Strong-motion Amplification Maps of the Olympia Area: Validation by the Nisqually Earthquake

Stephen P. Palmer[1], Timothy J. Walsh[1], and Brian L. Sherrod[2]
[1]Washington Department of Natural Resources
Geology and Earth Resources Division
PO Box 47007, Olympia WA 98504-7007
Tel: 360-902-1450; Fax: 360-902-1785
2U. S. Geological Survey

USGS Award No.: 1434-HQ-97-GR-02983

Introduction

In 1999, we began to prepare a prototype earthquake ground motion hazard map that is directed toward a variety of end-user communities, including structural and geotechnical engineers, building officials, emergency managers, land-use planners, private businesses, and the general public (Palmer and others, 1999). The final product will be a 1:24,000-scale GIS coverage delineating areas of moderate to severe ground shaking hazard, and a 1:48,000 printed map with an accompanying report documenting the methodology used in constructing the hazard map. The Olympia area was chosen for this prototype study for a number of reasons:

1. the Quaternary glacial geology of the Olympia area is less complex that of the Seattle-Tacoma area;
2. Olympia experienced significant building damage and ground failures during the 1949 and 1965 Puget Sound earthquakes;
3. accelerographs of the 1949 and 1965 Puget Sound earthquakes were recorded in downtown Olympia at a site with a measured shear wave velocity profile;
4. studies relating modified Mercalli intensity and weak-motion amplification to surficial geology have been previously published;
5. a large number of geotechnical borings and water wells in the study area allow for the development of a detailed three-dimensional geologic/soil model.

Bodle (1992) analyzed modified Mercalli intensity data from the 1965 Seattle-Tacoma earthquake (ML 6.5) and the 1981 Elk Lake earthquake (ML5.5) in the north Thurston County area. His investigation suggests a strong correlation of elevated Mercalli intensity at sites underlain by a fine-grained late Pleistocene glaciolacustrine/glaciofluvial deposit (designated unit Qvrs). King and others (1990) reported results from a weak-motion ground response at various sites in the Olympia area using portable seismometers that recorded large blasts from a nearby coal mine. Weak-motion amplifications in three spectral bands were calculated from these data using reference seismograms recorded on a local bedrock outcrop. King and others (1990) found that in general the highest amplifications were recorded on sites underlain by unit Qvrs.

The following tasks required to produce the ground motion amplification hazard map for the Olympia area performed to date are:

1. Preparation of surficial geologic map;
2. Acquisition of representative shear wave velocity data in Quaternary stratigraphic units and bedrock;
3. Parametric modeling of bedrock-to-surface amplification in spectral bands of importance to structural performance and hazard mapping procedure;
4. Preparation of subsurface geological model of Quaternary stratigraphic units and bedrock;
5. Solicitation of comments from end-users of the ground motion amplification hazard map.

Preparation of Surficial Geologic Map

The 1:24,000-scale surficial geologic map for the study area has been completed, and entered into a GIS digital format. Significant effort was directed toward mapping two distinct textural units within the recessional deposits of the Vashon (late Pleistocene) glaciation. These units are gravel-dominated recessional outwash sediments (unit Qvr), and glacio-lacustrine/fluvial deposits composed predominantly of sand and silt (unit Qvrs). Other important stratigraphic units mapped in the study area include Vashon till and advance outwash (units Qvt and Qva, respectively), and older Pleistocene glacial and non-glacial deposits (unit Qu).

Acquisition of Representative Shear Wave Velocity Data

Seven downhole shear wave velocity surveys have been conducted in geotechnical borings drilled in support of this investigation. These borings were located so as to collect velocity data in key geologic units. Shear wave velocity profiles from these surveys is summarized in Figure 1.

Data presented in Figure 1 indicate that there is a significant velocity contrast between unit Qvrs and older stratigraphic units (Qvr, Qvt, Qva, and Qu). In order to perform a regional ground motion hazard analysis we have assigned "characteristic" shear wave velocities to the various stratigraphic units encountered in the study area. The older stratigraphic units (Qvr, Qvt, Qva, and Qu) are assigned a shear velocity of 2100 ft/sec [640 m/sec]. In areas of deep ground water unit Qvrs is assigned a constant velocity of 1100 ft/sec [335 m/sec], whereas in shallow ground water areas the upper 60-80 ft [18-24 m] of the deposit has a lower velocity of approximately 600 ft/sec [180 m/sec].

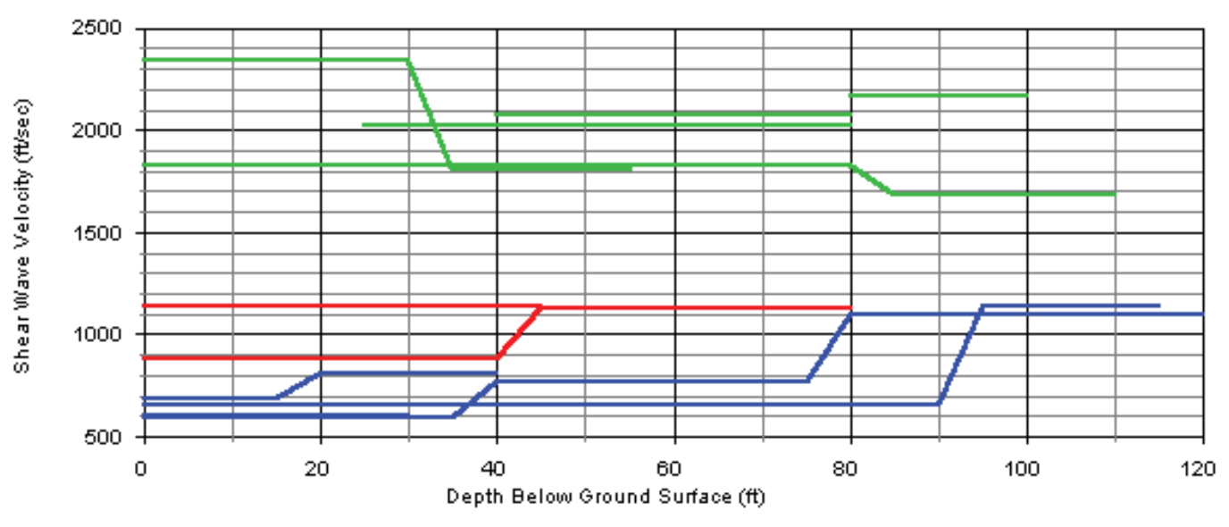

Figure 1. Summary of shear wave velocity measurements made in borings drilled in the Olympia area. Green lines are Vs measurements within stratigraphic units Qvr, Qvt, Qva, and Qu. Red and blue

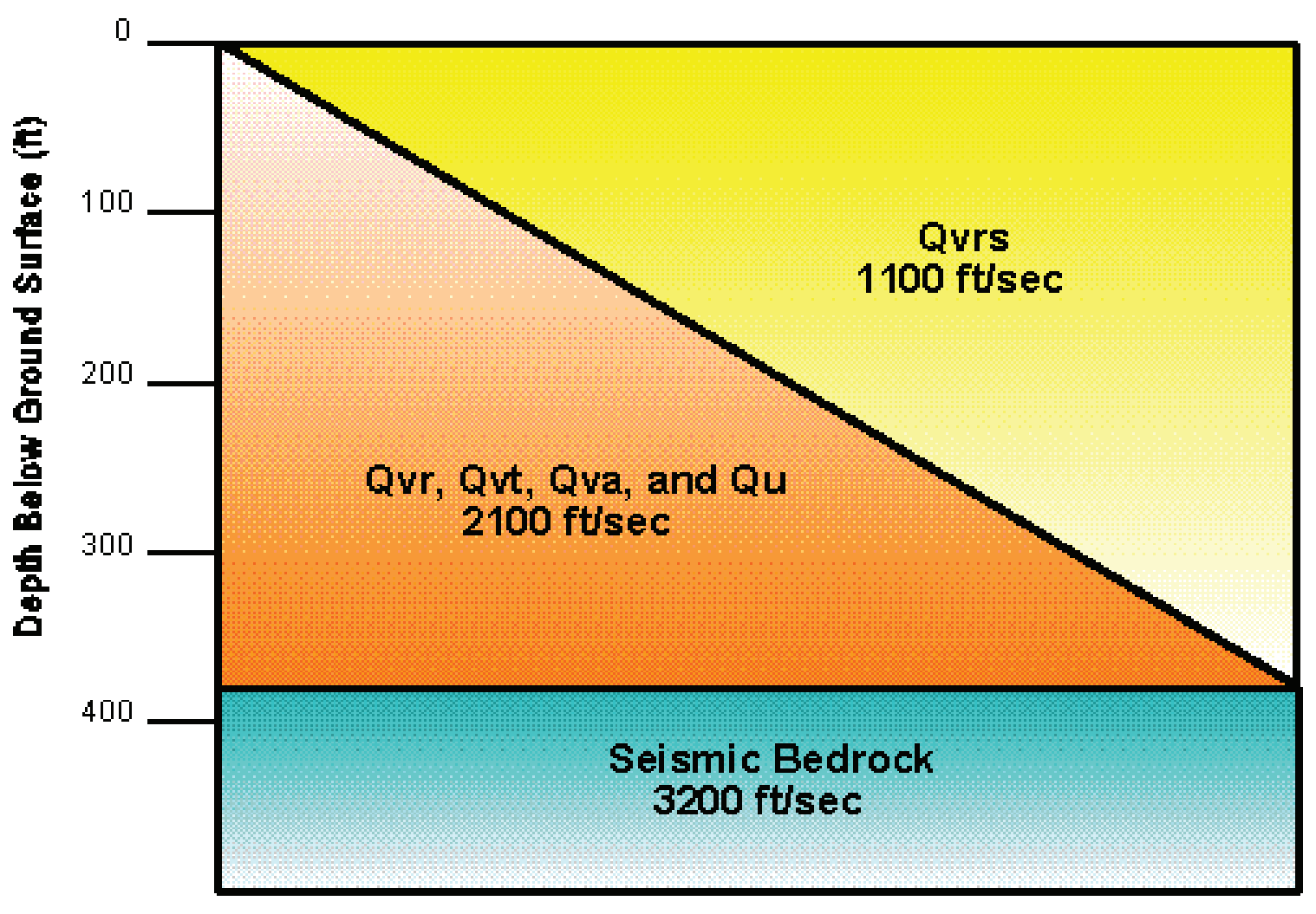

Figure 2 . Simplified shear wave velocity model representing the Qvrs unit having deep ground water overlying older Pleistocene deposits.

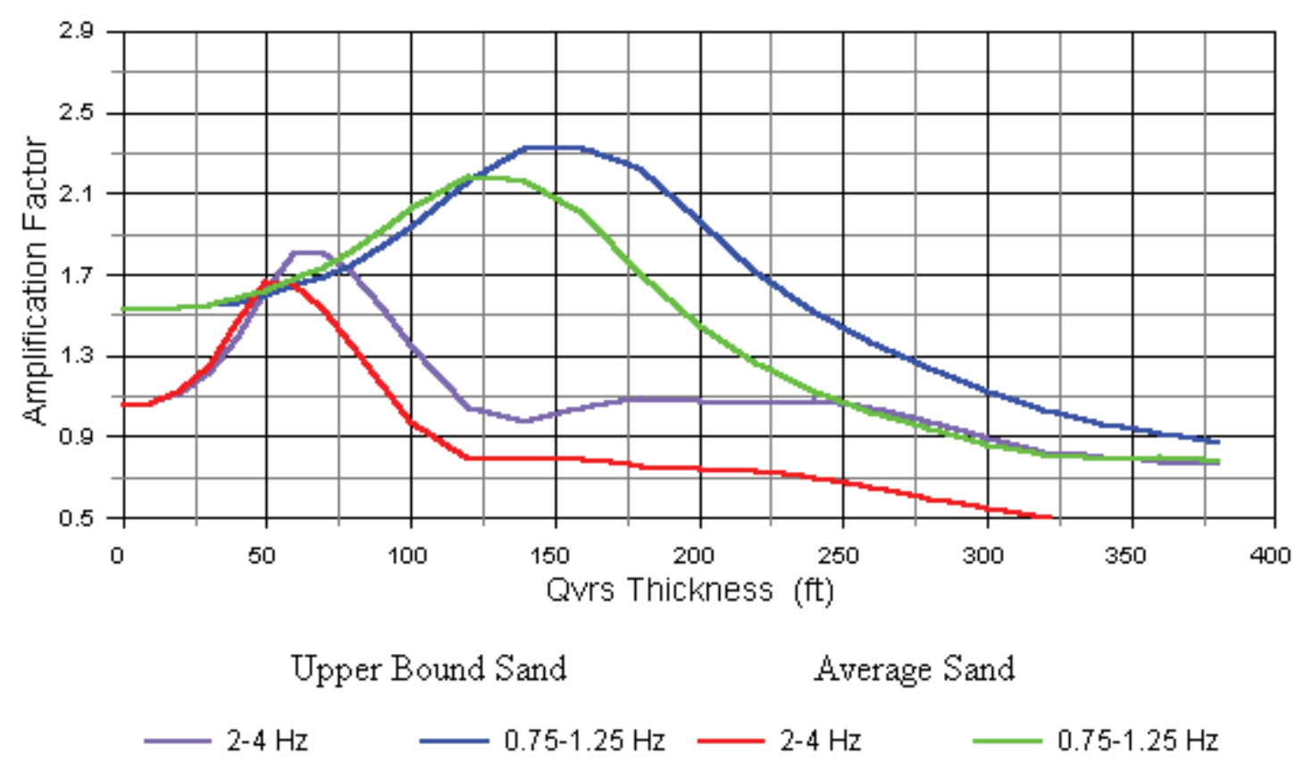

Figure 3 . Variation of spectral amplifications (averaged over 2-4 Hz and 0.75-1.25 Hz bands) with thickness of the Qvrs unit (1100 ft/sec [335 m/sec] layer). Modulus reduction and damping coefficients (Seed and Idriss, 1970) correspond to the upper and lower bound, respectively, for sand (Upper Bound Sand) and average coefficients for sand (Average Sand).

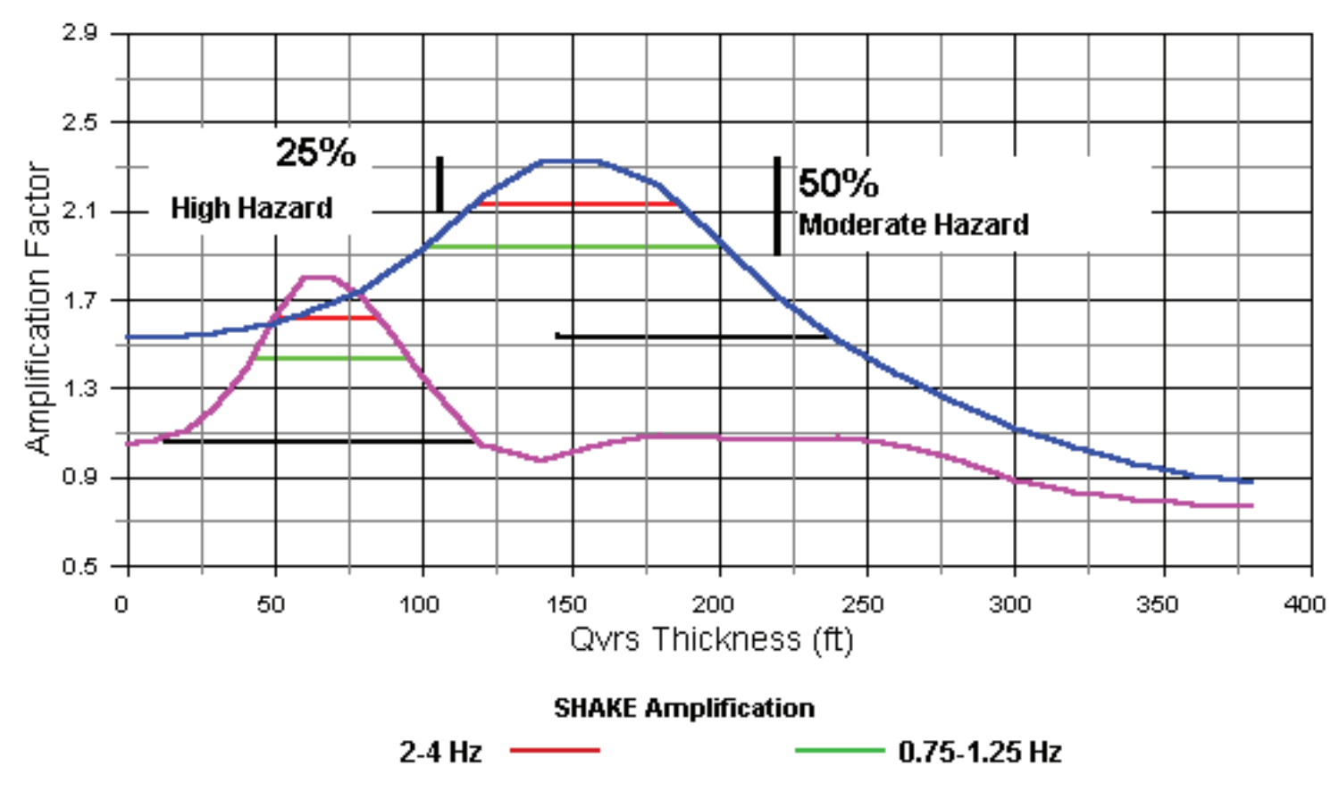

Figure 4. Method proposed for determining relative ground motion hazard based on 25 th and 50 th percentile thresholds. These correspond, respectively, to a high or moderate ground shaking hazard. Spectral amplification curves are those shown for the Upper Bound Sand in Figure 3.

Shear wave velocity profiles have been obtained at three of the western Washington accelerometer sites that recorded the 1965 Seattle-Tacoma earthquake (M L 6.5). These sites are located in Tacoma (County-City Building), Seattle (Federal Office Building), and Olympia (Highway Test Lab). At two of the accelerometer sites (Seattle and Olympia) a shear wave velocity exceeding 3000 ft/sec [915 m/sec] was measured in older Pleistocene deposits at depths of 300 ft [91 m] or greater.

Parametric Modeling of Bedrock-to-surface Amplification and Hazard Mapping Procedure

The general procedure adopted in this investigation for evaluating ground motion amplification is based on the use of the one-dimensional equivalent-linear model embodied in the computer code SHAKE (Schnable and others, 1972) and its PC-version SHAKE91 (Idriss and Sun, 1991). A series of soil models has been developed that represent a simplified version of the geologic conditions that occur within the study area. For example, Figure 2 shows the situation in which unit Qvrs having deep ground water overlies older Pleistocene deposits. Shear wave velocity for Qvrs is assigned a value of 1100 ft/sec [335 m/sec] and a velocity of 2100 ft/sec [640 m/sec] is specified for the older Pleistocene deposits (see Figure 1). SHAKE requires a constant velocity half-space at the base of the soil column, consequently a "seismic bedrock" with shear wave velocity of 3200 ft/sec [975 m/sec] is placed at a depth of 380 ft [116 m] as shown in Figure 2. The determination of depth and velocity values used for the half-space boundary are based on the deep shear wave velocity profile obtained at the Highway Test Lab accelerometer site.

The model shown in Figure 2 is used in a parametric analysis of the effect of Qvrs thickness on bedrock-to-surface amplification. Qvrs thickness is varied from 0 ft to 380 ft [0 m to 116 m] in 10 ft [3 m] or 20 ft [6 m] increments, and SHAKE is used to model amplification averaged within spectral bands determined to have engineering significance. Sensitivity of the resulting amplification values to choice of input time history and soil dynamic properties and variation of shear wave velocity can be evaluated.

Figure 3 is a graph showing the variation of bedrock-to-surface amplification with Qvrs thickness; amplification is averaged within spectral bands of 2-4 Hz and 0.75-1.25 Hz. The input time history is scaled so that Aa and A v (effective peak acceleration and velocity-related coefficients) have an approximate value of 0.2. Modulus reduction and damping coefficients correspond to the upper and lower bound, respectively, for sands (Seed and Idriss, 1970). Figure 3 shows the variation of averaged spectral amplification within the 2-4 Hz and 0.75-1.25 Hz bands with thickness of the Qvrs unit.

Sensitivity analysis of the model shown in Figure 2 indicates that calculated spectral amplifications are most affected by the choice of soil dynamic properties (modulus reduction and damping), and are less sensitive to variation in shear wave velocity within the range of values shown in Figure 1 . Figure 3 also shows the results of SHAKE modeling using average modulus reduction and damping values for sand (Seed and Idriss, 1970). Absolute amplification factors are decreased in this model run, but the general relation of spectral amplification with thickness of the Qvrs unit is preserved. This pattern of ground motion amplification with Qvrs thickness will be the basis of generating the hazard map for the Olympia study area. One approach for determining relative ground shaking hazard compares the amplification factors at various thicknesses of Qvrs to that where the Qvrs thickness is zero (i.e., in areas where older Vashon or other Pleistocene deposits outcrop). The 25 th and 50 th percentiles between the maximum amplification and baseline (zero thickness) value are used as criteria for determining areas of high or moderate ground shaking hazard as shown in Figure 4 .

Preparation of Subsurface Geological Model

A three-dimensional model of the subsurface geology was generated using logs from water wells and geotechnical borings. We are utilizing a digital database of water well data developed by the U.S. Geological Survey Water Resources Division as part of a cooperative ground water resource investigation of north Thurston County. These data are supplemented or in-filled with other water well and geotechnical boring data. Particular attention is made in the differentiation of the Qvr and Qvrs units. Most of the data have now been interpreted and entered in a GIS format. Part of the thickness model of the Qvrs deposit is shown in Figure 5.

On February 28, 2001, the Nisqually earthquake provided a fortuitous test of this map. Damage in the Olympia area was not uniformly distributed. Areas of ground failure caused much damage in low-lying, water saturated sandy soils. Building damage not related to ground failure was concentrated in the south Capital neighborhood (Figure 6 and 7) and downtown (Figure 8). Figure 9 shows similar downtown damage one block away from Figure 8 shows similar damage from the 1949 earthquake, about the same size and location as the Nisqually earthquake. Figure 10 shows the distribution of chimney damage in the Nisqually earthquake plotted on the thickness map of unit Qvrs. Note that the most intense damage occurred where unit Qvrs is between about 80 and 100 feet, where amplification is highest in the 2-4 Hz range (Figure 4). This is the natural frequency of low rise buildings. Note also that similar age residential neighborhoods where Qvrs is significantly thinner (for instance, a few miles northeast of the most concentrated damage, were much more lightly damaged.

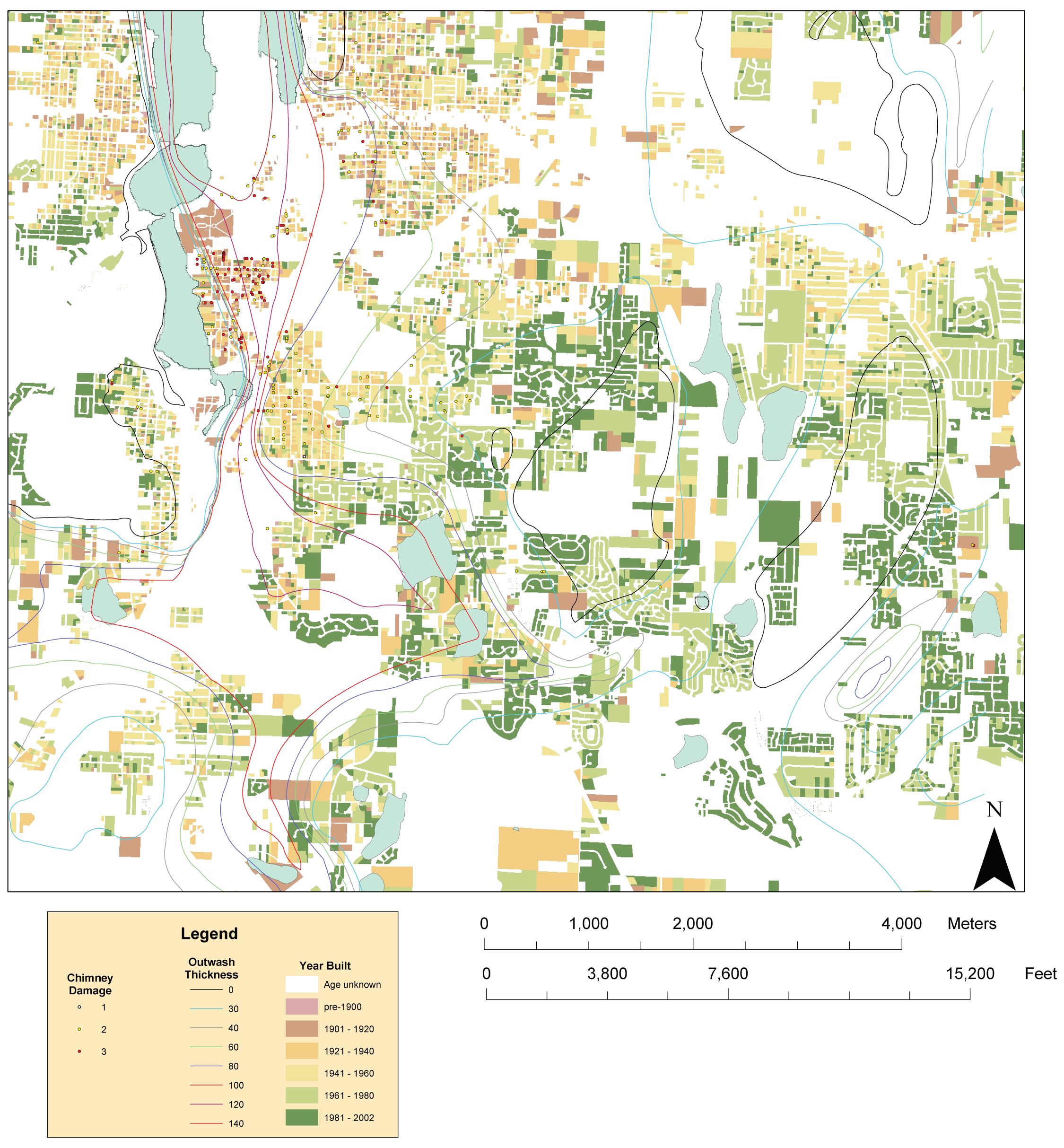

Figure 10. Severity of chimney damage(3 greatest) and approximate age of construction plotted on thickness of Qvrs. Note that the greatest damage occurs where Qvrs is 80-100 feet thick.

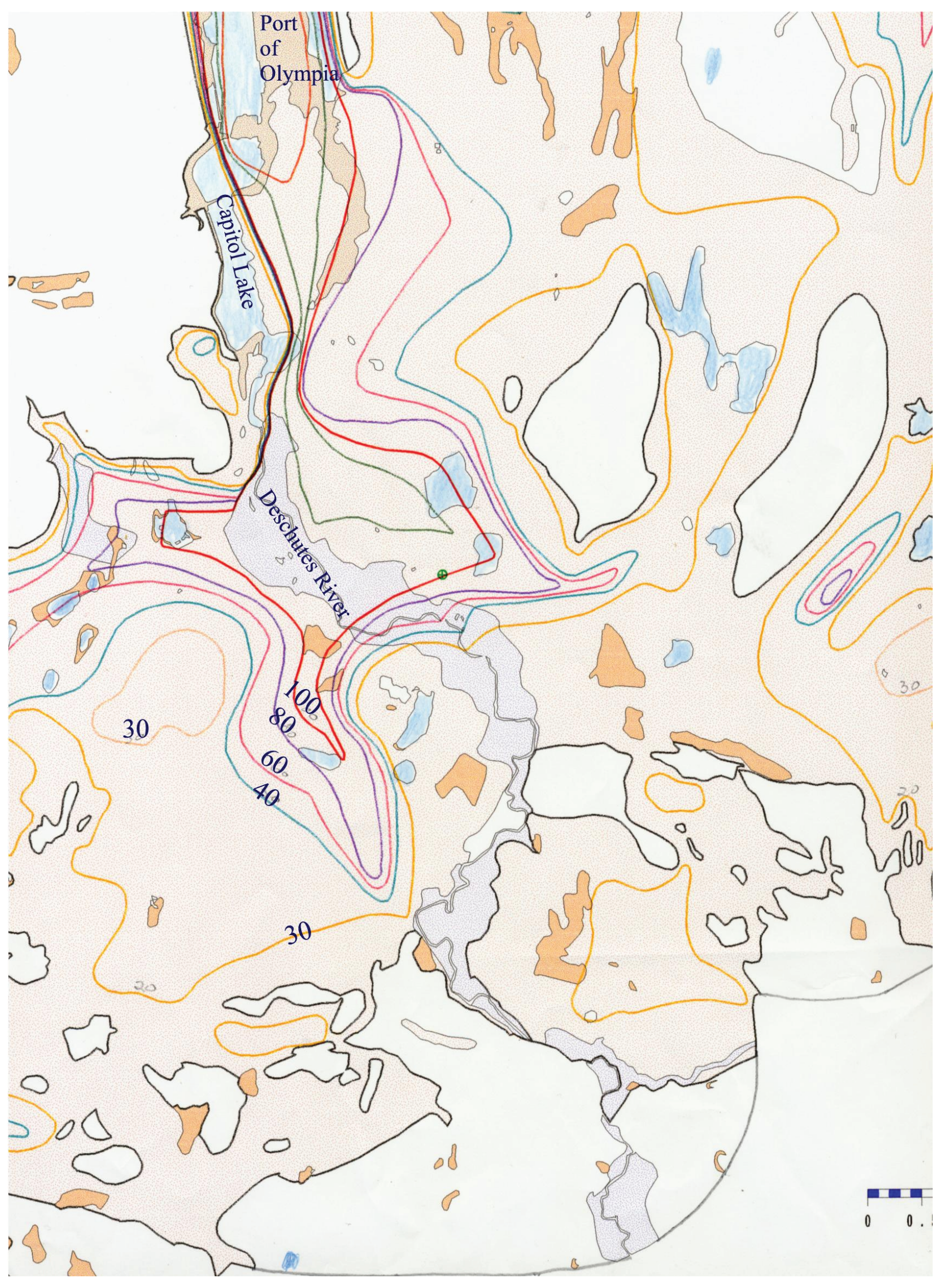

Figure 5. Thickness of unit Qvrs in the downtown Olympia area (in feet).

Figure 6. Typical chimney damage in the south Capital neighborhood, where many chimneys were completely destroyed.

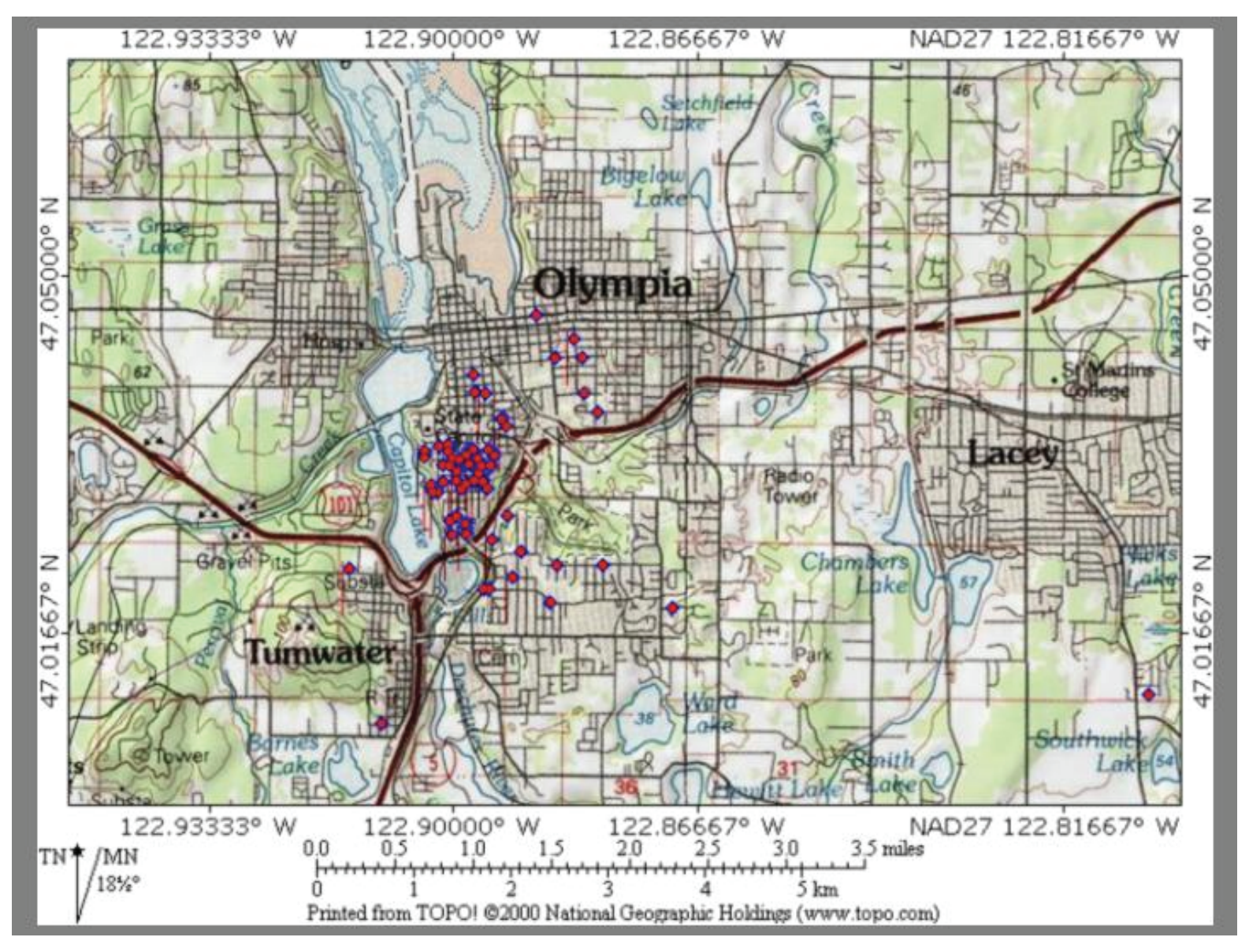

Figure 7. Location of completely destroyed chimneys in the Olympia are. Note that the are highly concentrated in the south Capital neighborhood east of Capitol Lake.

Figure 8. Parapet failure at the Washington Federal Savings Bank in downtown Olympia, which suffered significant damage to older unreinforced masonry buildings.

Figure 9. This unreinforced masonry building in downtown Olympia was damaged in the 1949 earthquake. Damage was extensive to this type of building in that event. This building is about one block east of Figure 8.

References

Bodle, T. R., 1992, Microzoning the likelihood of strong spectral amplification of earthquake motions using MMI surveys and surface geology: Earthquake Spectra, v. 8, no. 4, p. 501-528.

Building Seismic Safety Council, 1994, NEHRP Recommended Provisions for Seismic Regulations for New Buildings, Part 1 -- Provisions: prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency, Washington, D.C., 290 p.

Idriss, I.M.; Sun, J.I., 1992, User's Manual for SHAKE91 A computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits: Center for Geotechnical Modeling, University of California, Davis.

King, K. W.; Tarr, A. C.; Carver, D. L.; Williams, R. A.; Worley, D. M., 1990, Seismic ground response in Olympia, Washington, and vicinity: Bulletin of the Seismological Society of America, v. 80, n. 5, p. 1057-1078.

Palmer, S. P.; Walsh, T. J.; Gerstel, W. J., 1999, Strong-motion amplification maps of the Tumwater and Lacey 1:24,000-scale quadrangles, Washington. IN U.S. Geological Survey, National Earthquake Hazards Reduction Program, External Research Program, annual project summaries, Volume 40, Pacific Northwest: U.S. Geological Survey, 9 p. http://erp-web.er.usgs.gov/reports/annsum/vol40/pn/pn_vol40.htm]

Schnable, P. B., Lysmer, J., Seed, H. B., 1972, SHAKE -- A computer program for earthquake response analyses of horizontally layered sites: Earthquake Engineering Research Center Report No. EERC 72-12, University of California, Berkeley, 104 p.

Seed, H.B.; Idriss, I.M., 1970, Soil moduli and damping factors for dynamic response analyses: Earthquake Engineering Research Center Report No. EERC 70-10, University of California, Berkeley.