed event. Many of the earthquakes have magnitude determinations that are very small ($M_c < 0$) and highly uncertain. In Section 4, we define earthquakes as “minor” with magnitudes (M_c) smaller than 1.0. Coda-length magnitudes for events classified as explosions are not reported because they are biased by a prominent surface wave that extends the apparent duration in a way inconsistent with coda-length measurement.

4.2 Velocity Model

XPED uses the crustal velocity model for eastern Washington given in Table 4.2. The model does not include a surface layer for the Hanford or Ringold formations because most seismometer stations are sited on basalt. The crustal velocity model extends 38 km deep (to the mantle) and consists of six layers, each with uniform seismic velocity. The crustal velocity model was developed using available geologic information and calibrated from seismic data recorded from accurately located earthquake and blast events in eastern Washington. Time corrections (delays) are incorporated into the velocity model to account for significant deviations in station elevations or stations situated on sedimentary layers. Station delays also are determined empirically from accurately located earthquakes and blast events in the region.

Table 4.1 Local Seismic Data, April 1 – June 30, 2011

April 2011

DAY	TIME	LAT	LON	DEPTH	M	NS/NP	GAP	RMS	Q	MOD	TYP
2	3:44:51	46.2622	-120.9650	0.03*	1.3	5/006	209	0.34	CD	C3	
2	9:24:56	46.4065	-119.2633	0.45	0.6	4/004	206	0.02	AD	E3	
5	21:05:53	45.1220	-120.9542	19.12	2.7	37/039	102	0.28	BB	O0	
5	22:14:15	46.6483	-120.4822	0.60	2.1	4/004	132	0.15	AD	E3	P
7	6:58:55	45.1160	-120.9350	18.96	1.1	10/010	119	0.15	AB	O0	
8	19:19:27	46.1408	-119.5492	0.04*	1.3	6/006	280	0.05	AD	E3	P
9	6:17:38	45.1288	-120.9290	16.43	1.1	5/006	128	0.04	AD	O0	
9	19:35:31	46.5940	-119.8647	5.69	1.3	10/010	219	0.11	AD	E3	
10	4:29:40	46.4183	-119.2712	2.88	0.8	7/007	160	0.01	AC	E3	
10	17:20:10	45.1208	-120.9318	19.39	1.5	11/011	119	0.06	AB	O0	
12	13:02:57	46.4613	-119.7017	16.87	1.1	11/013	212	0.06	AD	E3	
12	13:48:43	46.5345	-121.4377	5.15*	1.1	18/019	248	0.13	AD	C3	
13	20:54:37	46.9807	-119.2072	2.16	1.3	10/010	119	0.11	AC	E3	
16	16:43:12	45.1213	-120.9348	15.93	1.4	12/012	118	0.12	AB	O0	
20	5:24:55	45.1197	-120.9368	19.46	1.4	10/010	118	0.13	AB	O0	
20	8:51:58	45.9222	-120.4742	8.77	1.1	6/007	93	0.24	BC	E3	
20	23:37:11	45.1085	-120.9300	21.54	1.2	8/008	124	0.13	BB	O0	
21	8:51:28	47.7202	-120.0192	5.66	2.6	19/022	47	0.19	BA	N3	
24	16:14:08	47.6915	-120.3457	1.64*	1.6	7/008	92	0.08	AB	N3	
26	8:27:02	46.4065	-119.2515	0.04*	0.2	6/008	161	0.08	AC	E3	
26	21:50:37	46.5470	-120.1342	19.66	0.8	4/005	162	0.05	AD	E3	
28	15:05:20	46.4037	-119.2645	3.22	1.6	14/017	139	0.13	AC	E3	

May 2011

1	4:13:55	46.4043	-119.2552	1.91	3.3	41/043	68	0.32	CA	E3	F
1	4:41:53	46.4123	-119.2645	2.71	0.5	8/008	129	0.04	AB	E3	
1	6:08:58	46.4130	-119.2648	1.71	0.8	9/009	128	0.04	AB	E3	
2	13:17:45	46.4043	-119.2543	1.29	0.8	12/014	143	0.10	AC	E3	
2	17:13:27	46.4053	-119.2605	1.11	2.0	19/020	136	0.12	AC	E3	

3	6:52:02	48.1580	-121.1715	7.84	1.3	5/008	137	0.37	CD	C3	
3	14:44:19	46.6047	-119.8543	6.83	1.3	10/012	136	0.07	AC	E3	
4	16:21:11	46.4027	-119.2567	0.41	0.8	8/010	172	0.09	AC	E3	
5	21:16:08	47.6657	-119.8817	0.28	2.7	9/009	85	0.61	DB	N3	P
12	7:50:39	47.7135	-120.0817	5.83*	1.2	6/010	107	0.20	BC	N3	
12	9:02:38	47.7087	-120.0787	5.90	0.9	3/006	141	0.04	AD	N3	
12	16:40:52	47.4348	-120.7140	17.38\$	1.2	7/008	137	0.30	BC	C3	
13	15:59:54	46.5875	-119.7945	0.04*	1.9	15/015	76	0.23	BA	E3	P
13	20:35:01	46.2427	-118.4370	0.03*	1.8	7/007	127	0.65	DC	E3	P
14	16:36:18	46.7340	-120.8520	7.17	2.0	20/022	97	0.22	BB	C3	
15	16:18:01	46.4027	-119.2598	0.03*	1.0	8/010	139	0.11	AC	E3	
16	10:56:35	46.7738	-119.5693	16.01	0.9	8/011	208	0.12	AD	E3	
17	16:45:47	47.4087	-121.4692	6.17\$	1.8	24/026	94	0.30	CC	C3	
17	23:11:24	46.6338	-120.4928	0.03*	1.9	7/007	102	0.23	BC	E3	P
19	4:29:40	46.4087	-119.2653	0.02*	1.0	10/011	167	0.07	AC	E3	
19	19:52:47	47.7242	-119.9100	0.03*	2.5	8/008	135	0.22	BB	N3	P
24	19:49:43	46.2333	-119.4713	0.04*	1.6	9/010	214	0.32	CD	E3	P
27	6:16:58	46.2700	-119.9993	10.16	1.3	5/007	155	0.16	CD	E3	
28	15:23:09	47.0477	-121.2662	1.56	1.6	15/016	107	0.26	BC	C3	

June 2011

1	18:08:24	46.6385	-120.4882	2.66	2.7	9/009	123	0.33	CC	E3	P
4	1:27:50	47.2405	-120.5825	9.23	2.0	22/023	53	0.25	BA	N3	
9	23:57:03	47.7972	-118.3163	0.33	2.3	8/008	115	0.21	BB	N3	P
10	4:01:13	47.6623	-120.1870	4.34	1.5	7/008	141	0.11	AC	N3	
10	21:50:06	47.9063	-120.8467	10.94	0.7	4/006	111	0.18	BD	C3	
11	7:19:32	46.7613	-120.4823	12.03	1.3	4/005	167	0.04	AD	E3	
11	15:35:23	46.6365	-119.6692	8.16	-0.1	3/004	245	0.05	AD	E3	
12	3:13:24	46.5735	-119.6780	7.97*	0.4	5/007	117	0.06	AD	E3	
14	5:57:42	46.9232	-120.7557	9.82\$	2.0	25/026	62	0.28	BB	C3	
14	19:40:24	44.2772	-121.2902	3.42	1.6	5/005	131	0.18	BD	O0	
15	19:02:24	46.9737	-120.3938	0.30	2.0	6/006	124	0.32	CC	E3	P
19	12:38:10	46.6973	-120.9103	3.88	1.9	12/016	112	0.10	AB	C3	

21	5:53:25	47.8462	-120.9065	5.00	0.7	4/006	266	0.20	BD	C3
22	10:47:17	46.4032	-119.2123	0.52	0.8	7/008	239	0.18	CD	E3
22	21:44:10	46.8185	-119.2288	15.25	1.1	13/016	98	0.21	BB	E3
25	16:21:50	47.8950	-120.8982	6.61	1.8	8/009	100	0.25	BB	C3
27	6:40:19	45.1348	-120.9388	15.62	1.4	8/008	113	0.13	BB	O0
27	13:51:07	45.1257	-120.9425	18.44	1.3	7/007	129	0.05	AB	O0

Explanation of Table 4.1

Type:	P is Probable Blast; X is Confirmed Blast; blank is local earthquake.
Date:	The year and date in Universal Time Coordinated (UTC). UTC is used throughout this report unless otherwise indicated.
Time:	The origin time of the earthquake given in Coordinated Universal Time (UTC). To covert UTC to Pacific Standard Time, subtract eight hours; to Pacific Daylight Time, subtract seven hours.
Lat:	North latitude, in degrees and minutes, of the earthquake epicenter.
Lon:	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, a determination was not 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 useful as a measure of quality of the solution only 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 s.
Q:	Quality factors; indicate the general reliability of the solution/location (A is best quality, D is worst). See Section 4.3 of this report, "Quality Factors."

4.3 Quality Factors (Q)

XPED assigns a two-letter **Quality factor** (Table 4.1) 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 arrival time residuals. For example: Quality **A** requires a root-mean-square residual (**RMS**) less than 0.15 s, while a **RMS** of 0.5 s 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 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**. Uncertainties associated with estimated depths depend upon the number of stations and number of phase measurements (**NS/NP**) utilized in the XPED calculation. Generally speaking, if the number of phases exceeds 10 measurements, the depth estimate is considered to be reliable. In this case, the second letter in the quality evaluation is either “A” or “B” (cf. Table 4.1). For example, the number of phase measurements from earthquakes ultimately classified as “deep” events typically falls within the 10-20 measurement range; these depth estimates are considered reliable. However, the number of phase measurements from earthquakes classified as “shallow” or “intermediate” may be less than 10 readings; in this case the depth estimate is less certain and the event could be classified as occurring in the CRBG or pre-basalt layers.

Table 4.2. Crustal Velocity Model for Eastern Washington (from Rohay et al. 1985)

Depth to Top of Layer (km)	Layer	Velocity (km/s)
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	Basement, Layer 1	6.1
13.0	Basement, layer 2	6.4
23.0	Sub-basement	7.1
38.0	Mantle	7.9

5.0 Seismic Activity – Third Quarter FY 2011

5.1 Summary

The Hanford Seismic Network recorded 53 local earthquakes during the third quarter of FY 2011. Sixteen earthquakes were located at shallow depths (less than 4 km), five earthquakes at intermediate depths (between 4 and 9 km), most likely in the pre-basalt sediments, and two earthquakes were located at depths greater than 9 km, within the basement. Geographically, 12 earthquakes were located in known swarm areas, 3 earthquakes occurred on or near a geologic structure (Saddle Mountain anticline), and 8 earthquakes were classified as random events. The largest event (3.3 M_a) occurred on May 1, 2011 at a depth of 1.9 km in the Wooded Island swarm (Wye swarm area).

Eleven other earthquakes were detected in the vicinity of Wooded Island, located about eight miles north of Richland just west of the Columbia River. The Wooded Island events recorded this quarter were a continuation of the swarm events observed during the 2009 and 2010 fiscal years and reported in previous quarterly and annual reports (Rohay et al. 2009a, 2009b, 2009c, 2010a, and 2010b). All events were considered minor (coda-length magnitude [M_a] less than 1.0) with the maximum depth estimated at 1.7 km. This placed the Wooded Island events within the Columbia River Basalt Group (CRBG).

Historically, most of the earthquakes at the Hanford Site have been located at shallow depths with the next greatest number of earthquakes located in the basement. Intermediate depth events have historically shown the fewest number of earthquakes.

5.2 Third Quarter FY 2011 Earthquakes

During the third quarter of FY 2011, 53 events were estimated as being located in the Hanford monitoring zone with a further 11 earthquake-like signals being categorized as probable surface explosions (Table 4.1).

The depth distribution and geographic pattern of the 23 earthquakes that occurred in the Hanford area are classified in Table 5.1 and Figure 5.2. Epicenters of the Table 4.1 events are shown in Figure 5.1. Epicenters of earthquakes in the immediate vicinity of the Hanford site, and their relationship to known faults and swarm areas is shown on Figure 5.2.

5.2.1 Location and Depth of Earthquakes

During the third quarter of FY 2011, 12 events occurred in swarm areas, 8 events were classified as random, and 3 events located near geologic structures.

5.2.2 Major Anticlinal Ridges

No notable or unusual seismicity was clearly or unambiguously associated with the region's

major anticlines or their underlying faults.

5.2.3 Earthquake Swarm Areas

Twelve earthquakes were characterized as swarm events in the third quarter of FY 2011. Small geographic areas not known to contain any geologic structures produce clusters of events (swarms), usually located in synclinal valleys. Swarms were generally thought to occur only at relatively shallow depths within the CRBG, however, in recent years swarms have also been recorded at deeper locations, for example, within the Horse Heaven Hills (Rohay et al. 2008).

5.2.3.1 Coyote Rapids Swarm Area

No notable or unusual seismicity was clearly or unambiguously placed within the Coyote Rapids swarm area.

5.2.3.2 Wahluke Slope Swarm Area

A minor event was recorded on May 16, 2010 at depth 16 km.

5.2.3.3 Wye Swarm Area

During the third quarter FY 2011, 12 Wooded Island events were recorded (Table 4.1). The Wooded Island swarm is located about eight miles north of Richland, west of the Columbia River about halfway between Hanford's 300 Area and Energy Northwest. All events were considered minor (coda-length magnitude [M_c] less than 2.0) with the maximum estimated depth at ~2 km. This placed the Wooded Island events within the CRBG.

The Wooded Island events recorded this quarter were a continuation of the swarm events observed during the 2009 and 2010 fiscal years and reported in previous quarterly and annual reports (Rohay et al. 2009a, 2009b, 2009c, 2010a, and 2010b). Based upon this quarter's data, swarm activity at the Wooded Island area has largely subsided.

5.2.4 Random or Floating Events

The majority of the earthquakes occurring during the quarter, and not discussed above, may be considered Random, or Floating earthquakes.

Table 5.1. Depth Distribution of Earthquakes for 3rd Quarter, FY 2011

Category	Number of Earthquakes (%)
Shallow (0-4 km deep)	19 (~36%)
Intermediate (4-9 km deep)	15 (~28%)
Deep (greater than 9 km deep)	19 (~36%)
Total	53

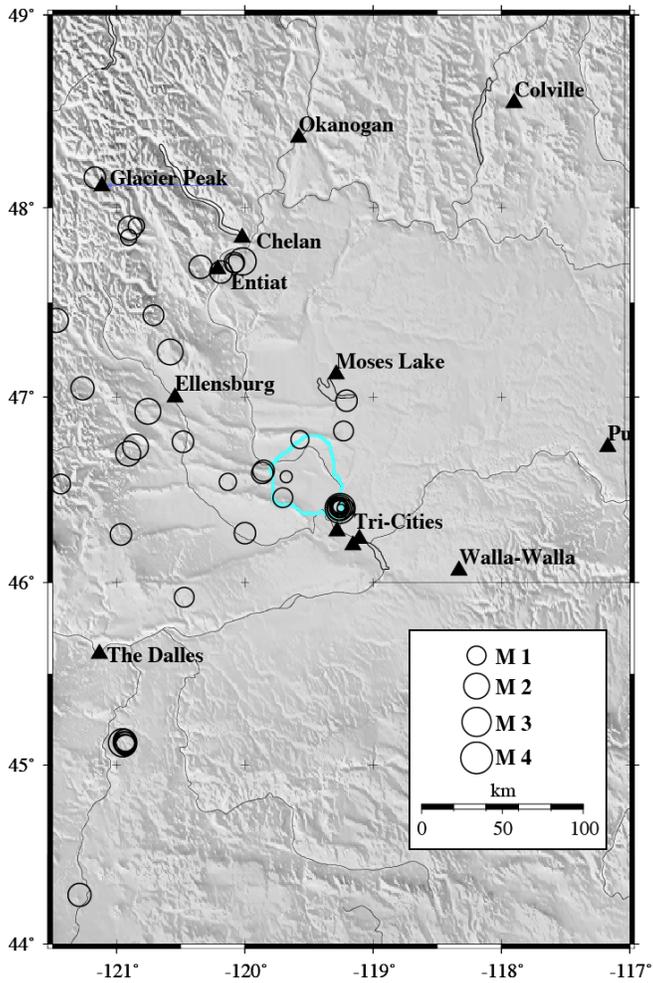


Figure 5.1 Epicenters of earthquakes recorded in the wider Hanford area during the 3rd Quarter of 2011.

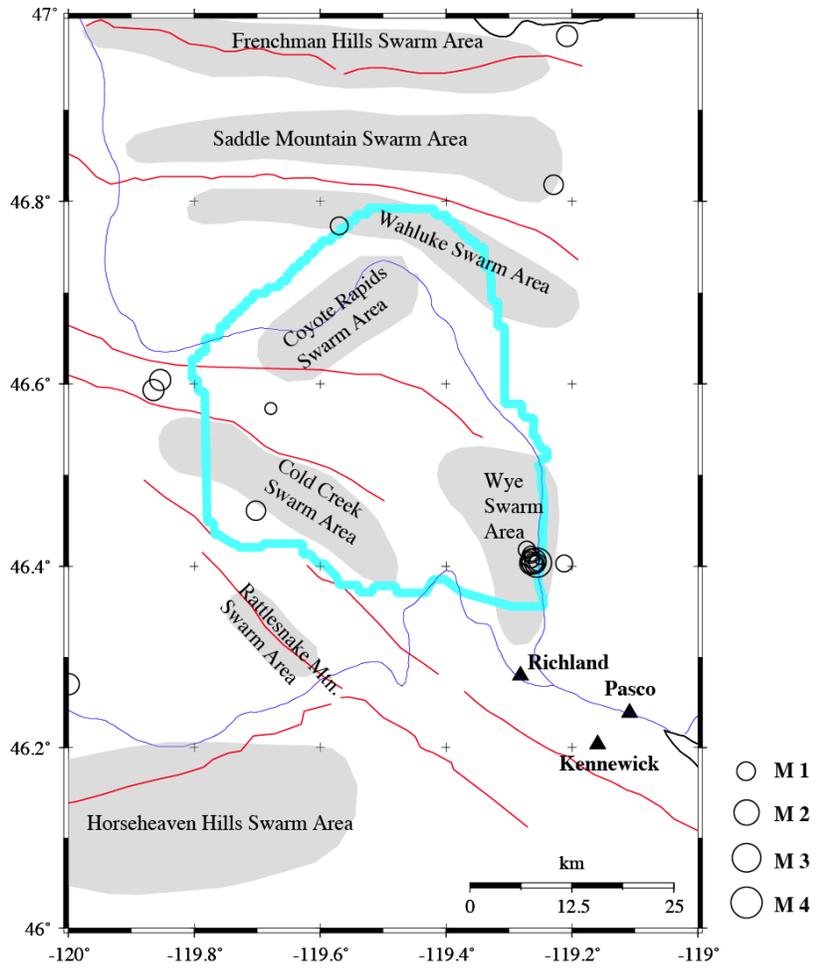


Figure 5.2 Epicenters of earthquakes occurring during the 3rd Quarter of 2011 in the vicinity of the Hanford site (blue outline), and their relationship to known structures (red lines), swarm areas (shaded bits), and cultural features.

6.0 Strong Motion Accelerometer Operations

6.1 Third Quarter FY 2011 Performance of the Hanford SMA Network

All of the SMA stations on the Hanford site were converted to telemeter data continuously. So continuous data are now available in near real time from the PNSN data archive. But they are also automatically included with the “snippets” of all data from all seismic stations triggered and analyzed automatically, and reviewed by PNSN seismic analysts. Figure 6.1 shows the analyst’s screen view of the M_d 3.3, 1 May, 2011, Wooded Island swarm event (for location see the map inset in the figure). The waveforms of the nearest SMA stations are seen sorted by distance from the event, with the analyst’s reviewed P and S wave phase picks showing as red flags on the individual traces.

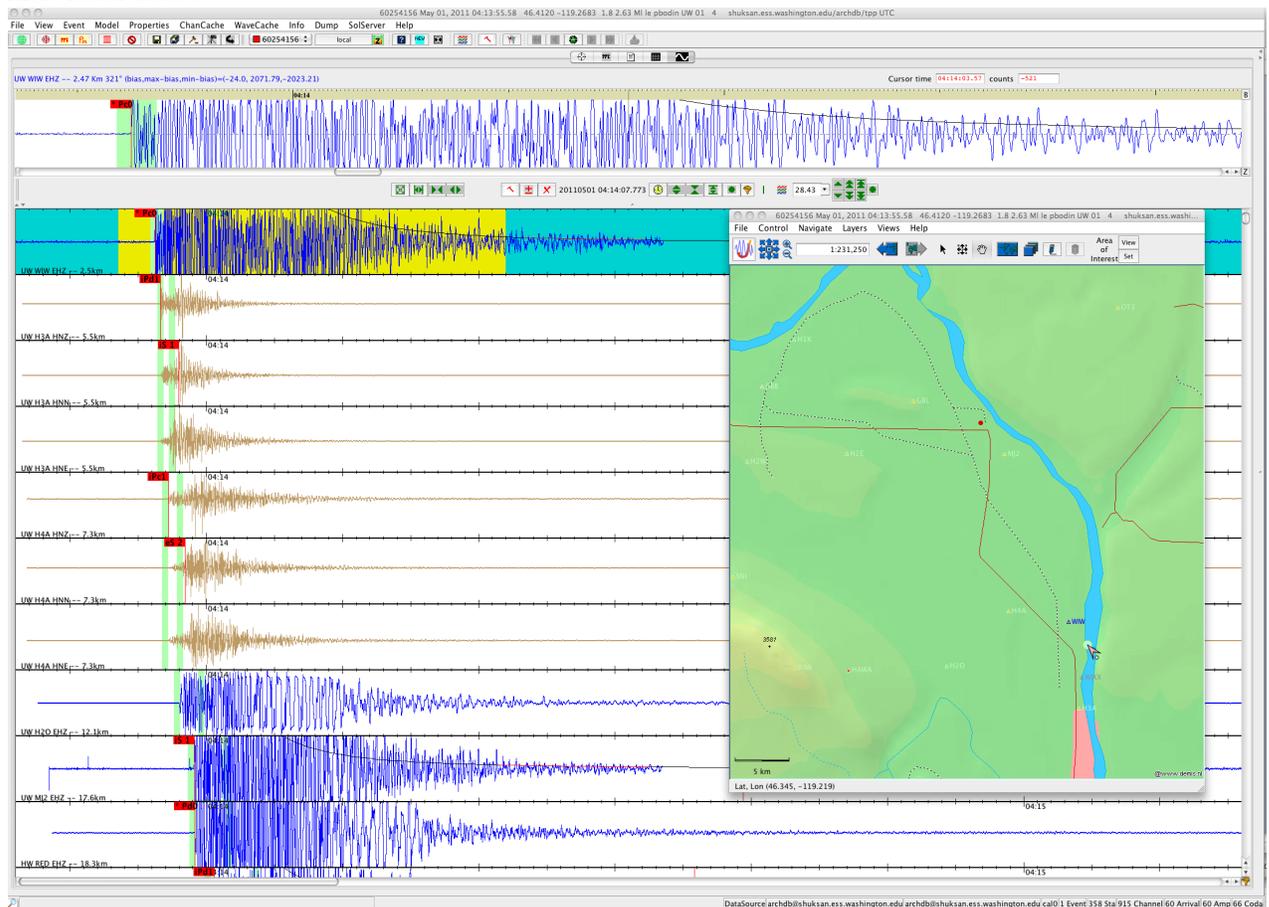


Figure 6.1 Screen shot of analyst’s view of the data from the 1 May, 2011 M_d 3.3 Wooded Island swarm earthquake. Note the clipped seismograms from the high-gain analog station (blue traces), and the data from the strong motion stations H3A and H4A (brown traces). Red label “flags” attached to thin red bars reveal time of analyst-reviewed phase picks, labeled with pick type and weight.

The 1 May earthquake traces from the nearest SMA station, H3A, are shown in Figure 6.2. The site experienced significant ground motions. Shaking levels were not damaging, but strong, probably because of the shallow source depth of the swarm event.

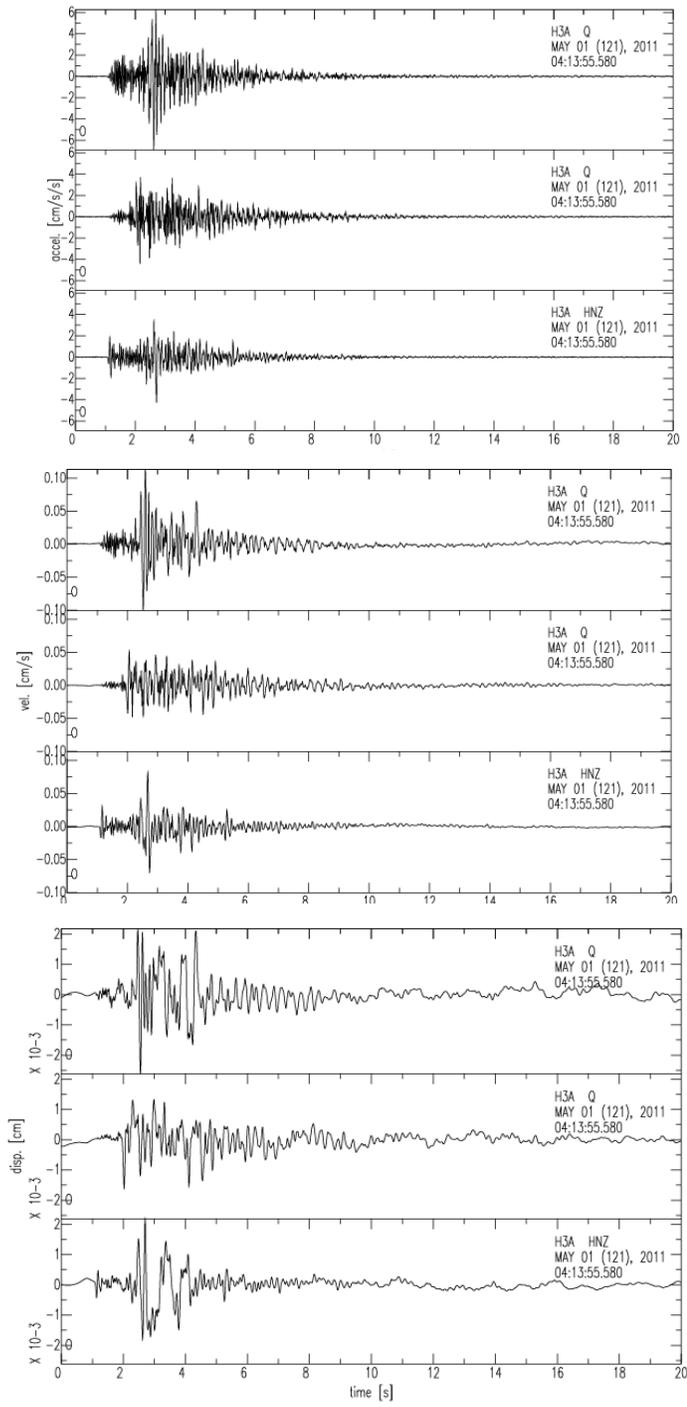


Figure 6.2 Instrument-corrected ground motions from the 1 May, 2011, Ma 3.3 earthquake, recorded at H3A. Top panel shows ground accelerations, Middle panel the ground velocities and the Bottom panel shows ground displacements. In each panel the top trace is the transverse component, the middle trace is the radial trace, and the bottom trace is the vertical component of ground motion.

7.0 Capabilities in the Event of a Significant Earthquake

The SMA network was designed to provide ground motion data in areas at the Hanford Site that have high densities of people and/or facilities containing hazardous materials, to ensure that the Hanford Site is in compliance with DOE Order 420.1B, Chapter IV, Section 3.d, “Seismic Detection.” The network also allows the HLSMP 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 PNSN network in the event of an earthquake at Hanford.

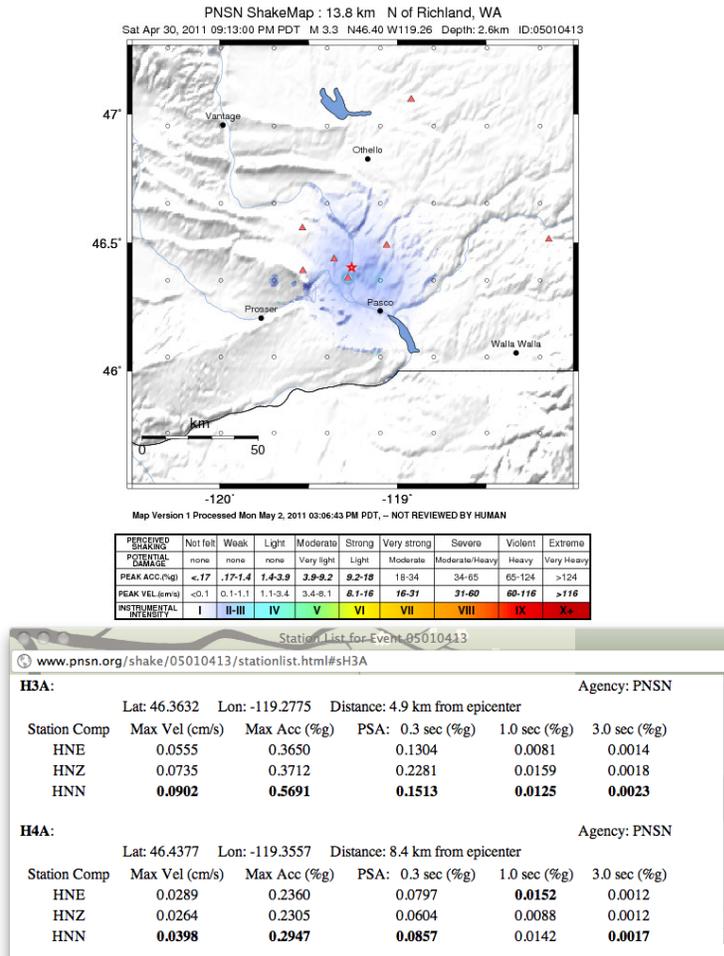


Figure 7.1 ShakeMap produced from ground motion recordings of the 1 May, 2011, M_d 3.3 earthquake. The top shows the “instrumental intensity” and illustrates that while the ground motion was strong enough to be felt, they were not close to being damaging intensities. These data and analyses were prepared and available within minutes of the event.

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 current 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, and the 300 and 400 Area facilities, which have the greatest concentration of people and also contain hazardous materials (Moore and Reidel 1996).

Many facilities at the Hanford Site have undergone various degrees of seismic analysis, either during design or during requalification. Although the seismic design of a building may be known, when an earthquake is “felt” in a facility on the Hanford Site, 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 building’s possibility of having damage may be impossible.

We now automatically produce “ShakeMaps” for any earthquake that might be widely felt at the Hanford site. As an example, Figure 7.1 shows the ShakeMap for the 1 May 2011 M_d 3.3 earthquake.

In the event of a major regional earthquake such as the 2001 Nisqually event, building managers, emergency directors, and engineers can obtain ground motion data recorded by the SMA network from the PNSN website within minutes of the event. This information is also passed on to Hanford Site Emergency Services personnel 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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