Annual Hanford Seismic Report for Fiscal Year 2012

(October 2011–September 2012)

University of Washington

Pacific Northwest Seismic Network

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December 2012

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Summary

The Pacific Northwest Seismic Network (PNSN) and MSA Mission Support Alliance (MSA) continue to provide uninterrupted collection of high-quality raw and processed seismic data from the combined Hanford Seismic Network (HSN) and Eastern Washington Regional Sub-Network (EWRSN) 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 HSN and the EWRSN together consist of 49 individual sensor sites and 15 radio relay sites maintained by the PNSN.

During FY2012 seismic activity was relatively quiet throughout eastern Washington. 229 earthquakes were cataloged in the region, of which about 42% (97) took place on or in the immediate vicinity of the Hanford site. While no damaging earthquakes took place in the region, a handful of notable or significant earthquakes illustrated interesting features of regional seismotectonics. One local earthquake caused nearly 1.5% g horizontal accelerations. Another earthquake, 200 km north of the Hanford site but well-recorded on the HSN accelerographs, was one of the larger regional earthquakes recorded by the network in recent times. A coda-duration magnitude (M_d) = 2.4 earthquake 24.6 km beneath the 200E area on the site produced very low levels of ground motion on the site, but serves as a reminder that larger earthquakes may take place on site. Several earthquakes took place in the historically active area of Entiat and Chelan, as well as a few earthquakes northeast of The Dalles. Within the vicinity of the Hanford site, there was typical swarm-type activity, most strongly observed in the Wye Swarm Area.

The network was challenged in FY2012 by a number of storms that caused damage at sites, particularly the lower Rattlesnake site. Further challenges were presented by severely dry, hot conditions during the summer that reduced accessibility to the seismic stations due to prolonged periods of extreme fire hazard. Notwithstanding these challenges, a number of telemetry changes and site visits have led to increased overall network performance.

Network advances in producing and communicating ShakeMap and ShakeCast products were made which will improve the resolution, accuracy, speed and utility of these situational awareness products for future earthquakes.

Abbreviations and Acronyms

ANSS - Advanced National Seismic System
AQMS - ANSS Quake Management System
BPA - Bonneville Power Administration
CRBG - Columbia River Basalt Group
Dmin - Minimum distance (closest distance from an earthquake epicenter to a station)
DOE - U.S. Department of Energy
Etyp - Event type
EWRSN - Eastern Washington Regional Sub-Network
FY - Fiscal year
g - typical value of gravitational acceleration at Earth's surface (~978 cm/sec/sec).
GPS - Global Positioning System
HLSMP - Hanford Lifecycle Seismic Monitoring Program
HSN - Hanford Site Network
Lat - Latitude
Lon - Longitude
km - kilometer
M_d - coda-duration magnitude
M_L - local magnitude
MAG - Magnitude of earthquake
MMI – Modified Mercalli Intensity
MOD - Velocity model
Mtyp - Magnitude type
NS/NP - Number of stations/number of phases
PNSN - Pacific Northwest Seismic Network
Q - Quality factor (of earthquake location)
Rms - Root Mean Square (error of earthquake location)
RSLW – Lower Rattlesnake (Mountain) data acquisition/telemetry site
SMA - strong motion accelerometer
USGS - U.S. Geological Survey
UTC - Coordinated Universal Time
UW - University of Washington
WSUR – Washington State University Richland

1.0 Introduction

This annual report documents the locations, magnitudes, and seismic interpretations of earthquakes recorded for the Hanford monitoring region of south-central Washington during the fiscal year (FY) 2012 (October 2011 through September 2012). Seismic monitoring for Public Safety and Resource Protection (PSRP) at the Hanford site is 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 seismic events. 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 and explosions proximal to or on the Hanford Site, specifically, between 46°-47° north latitudes (LAT) and between 119°-120° west longitudes (LON). 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 Strong Motion Accelerometer (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 networks were assumed by HLSMP.

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 cataloged seismic event locations and magnitudes and related waveform data from the HLSMP is maintained by PNSN on computer servers at the UW. Continuous waveform data and associated station metadata from all available seismic stations is permanently archived at the Incorporated Research Institutions in Seismology (IRIS) seismic data archive in Seattle, with backup copies at IRIS facilities in Seattle and in Boulder, Colorado.

2.0 Network Operations

2.1 Seismic Station Overview

The seismic network consists of three types of earthquake sensors—short-period seismometers, broad-band seismometers, and strong motion accelerometers (SMAs).

Short-period seismometers are very sensitive passive sensors (they do not use external electric power) designed primarily to detect micro earthquakes. While most short-period stations have a single component, sensitive only to the vertical motion of the ground, several HLSMP short-period stations record the ground in three orthogonal directions. In a regional network like the HLSMP networks, the time of arrival of waves, and the signal duration derived from short-period stations are used to determine the locations and magnitudes of seismic events; the polarities of ground motions may be used to constrain estimates of the geometry of fault that ruptured in an earthquake.

Broad-band seismometers are active sensors (they use electricity to power advanced electronic circuitry that is integral to the sensor) that faithfully record ground motions over a wide frequency range. The data they produce are acquired digitally with 24-bit dynamic range; a broad-band system will therefore stay “on-scale” over a much broader range of ground motions than a short-period sensor. In addition to locations and magnitudes derived from signal durations, details of the observed waveforms are used to reveal the source processes of small to moderately large earthquakes. HLSMP broad-band stations are all 3-component.

Both short-period and broad-band sensors will ultimately “clip”, or fail to record properly, if subjected to more than moderate levels of shaking (well below damaging levels). SMA stations, however, are designed to measure even the damaging ground motions from larger earthquakes. They are 3-component stations and must be carefully and strongly anchored to the ground so that the details of ground shaking up to 2g (twice the vertical acceleration of gravity) is accurately recorded. In addition to helping to characterize the earthquake source, they are critically important in measuring the ground motions that impact a particular site. They aid in determining what the built environment has been exposed to for earthquake response activities, and they are used by engineers and others in designing appropriate structures. Because of their importance to seismic monitoring on the Hanford site, the distribution, design, and operations of SMA stations within the HLSMP is 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).

Table 2.1. Hanford Site Network (HSN) Stations. *Italic font* indicates a 3-channel station, **bold font** indicates a Strong Motion Accelerometer.

	Latitude	Longitude	Elevation (m)	Station Name
BEN	46.5200	-119.7217	335	Benson Ranch
GBB	*46.6081*	*-119.6290*	*185*	*Gable Butte*
GBL	46.5982	-119.4610	330	Gable Mountain
H1K	***46.6447***	***-119.5929***	***152***	***100 K Area (SMA)***
H2E	***46.5578***	***-119.5345***	***187***	***200 East Area (SMA)***
H2O	46.3956	-119.4241	175	Water Station
H2W	***46.5517***	***-119.6453***	***129***	***200 West Area (SMA)***
H3A	***46.3632***	***-119.2775***	***99***	***300 Area (SMA)***
H4A	***46.4377***	***-119.3557***	***171***	***400 Area (SMA)***
LOC	46.7169	-119.4320	210	Locke Island
MDW	46.6130	-119.7621	330	Midway
MJ2	46.55736	-119.3601	146	May Junction Two
RSW	46.39436	-119.5925	1045	Rattlesnake Mountain
SNI	46.4639	-119.6609	323	Snively Ranch
WA2	46.7552	-119.5668	244	Wahluke Slope
WIW	46.4292	-119.2888	128	Wooded Island

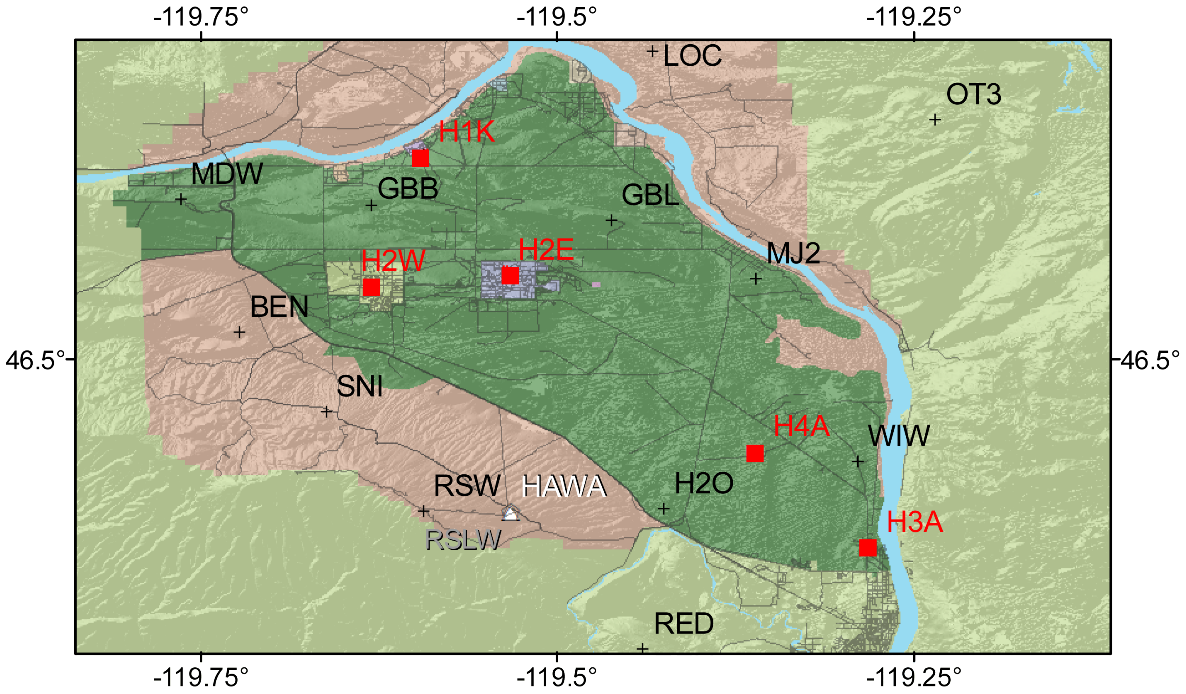

Figure 2.1 Seismic monitoring stations of the Hanford Seismic Network, on the Hanford site. Red squares and text are strong motion accelerographs (SMA) stations. Black text and plusses are short period stations. HAWA is a broadband and SMA US National Seismic Network Station operated by the US Geological Survey (USGS). RSLW is the data collection/telemetry node at Rattlesnake Mountain.

Table 2.2. Eastern Washington Regional Sub-Network (EWRSN) Stations. *Italic font* indicates a 3-channel station, **bold font** indicates a Strong Motion Accelerometer. Note that station ET4 replaced the previous station ET3 in the fourth quarter of FY2012.

	Latitude	Longitude	Elevation (m)	Station Name
BLT	45.915	-120.177	659	Bickleton
BRV	46.486	-119.992	920	Black Rock Valley
BVW	46.811	-119.883	670	Beverly
CBS	47.805	-120.043	1067	Chelan Butte South
CCRK	*46.559*	*-119.855*	*561*	*Cold Creek*
CRF	46.825	-119.388	189	Corfu
DDRF	*46.491*	*-119.060*	*233*	*Didier Farms*
DPW	47.871	-118.204	892	Davenport
DY2	47.986	-119.773	890	Dyer Hill Two
ELL	46.910	-120.568	789	Ellensburg
EPH	47.356	-119.597	661	Ephrata
ET4	46.563	-118.945	236	Eltopia Four
ETW	47.604	-120.334	1477	Entiat
FHE	*46.952*	*-119.498*	*455*	*Frenchman Hills East*
LNO	45.872	-118.286	771	Lincton Mountain Oregon
MOX	46.577	-120.299	501	Moxee City
NAC	46.733	-120.825	728	Naches
NEL	48.070	-120.341	1500	Nelson Butte
OD2	47.388	-118.711	553	Odessa Two
OT3	46.669	-119.234	322	Othello Three
PAT2	45.884	-119.757	262	Paterson Two
PHIN	*45.895*	*-119.928*	*227*	*Phinney Hill*
PRO	46.213	-119.687	553	Prosser
RED	46.297	-119.439	330	Red Mountain
SAW	47.706	-119.402	701	St. Andrews
TBM	47.170	-120.599	1006	Table Mountain
TRW	46.292	-120.543	723	Toppenish Ridge
TWW	47.138	-120.870	1027	Teanaway
VT2	46.967	-120.000	385	Vantage Two
WAT	47.699	-119.955	821	Waterville
WRD	46.970	-119.146	375	Warden
YA2	46.527	-120.531	652	Yakima Two
YPT	46.049	-118.963	325	Yellepit

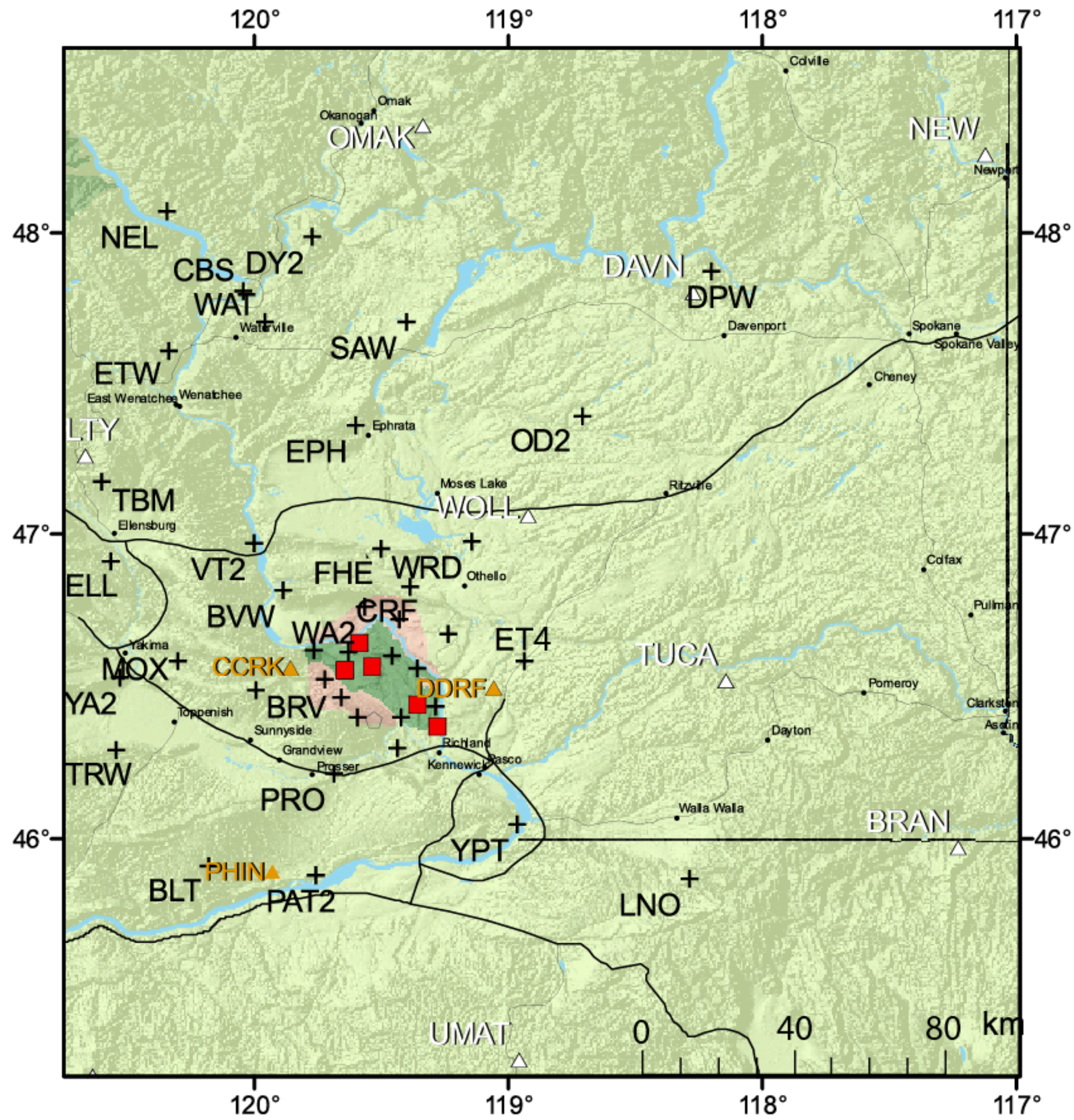

Figure 2.2 Seismic stations of the Eastern Washington Region Sub-Network. Black font and pluses are short-period EWRSN stations. Gold font and triangles are EWRSN broadband stations. White font and triangles are broadband stations contributed by other agencies to the PNSN data collection in eastern Washington.

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 Foundation funded US Array, "Transportable Arrays (TA)" experiment that are broad-band seismometers with digital telemetry via satellite or cellular telephone. GBB and FHE are tri-axial short-period 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 sub-networks to continuously transmit seismogram data to the PNSN in Seattle, Washington, for processing and archiving.

2.2 Strong Motion Accelerometer Stations

2.2.1 Strong Motion Station Location

SMAs provided ground motion observations critical to understand the impacts of strong ground shaking that affect the Hanford site itself. The Hanford SMA network consists of five free-field SMA stations (see Figure 2.1; Table 2.1). 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 Strong Motion 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. Cellular modems provide communication from all five SMAs. 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 Kinemetrics, 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 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 are continuously telemetered to UW. 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 provides timing of the ground motions accurate to several microseconds, coordinated to Universal Coordinated Time (UTC). 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 hours 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).

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

2.2.3 Strong Motion Operational Characteristics

Signals from the three accelerometer channels use an 18-bit digitizer with data sampled at 200 samples/s. Data are sent continuously in real-time to the PNSN offices at the UW in Seattle. 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.

For security and robustness, the Etna also stores triggered event files. When one of the accelerometer channels exceeds the trigger threshold (0.02%g), the recorders save information within the data buffers on memory cards within the Etna. 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 files created by a triggered event can be retrieved and examined by HLSMP staff, in the event of telemetry failure. The retrieval can be accomplished either remotely when telemetry is re-established, or manually by a technician traveling to the site.

2.3 Data Analysis

Signals from the seismometers are monitored in real time for changes in signal amplitudes and frequency that are expected from earthquakes. The seismic network is subdivided into spatial groupings of stations that are monitored for nearly simultaneous amplitude changes, 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. All data, whether triggered or not, is saved in a permanent seismic data archive at the Seattle-based IRIS data management center, and is available for download and analysis.

The HLSMP uses Earthworm, an automated computer-based software system developed by the US Geological Survey (USGS) and used throughout the region by the Pacific Northwest Seismic Network at the UW, to acquire seismic data and automatically detect and locate events. We currently run Earthworm Versions 7.4 through 7.6 on a variety of computer servers. Redundant Earthworm systems run continuously at the PNSN. If one fails, a second one serves as a "backup". Two complete systems are located in different buildings on separate computer servers with redundant power supplies, backed up by different uninterruptable power supplies and a diesel-powered electric generator capable of powering the network 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).

Data from HLSMP-operated seismic stations are combined at the UW analysis center with seismic data from regional seismic stations operated by other entities and contributed in real-time to PNSN. The earthquake locations and ground motion we report in this catalog include these valuable contributed data. This contributed data improves the accuracy of the seismic products we provide at Hanford, and adds to the robustness of the entire network in the event that any particular portion of the network suffers temporary data loss from environmental or other causes.

2.4 Station Maintenance Activities in FY2012

In the first quarter of FY2012, site visits were made to the Waterville Bonneville Power Administration (BPA) facility and the Chelan Butte South (CBS) relay sites to balance analog telemetry lines. Site visits were made to H2W and H2E to replace batteries at these strong motion sites. Also the Rattlesnake Mountain "Glowworm" remote Earthworm digitizer site was visited and a second GPS antenna was added.

Fieldwork during the second quarter of FY2012 focused on problems related to the Lower Rattlesnake (Mountain) data acquisition/telemetry site (RSLW) site on the slopes of Rattlesnake Mountain. Several issues demanded site visits to rectify conditions that took stations that pass data through this site off-line. In January, both the RSLW "Glowworm" remote Earthworm data acquisition node, and the co-located USGS seismic station HAWA went off-line. A site visit by PNSN and MSA staff ascertained that an electrical power breaker that provided power to both sites, located in the silo, had been turned off by mistake. Once power was restored, the site resumed normal operation. The power switch was labeled clearly to prevent future occurrences. Then on March 20th, a wind gust exceeding 70 mph at a nearby meteorology station blew over the small shed that houses the radio telemetry equipment and the data acquisition node. The solar panel that provided power for the station was blown 100 meters away and suffered damage. On March 22nd, PNSN staff visited the site and righted the shed, restoring the site to operating conditions. Since that time, PNSN and MSA have been discussing options to move the equipment into a more secure location.

During the third quarter of FY2012, there were many false noise triggers on the Ashe line, which includes stations OT3, WA2, H2O, MDW, RED, LOC, WIW, and GBL. The noise was coming in at the receiving site at Ashe BPA and a quick remedy for the issue was not possible. Instead, the "Glowworm" remote Earthworm data acquisition node was re-tasked to receive all of the Ashe line. Because of that change, the line is now being digitized at Hanford. As a result of the Ashe line change, station SNI went down in May 2012 and was restored to operations during the summer. At the very end of the third quarter of FY2012, another unusual problem affected Glowworm data. Due to a leap-second being added to UTC on June 30, 2012, the GPS timing system had an error of -1 second between 5:00pm PDT on June 30, 2012, until Glowworm was rebooted by PNSN staff at 9:30am PDT on July 2, 2012.

In the fourth quarter of FY2012, the old Ashe BPA site was reconfigured as a functional backup; not in operation, but capable of being turned on quickly should the need arise. The noise on this backup line is still present and is due to electromagnetic discharge (corona) during high-peak hours from the BPA station itself. Also, Station ET3 was moved about 2 kilometers (km) and renamed ET4.

Several issues have intermittently affected performance of individual sites that we are still in the process of resolving. Near-record drought and, thus, extreme fire hazard dogged our ability to visit stations during the quarter. Stations YA2 and MOX went down during the fourth quarter for unknown reasons. Station RED is receiving sporadic radio frequency interference that we are trying to diagnose and fix. Station WRW is in need of a new battery. Station CCRK needs an antenna system upgrade. Despite these problems, the performance of the network and capability to carry out its mission has improved greatly over the past year.

A new digital telemetry link was installed during the 4th quarter. Station data we were receiving from a cell modem at the Rattlesnake repeater is now being received from Washington State University Richland (WSUR). This reduces telemetry cost and provides additional bandwidth.

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.

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 Columbia River Basalt Group (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 produce clusters of events (swarms), usually located in synclinal valleys not known to contain any mapped geologic faults. 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. It is traditional to regard swarms as occurring within one of seven earthquake swarm areas in the HSN area. 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 5.2 for a map of these swarm areas). The other earthquake swarm areas are active less frequently. There is, however, no compelling theory to suggest a generative mechanism active within these swarm areas. They are deduced purely empirically, are rather conjectural, and will likely be updated or reconfigured as new swarm areas develop.
- **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.

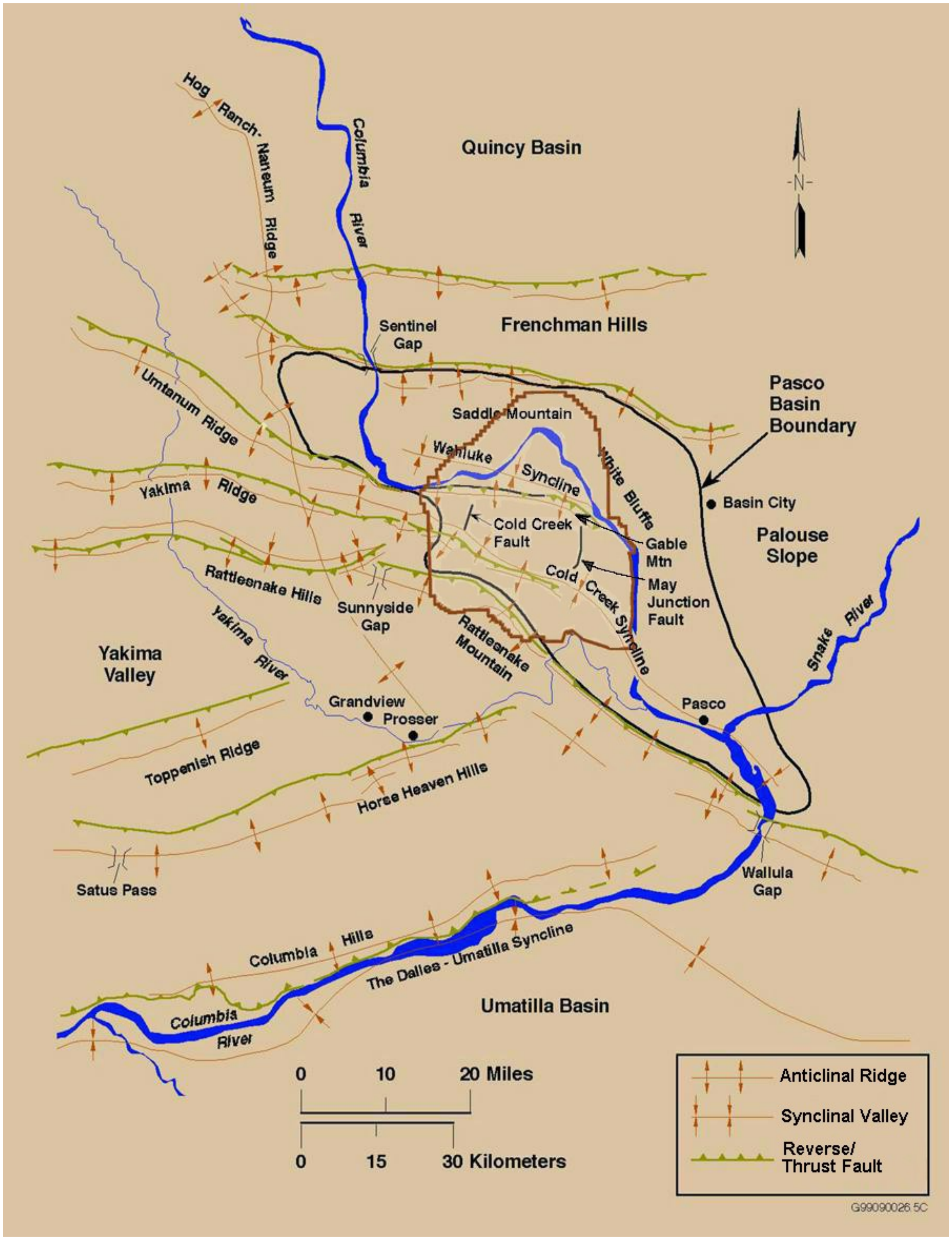

Figure 3.1 Tectonic features of the Hanford site within eastern Washington. (from Rohay et al., 2010b).

4.0 Earthquake Catalog

Within the Advanced National Seismic System (ANSS) Quake Management System (AQMS) seismic network processing software, an interactive program called Jiggle is used to manually review and revise automatic phase arrival picks and signal durations, as well as their polarities, uncertainties and quality factors. Arrival and duration times and uncertainties are used as input to an earthquake location program (Klein, 2002) to compute locations and magnitudes of the seismic events. Resulting locations for local earthquakes (46°-47° north latitude, 119°-120° west longitude) are reported in Table 4.1. Additional seismic events located outside the reporting region for this report are also evaluated. These surrounding events are not reported in this document, but are used as a check to confirm that the HSN and EWRSN are functioning properly (*e.g.,* quality checks on data recording). All processing results are available through the PNSN at www.pnsn.org.

4.1 Velocity Models

Earthquake location uses the arrival times of seismic phases at seismic stations and a model of the seismic wave speeds of crustal rocks of eastern Washington called a “velocity model” (MOD), to solve for the most likely location for the earthquake source. AQMS divides the eastern Washington region into 4 sub-regions. The velocity models for each sub-region were 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 models 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 4.2**. 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

4.2 Earthquake Magnitudes

AQMS computes several different magnitude estimates (Mtyp) for earthquakes. Table 4.1 shows the analyst-preferred value of either: 1) the coda-duration magnitude (M_d), or 2) the local magnitude (M_L) (Richter 1958). We report the median magnitude provided by all stations contributing estimates for an event.

The coda duration magnitude is based on a relationship developed for Washington State by Crosson (1972), modified for application within the AQMS software. The formula we use for M_d is:

$$M_d = -1.61 + 2.82 \log(D) - 2.46$$

where D is the duration of the observed event (in seconds), starting from the P-wave arrival. Many earthquakes yield magnitude determinations that are very small ($M_d < 0$) and highly uncertain. We define earthquakes with magnitudes (M_d) smaller than 3.0 as “minor”. Coda-duration magnitudes for events classified as explosions are reported although they may be biased by a prominent surface wave that extends the apparent duration in a way inconsistent with coda-length measurement.

M_L is computed from the maximum amplitudes of the signals on the horizontal components recording an event, filtered to mimic the instrument response of a Wood-Anderson torsion seismograph. The formula is:

$$M_L = \log(A) - \log(A_0) + S$$

where A is the average zero-to-peak amplitude of the two horizontal components at a station after they have been converted to pseudo-Wood-Anderson traces. $\log(A_0)$ is a distance correction, for which we use the Jennings and Kanamori (1983) values, and S is a site correction term that accounts for differences in local geological conditions amongst stations.

The choice of preferred magnitude type involves some subjectivity, as the relative strength of each depends on conditions that differ from event to event. In general, M_L is preferred for an event that is well recorded on a sufficient number of suitable channels. [This is because there may be subjectivity in determining the durations used by the M_d algorithm (although AQMS does this in a largely automatic, and hence objective, way), and because the determination of the duration is biased by background noise levels.] In practice, this usually means that M_L is preferred for earthquakes sufficiently large to be observed at several regional broadband stations (CCRK, DDRF, PHIN, HAWA), or approximately M2.5. Although occasionally smaller earthquakes yield robust M_L estimates, depending on the background noise level at the time of the earthquake. M_d, on the other hand can be obtained from smaller earthquakes, even if the recording should “clip”. For earthquakes larger than about M4.5, only the M_L should be used. The two magnitude scales are defined to be consistent for the events for which they overlap.

4.3 Quality Factors

Table 4.1 tabulates a two-letter **Quality factor** (Q) for each event that indicates the general reliability of the solution (**A** is best quality, **D** is worst). 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 – not shown**). 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 by the Hypoinverse location program. 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.

4.4 FY 2012 Earthquake Catalog for Eastern Washington

October 2011

Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
05	20:46:20	46.6220	-120.6537	0.7	1.9	Md	005/005	146	0.14	AD	E3	px
06	15:43:23	46.6188	-120.6888	0.0*	0.7	Md	006/006	159	0.36	CC	E3	px
08	07:49:50	46.6962	-120.9522	8.0	1.9	Md	024/022	82	0.11	AB	C3	le

09	08:42:43	46.3935	-119.2643	0.4	0.7	Md	007/009	214	0.15	BD	E3	le
09	18:50:06	47.6820	-120.2260	0.5	1.5	Md	006/007	125	0.22	BC	N3	le
10	18:52:11	47.6823	-120.2297	4.6	1.2	Md	003/005	183	0.04	AD	N3	le
11	04:21:29	47.6783	-120.2252	8.2	0.8	Md	003/005	140	0.06	AD	N3	le
14	04:29:36	46.1703	-120.4678	16.5	1.9	Md	011/014	95	0.35	CB	E3	le
14	04:35:58	46.1597	-120.4505	16.5$	1.9	Md	014/012	83	0.49	CA	E3	le
14	19:40:47	48.1757	-121.3198	10.2$	1.7	Md	008/011	140	0.27	BC	C3	le
15	06:11:53	46.4083	-119.2623	1.4	3.4	Md	070/038	68	0.24	BA	E3	le
15	07:39:02	46.4797	-119.2692	0.5	0.8	Md	003/005	310	0.11	BD	E3	le
15	07:48:16	46.4600	-119.2880	0.1*	0.0	Md	004/005	190	0.02	AD	E3	le
15	08:37:32	46.4047	-119.2602	0.4	0.8	Md	008/010	137	0.10	AC	E3	le
15	11:24:31	46.4760	-119.2902	0.5	0.4	Md	004/006	201	0.16	BD	E3	le
15	11:55:49	46.3962	-119.2625	0.5	0.4	Md	004/005	212	0.05	AD	E3	le
15	13:06:18	46.3973	-119.2603	0.4	0.6	Md	005/008	212	0.15	BD	E3	le
15	18:54:07	46.3982	-119.2568	0.0*	0.9	Md	006/008	212	0.11	AD	E3	le
15	23:30:32	46.4057	-119.2590	0.5	1.3	Md	009/011	138	0.07	AC	E3	le
16	01:15:57	46.4017	-119.2525	0.1	1.7	Md	014/018	94	0.20	BB	E3	le
17	00:27:19	46.4090	-119.2590	0.6	2.0	Md	030/031	91	0.23	BB	E3	le
17	01:22:56	46.7728	-120.7092	9.7	1.4	Md	010/010	95	0.17	BB	C3	le
18	04:05:31	45.1272	-120.9278	9.6*	1.5	Md	006/004	199	0.00	AD	C3	le
18	04:49:42	45.1240	-120.9312	17.6	1.7	Md	012/012	118	0.15	BB	C3	le
18	07:25:18	46.3975	-119.2578	2.0	0.6	Md	007/011	145	0.12	AC	E3	le
18	12:09:06	46.3945	-119.2527	0.0*	0.4	Md	005/007	215	0.15	BD	E3	le
18	12:25:55	45.1232	-120.9387	20.9	2.9	Md	032/029	103	0.20	BB	E3	le
19	08:58:42	46.3887	-120.9798	1.8	2.2	Md	016/017	79	0.28	BC	C3	le
21	18:55:19	46.4023	-119.2647	0.8*	0.8	Md	005/007	208	0.05	AD	E3	le
23	06:17:14	46.3855	-119.1983	2.4	0.2	Md	003/004	306	0.00	AD	E3	le
25	17:25:05	46.6248	-120.6387	0.1*	1.6	Md	008/008	141	0.19	BC	E3	px
27	20:30:05	45.8827	-119.7235	0.0*	2.3	Md	008/007	176	0.43	CC	E3	px
29	05:50:07	46.4448	-119.2830	2.5	0.4	Md	004/006	180	0.03	BC	E3	le
29	07:25:46	46.4562	-119.2787	0.8	0.0	Md	003/004	187	0.01	AD	E3	le
29	15:09:48	46.3783	-119.2755	5.5	1.3	Md	010/011	131	0.18	BB	E3	le

November 2011

Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
01	20:35:14	46.9500	-119.1042	0.0*	1.1	Md	004/004	148	0.04	AD	E3	px
02	21:35:36	46.6295	-120.5010	0.0*	2.2	Md	009/010	103	0.17	BC	E3	px
04	01:30:23	47.6765	-120.4157	0.8*	1.3	Md	007/008	110	0.09	AB	N3	le
04	09:58:48	46.7278	-121.1220	1.6	2.4	Md	046/047	31	0.20	BC	C3	le
04	15:41:03	47.3708	-120.0568	0.0*	0.0	Md	004/004	162	0.11	AD	N3	le
12	11:29:11	46.5983	-119.8602	7.4$	1.0	Md	008/011	181	0.09	AD	E3	le
16	14:57:05	48.5212	-119.9112	0.0*	2.5	Md	013/010	107	0.12	AC	N3	le
18	13:09:25	48.4693	-119.6075	11.9	4.6	Md	053/018	121	0.26	BB	N3	le
18	15:17:00	48.5162	-120.6790	10.2	1.7	Md	005/005	224	0.30	CD	C3	le
26	21:22:49	46.4120	-119.2613	0.0*	0.6	Md	005/006	201	0.03	AD	E3	le
30	01:02:25	46.4475	-119.2767	0.3$	0.4	Md	004/005	181	0.10	DD	E3	le
30	03:20:50	46.4513	-119.2793	0.2	0.2	Md	004/004	183	0.00	AD	E3	le

December 2011

Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
01	01:46:23	46.4183	-119.2642	2.2	0.8	Md	007/008	126	0.09	AB	E3	le
01	18:54:12	46.2717	-117.9652	16.8	1.7	Md	011/018	160	0.35	CD	E3	le
02	18:37:18	46.4098	-119.2642	1.6	0.9	Md	008/012	130	0.08	AB	E3	le
03	15:56:39	47.7328	-120.2512	3.8	1.4	Md	008/009	103	0.06	AC	N3	le
07	00:11:06	45.0765	-121.3103	0.3	2.3	Md	012/011	86	0.12	AC	N3	px
07	05:33:08	44.9688	-121.4965	12.8	1.3	Md	007/008	144	0.08	AC	N3	le
07	11:49:27	46.7128	-119.7023	14.7	0.6	Md	009/011	93	0.10	AB	E3	le
09	03:21:30	47.6693	-120.2157	0.6	1.5	Md	010/011	116	0.07	AC	N3	le

14	19:30:45	45.7963	-120.8523	0.0*	1.6	Md	013/012	83	0.43	CC	C3	px
14	22:10:12	46.6452	-120.4925	0.0*	1.7	Md	009/009	91	0.27	BC	E3	px
15	07:43:29	47.6337	-120.3847	0.7	1.2	Md	008/009	129	0.09	AC	N3	le
16	20:16:36	45.0795	-121.3085	0.5	2.2	Md	014/015	127	0.30	CC	N3	px
17	03:30:07	46.7172	-121.1267	9.0$	1.1	Md	010/014	124	0.31	CC	C3	le
17	03:30:37	46.7113	-121.1378	4.2*	1.9	Md	030/031	96	0.20	BC	C3	le
17	03:52:14	46.7257	-121.1297	12.3	0.7	Md	006/009	155	0.08	AC	C3	le
17	04:24:04	46.7300	-121.1178	1.2	1.2	Md	010/013	153	0.17	BC	C3	le
22	14:07:23	46.4155	-119.2725	0.4	0.7	Md	005/006	120	0.16	BC	E3	le
22	20:00:17	46.6408	-120.4918	0.6	2.1	Md	012/010	104	0.28	BC	E3	px
23	03:16:28	46.3993	-119.2648	1.0$	0.3	Md	005/006	210	0.06	CD	E3	le
25	17:16:16	46.4250	-119.2987	1.6	0.4	Md	006/010	190	0.09	AD	E3	le
January 2012												
Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
04	16:02:10	47.7460	-120.2397	0.8*	2.4	Md	025/024	55	0.13	CC	N3	le
07	10:48:24	48.4098	-120.6053	10.8*	1.5	Md	006/007	171	0.18	CC	C3	le
07	14:47:50	46.5652	-119.5487	24.6	2.4	Md	031/021	78	0.08	AA	E3	le
10	19:56:30	46.6493	-120.4782	0.0*	1.7	Md	011/005	133	0.11	CD	E3	px
14	00:21:52	46.3988	-119.2732	0.4*	1.3	Md	007/009	128	0.24	CB	E3	le
16	19:18:01	46.5603	-121.4555	6.0	0.8	Md	009/012	268	0.10	BD	C3	le
18	18:30:06	46.9145	-119.2928	0.3	1.7	Md	009/010	110	0.11	AC	E3	le
25	14:29:47	46.6307	-119.2878	15.7	0.8	Md	008/008	87	0.08	AA	E3	le
29	01:18:31	46.4100	-119.2540	0.0	1.1	Md	008/010	142	0.29	BC	E3	le
29	16:14:13	46.4032	-119.2685	0.4*	0.6	Md	006/006	268	0.08	CD	E3	le
February 2012												
Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
01	11:59:13	48.4592	-119.6138	0.0	2.5	Md	011/013	225	0.14	BD	N3	le
02	06:59:47	47.1127	-119.3878	13.2	2.1	Md	022/026	70	0.22	BB	N3	le
02	07:00:13	47.0987	-119.3713	14.3	1.2	Md	004/006	246	0.07	BD	N3	le
03	19:49:30	46.4115	-119.2492	0.3	1.8	Md	014/017	122	0.14	AB	E3	le
05	03:50:56	46.5555	-119.3328	18.8	1.0	Md	013/012	163	0.08	AC	E3	le
05	17:28:16	45.1240	-120.9500	18.2	2.5	M_L	015/018	129	0.26	BB	E3	le
07	23:20:52	45.7097	-119.1590	0.0*	1.6	Md	012/016	155	0.52	DC	E3	px
17	20:14:31	47.6643	-120.2962	1.3*	0.7	Md	005/009	131	0.09	CC	N3	le
19	22:18:37	47.6860	-120.2988	1.2*	0.6	Md	006/010	123	0.08	CC	N3	le
29	01:41:36	44.0577	-120.9385	0.0	2.4	Md	014/022	93	0.75	DC	N3	px
March 2012												
Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
02	08:52:57	46.9315	-120.7350	8.1	0.8	Md	012/015	98	0.19	BB	C3	le
03	05:03:36	46.4080	-119.2595	0.0	1.9	Md	017/021	115	0.22	BB	E3	le
03	08:51:00	46.4193	-119.2600	0.5*	0.7	Md	004/006	197	0.07	CD	E3	le
04	04:03:29	46.4212	-119.2657	0.5*	0.9	Md	004/006	194	0.07	CD	E3	le
04	04:15:41	46.4037	-119.2657	0.0	1.2	Md	013/015	134	0.20	BB	E3	le
08	17:25:31	46.4122	-119.2600	0.5*	1.0	Md	007/011	134	0.16	CB	E3	le
09	19:03:17	46.7392	-121.2003	1.4*	0.7	Md	004/004	170	0.35	DD	C3	le
10	18:37:52	46.5593	-119.8218	11.0	0.5	Md	004/008	199	0.17	BD	E3	le
12	18:59:39	46.1648	-119.1712	0.0*	2.6	Md	010/012	108	0.31	CC	E3	px
12	19:38:35	46.6462	-120.6958	0.0*	1.3	Md	005/005	152	0.45	CD	E3	px
14	20:31:06	47.3777	-117.8732	0.0*	1.7	Md	006/008	164	0.27	CD	N3	px
16	18:53:09	44.4037	-121.0125	0.0*	1.7	Md	008/010	139	0.25	CC	N3	px
17	23:59:09	46.4647	-120.0317	10.5	1.2	Md	011/013	73	0.32	CC	E3	le
20	10:05:15	46.8298	-121.1982	9.1	0.8	Md	014/017	115	0.20	BC	C3	le
21	19:55:33	47.0015	-119.1490	0.0*	0.8	Md	011/013	81	1.66	DC	N3	px
23	19:46:57	46.6652	-119.1092	5.9	1.2	Md	013/014	108	0.13	AB	E3	le
26	04:10:56	48.5498	-120.0202	6.0	1.7	Md	010/013	100	0.31	CD	N3	le
26	19:32:06	47.8758	-120.8993	10.3*	2.1	Md	008/012	95	0.36	CC	C3	le

27	01:01:47	47.8978	-120.8872	8.2	2.2	Md	008/011	101	0.09	AC	C3	le
28	08:50:13	46.7098	-120.9058	8.1	1.1	Md	016/017	105	0.16	BB	C3	le
30	07:39:39	47.6377	-119.7222	12.6	1.0	Md	005/008	167	0.09	AC	N3	le

April 2012

Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
02	12:53:19	47.5988	-118.9830	1.2*	2.0	Md	009/011	109	0.14	CC	N3	le
05	06:30:25	46.4125	-119.2700	2.1	0.8	Md	008/011	126	0.06	AB	E3	le
08	20:11:47	46.1110	-120.4792	16.8	1.7	Md	016/022	84	0.32	CB	E3	le
10	04:43:59	46.0455	-118.7123	14.4	3.2	M_L	033/033	55	0.29	BB	E3	le
11	00:04:48	46.9958	-119.2443	0.0*	1.7	Md	015/015	70	0.99	DC	E3	px
12	01:42:53	46.8265	-120.9632	3.8	1.2	Md	019/021	101	0.11	AC	C3	le
13	16:18:58	46.9595	-120.3932	0.0*	1.9	Md	013/015	96	0.40	CC	E3	px
14	21:48:24	47.8698	-120.8985	8.2	1.4	Md	007/010	157	0.28	BC	C3	le
14	21:50:33	47.8638	-120.8718	8.4	1.9	Md	021/026	90	0.26	BA	C3	le
17	10:11:28	47.7022	-120.1905	5.4	2.0	Md	019/013	70	0.09	AC	N3	le
19	05:21:03	47.5875	-121.4277	98.6	1.8	Md	022/030	55	0.32	CA	C3	le
19	17:41:22	47.6538	-120.2453	3.5	1.6	Md	006/007	139	0.10	CC	N3	le
19	18:36:32	46.9098	-119.0255	0.0*	1.8	Md	009/009	182	0.37	CD	E3	px
19	21:02:02	46.9677	-119.0657	0.0*	1.4	Md	004/004	155	0.45	CD	E3	px
20	14:45:14	46.4118	-119.2732	3.2	0.4	Md	005/007	123	0.06	AB	E3	le
26	07:07:59	47.2223	-119.4853	16.3	1.6	Md	017/023	60	0.19	BB	N3	le
28	13:34:34	46.6850	-119.2227	1.1	1.6	Md	015/015	153	0.10	AC	E3	le

May 2012

Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
02	01:51:36	46.7355	-119.4197	0.7*	0.9	Md	010/016	104	0.18	CB	E3	le
02	13:48:09	47.9087	-119.6415	2.5*	0.8	Md	006/007	117	0.50	DC	N3	le
08	12:19:35	46.4162	-119.2733	2.5	0.6	Md	004/007	121	0.12	AB	E3	le
08	12:54:43	46.4132	-119.2612	0.0	0.7	Md	009/013	133	0.23	BB	E3	le
10	08:08:37	46.0263	-120.7508	9.2	1.6	Md	028/033	69	0.23	BA	C3	le
13	05:26:56	47.4277	-120.6522	1.6	1.0	Md	010/010	113	0.14	BC	C3	le
13	11:56:59	47.8375	-121.3655	2.5*	0.5	Md	003/004	283	0.04	CD	C3	le
15	22:23:43	47.6692	-120.1237	1.1*	1.4	Md	006/007	147	0.08	CC	N3	le
16	21:24:20	44.5627	-117.4092	5.8*	2.2	Md	007/005	199	0.01	CD	N3	le
18	09:30:30	46.4267	-119.2623	1.1	0.3	Md	005/009	190	0.08	AD	E3	le
19	12:53:42	45.8795	-120.7395	15.1	1.4	Md	005/008	209	0.21	BD	C3	le
20	00:54:28	46.6062	-119.8552	6.6	2.3	Md	028/022	124	0.42	CB	E3	le
20	15:38:53	46.6120	-119.8265	6.4	1.6	Md	019/017	100	0.29	BB	E3	le
20	21:48:16	44.2680	-120.9165	0.0*	1.7	Md	006/007	192	0.32	CD	E3	px
21	21:48:29	48.3883	-119.5993	0.0	2.5	Md	018/020	99	0.40	CC	N3	le
22	02:59:08	46.8335	-119.5580	6.9	-0.1	Md	003/005	194	0.06	BD	E3	le
22	19:48:33	46.5777	-119.8247	10.0	0.7	Md	004/006	152	0.14	BC	E3	le
22	22:49:00	46.6297	-120.5025	0.0*	1.7	Md	008/007	117	0.07	CC	E3	px
23	23:05:15	46.5722	-119.8018	10.2	1.0	Md	006/008	117	0.12	AB	E3	le
24	20:35:00	46.4528	-119.2797	0.5*	0.6	Md	006/007	183	0.05	CD	E3	le
24	23:52:40	47.7593	-120.0368	3.1	1.9	Md	007/007	134	0.04	AB	N3	le
26	07:52:49	46.4028	-119.2548	0.6*	0.4	Md	006/008	211	0.13	CD	E3	le
26	13:59:25	45.0525	-117.0457	4.9*	0.5	Md	003/004	230	0.06	CD	E3	le
28	18:58:45	47.6287	-120.2952	7.7	2.2	Md	027/026	51	0.16	BA	N3	le
28	19:14:38	47.7095	-120.0305	9.3	1.4	Md	006/005	229	0.05	AD	N3	le
28	23:40:52	46.6043	-119.8552	7.1	0.8	Md	004/007	176	0.07	AC	E3	le
29	18:46:14	44.4093	-121.0492	0.0*	1.7	Md	012/013	107	0.29	CB	E3	px

June 2012

Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mdo	Etyp
06	02:33:40	47.6882	-120.1125	7.7	0.8	Md	006/007	138	0.05	BC	N3	le
07	00:49:45	48.5998	-119.3592	8.6	2.0	Md	007/008	145	0.06	AC	N3	le
09	10:05:58	46.0292	-118.2395	3.6	1.7	Md	009/006	98	0.12	AC	E3	le

11	16:44:33	48.6072	-119.3103	0.8	1.8	Md	010/014	149	0.26	BC	N3	le
12	01:58:04	47.8132	-120.0988	0.6*	1.7	Md	008/007	134	0.06	CB	N3	le
14	04:32:03	47.6845	-120.3297	2.5*	1.0	Md	005/005	209	0.03	CD	N3	le
15	16:40:08	46.7982	-119.6918	3.1	1.2	Md	008/012	124	0.33	CC	E3	le
15	22:52:14	46.4705	-119.5517	0.6*	0.3	Md	007/009	123	0.77	DB	E3	le
18	16:01:00	46.7428	-121.0497	9.1	0.9	Md	010/013	138	0.27	BC	C3	le
21	23:55:11	44.0615	-121.3565	0.0*	1.4	Md	016/017	97	0.31	CB	C3	px
22	19:13:11	46.5613	-119.7910	6.9	1.1	Md	005/007	137	0.09	AC	E3	le
22	19:13:37	46.5852	-119.8175	8.0	-0.3	Md	003/005	189	0.01	BD	E3	le
23	17:06:16	48.9020	-120.6753	10.0*	1.6	Md	011/016	139	0.39	CD	C3	le
25	07:09:16	46.1390	-119.8022	19.8	1.2	Md	015/022	102	0.38	CB	E3	le
25	18:50:11	46.7995	-119.6980	2.0	2.2	Md	030/025	91	0.40	CC	E3	le
28	19:59:19	45.8977	-119.2848	0.0*	1.9	Md	008/011	181	0.74	DD	E3	px
29	00:25:48	46.6565	-120.4835	0.0*	1.6	Md	010/010	105	0.30	CC	E3	px
29	08:08:34	46.7400	-120.7258	0.0	0.7	Md	008/010	125	0.37	CB	C3	le
29	17:00:52	45.5410	-119.5478	0.0*	2.0	Md	009/010	324	0.29	DD	E3	px
July 2012												
Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
03	21:48:40	45.8732	-119.2983	0.0*	1.9	Md	009/012	134	0.21	CC	E3	px
06	17:21:36	46.4148	-119.2665	1.7	1.1	Md	011/014	200	0.06	AD	E3	le
06	17:32:20	46.4162	-119.2655	1.0	0.8	Md	007/010	198	0.07	AD	E3	le
06	18:01:56	46.4140	-119.2683	0.0	0.9	Md	008/013	127	0.08	AB	E3	le
06	19:11:09	44.2907	-121.0812	0.0*	1.4	Md	005/005	316	0.35	DD	E3	px
06	19:59:31	46.4233	-119.2727	1.8	0.4	Md	005/008	191	0.12	AD	E3	le
06	22:29:39	46.7122	-120.7107	10.5	0.5	Md	006/008	199	0.08	BD	C3	le
06	22:50:34	46.4545	-119.2835	1.0*	0.5	Md	004/007	185	0.05	CD	E3	le
07	00:18:53	46.4088	-119.2597	0.5*	0.6	Md	005/007	205	0.06	CD	E3	le
07	06:50:32	46.4130	-119.2603	0.1	0.9	Md	009/012	202	0.04	AD	E3	le
07	06:55:17	46.4133	-119.2607	1.1	0.6	Md	005/008	202	0.05	BD	E3	le
07	07:44:47	46.4060	-119.2692	0.0	1.1	Md	008/013	206	0.17	BD	E3	le
07	07:49:12	46.4112	-119.2598	0.4*	0.9	Md	008/010	204	0.05	CD	E3	le
07	08:18:07	46.4112	-119.2602	0.5*	1.1	Md	008/009	204	0.06	CD	E3	le
07	08:22:28	46.4172	-119.2633	0.3	0.9	Md	011/015	129	0.10	AB	E3	le
07	08:29:20	46.6695	-120.6367	6.1	0.4	Md	008/008	100	0.05	AC	E3	le
07	09:58:08	46.4182	-119.2725	0.6	1.6	Md	020/024	86	0.14	AA	E3	le
07	10:14:40	46.4172	-119.2680	0.0	0.6	Md	005/009	197	0.15	BD	E3	le
08	00:52:17	46.4115	-119.2620	0.7	0.4	Md	006/009	202	0.08	BD	E3	le
09	14:41:24	48.6800	-119.4165	0.9	2.3	Md	012/014	115	0.40	CC	N3	le
10	13:12:12	46.6018	-119.8562	6.4	0.8	Md	007/008	177	0.08	AC	E3	le
11	16:47:27	48.8037	-118.9157	0.0*	1.1	Md	006/010	238	0.50	DD	N3	px
11	19:25:32	46.6240	-120.6692	0.0*	1.7	Md	019/027	58	1.03	DC	E3	px
14	03:52:13	45.7438	-120.7878	0.3	1.3	Md	010/011	147	0.13	AC	C3	le
18	02:09:44	47.7262	-120.1995	0.6*	2.2	Md	024/014	64	0.07	CC	N3	le
20	19:54:40	48.1028	-120.7350	1.6	1.9	Md	011/013	144	0.12	AC	C3	le
21	11:29:34	46.4085	-119.2680	1.9	1.0	Md	011/012	204	0.04	AD	E3	le
21	23:29:31	46.6437	-119.3823	13.9	0.3	Md	009/015	164	0.08	AC	E3	le
27	16:22:47	46.7002	-120.4970	19.6	1.6	Md	011/014	81	0.23	BA	E3	le
30	07:37:30	46.5598	-119.2068	16.1	0.7	Md	015/021	93	0.12	AB	E3	le
30	20:58:56	48.3622	-120.8275	5.2	1.7	Md	019/025	87	0.39	CC	C3	le
31	21:27:54	46.1430	-119.2080	0.0*	2.3	Md	015/016	164	0.17	CC	E3	px
August 2012												
Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
07	23:59:45	47.6903	-120.3022	8.9	3.2	M_L	028/030	46	0.14	AC	N3	le
09	12:36:35	46.8205	-119.4062	17.8	0.4	Md	006/010	261	0.10	AD	E3	le
15	17:51:15	47.6320	-120.1140	3.1	1.0	Md	007/009	145	0.09	BC	N3	le
17	04:23:13	46.6625	-121.4470	7.2	0.7	Md	017/024	252	0.08	AD	C3	le

19	13:28:31	47.6793	-120.0500	5.5	2.1	M_L	010/011	119	0.04	AB	N3	le
21	19:22:28	48.1295	-120.3692	3.4	2.0	Md	014/018	88	0.40	CB	N3	le
22	04:55:44	46.4128	-119.2685	0.0	1.0	Md	009/013	106	0.11	AB	E3	le
31	23:34:09	47.6658	-120.3302	1.7*	1.3	Md	005/008	128	0.08	CC	N3	le
September 2012												
Day	Time	Lat	Lon	Depth	Mag	Mtyp	NS/NP	Gap	Rms	Q	Mod	Etyp
02	08:25:39	46.2438	-120.7248	17.7	1.7	Md	027/036	53	0.40	CA	C3	le
02	11:30:00	46.5680	-119.6682	12.4	0.4	Md	009/015	162	0.25	BC	E3	le
02	19:15:30	46.5938	-119.8278	6.1	1.0	Md	015/019	76	0.40	CA	E3	le
04	09:06:49	48.9025	-120.6897	10.1*	1.5	Md	008/012	152	0.30	CD	C3	le
06	03:56:02	48.0595	-120.8233	5.6	0.8	Md	006/007	130	0.06	AC	C3	le
11	19:29:23	47.3370	-117.8560	0.0*	2.2	Md	011/016	205	0.53	DD	N3	px
13	17:34:10	47.3425	-120.0190	10.2	3.4	M_L	037/038	61	0.21	BC	N3	le
15	02:37:50	46.4853	-119.8057	0.6*	1.5	Md	009/011	149	0.36	CC	E3	le
15	07:25:45	48.8770	-120.6848	10.0*	1.6	Md	009/011	137	0.14	CD	C3	le
19	21:10:32	46.5780	-119.7833	8.1	0.8	Md	005/008	133	0.22	BB	E3	le
22	19:26:19	46.6600	-120.5885	6.7	1.2	Md	012/010	141	0.12	AC	E3	le
23	18:15:49	47.6873	-120.3332	5.5	0.3	Md	004/007	210	0.07	BD	N3	le
25	02:16:03	46.7433	-121.0363	3.8	2.3	M_L	044/050	53	0.26	BC	C3	le
25	22:06:58	46.6510	-120.5165	0.0*	1.5	Md	011/013	76	0.35	CC	E3	ex
26	20:31:21	48.2073	-121.3183	8.9	1.2	Md	014/019	120	0.29	BB	C3	le
28	19:40:37	47.8067	-117.4277	0.0*	2.4	Md	015/021	115	0.58	DD	N3	px
30	15:46:33	47.7490	-120.2012	4.7	2.0	Md	017/013	106	0.06	AC	N3	le

Explanation of Table 4.1 – also see section 4.3 of this report

Etyp	Event Type. le is local earthquake, px is Probable Blast; ex is Confirmed Blast
Day	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	Latitude of the earthquake epicenter, in decimal degrees
Lon	Longitude of the earthquake epicenter, in decimal degrees
Depth	The depth of the earthquake in kilometers (km). * = Depth constrained by location program, $ = location program had trouble converging and constrained both location and depth.
Mag	The analyst-preferred magnitude. If magnitude is blank, a determination was not made.
Mtype	Preferred magnitude type (see section 4.2, "Earthquake Magnitudes")
NS/NP	Number of stations/number of phases used in the location.
Gap	Azimuthal gap; the largest horizontal angle (relative to the epicenter) containing no stations.
Mod	Primary velocity model used in the location. (see section4.1, "Velocity Models")
Rms	Average misfit, in seconds, between the model-predicted and observed travel time. Computed as the square root of the summed squares of individual phase time residual (observed phase arrival time minus predicted arrival time) of all phases used to locate the earthquake. It is a meaningful 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 smaller than ~ 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."

5.0 Discussion of Seismic Activity – FY 2012

5.1 Summary

During FY2012 seismic activity was relatively quiet throughout eastern Washington. 229 earthquakes were cataloged in the region, of which about 42% (97) took place on or in the immediate vicinity of the Hanford site (Tables 5.1 and 5.2). Notwithstanding the relatively low seismicity rate, one local earthquake caused nearly 1.5%g horizontal accelerations. Another earthquake, 200 km north of the Hanford site but well-recorded on the HSN accelerographs, was one of the larger regional earthquakes recorded by the network in recent times. An M_d = 2.4 earthquake 24.6 km beneath the 200E area on the site produced very low levels of ground motion on the site, but serves as a reminder that larger earthquakes may take place on site. Several earthquakes took place in the historically active area of Entiat and Chelan, as well as a few earthquakes northeast of The Dalles. Within the vicinity of the Hanford site, there was typical swarm-type activity, most strongly observed in the Wye Swarm Area.

The depths of the earthquakes during the year also followed the historical pattern. 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.

The depth distribution and geographic pattern of the earthquakes are tabulated in Tables 5.1 and 5.2 and plotted on Figures 5.1 and 5.2. Figure 5.3 is a perspective plot showing the hypocenters in the vicinity of the Hanford site and their location at depth and their relationship to the surface topography.

There may be differences in the number, depth, and magnitude of earthquakes in the FY2012 Annual Report versus the individual quarterly reports (Bodin et al., 2012a, 2012b, 2012c, and 2012d) for FY2012. These differences in the text and shown on the following tables are due to events being re-analyzed at later dates. Seismic analysts at PNSN will sometimes re-review locations after internal discussion and/or if more data channels are added, or perhaps omitting data from a particular station if the timing was found to be out of tolerance. Such reanalysis may move them from the preliminary locations, or earthquake types (Etype), that were reported in the quarterly report. Because the FY2012 annual report supersedes the quarterly reports for FY2012, this annual earthquake catalog should be considered the most accurate product.

The FY2012 quarterly reports (Bodin et al., 2012a, 2012b, 2012c, and 2012d) also contain figures showing data from some of the significant earthquakes, and provide further discussion of the earthquakes.

Table 5.1. Depth distribution of eastern Washington earthquakes for FY 2012

Category	1st Quarter	2nd Quarter	3rd Quarter	4th Quarter	FY 2012
Shallow (0-4 km deep)	47	23	37	34	141
Intermediate (4-9 km deep)	7	6	14	14	41
Deep (greater than 9 km deep)	13	12	12	10	47
Total	**67**	**41**	**63**	**58**	**229**
Felt	2	0	1	2	5

Table 5.2. Earthquake counts for FY 2012 for earthquakes near the Hanford site.

Seismic Sources		1st Quarter	2nd Quarter	3rd Quarter	4th Quarter	FY 2012
Geologic Structure		0	1	0	0	1
Swarm Areas	Frenchman Hills	0	0	0	0	0
	Saddle Mountains	0	0	0	0	0
	Wahluke Slope	0	0	4	0	4
	Coyote Rapids	0	0	0	0	0
	Wye	26	9	7	17	59
	Cold Creek	0	1	2	0	3
	Rattlesnake Mountain	0	0	0	0	0
	Horse Heaven Hills	0	0	1	0	1
	Total for swarm areas	26	10	14	17	67
Random Events		4	6	11	9	30
Total For All Earthquakes		**30**	**16**	**25**	**26**	**97**

5.1.1 First Quarter FY 2012 Earthquakes

67 earthquakes were cataloged in eastern Washington during the first quarter of FY 2012, 30 local to the Hanford site (local), and 28 off of the site (regional). Of the local earthquakes, 26 were located at shallow depths (less than 4 km) all located in the Wye swarm area, 2 at intermediate depths (between 4 and 9 km), most likely in the pre-basalt sediments, and 2 deeper than 9 km, within the basement. The four non-swarm local earthquakes were classified as random events. Of the regional earthquakes, 47 were shallow, 7 intermediate, and 13 deep.

The largest regional event (M_d = 4.6) took place on November 18, 2011 at depth of 11.9 km with the epicenter located in the vicinity of Okanogan, about 200 km north of the Hanford site. The largest earthquake near the Hanford site (M_d = 3.4) was located in the Wye swarm area in the vicinity of Wooded Island, a few miles north of Richland, on October 15, 2011 at a depth of 1.43 km. A further 5 earthquake-like signals were categorized as probable surface explosions.

During the first quarter FY 2012, 26 Wye Swarm events were recorded (Table 5.2). The majority of these were in a small area about eight miles north of Richland, west of the Columbia River about halfway between Hanford's 300 Area and Energy Northwest. 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).

5.1.2 Second Quarter FY 2012 Earthquakes

The EWRSN and HSN recorded 41 eastern Washington earthquakes during the second quarter of FY 2012, 16 local to the Hanford site (local), and 23 off of the site (regional). Of the local earthquakes, 10 were located at shallow depths (less than 4 km), 1 at intermediate depths (between 4 and 9 km), most likely in the pre-basalt sediments, and 4 deeper than 9 km, within the basement. Geographically, 9 shallow local earthquakes were located in the Wye swarm area, and one in the Cold Creek swarm area. Five other local earthquakes were classified as random events. Of the regional earthquakes, 5 were shallow, 5 intermediate, and 8 deep. The network also located eight (8) events that have been categorized as probable surface explosions.

The largest event ($M_L = 2.5$) took place 5 February 2012 at depth of 18.2 km with the epicenter located in the 2009 Maupin, Oregon, deep swarm area. Probably of greatest seismological interest was the $M_d = 2.4$ earthquake that took place on the 7th of January 2012 at a depth of 24.6 km directly beneath area 200E in the Hanford site.

5.1.3 Third Quarter FY 2012 Earthquakes

The EWRSN and HSN recorded 63 eastern Washington earthquakes during the third quarter of FY 2012, 25 local to the Hanford site (local), and 38 off of the site (regional). Of the local earthquakes, 16 were located at shallow depths (less than 4 km), 6 at intermediate depths (between 4 and 9 km), most likely in the pre-basalt sediments, and 3 deeper than 9 km, within the basement. Geographically, 7 shallow local earthquakes were located in the Wye swarm area, 4 in the Wahluke swarm area, 2 in the Cold Creek swarm area, and one in the Horseheaven Hills swarm area. Eleven other local earthquakes were classified as random events. Of the regional earthquakes, 22 were shallow, 8 intermediate, and 9 deep. The network also located eleven local and regional events that have been categorized as probable surface explosions. (Tables 4.1 & 4.2). Perhaps the most notable event of the quarter was a $M_d = 1.8$ earthquake on April 19, 2012. This earthquake is the second deepest in the entire PNSN catalog with a depth of 96.8 km. It is within 40 km of the location of nearly every event deeper than 70km. It arises from the internal deformation in the subducting Juan de Fuca slab, and is not connected to the earthquakes far above in the crust. The largest event ($M_L = 3.2$) took place 10 April 2012 at depth of 14.4 km with epicenter located 36 km southeast of the Tri-Cities and 30 km west of Walla Walla.

5.1.4 Fourth Quarter FY 2012 Earthquakes

The EWRSN and HSN recorded 58 eastern Washington earthquakes during the fourth quarter of FY 2012, 26 local to the Hanford site (local), and 32 off of the site (regional). Of the local earthquakes, 19 were located at shallow depths (less than 4 km), 3 at intermediate depths (between 4 and 9 km), most likely in the pre-basalt sediments, and 4 deeper than 9 km, within the basement. Geographically, all 17 shallow local earthquakes were located in the Wye swarm area. Nine other local earthquakes were classified as random events. Of the regional earthquakes, 15 were shallow, 11 intermediate, and 6 deep. The network also located eight local and regional events that have been categorized as probable surface explosions.

The largest event ($M_L = 3.4$) took place on 13 September 2012 at a depth of 10.2 km with epicenter located 24 km east-southeast of Wenatchee, WA.

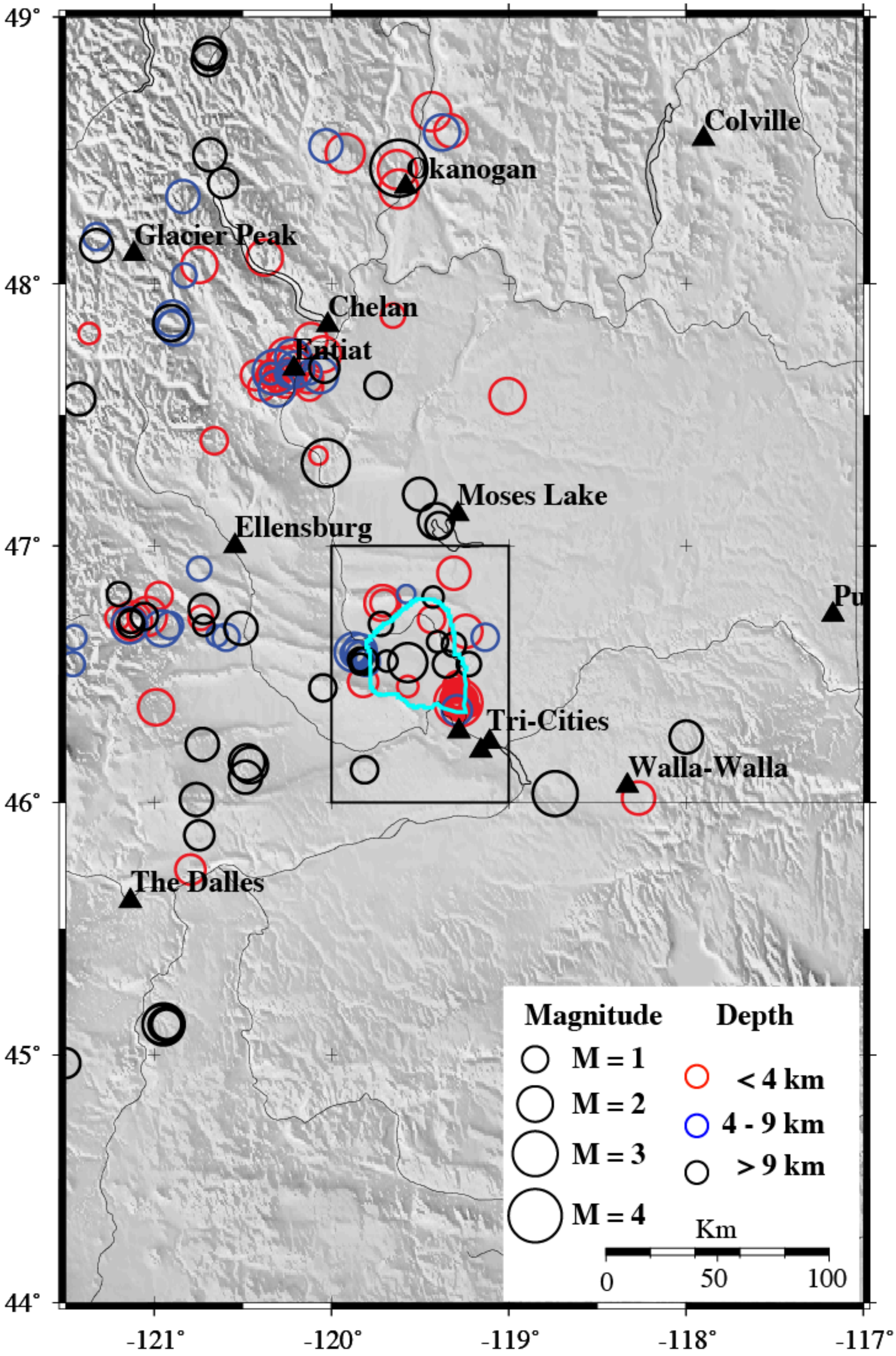

Figure 5.1 Epicenters of earthquakes recorded in the wider Hanford area during FY 2012. Red circles stand for shallow earthquakes (0-4 km), blue circles for intermediate-depth earthquakes (4-9 km), and black circles deep earthquakes (>9km).

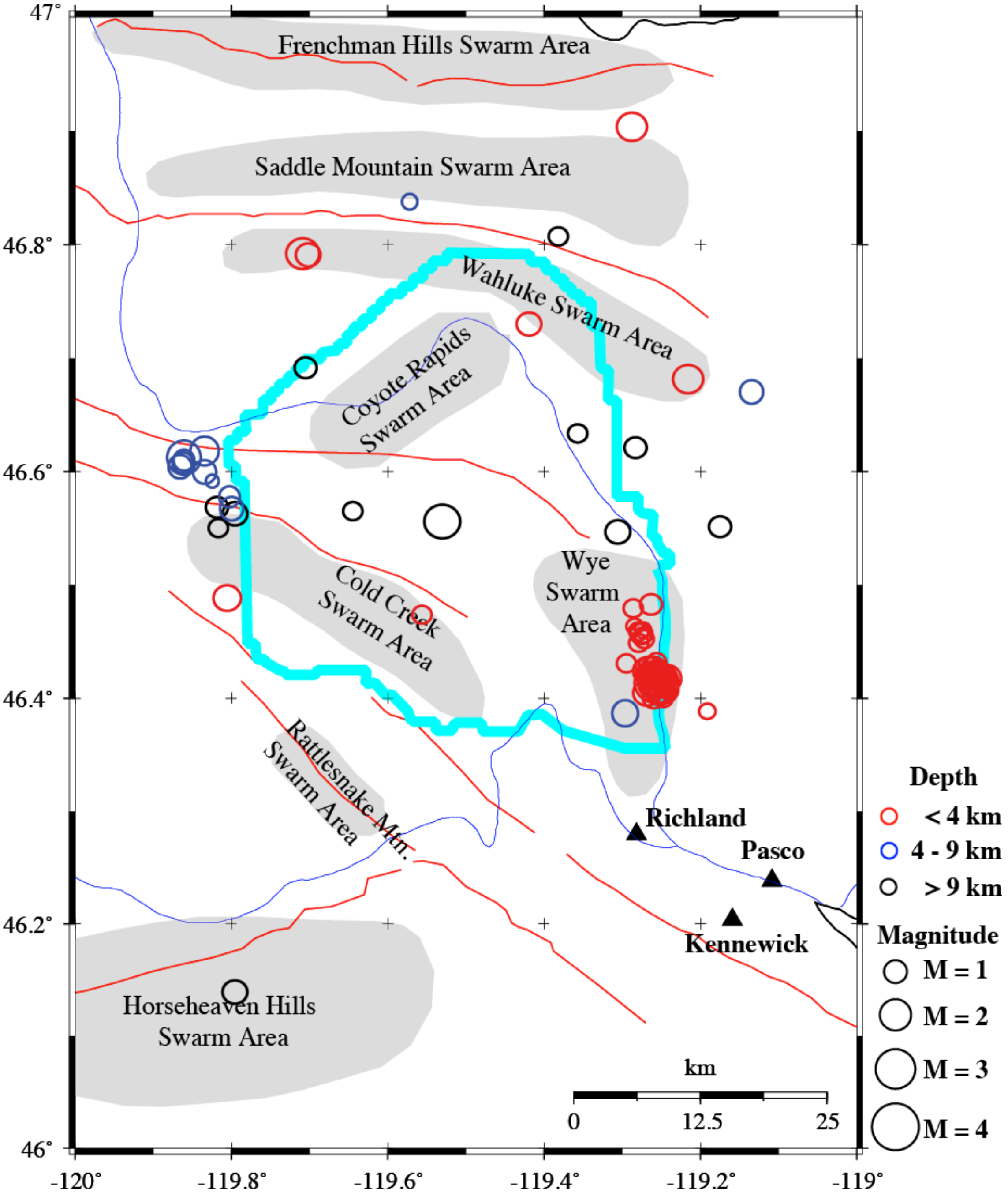

Figure 5.2 Epicenters of earthquakes occurring during FY 2012 in the vicinity of the Hanford site (light blue outline), and their relationship to known structures (red lines), swarm areas (shaded bits), and cultural features. Red circles stand for shallow earthquakes (0-4 km), blue circles for intermediate-depth earthquakes (4-9 km), and black circles deep earthquakes (>9km).

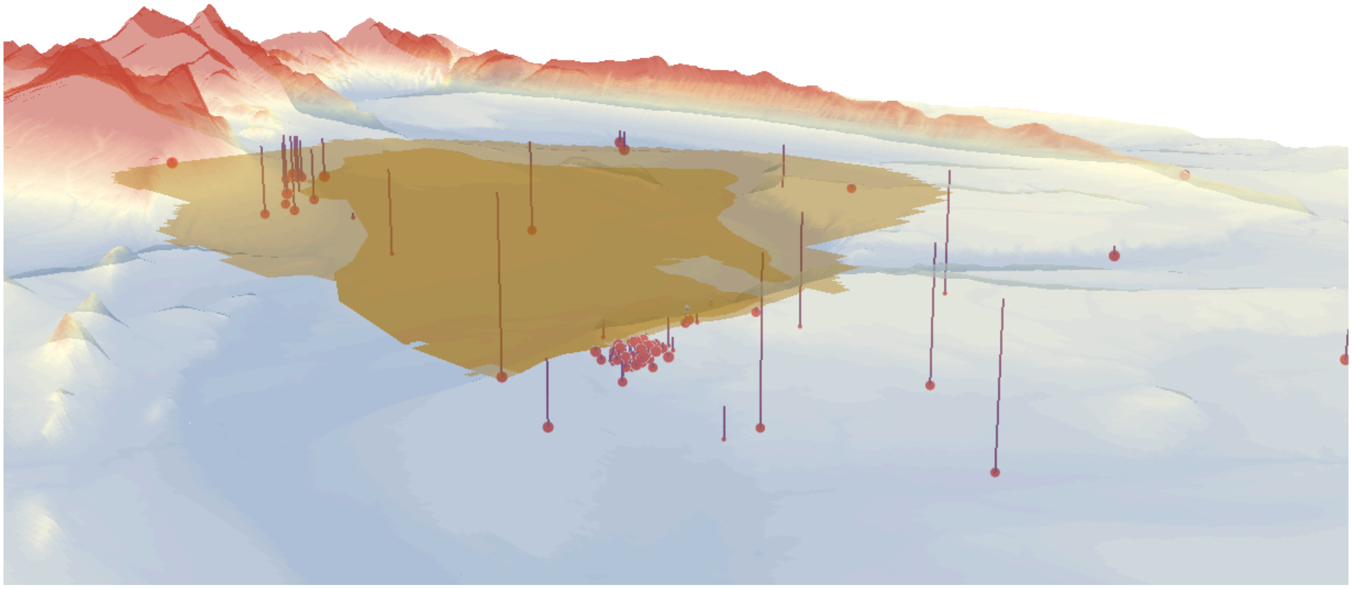

Figure 5.3 Perspective plot showing topography (exaggerated) and hypocenters (red dots, connected to epicenter with fine vertical line) of earthquakes occurring during FY2012 in the vicinity of the Hanford site, both overall (lightly shaded region), and inner (darker shading). Probable blasts are not shown in this figure.

5.2 Significant and/or Notable Events

We consider earthquakes that were felt widely, generated public interest, or that produced notable shaking on the Hanford site to be significant earthquake events. We generally include any earthquake exceeding M3.0 in this category.

The M_d =3.4, 15 October, 2011, Wooded Island swarm event (Table 5.1, Figures 5.1, 5.2) produced peak horizontal ground accelerations of 1.386 cm/s^2 at H3A. Undoubtedly this is due to the proximity of the station to the very shallow earthquake. The 18 November, 2011, M_d = 4.6 Okanagan earthquake produced ground motions felt over a wide area. However the sparse population and relatively sparse infrastructure in the region meant that the earthquake's impact was relatively muted.

In the second quarter, the most notable earthquake was the 24.6 km deep, M_d = 2.4, earthquake on 7 January 2012. One of the largest events of the quarter, this earthquake reminded us of the potential for even larger earthquakes on the Hanford site. This earthquake was directly beneath area 200E. The focal mechanism suggests a reverse sense of slip on a WNW-striking fault, *i.e.,* resulting from NNW-oriented horizontal compression (http://www.pnsn.org/event/60379986#technical-data). So the earthquake probably took place on a fault that participates in the regional fold-and-thrust tectonics of the area. Ground motions were quite weak on the site, despite the earthquake's proximity. One reason, of course, is that it is quite a small earthquake. Another reason is that the earthquake was quite deep, so that even station H2E, pretty much directly above the earthquake, was almost 25 km removed from the buried source. Peak ground motions recorded on the SMA stations became stronger with increasing distance from the earthquake. We suspect this is a combined effect of the focal mechanism and the geometry of the stations, such that stronger (particularly shear wave) radiation was directed toward these stations.

In the third quarter, there was a M_L= 3.2 earthquake on 10 April 2012. The earthquake was not in the vicinity of the Hanford site and was not widely felt. This event caused only four felt-reports, which can be found at *http://earthquake.usgs.gov/earthquakes/dyfi/events/uw/60407926/us/index.html*.
Arguably the most notable earthquake was the 98.6 km deep, M_d = 1.8, earthquake on 19 April 2012. This earthquake is the second deepest in the entire PNSN catalog with a depth of 96.8 km. It is within 40 km of the location of nearly every event deeper than 70km. Such deep earthquakes are cased by internal deformation of the subducted Juan de Fuca tectonic plate, and are unrelated to the earthquakes far above in the crust.

The first significant earthquake of the fourth quarter occurred on August 7, 2012, 6.5 km west-northwest of Entiat at 0 km depth and with M_L = 3.2. The second was on September 13, 2012, 24 km east-southeast of Wenatchee at 10 km depth and a M_L = 3.4.

6.0 Seismic Monitoring Enhancements In Preparation for a Significant Earthquake

One overarching goal of the HLSMP, recognized in its mission as outlined in Section 1.1 of this report, is to provide the information necessary to understand the potential impacts of earthquakes that might affect the operations or personnel at the site. This goal is best served not only by operating seismic stations, but by providing rapid and accurate information in the aftermath of an earthquake to the correct emergency responders needed to for them to respond quickly and effectively to the situation. This section summarizes the advances of the HLSMP network in support of this goal.

The SMA network in particular 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.

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.

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.

Since HLSMP has operated the seismic monitoring network, we have made significant progress toward the goal of providing the right information to the right people at the right time (*i.e.,* quickly). We started by converting the SMA stations to real-time telemetry and continuous (not triggered) operation. We also started routinely including data from the USGS-operated USNSN strong motion data channels at RSLR (station HAWA), effectively gaining a sixth SMA on-site. And we started to automatically produce "ShakeMaps" for any earthquake that might be felt widely at the Hanford site. ShakeMaps provide quantitative estimates the expected ground motion based on a model of seismic wave propagation through Earth's crust, including the important effects of the shallow geological composition.

In FY2012 we have implemented or initiated a series of interconnected developments in order to improve these capabilities. While much of these developments are technical in nature, they also recognize that a critical element in reducing risk is to communicate the information in the most effective manner to the appropriate recipient.

Table 6.1. Modified Mercalli Intensity Estimation Table
Distance

Magnitude	<10 km	10-20 km	20-50 km	>50 km
<2.5	III	< III	< II	I
2.5 – 3.5	III - IV	III	II	< II
3.5 – 4.5	V	IV - V	III - IV	<III
4.5 - 5.0	VI	V - VI	IV - V	< IV
>5.0	VI - VII	VI	V - VI	V

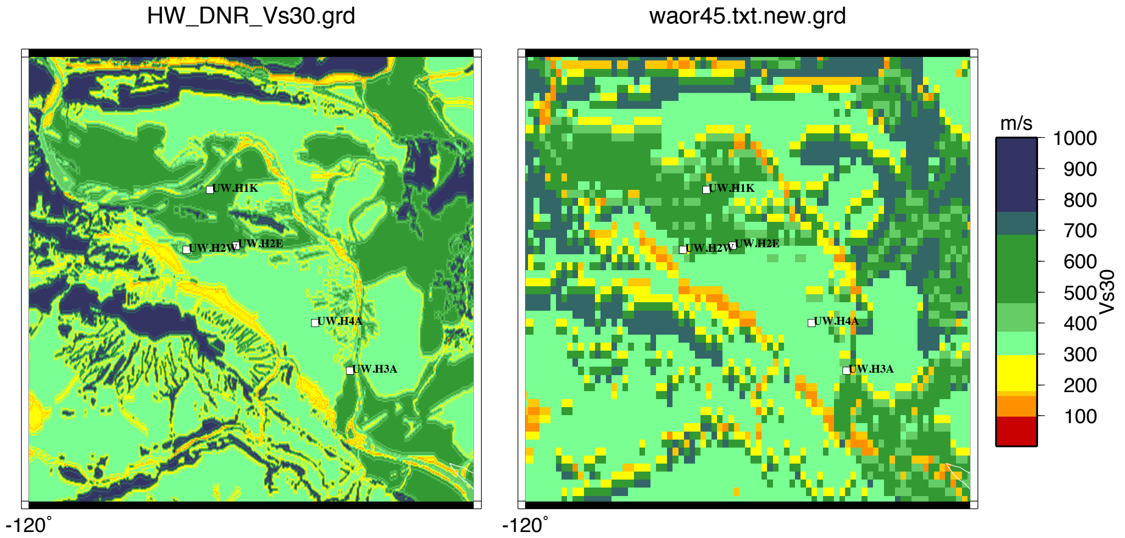

Figure 6.1 - Improved resolution of the site conditions (NEHRP site class) map (left side) compared to what had been used previously (right side). Source material from the Washington Department of Natural Resources NEHRP site classes are letter codes this is the scheme used to translate them to shallow shear wave velocity speeds shown in Vs30 legend: Site class A: > 1520 m/s, not present in our region. Site class B: 760 - 1520 m/s. Site class BC: 760 because it is the low end of B. Site class C: 360 - 760 m/s. Site class CD: 360 because it is the low end of C. Site class D: 180 - 360 m/s. Site class DE: 180 because it is the low end of D. Site class E: <180 m/s.

The first advance was the elaboration of a simple table (Table 6.1) enabling site personnel to make the most rapid assessment of whether a given earthquake is likely to cause damage or require quick action. To use the table, the only information that is needed are the magnitude and the location—specifically the distance from the earthquake to the site. While initial automatic magnitude estimates may uncertain, for the purpose of this product the uncertainty is unlikely to be larger than the relative crudeness of the intensity estimate. It is good enough for a rapid categorization in the few minutes before more quantitative estimates are available. To use the table, the user matches the appropriate magnitude and distance ranges, to determine a likely Modified Mercalli seismic intensity (MMI). The color code and an accompanying MMI chart reveal the range of expected seismic impacts.

The second advance is a new High-Resolution ShakeMap product for the Hanford site. This enables us to quickly forecast the seismic shaking levels from an earthquake at any place over the entire Hanford site, and is based on two important enhancements. One is the calculation of expected ground motion parameters (Peak Ground Acceleration, Peak Ground Velocity, and Peak Ground Spectral Accelerations at frequencies of 10 Hz, 3 Hz and 1 Hz) at a much more dense grid than the regional ShakeMap (200 meters, vs. 2000 meters). The other is the incorporation of detailed shallow geology provided by the State of Washington Department of Natural Resources' detailed surface mapping (Figure 6.1). The critical parameter used in ShakeMap to estimate the effect of the near surface geology on seismic waves is the seismic shear wave speed of the upper 30 meters.

The third advance is instrumentation. ShakeMap and soon-to-be ShakeCast models are exact only at sites where the ground motion from an earthquake is measured, and their accuracy is decreased with increasing distance from observing stations. Therefore, the more observations (i.e. seismic stations) there are, the better the overall predictions will be. And, of course, the closer to locations of concern the stations are, the better the estimates will be at those sites. So improvements in response to earthquakes depend on increasing the SMA coverage on the Hanford site, with special attention to locations of great concern. To this end, near the close of FY2012 we were able to acquire equipment to instrument five more SMA sites. We are currently in the process of determining the best locations for the new instrumentation.

The fourth advance involves instrumentation and telemetry, and was discussed briefly in section 2.4. This is the new digital telemetry link through WSUR facilitated by our colleagues there. While the primary purpose of the telemetry they provided was to reduce the noise and increase the robustness of our Lower Rattlesnake line, WSUR was also interested in having an on-site monitoring station. So we deployed a relatively inexpensive "NetQuakes" accelerograph that we had in-house. The NetQuakes station, while only operating in a triggered mode and certainly not observatory-quality will, in the event of strong shaking provide important information that can be automatically and routinely (although with some latency) incorporated into our situational awareness products. To date the WSUR site has not triggered on any earthquakes.

6.0.1 ShakeCast Advance

Another soon-to-come advance is the implementation of a ShakeCast system. ShakeCast is a product of the ANSS that uses the information from a ShakeMap to predict the ground motions at a predetermined set of sites. Moreover, ShakeCast uses a pre-loaded set of "fragility" information (specifying the seismic performance of a structure at a site) in order to forecast the likelihood of damage at that location. Therefore, within about 15 minutes after a significant earthquake, HLSMP will make available to the Hanford site a list of locations and their probable damage states, based on the High-Resolution ShakeMap. The ShakeCast system requires the coordination of the acquisition of the fragility curves, the calculation of ShakeMap, the feeding of that information to the ShakeCast servers, and the triggering of the system. In FY2012, all of the components of the system are in place; FY2013 will bring the finalization of the triggering mechanism, working out a test procedure, and the finished product.

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