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5.0 SSC Database: Geological/Seismicity Studies and Analyses

This chapter summarizes the new data collection and analyses that were conducted as part of the Hanford PSHA with the specific purpose of achieving more detailed characterization and reduction of uncertainties in key aspects of the SSC model. This chapter describes the scope of the studies and analyses, and the data reports for each study are attached to this PSHA report in Appendices E and F. The results of the studies and their use by the SSC Technical Integration (TI) Team in the development of the SSC model are described in the discussion of each of the model elements in Chapter 8.0.

5.1 Overview and Purpose of Studies Relative to SSC Uncertainty Reduction

A key part of the evaluation phase of a Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 project is the compilation and review of available data that pertain to the SSC and GMC models. As discussed by the NRC (2012), consideration can also be given to the possibility of collecting new data:

> "Early in the project during the data compilation stages, it may be possible to identify significant gaps in the available data that may significantly impact the hazard results. If project resources allow, focused new data collection efforts can be conducted within the timeframe of the SSHAC study to assist in the technical evaluations. Several past studies have benefited from such data collection efforts." (NRC 2012, Section 4.5.2)

Early in the planning for the Hanford PSHA project, the opportunity to conduct additional studies and analyses that would have a significant influence on the SSC model uncertainties was identified. Further, Workshop 1 (WS1) provided a clear view of the amount and quality of the existing databases, including gaps in data relevant to important SSC issues. Given the limited time and resources available, the activities were very focused, limited in scope to fit in the PSHA project schedule, and designed to address specifically those SSC issues judged by the SSC TI Team to have the largest potential hazard significance. In particular, the issues were related to the Yakima folds and faults that are closest to the Hanford Site, the geometry of those faults in the subsurface, evidence for the recency of faulting and particularly for Quaternary deformation, and the rates of deformation including fault-slip rates. The studies and analyses that were conducted to gather new data about these issues are summarized in this chapter and consisted of Quaternary geologic studies (QGS) and high-resolution seismicity relocation analyses.

5.2 Quaternary Geologic Studies

The overall objectives of the field and office-based studies conducted as part of the Hanford PSHA were to 1) develop data to characterize the geometry of the Yakima folds and underlying thrust faults, 2) provide additional data and information that can be used to evaluate the presence or absence of Quaternary activity of structures within the Yakima Fold Belt (YFB), and 3) to constrain rates and styles of deformation for individual structures. These studies included the following activities:

- structural geologic analysis of topographic and subsurface data
- kinematic analysis of focal mechanisms from small earthquakes in the YFB
- geologic mapping and field reconnaissance

- geochronologic investigations
- Yakima River fluvial geomorphology analyses
- paleoseismic investigations at Finley quarry.

A brief summary of the objectives and results of these studies is provided in the following sections. A more complete description of the studies and GIS database that was developed to support these studies is provided in Appendix E.

5.2.1 Structural Analyses

Topographic data in conjunction with a 3-D hydrogeologic model of the Columbia Plateau (Burns et al. 2011) and structure contour maps on the top of basalt (Myers et al. 1979; Thorne et al. 2014) were used to evaluate the geometry of the YFB anticlines and derive models for the location, dip, and long-term slip rate of underlying thrust faults. This analysis consisted of three primary activities:

- **Topographic Analysis.** Using geographic information systems software (ArcGIS) to visualize data from a 10-m digital elevation model (DEM), the geometry of individual YFB structures was determined by measuring the length and width (i.e., wavelength) of the anticlines, and their topographic relief normal to the crests of the folds (i.e., fold amplitude). The measurements were performed by extracting and analyzing numerous 2-D topographic profiles across the folds using a standard ArcGIS tool. Profiles acquired normal to the trend of the folds were used to determine the locations of synformal hinges at the base of the forelimb and backlimb of each fold, and to precisely measure the full width or wavelength of the structure, as well as topographic relief across the fold crest. Profiles acquired along the fold axis were used to assess lateral variations in topographic relief and identify discrete structural or geometric reaches of the fold that potentially indicate variations in underlying thrust fault geometry and/or activity.
- **Comparison of Topographic Relief to Structural Relief.** The Burns et al. (2011) hydrogeologic model is a 3-D representation of the first-order stratigraphic and structural framework of the Columbia Plateau. The model is derived from surface geology and data from more than 13,000 wells, and depicts uplift, folding, and faulting of Miocene Columbia River basalt (CRB) units across the major YFB structures. Using an interactive web-based tool, arbitrary 2-D cross sections were extracted from the model from which the relief of key stratigraphic contacts (e.g., the tops of the Saddle Mountain and Wanapum basalts) was measured across individual Yakima folds. This tool was used to compare structural relief on the CRB units across the folds to topographic relief. The results showed that the two are similar, thus establishing a basis for using topographic relief as a proxy for assessing long-wavelength variations in structural relief. Locally, where erosion and deposition related to cataclysmic floods have significantly modified the surface expression of the folds, the top of basalt structure contour map (Myers et al. 1979; Thorne et al. 2014) also was used to assess structural relief.
- **Derivation of Source Geometry and Long-Term Slip Rate.** The fold geometry and estimates of structural relief from the previous two activities were used to derive thrust fault geometry beneath the folds and estimate long-term average reverse slip rate.

Detailed discussion of the analyses and results is provided in Section 5.0 of Appendix E. The use of these results to evaluate the location, structural relief, dip, and long-term vertical slip rate of individual fault sources is discussed in Sections 8.4.3.1, 8.4.3.2, 8.4.3.4, and 8.4.3.6, respectively.

5.2.2 Kinematic Analysis of Focal Mechanisms

Available focal mechanisms from small earthquakes were analyzed to characterize seismogenic deformation in the YFB and parts of the adjacent Cascade Range. The spatial domains were selected to evaluate deformation associated with specific structures or subdomains in the YFB. In addition, the data were further subdivided into discrete depth domains to compare and contrast seismogenic deformation in the upper 3 km, which generally encompasses the depth of the CRB, from seismicity below 8 km in the sub-basalt sedimentary and crystalline basement rocks.

Earthquakes were sorted into groups based on patterns of spatial groupings associated with geologic structure, and their focal mechanisms were used to invert for components of a reduced incremental strain tensor using the approach of Twiss and Unruh (1998). The inversion involves two key assumptions: 1) slip on faults during earthquakes occurs in the direction of maximum resolved shear strain, and 2) the local deformation accommodated by small earthquakes reflects the regional strain (Twiss et al. 1993; Twiss and Unruh 1998). The orientations and relative magnitudes of the principal strains derived from the inversions can be used to interpret how the crustal volume in which the earthquakes occurred changes shape as a consequence of distributed brittle faulting. In particular, the analysis can be used to quantitatively evaluate the relative contributions of horizontal shear and vertical thickening or thinning of the crust during deformation (i.e., a horizontal plane strain vs. transpression or transtension).

The results of these analyses, which are described in Section 6.0 of Appendix E, and the implied deformation kinematics were considered in the evaluation of the style of faulting for individual YFB fault sources, as discussed in Section 8.4.3.

5.2.3 Geologic Mapping and Geomorphic Analysis (Field and LiDAR-Based)

Office-based interpretation of high-resolution Light Detection and Ranging (LiDAR) data and field mapping and reconnaissance along selected faults were conducted to provide information about the style of faulting, slip rate, and timing of the most recent deformation. Faults closest to the DOE facilities and the Columbia Generating Station for which there was greater uncertainty in the source characterization parameters were prioritized. These included structures along the Rattlesnake-Wallula (RAW) lineament or trend (Rattlesnake Mountain, the Rattles, and Wallula faults). Reconnaissance along more distant faults such as the Saddle Mountain and Frenchman Hills faults was conducted to evaluate the inception time of folding and relationship of Ringold Formation sediment deposition and fold deformation. In conjunction with the cosmogenic dating studies described in Section 5.2.4, limited reconnaissance was conducted in Kittitas Valley and along the reach of the Yakima River where it crosses Manastash and Umtanum Ridges and the intervening synclinal region.

Three high-resolution LiDAR data sets were available for detailed study; each data set has a roughly 1-m resolution. The newly acquired LiDAR data sets are a significant improvement over the National Elevation Dataset (NED) 1/3 arc-second DEM provided by the USGS. The 1-m resolution LiDAR data allow for production of terrain models with roughly 100 times the resolution of the publicly available 1/3 arc-second DEM. The three data sets cover 1) a ~6-km strip along the Yakima River, extending from the southern end of Kittitas Valley to near the confluence of the Yakima River and the Columbia River; 2) a ~700-km^2 area including Rattlesnake Mountain; and 3) a ~31- by 8-km northwest-trending strip that extends from Badger Mountain to Vansyckle Canyon (Figure 5.1).

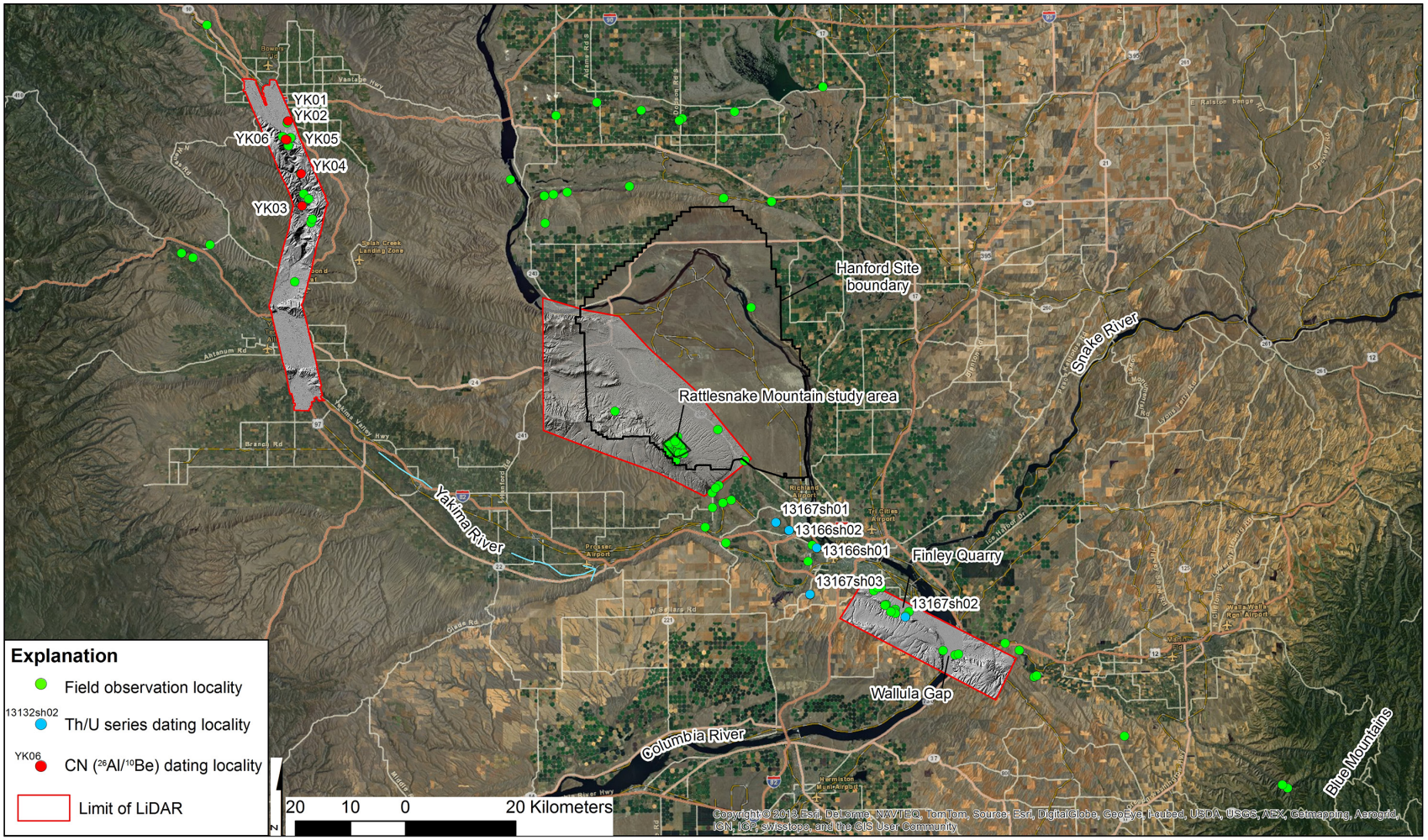

Figure 5.1. Map showing the locations of high-resolution LiDAR DEMs, field, and geochronology sample localities related to field studies conducted as part of the Hanford SSHAC Level 3 Quaternary studies program.

The results of field investigations completed as part of this study are considered in light of observations and conclusions outlined in various licensing and site characterization reports of studies conducted during the late 1970s and early 1980s, peer-reviewed publications, as well as ongoing research by other researchers and the USGS, funded in part by this project (see Sections 5.2.3, 5.2.4, and 5.2.5; also see Section 7.0 of Appendix E).

Quaternary field studies provided information to evaluate the style of faulting (sense of slip) (Section 8.4.3.3) particularly for Rattlesnake-Wallula structures (Rattlesnake Mountain, RAW-Rattles, and Wallula faults) and to assess Quaternary rates of vertical stratigraphic separation across the Rattlesnake Mountain fault (Section 8.4.3.6.1) and recurrence intervals for the RAW fault source (Section 8.4.7.4.3). Unconformable field relationships between sediments mapped as Ringold Formation and Saddle Mountains basalt on the backlimb of the Saddle Mountains anticline also were used to infer the start time for deformation expressed by current topographic relief (Section 8.4.3.5).

5.2.4 Geochronological Analyses

To assist in developing a chronostratigraphic framework for alluvial fan and other Quaternary deposits and surfaces in the Hanford study region, two geochronology approaches were used—Th/U-series dating of pedogenic carbonate and cosmogenic nuclide burial dating.

Dr. James Paces, USGS Denver, was responsible for the processing and analysis of pedogenic carbonate using uranium-series (^{230}Th/U, ^{234}U/^{238}U) dating methods. Analysis of the innermost rinds of pedogenic carbonate accumulations on clasts provides a method of estimating the minimum depositional age of the deposit sampled. Older flood gravels preserved in terraces above the Yakima River in the southern part of the Pasco Basin had been evaluated by Dr. TL Ku, University of Southern California, using this dating approach as part of previous licensing investigations (e.g., WCC 1981b; Baker et al. 1991). Key localities were re-sampled and re-analyzed as part of this SSHAC Level 3 study. Techniques have evolved since the approach was first implemented, and the objectives of the dating were to confirm previous dating results and to provide a consistent basis to the Quaternary Studies Team with regard to carbonate soil profile development that could be used to assess ages for similar soils observed elsewhere in the study region. Members of the Quaternary Studies Team (Kathryn Hanson and Christopher Slack) assisted Dr. Paces in the sampling and description of sampling localities.

In conjunction with fluvial terrace mapping investigations along the Yakima River (see Section 5.2.5) Dr. Paul Bierman, University of Vermont, collected and analyzed ^{10}Be and ^{26}Al ratios in quartz-bearing clasts from fluvial terrace deposits to estimate isochron burial ages for selected terraces along the Yakima River. Tyler Ladinsky provided recommendations for sampling sites in the vicinity of Manastash Ridge. Drs. Harvey Kelsey, Brian Sherrod, and Colin Amos, along with Skyler Sorsby and members of the Quaternary Studies Team (Ryan Coppersmith, Jeff Unruh, Kathryn Hanson, and Christopher Slack) participated in the sampling and prioritization of samples for dating.

Reports summarizing these two dating studies (^{230}Th/U-series and cosmogenic ^{26}Al/^{10}Be analyses—Paces 2014 and Bierman 2014, respectively) are provided as appendices to Appendix E. The results are discussed in Section 4.3 of Appendix E.

The estimated ages of alluvial fans on the flanks of Rattlesnake Mountain are based on comparison of relative carbonate soil profile development to nearby middle to late Quaternary deposits dated using the

^{230}Th/U-series methodology. Measurements of the vertical deformation of fan surfaces based on field observations and topographic profiles combined with these age estimates are used to evaluate the long-term Quaternary vertical rates of deformation and timing of most recent deformation (Section 8.4.3.6.1). Dating of pedogenic carbonate in deposits at Finley quarry where exposures of faulted Quaternary deposits have been observed provides a constraining age used to estimate timing and recurrence intervals for Quaternary faulting events (Section 8.4.3.7.3).

The cosmogenic ^{26}Al/^{10}Be isochron ages for fluvial terrace deposits in the Yakima River Canyon combined with previous (Ladinsky 2012; Ladinsky and Kelsey 2012) and preliminary fluvial terrace mapping of Yakima River fluvial terraces (Section 5.2.5) were used to compare Quaternary rates of incision to long-term post-CRB vertical rates of deformation for the Manastash and Umtanum structures (Section 9.0 of Appendix E). In general the results suggest Quaternary rates comparable to the long-term rates assessed based on the structural analyses described in Section 5.2.1. In light of this general agreement in rates and the preliminary stage of both cosmogenic dating and mapping of fluvial terraces along the Yakima River, these data were not explicitly included in the slip rate logic trees for the YFB fault sources.

5.2.5 Yakima Canyon Fluvial Response Studies

A fluvial geomorphic analysis to identify and characterize tectonic deformation was completed by Dr. Colin Amos and Mr. Skyler Sorsby, Western Washington University. The study used a combination of lab and field-based techniques to identify and isolate tectonically induced channel adjustments across major anticlinal ridges intersected by the Yakima and Columbia Rivers. This work is based on the assumption that river channel geometry (specifically width and slope) adjusts in concert with incision driven by active surface deformation, and that such adjustments can be used to identify and assess relative rates of tectonic activity. Preliminary LiDAR-based 1:5,000-scale terrace mapping of the Yakima River fluvial terraces also was conducted to identify additional evidence for potential Quaternary deformation in the YFB.

The results of this study are discussed by Amos and Sorsby (2013; in Appendix E.2). As discussed in Section 8.4.1, the results of these analyses provide evidence for late Quaternary deformation across the Manastash, Umtanum, and Yakima Ridges, as well as Selah Butte.

5.2.6 Paleoseismic Investigations-Finley Quarry

A key locality for assessing the style of faulting and the timing of most recent faulting on the RAW-Rattles fault is a quarry exposure near Finley, Washington. Previous fault studies conducted during site characterization for both the Columbia Generating Station (originally referred to as WNP 2) and the Basalt Waste Isolation Project, which involved logging the then existing quarry wall and a trench excavation into the floor of the quarry, recognized evidence of Quaternary faulting (Farooqui and Thoms 1980; WCC 1981a,b). As part of the Hanford PSHA Quaternary Studies tasks, the USGS, under the direction of Drs. Brian Sherrod and Richard Blakely, completed a paleoseismic log of the present quarry wall exposure, obtained new age constraints based on optically stimulated luminescence ages and tephra correlations, and conducted additional mapping, geomorphic interpretation of high-resolution LiDAR data, and ground-based magnetic surveys in the vicinity of the Finley quarry.

Sherrod and co-workers interpret particular aspects of the stratigraphic sequence observed in the quarry exposure as evidence of up to four paleoearthquakes along the Wallula fault (which is defined by the USGS to include both RAW-Rattles and the Wallula fault) during the late Pleistocene and Holocene (Sherrod et al. In Review). This contrasts with previous interpretations and conclusions outlined in licensing documents (Columbia Generating Station Final Safety Evaluation Report, Energy Northwest 1982; NRC 1982) that the most recent surface rupturing earthquake pre-dates deposition of sediments having a minimum age of greater than 69–160 ka (WCC 1981b).

The three youngest events identified by the USGS based on mapping of the Finley quarry exposure are estimated to post-date a late Pleistocene erosional unconformity. Based on ^{230}Th/U-series dating of carbonate rinds in deposits truncated by this unconformity these events would all post-date 17 ± 1.8 ka.

Alternative hypotheses related to Ice Age flooding erosion and deposition can explain some of the features inferred as evidence of post-flooding (late Pleistocene and Holocene) surface faulting (see Section 8.0 in Appendix E). The incorporation of the new data and interpretations of the Finley quarry exposures in the assessment of recurrence intervals for the RAW-Rattles fault is discussed in Section 8.4.3.7.3.

5.3 High-Resolution Seismicity Relocation Analyses

Instrumental seismicity data have been gathered at the Hanford Site and in the region of the site as part of the Pacific Northwest Seismic Network (PNSN) since 1970 (Section 6.0), and the interpretation of the data has been central to understanding the contemporary seismotectonics of the region. Current network operations provide for the routine determination of the locations and magnitudes of earthquakes, and interpretive studies have developed derivative products such as focal mechanisms. Much of the understanding of the seismogenic crust in the Hanford Site region comes from analysis of the seismicity, its spatial associations with major geologic boundaries such as the CRBs, and interpretations of the spatial and temporal swarms of seismicity during such events as the Wooded Island swarm.

Given the high quality of the PNSN data and the success that has come from interpreting the seismicity data in the Hanford region, a data analysis task was identified that would allow the project to obtain the highest-resolution earthquake hypocenter locations. The task was designed to support two resource experts with acknowledged expertise in earthquake relocations in applying their different and independent relocation algorithms to the PNSN data set.

5.3.1 Purpose of Studies

The purpose of the high-resolution seismicity relocation analyses was to use the existing PNSN data and state-of-the-art hypocenter location techniques to develop a refined catalog of hypocenters that could be used by the SSC TI Team. Uses of this catalog of relocated earthquakes were envisioned to include possible associations with faults and folds mapped at the surface, such that the downdip geometries could be better defined. Further, the relocated seismicity could be used to further define the thickness of the seismogenic crust in the region, the depth distribution of earthquake hypocenters (relative frequency of various hypocenter depths), and, together with earthquake focal mechanisms, might define faults at depth that were not well-determined from surface geologic observations.

An additional purpose of this task was to allow for multiple experts to use the same input data but also their own relocation techniques to conduct the relocations. By then examining the differences in the results of the two studies, the range and uncertainty of possible interpretations could be assessed by the TI Team. Similar approaches have been used on other studies with much success (PG&E 2011).

5.3.2 Approaches Taken and Methodologies

The approach taken in the high-resolution seismicity relocation analysis task consisted of contracting two prominent seismologists, Dr. Felix Waldhauser and Dr. Clifford Thurber, to relocate selected PNSN seismicity data using their unique double-difference relocation methods. Both researchers were provided with phase arrival time picks from earthquakes recorded by the PNSN in the YFB region in eastern Washington, between 121.25°W to 117.5°W and 46°N to 47.5°N during the period of August 1970 through October 2011.

The scope of work for each of the investigators consisted of the following:

- Clifford Thurber Scope of Work
  - Apply conventional seismic tomography, using the public domain code simul2000 (Thurber and Eberhart-Phillips 1999), to the YFB region (121.25°W to 117.5°W and 45.5°N to 47.5°N) data set of approximately 5,000 earthquakes using available P-wave catalog earthquake picks and refraction picks, carrying out a trade-off analysis to estimate the optimal model-smoothing parameter, and using four different starting velocity models.
  - Apply double-difference (DD) seismic tomography, using the code tomoDD (Zhang and Thurber 2003), which requires a commercial use license, to the YFB region data set using available P-wave catalog earthquake picks and their differential times and refraction picks using the best final model from Phase 2, carrying out a trade-off analysis to estimate the optimal model-smoothing parameter.
  - Evaluate earthquake location uncertainties using an estimate from a simplified bootstrap test.
- Felix Waldhauser Scope of Work
  - Reformat and check the quality of the PNSN P- and S-wave arrival time data for 7,667 earthquakes, associated focal mechanism data, and available mapped surface fault data.
  - Conduct high-precision relocation of the seismicity in the YFB study area using the HypoDD algorithm together with a suit of 1-D and 3-D velocity models, including determination of optimal weighting and inversion parameters and estimates of location uncertainties.
  - Complete an evaluation and analysis of a final set of 5,761 high-precision hypocenter locations and associated bootstrap error estimates for the YFB study area, including investigation of discrepancies between locations obtained in this scope of work and those obtained by Cliff Thurber.
  - Perform a combined analysis of relocated seismicity, fault information, and focal mechanisms, focusing on the Wooded Island, Umtanum Ridge, and Saddle Mountain regions. Compare results with previously published results.

After the earthquakes were relocated using the two approaches, the results were compared to each other and to the routine locations given in the PNSN network bulletins. The reports provided by Drs. Thurber and Waldhauser are presented in Appendix F. The results of their analyses were considered by the SSC TI Team in the development of several aspects of the SSC model, including the seismogenic thickness (Section 8.3.2.3), focal depth distribution (Section 8.3.2.4), and spatial variation of recurrence (Section 8.3.2.9).

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