FINAL TECHNICAL REPORT
**Project period May 16, 2006 – December 31, 2008**

TITLE: THE QUATERNARY GEOLOGY OF THE SEATTLE-TACOMA URBAN CORRIDOR—BUILDING THE FOUNDATION FOR GEOLOGIC-HAZARD MAPPING

**Cooperative Agreement Number:** 06HQAG0125

**Investigator:** Kathy G. Troost, University of Washington, Department of Earth and Space Sciences, Box 351310, Seattle, WA 98195-1310

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**NEHRP Element:** I, Pacific Northwest region
**Keywords**: Geologic Mapping, Surficial Deposits, Tectonic Structures, Urban Geology

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS agreement number 06HQAG0125. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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## INVESTIGATIONS UNDERTAKEN

### Overview

Our investigations during this project represent both continuation of and greater focus on specific elements of the Quaternary geologic framework of the Seattle-Tacoma urban corridor. Major accomplishments include new surficial geologic mapping in the Mercer Island and Kirkland quadrangles; completion of an unprecedented cooperative project with Washington State's Department of Geology and Earth Resources in mapping the geology and landslides around the shoreline of Puget Sound; continued population of our subsurface geologic database; and dissemination of data and results through publication of maps and reports, and free public internet access of our entire geologic database, currently numbering 83,100 exploration sites. We also advanced seven geologic quadrangles through USGS review and into the publications queue.

We continue with confidence that our emphasis on Quaternary geologic data is critical for the variety of ongoing geologic, hydrologic, and seismic-hazard assessments in the central Puget Lowland. This is ultimately a result of the recent sedimentary cover in this region that is zero to over one thousand meters thick.

We also achieved more than a four-fold leveraging of USGS NEHRP funds for the project period, which has enhanced both the data collection and the geographic scope of the project.

### Background

Our investigations represent both continuation and expansion of a wide range of tasks that focus on the Quaternary framework of the Seattle area. We originally defined five major components to develop this framework and to disseminate the resulting information:

1. Develop the regional stratigraphy and chronology for the central Puget Lowland;
2. Create a subsurface geologic database for the urban areas in the region;
3. Prepare new surficial geologic maps of the urban areas;
4. Develop the geologic model (3-D map and database) of urban areas; and

5. Provide education and technical outreach.

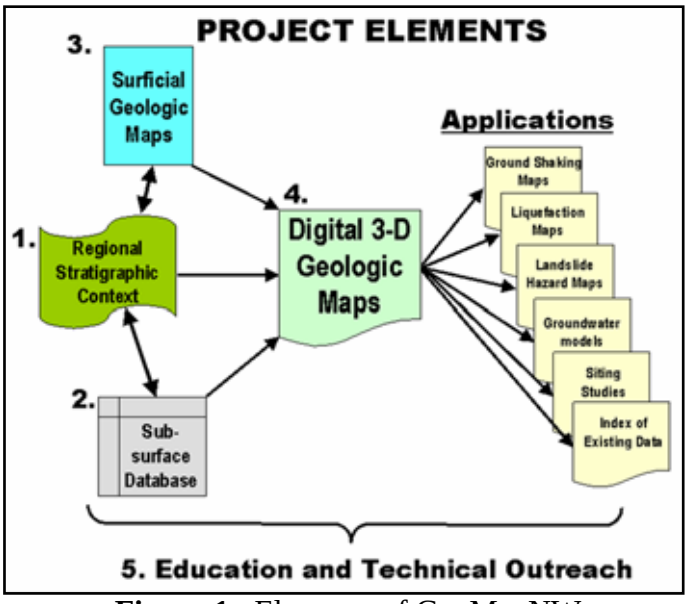



**Figure 1**: Elements of GeoMapNW

The overall progress of this effort has been summarized in previous Annual Reports, of which the most recent (summarizing the previous five years) can be accessed at: *http://earthquake.usgs.gov/research/external/reports/01HQAG0017_FTR.pdf*

Our focus with this project's funding has been on understanding and mapping the Quaternary deposits in areas adjacent to Lake Washington and along the Puget Sound coastline. These deposits are primary determinants of the magnitude and location of strong ground shaking, and so knowledge of the age, thickness, geometry, and density variations of these deposits is critical to the ongoing seismic evaluations across this region. Our studies provide both the raw data and the geologic interpretations to characterize the material properties and topography of Quaternary and bedrock materials, which in turn are necessary for a variety of geologic-hazard investigations, both seismic and non-seismic alike. We are actively developing a detailed understanding and representation of the three-dimensional distribution of geologic materials beneath Seattle and surrounding urban areas and embedding that information in the context of a coherent, regionally integrated geologic framework for the central Puget Sound region. This work, which includes detailed geologic mapping and database development, is already supporting both seismic research and a host of other earthquake-related investigations, including liquefaction, landsliding, and lateral-spreading analyses.

## RESULTS

### Regional Stratigraphy and Chronology

We are developing a chronological and lithologic composite section of glacial and nonglacial deposits in the central Puget Lowland that can be used to evaluate the distribution, correlation, and deformation of individual geologic units across the region. This has been developed primarily through geologic mapping and associated analyses across the central Puget

Lowland, and it is being disseminated through published geologic maps, reports, short courses, workshops, field trips, and presentations.

Over the last several years, support from NCGMP enabled us to complete field work on eleven 7.5-minute maps at 1:24,000-scale, four 7.5-minute maps at 1:12,000-scale in the Seattle-Tacoma area (Table 1 and Figure 2); in combination with modest past support from NEHRP, these maps are in various stages of USGS technical review and final publication. In addition, we are coauthors on the Suquamish and Bremerton East 7.5-minute quadrangles from our geologic cross sections and subsurface database work.

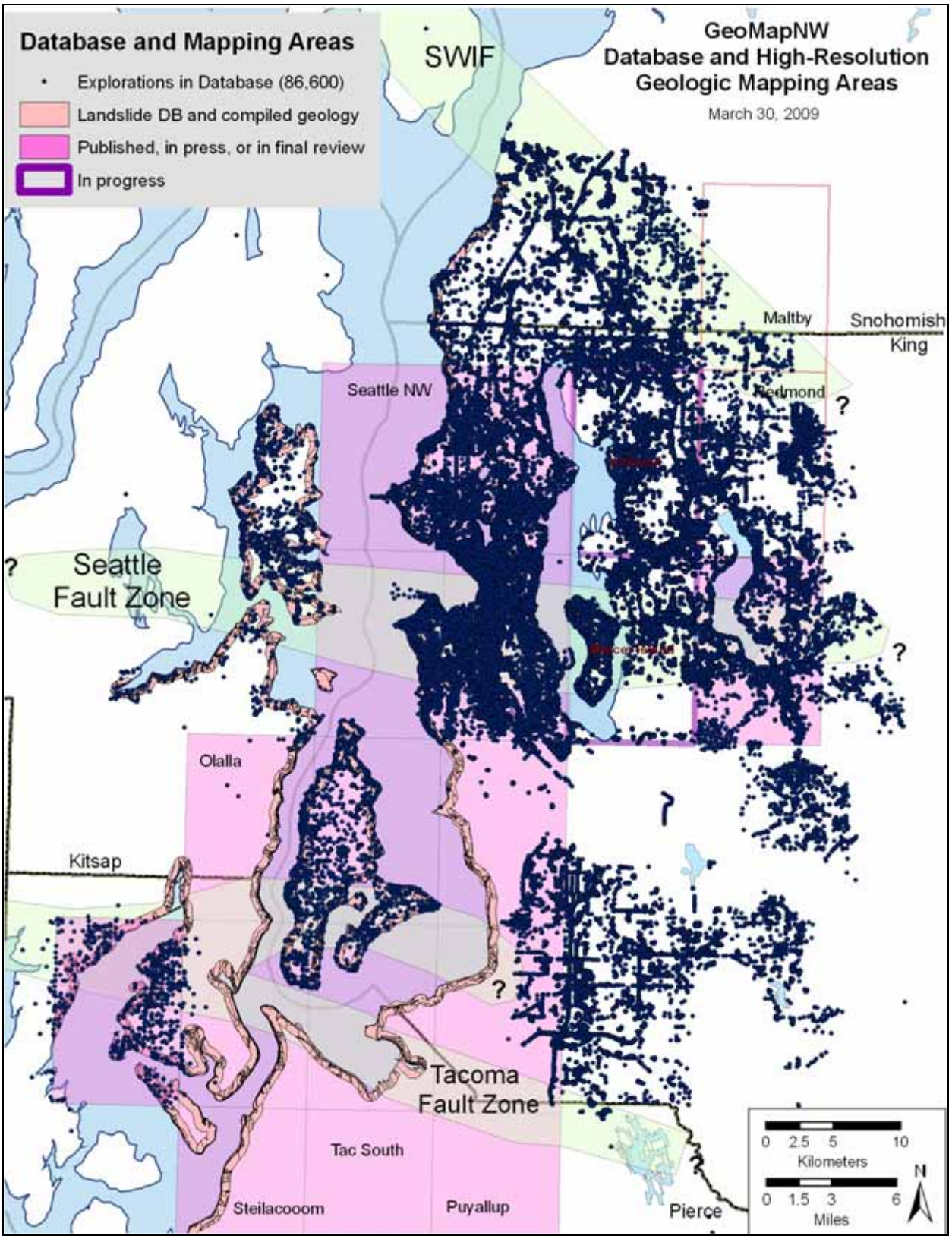
**Table 1**: 7.5-Minute Quadrangles Mapped by GeoMapNW at the UW

| GeoMapNW Quads | publisher USGS | publisher WDNR/WDGER | Status | Scale | DB? |
|---|---|---|---|---|---|
| DesMoines | x | | published | 24K | N |
| Poverty Bay | x | | published | 24K | N |
| Olalla | x | | published | 24K | N |
| Seattle NW (Shilshole Bay) | x | | published | 12K | Y |
| Seattle NE (Seattle North) | x | | published | 12K | Y |
| Seattle SW (Duwamish Head) | x | | final prep | 12K | Y |
| Seattle SE (Seattle South) | x | | in review | 12K | Y |
| Issaquah | x | Co-author | published | 24K | Y |
| Tacoma North | x | | final prep | 24K | N |
| Tacoma South | x | | final prep | 24K | N |
| Steilacoom | x | | final prep | 24K | N |
| Puyallup | x | | published | 24K | N |
| Gig Harbor | x | | final prep | 24K | N |
| Fox Island | | x | published | 24K | Y |
| Vashon Quad | x | | published | 24K | Y |
| Mercer Island | x | | in progress | 12K* | Y |
| Kirkland | x | | in progress | 12K* | Y |
| Redmond | x | | proposed | 24K* | Y |
| Maltby | x | | proposed | 24K | Y |
| Bothell | x | | proposed | 24K | Y |
| Lake Wooten (O'Neal) | | | EDMAP | 24K | N |
| Lillwaup (O'Neal) | | | EDMAP | 24K | N |

24K* = urban areas at 1:12,000

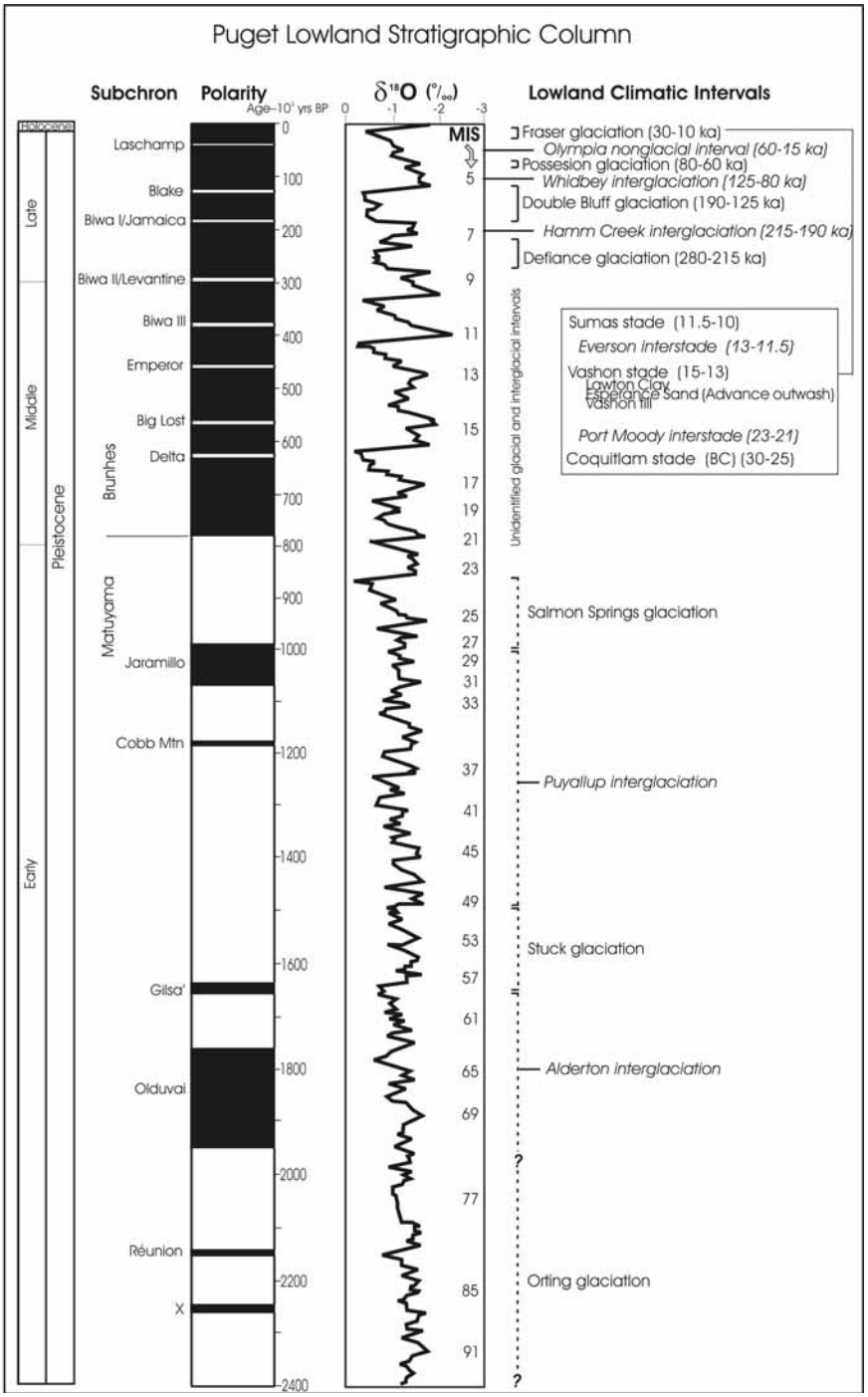
DB=database-supported mapping, WDNR/WDGER=Washington State Department of Natural Resources Division of Geology and Earth Resources

**Figure 2.** Map Showing Status of Project Areas and Data points within the GeoMapNW Subsurface Database Relative to Major Active Faults in the Central Puget Lowland



As a result of this mapping and stratigraphic and chronologic work for these maps, we have established a regional nomenclature, unit descriptions, and an updated stratigraphic timescale (Figure 3). These stratigraphic products are experiencing widespread use in the research and consulting community. For example, we have identified one new glacial drift and one new interglacial formation in the geologic record and have linked the Quaternary stratigraphy from the north and south Puget Sound regions (once thought to be widely different).

**Figure 3**: Puget Lowland Stratigraphic Column developed by GeoMapNW



We are still shepherding several 7.5-minute quadrangles in the greater Seattle area through the final USGS publication process. We also prepared one major research paper on the stratigraphy and paleogeography of the Seattle area, particularly as it relates to the subsurface distribution of geologic materials; and contributed the data and co-authored a second paper describing a NEHRP soils class and shear wave 3-D model for Seattle. Both papers are published in a GSA special paper.

Our understanding of the subsurface geology is allowing us to evaluate locations of fault and fault-related structures beneath Seattle. We are co-authoring a paper with a USGS geophysicist regarding a more northerly position for the leading edge of the Seattle fault. Part of this interpretation is based on buried beach deposits, stratigraphic offsets, and anomalous map patterns discernable only as a result of the GeoMapNW database and high-resolution geological mapping of Seattle.

Over the project period we cooperated with many research projects, providing geologic expertise. In 2007 we supplied the baseline geologic information for the USGS to use in their landslide probability maps and seismic shaking maps of the Seattle area. These were published in 2008. We participated in numerous discussions about locating seismic lines, particularly on Mercer Island and in West Seattle, based on our knowledge of the region and utilizing our subsurface database. As a result of our input, some lines were shifted and faults were detected.

## Subsurface Geologic Database

We have developed, and are continuing to populate, a database of existing subsurface geologic and geotechnical data that covers broad areas of the Puget Lowland (Figure 4). This database accommodates both spatial and nonspatial data by following a GIS-based approach. The design facilitates spatial analyses, visualization, and other representations of the data. Groundwater and well data are included in the database.

Since the project's inception, the land area covered by the database has expanded significantly from its original Seattle-only coverage. This has been a direct consequence of additional funding obtained from both NEHRP and local agencies. Our progress to date in populating the main tables of the database is as follows (Table 2):

**Table 2**: Status of Database (3/09)

| | Total study area | City of Seattle only | Other areas |
|---|---|---|---|
| Geotechnical Documents | 17,845 | 6,938 | 10,907 |
| Exploration Points | 83,100 | 33,975 | 49,125 |
| Subsurface Layers | 335,018 | 141,297 | 193,721 |

In addition the database contains 3557 outcrop locations.

Our database area has expanded to meet the needs of the municipalities and communities, driven by the need for groundwater data as well and hazard mapping data. In 2007 and 2008, our focus was on the eastside of Lake Washington where urban centers and urban growth are at the greatest. We also added new data in the Bremerton East and West quadrangle areas to facilitate our coastal landslide mapping.

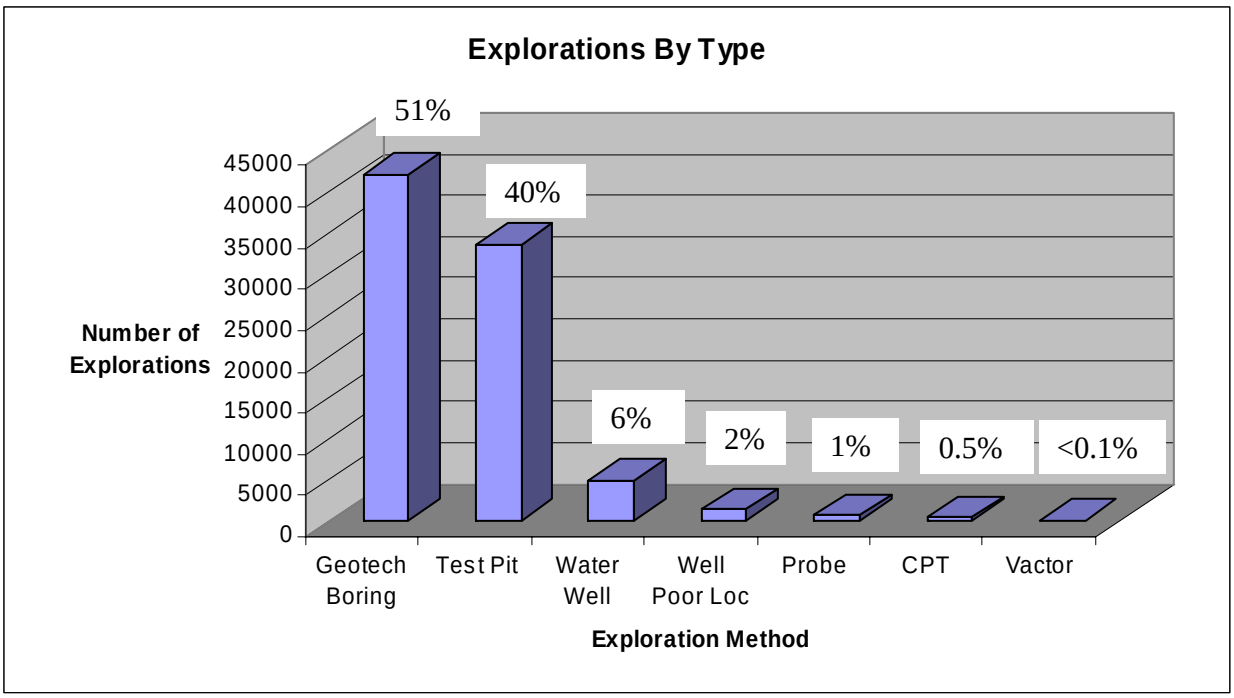
**Table 3:** Status of Data Entry for Eastside Quads

| | Kirkland Quad | Mercer Island Quad |
|---|---|---|
| Geotechnical Documents | 1588 | 1795 |
| Explorations Points | 8832 | 8637 |

We have a contract with the City of Bellevue and a Pilot project with the City of Redmond that together will generate ~ 1000 more documents in 2009.

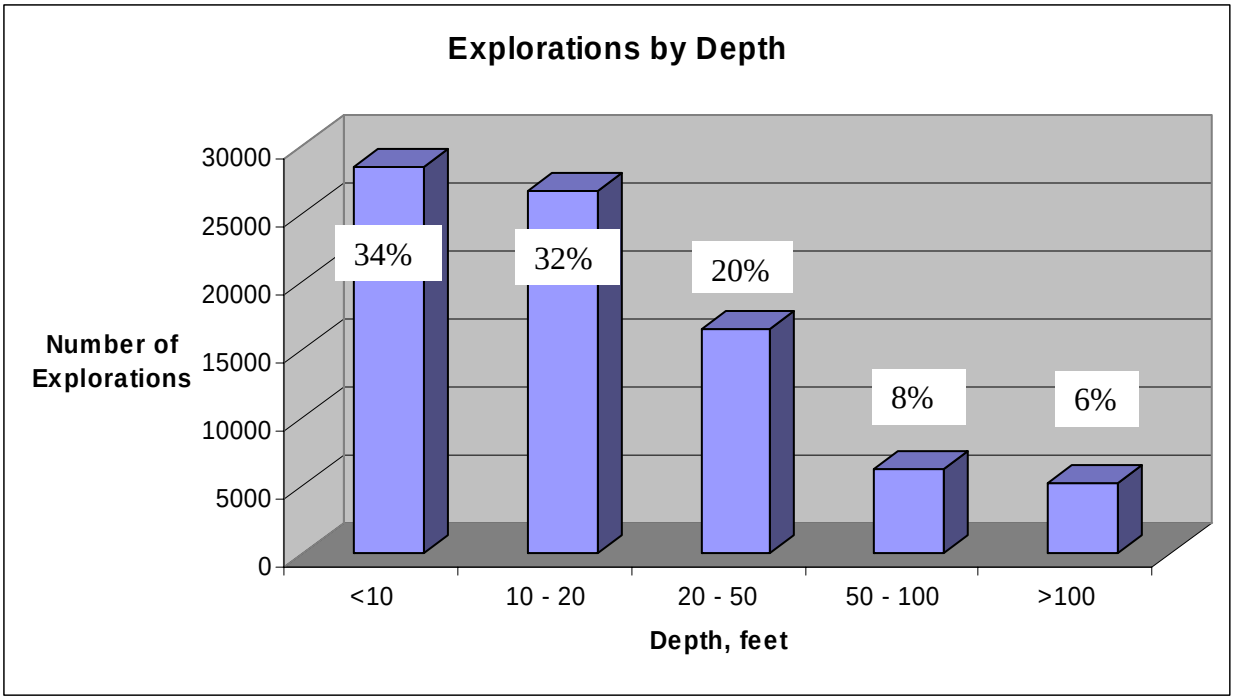
Most of the subsurface data in the database are from geotechnical borings and test pits that have been logged by a trained geologist or engineer. However, there are several exploration types in the database including cone penetrometers, probes, wells, and vactor methods; each provides important subsurface information. The following graph depicts the distribution of these subsurface exploration methods within the database.

**Figure 4:** Explorations by Type



Depth of exploration varies greatly within the 83,100 exploration points in the database. Shallow borings (<10 feet) are often just as useful for the making of geological maps as are the deep (>100 feet) borings. Shallow borings and test pits are useful if they penetrate fill layers that are so often present at the ground surface across the urbanized area of the Puget Lowland. Although we map fill, we also map the geological material beneath the fill. This benefit of high-resolution geological mapping is a direct result of having a borehole database for such information.

**Figure 5:** Depth of Explorations




Since inception, GeoMapNW has collected data from a variety of sources. Typically the most prolific sources are the building and planning departments in the cities and counties where we are mapping. Developers/owners must submit geotechnical reports in order to receive building permits, particularly in critical/sensitive areas (steep slopes, liquefaction-prone areas, landslide-hazard areas, etc). Once submitted, these reports become public record and it is these reports that we mine for the database. Our city partners have helped to varying degrees to retrieve these reports from both archive and active files. Over the 9 years that the database has been in growth mode, we have also collected from other high-yield sources. The following table depicts the top twenty data sources represented in our database.

**Table 4**: Top Twenty Sources of Subsurface Data

| Source | No. of Documents |
|---|---|
| Washington State Department of Ecology | 4819 |
| Seattle Department of Planning and Development | 4685 |
| King County Department of Development and Environmental Services | 893 |
| Seattle Public Utilities - Records Vault | 890 |
| Bellevue Planning and Community Development | 757 |
| Mercer Island Development Services Group - Engineering | 677 |
| Seattle Public Utilities - Materials Lab | 541 |
| Kitsap County Public Utilities Department | 351 |
| Washington State Department of Transportation - Tumwater | 341 |
| Bothell Community Development | 293 |
| King County Road Services | 241 |
| Associated Earth Sciences, Inc. | 229 |
| Creative Engineering Options | 202 |
| Yonemitsu Geological Services | 190 |
| Washington State Department of Ecology, Environmental Div. | 175 |
| Washington State Department of Natural Resources | 168 |
| City of Kirkland, Public Works Department | 149 |
| King County Technical Library | 143 |
| Snohomish County Planning and Development Services | 137 |
| Redmond Public Works | 130 |

The database contains explorations dating back into the early 1900's. Many of the older records are from water and oil exploration wells drilled in our mapping areas.

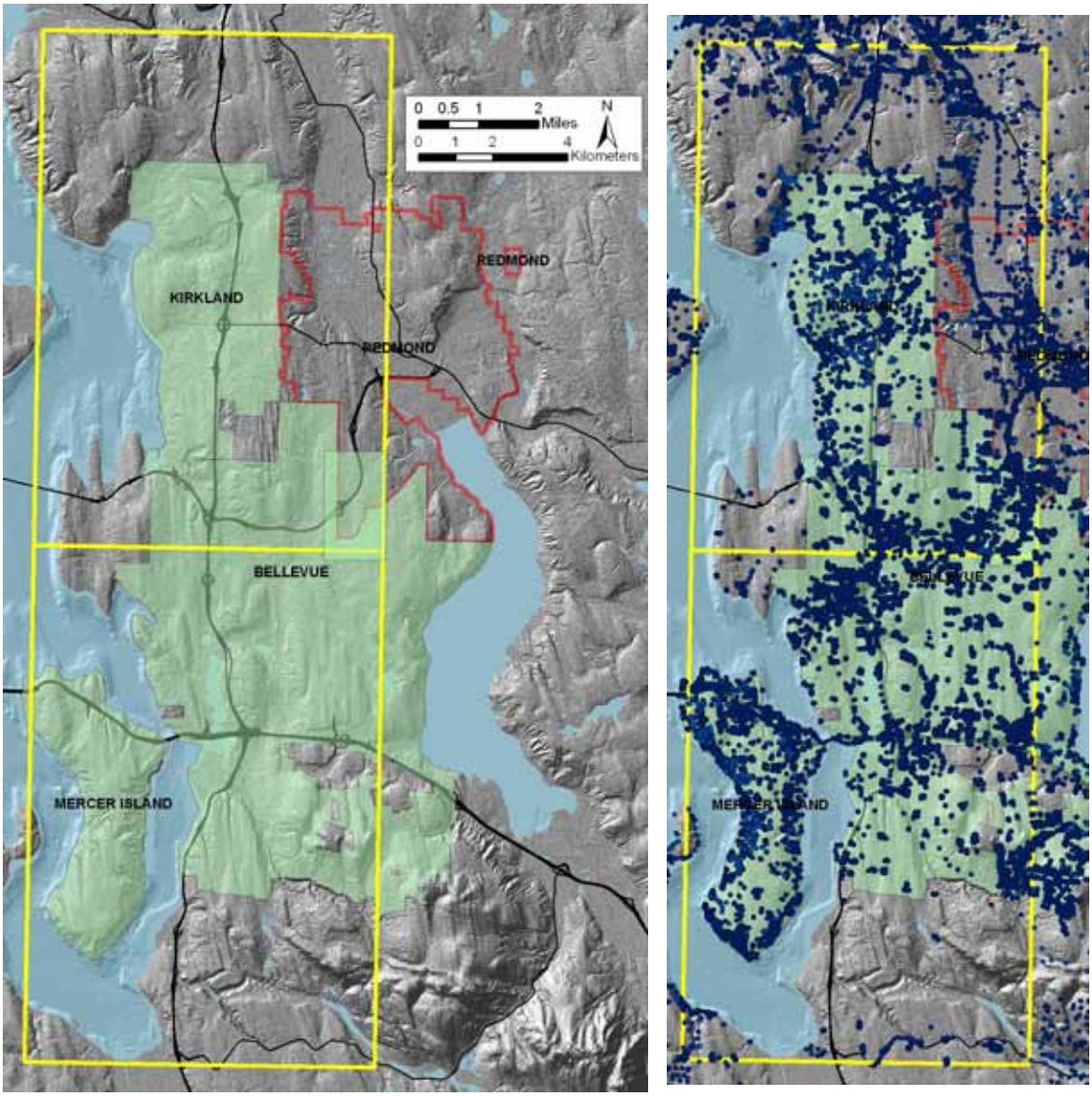
**Table 5**: Subsurface Data by Year

| Year Exploration Completed | Number of Explorations |
|---|---|
| 1900's | 2 |
| 1910's | 131 |
| 1920's | 230 |
| 1930's | 190 |
| 1940's | 235 |
| 1950's | 1,424 |
| 1960's | 6,170 |
| 1970's | 8,348 |
| 1980's | 20,917 |
| 1990's | 32,477 |
| 2000's | 11,972 |

**Figure 6a and b.** Kirkland and Mercer Island Quadrangle geologic database coverage

Yellow outline corresponds to area listed in Table 3. Green shading shows areas funded by city partners. Dark blue dots in Figure 6b show locations of explorations in database.

6a. 6b.




## Geologic Mapping

In 2006-2008, we advanced seven USGS SIM-series 7.5-minute maps (Issaquah, Seattle NW and NE, Seattle SW, Puyallup, Tacoma South, and Vashon Island) into publication. We focused new mapping on the Mercer Island and Kirkland quadrangles (Figure 6); and some in the Redmond quadrangle and in the Preston Area along I-90. These areas are the growing population and economic centers of the greater Seattle area. All of Mercer Island itself has now been mapped. We began work with the City of Bellevue in December 2008 that will be contributing to a large part of the unmapped areas of the mainland of the Mercer Island

quadrangle. Mapping of the City of Kirkland will be complete in April of 2009 and hence the City of Kirkland has contributed to the mapping of the Kirkland quadrangle. By the end of 2009, geologic maps of the Mercer Island and Kirkland Quadrangles will be 80% complete.

The style of geological mapping produced by GeoMapNW is considered "High-resolution geological mapping". This technique was developed by GeoMapNW and involves using lidar topographic data, geomorphic analyses, a subsurface database, new field mapping, accessing excavations, and using historic records and maps. These high resolution maps are produced at 1:12,000 scale. The Seattle area and City of Mercer island were mapped using this technique. The cities of Kirkland, Bellevue and the pilot area of Redmond will also be high-resolution geological maps. The benefits of this mapping technique were described in our previous FTR, but are summarized simply: in the Puget Lowland, we have found that 50 to 75% of the land area is reclassified as a different geological unit. For example, instead of Vashon till at the ground surface, 25% of the time we are encountering sandy, well-draining material. Instead of a map with 7 geological units, we produce a map with 50 units. The new maps are more detailed, more accurate, and more informative than standard 1:24,000-scale maps.

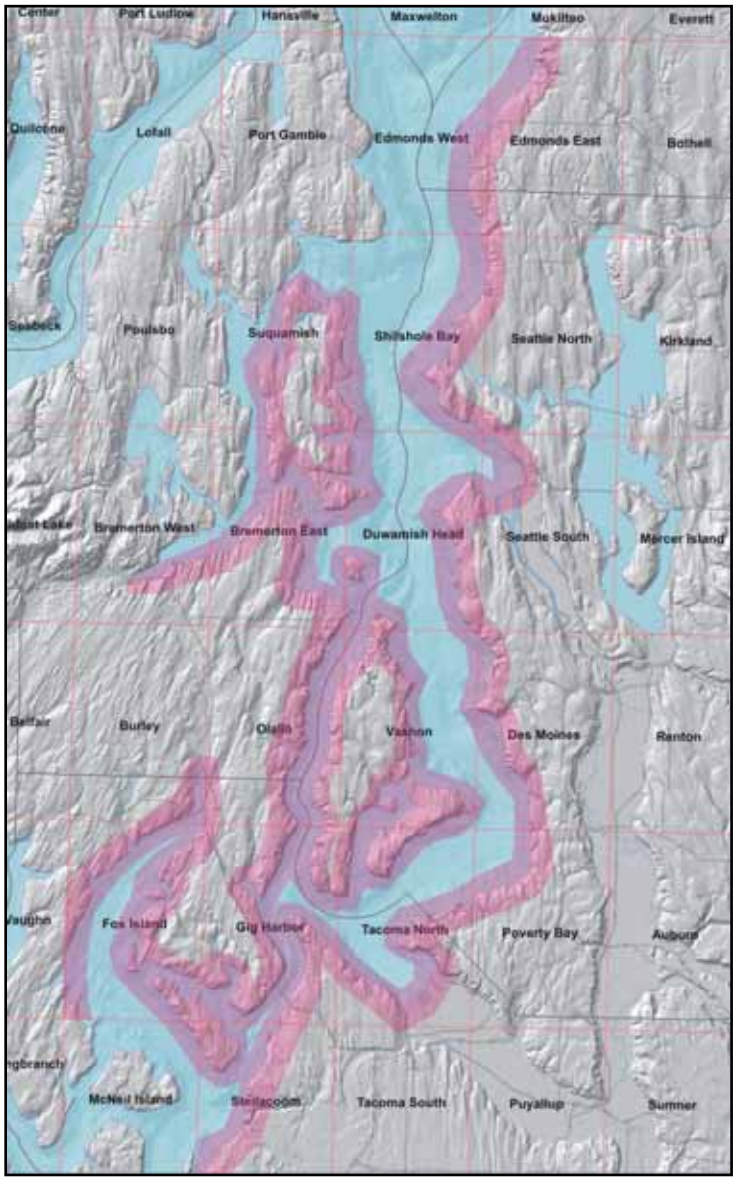
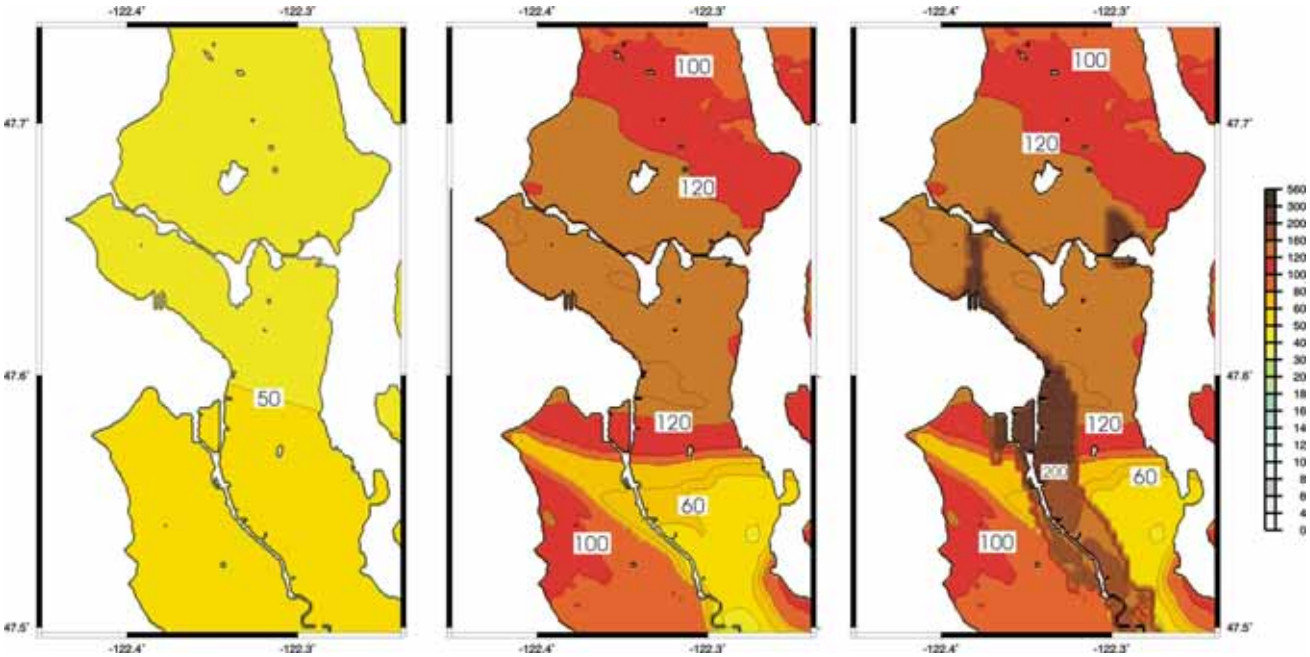



**Figure 7.** Area of landslide delineation and geologic compilation for coastal geologic-hazard work with (WDGER).

In previous years we initiated a partnership with the Water and Land Resources Division of King County to expand our geologic database and mapping efforts, and to populate our database with groundwater information. In 2007, that effort was directed to the greater Kirkland, Woodinville, and Redmond areas, which overlaps with our NEHRP effort and also includes areas near to the projected southeastern extension of the South Whidbey Island fault zone. Under these contracts, we have worked in the Redmond quadrangle, and added a tremendous amount of data to the Fall City and Issaquah quadrangles.

Geologic mapping in 2007 also included a landslide-oriented compilation of geology and identified slope failures along much of the major inland coastlines of western Washington, areas of greatest population density and thus greatest potential risk from geologic hazards. The final compilation of data is being released by the Washington State's Division of Geology and Earth Resources (WDGER). Geologic and landslide mapping of 475 km of coastline yielded 1075 landslides for the database that we constructed for WDGER (Figure 7).

Much of our mapping has been used for derivative products like seismic hazard maps (Figure 8). In 2007, Art Frankel's group of the USGS released new seismic hazard maps for the Seattle area based on earthquake shaking modeling using, in part, our new geology of Seattle and our depth to glacially-overridden material (Figure 9). This latter layer was developed by querying the database and applying standard geologic interpretations based on the glacial geologic history of the region. The following figure shows a comparison between a prior shaking map (far left) and the new map using the new geologic information. The new geologic map and derivative map allowed a significantly improved shaking map for the Seattle area.




From national map rock-site condition

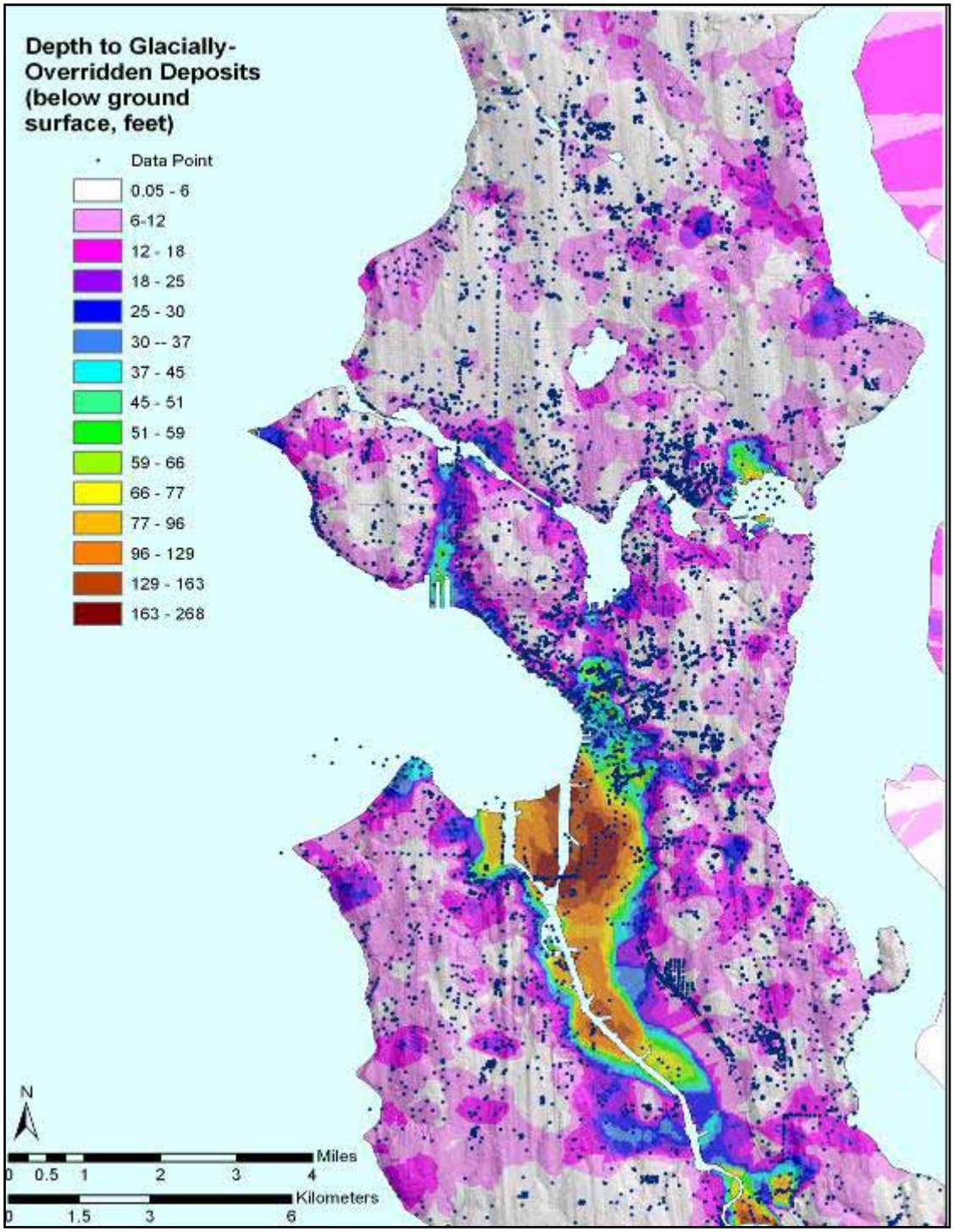
From 3D simulations simulations

From 3D simulations and nonlinear amplification of fill/alluvium

**Figure 8**: 1 Hz Spectral Acceleration, 2% probability of exceedance in 50 yr, from Art Frankel, USGS

Depth to the top of glacially-overridden material is an important factor for foundation design here in the Puget Lowland. Finalizing such a map would be of great benefit to the consulting and scientific community, e.g. this map helped delineate buried bogs in Seattle, now a regulated feature.

**Figure 9** Draft Map of Depth to Glacially Overridden Deposits in Seattle



We have also compiled existing geologic mapping in much of the lowland to assist in the area-wide assessment of hazards (Figure 10). This map has been used by WSDOT to assess potential new transportation routes.

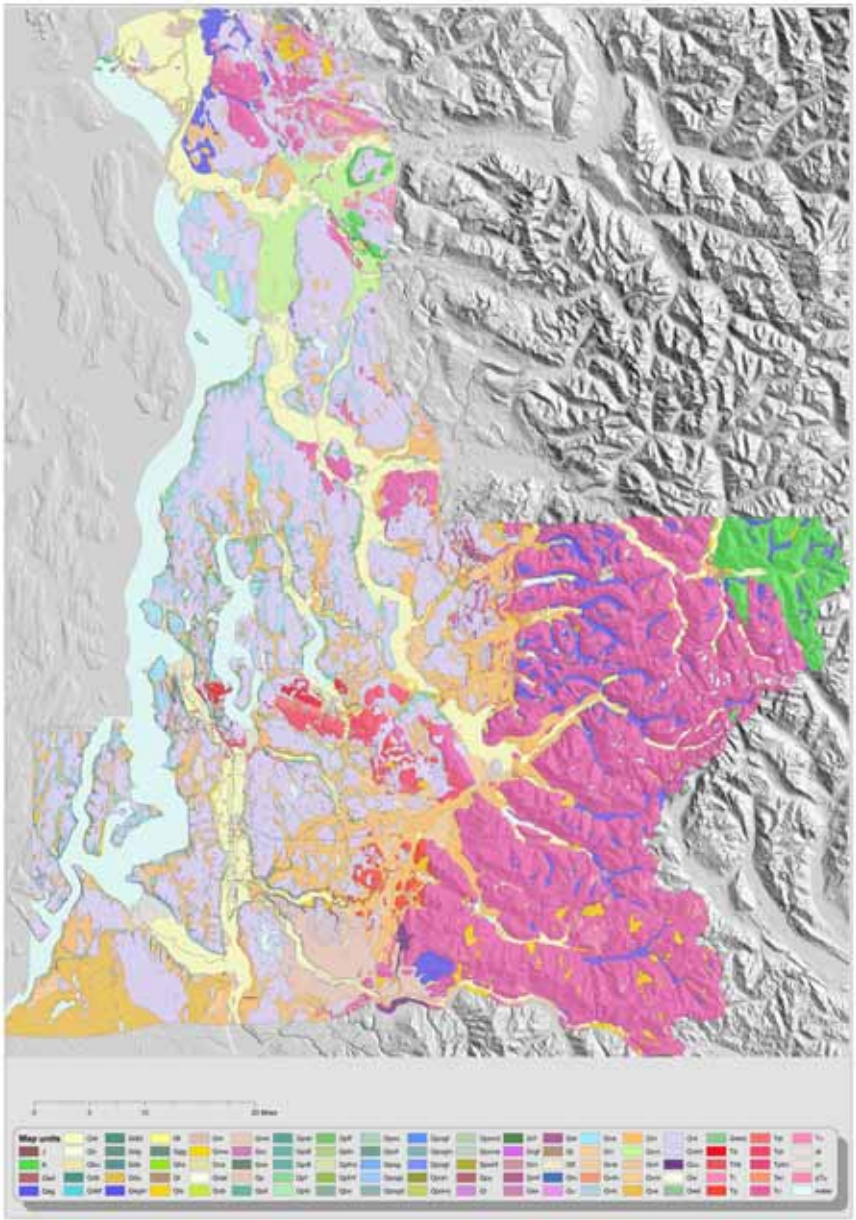


**Figure 10:** Lowland Composite Geologic Map

## 3-D Geologic Mapping and—Public Access to Geologic Data

We have made much progress in these areas over the term of this grant. Borehole metadata, subsurface layer data, scans of borehole logs, geologic maps, and recent publications can be accessed through our website (http://geomapnw.ess.washington.edu).

A modest amount of funds from the grant allowed us to make substantial improvements to web serving of data. Prior to this grant, our web server was running on an unstable platform in a room without temperature control. Now, we have upgraded to a dedicated web server and have moved the server into a climate-controlled room. We also upgraded the software and associated software versions allowing us to increase user availability and add statistical analyses. We are able to verify that our web site is heavily used (80,000 hits/month), we can identify our core user groups (cities, universities, agencies, and consultants), and we can determine the most heavily used aspects of our website (explorations and maps), allowing us to focus improvements to our website.

As geologic maps reach final draft stage, they are posted on our website. As of the end of 2008, 21 maps were available online: the Seattle NW, NE, and SW, Mercer Island and derivative geologic maps at 1:12,000 scale; the composite geologic map of Seattle at 1:24,000 scale; the Issaquah, Olalla, Gig Harbor, Vashon, Des Moines, Poverty Bay, Tacoma North, Tacoma South, Steilacoom, and Puyallup quadrangles (1:24,000); northwestern King County and southwestern Snohomish County (1:24,000); and the geologic map of King County (1:100,000).

As new data are added to the database, and pass 2 levels of QA, they are added to the web site. All of the boreholes in our database have been scanned and are also available on the web as pdf files. New files are added quarterly when we mail our quarterly database updates to partners. At present 17,600 scanned documents (with their explorations) are available on the website, the remainder of the documents in our database will be added as scanned images following our next quarterly update in March of 2009. This is a major accomplishment since the end of 2007 and was done in response to request from our users. The public can also view our originals and make copies of our borehole documents at our office. Many consultants, scientists, and other interested parties have taken full advantage of this resource both online and in person. Examples of the web-based interfaces are shown in Figures 11 and 12.

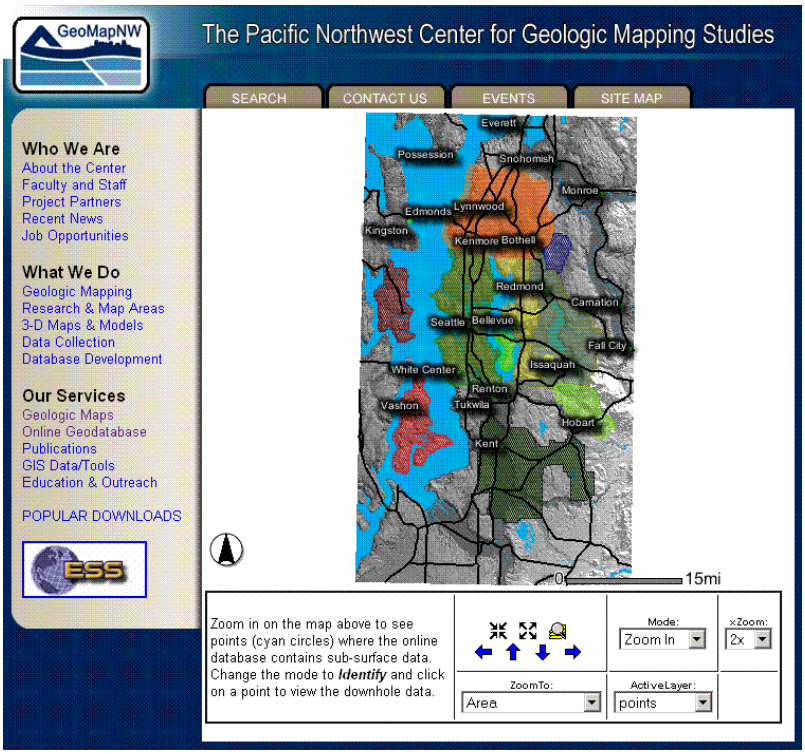
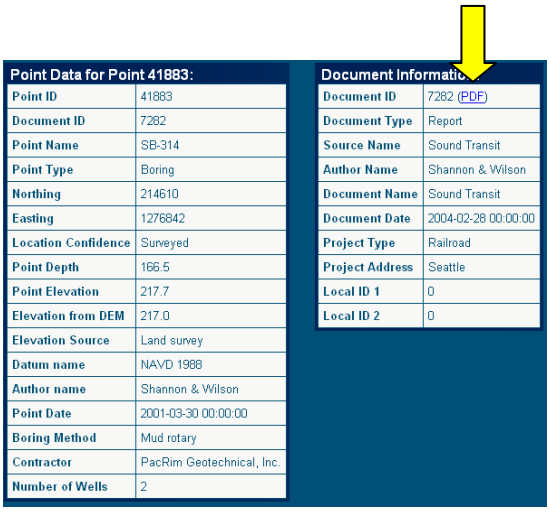



**Figure 11.** Web-based access to borehole data in regional geologic database.


12a.



Point Data for Point 41883:

| | |
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| Point ID | 41883 |
| Document ID | 7282 |
| Point Name | SB-314 |
| Point Type | Boring |
| Northing | 214610 |
| Easting | 1276842 |
| Location Confidence | Surveyed |
| Point Depth | 166.5 |
| Point Elevation | 217.7 |
| Elevation from DEM | 217.0 |
| Elevation Source | Land survey |
| Datum name | NAVD 1988 |
| Author name | Shannon & Wilson |
| Point Date | 2001-03-30 00:00:00 |
| Boring Method | Mud rotary |
| Contractor | PacRim Geotechnical, Inc. |
| Number of Wells | 2 |

Document Informatio

| | |
|---|---|
| Document ID | 7282 (PDF) |
| Document Type | Report |
| Source Name | Sound Transit |
| Author Name | Shannon & Wilson |
| Document Name | Sound Transit |
| Document Date | 2004-02-28 00:00:00 |
| Project Type | Railroad |
| Project Address | Seattle |
| Local ID 1 | 0 |
| Local ID 2 | 0 |

12b.

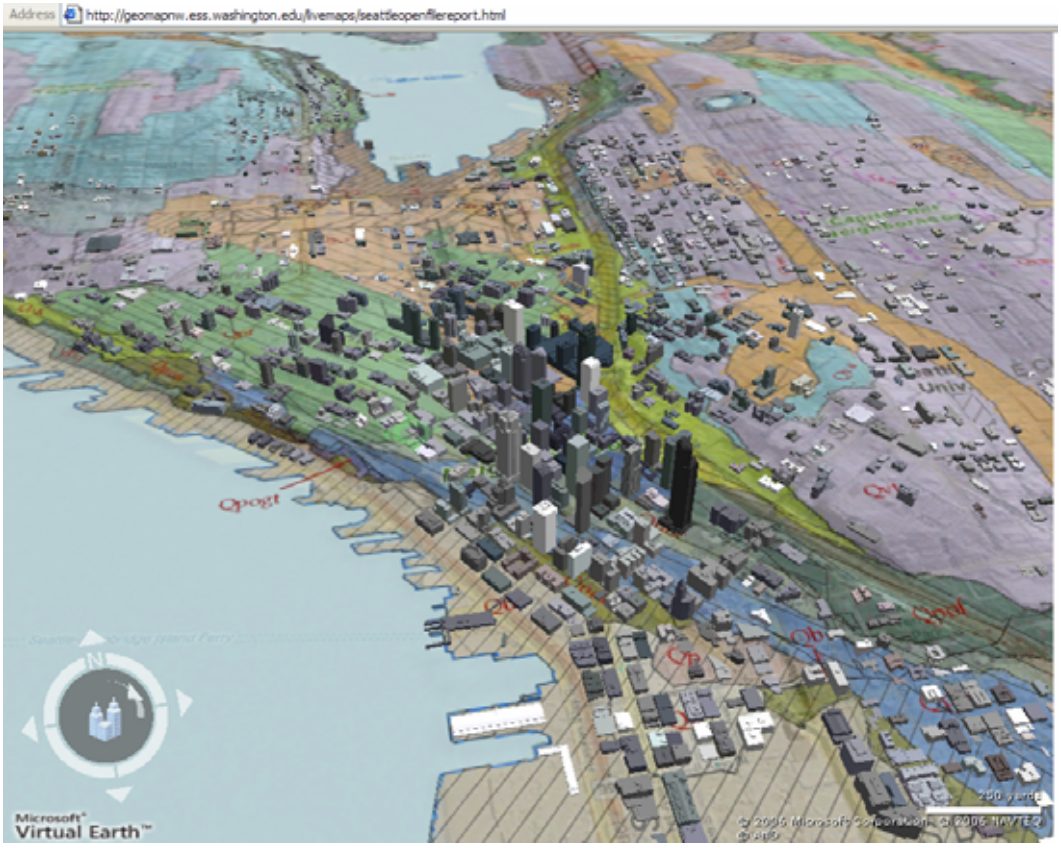
**Figure 12** View of boring selection window (a) and metadata (b) provided on our website for each data point. Note "PDF" annotation (b) indicating a link to the pdf file of the document containing the boreholes, site plan, report (if available) and cross section (if available).


Through our website, our center provides regional delivery of information to scientists, agencies, consultants, and citizens. We provide fast and efficient access to subsurface data via ArcIMS that would otherwise be unorganized in boxes in storerooms or in offsite archives. As developed, we provide access to new viewing tools developed by our group. In 2007, we added an interactive Geologic Map of Mercer Island to our website (similar to the one of Seattle, Figure 13, at left) to allow users to zoom in to an area of interest then obtain the geologic unit. A linked table allows the user to learn more about the geologic unit of interest such as density, general thickness, and other material properties.

**Figure 13** View of interactive Geologic Map of Seattle on the website.

We also now provide the Seattle Geologic map in 3-D mode by viewing it in Virtual Earth using Internet Explorer for web browsing. Examples of the map are shown below (Figures 14 and 15) or go to geomapnw.ess.washington.edu/3dlowland.html for full viewing of the Seattle Geologic Map, OFR 2005-1952.

**Figure 14.** View north of downtown Seattle with Lake Union in the background. Note that most of the high-rise buildings of downtown are built on older pre-glacial deposits (units Qpxx), whereas the buildings in the SODO area in the foreground are built on fill over former tideflats (line patterns over unit Qtf).



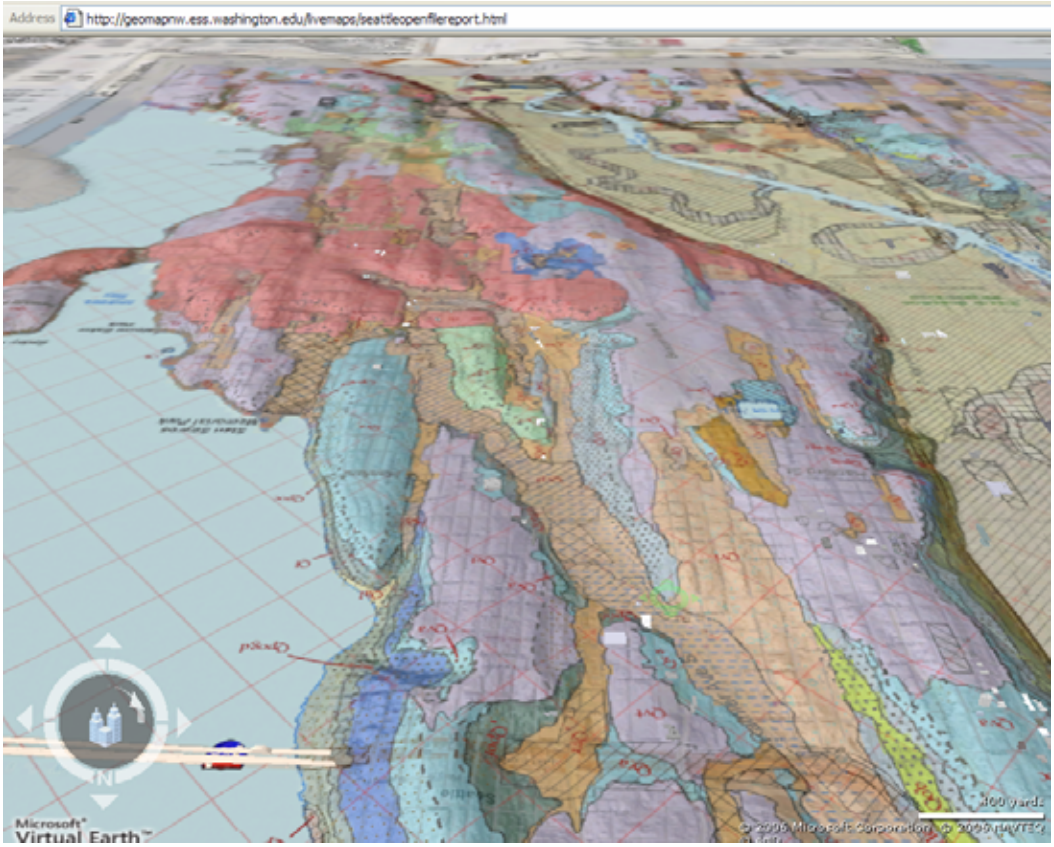
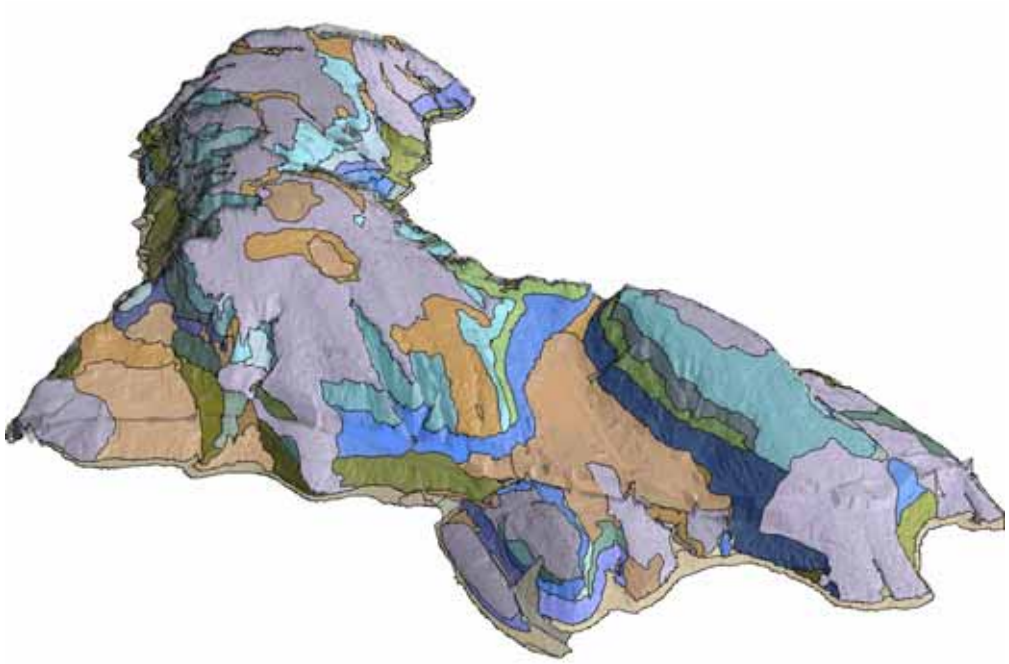



**Figure 15.** View south from Interstate 90 in vicinity of Baker Ridge tunnel. Note interconnecting Vashon recessional outwash channels (tan to orange colors) on the upland that grade to Lake Washington to the left, or east. The straightened Duwamish waterway is visible in the background as are the former (filled) channels of the river. Some of the filled channels experienced ground failure during the Nisqually earthquake of February 2001 while the surrounding alluvium did not. Bedrock is shown in reddish colors, and is exposed above ground here because the view is looking at the north end of the Seattle uplift from the Seattle fault.

**Figure 16.**. 3-D view of geology of Mercer Island looking south. Tan areas are Vashon recessional lake or outwash deposits, blues are sandy glacial outwash, greens are older non-glacial deposits, and purple is Vashon till.



## Component 5—Education and Technical Outreach

We are active leaders, conveners, and participants in seminars, conferences, and workshops to educate the scientific and non-technical community about the geologic setting of the Seattle and Tacoma areas. During the term of this grant, we gave ~25 presentations (mostly invited), led 7 field trips, chaired or co-chaired many research symposia, and taught 3 short courses. Some of our presentations were about the geology of certain areas and presented to communities such as Seattle, Kirkland, and Mercer Island. We lead several field trips combined with short courses aimed at consultants and their clients, bringing them up to speed on the latest tectonic and stratigraphic findings. We also participated in the geologic field trip for the WA state legislators and their aides coordinated by WDGER. We presented geologic hazards information to specialty groups, such as the American Institute of Architects, the Eastside Building Officials Group, City of Seattle Engineers, Utility Boards, and various college academic groups. Our director was invited to present before the National Research Council in Washington DC regarding 3-D geotechnical databases and is active in an international working group on 3-D mapping techniques.

A major emphasis is placed on bridging the gap between research and consulting geology. To this end the PI, our director, serves as the Chair of the WA Section of the Association for Environmental and Engineering Geology (AEG). She also serves on the Board of Directors for AEG and chairs a national committee. These efforts provide many opportunities for uniting both groups at meetings and presentations.

We convened a workshop to discuss active faults and the regulations in Washington. The target audience was the technical community and was aimed at communication between research and consulting geologists. We co-presented at a recent workshop for city and county planners regarding the Seattle and Whidbey Island fault zones to discuss the topics of "state of the science regarding active faults" and "potential for regulations".

The PI also serves on the board of directors for Northwest Scientific Association and coordinated a full-day symposium and led a field trip geared to share research findings with the academic, consulting, and decision-making community. The symposium had two parts: the Geologic History of the Pacific Northwest and the Tectonic/Seismic History of the Pacific Northwest.

In light of the economic climate, we have developed a backup plan for the database. We have a small contract with WDGER to help them establish a copy of our database at their office in Olympia, WA. WDGER wants to start building a state-wide database using our methodology and at the same time, they can serve as an emergency back-up for our system.

In addition to completing maps, we completed a manuscript in 2008: Geology of Seattle and the Seattle area. It is published in a GSA special paper, reviews in engineering geology.

We received a supplement in 2007 for software licensing. This software is used in a classroom setting and allows the processing and interpretation of geophysical data.

**NON-TECHNICAL SUMMARY**

**Project period May 16, 2006 – December 31, 2008**

**TITLE:** THE QUATERNARY GEOLOGY OF THE SEATTLE-TACOMA URBAN CORRIDOR—BUILDING THE FOUNDATION FOR GEOLOGIC-HAZARD MAPPING

**Cooperative Agreement Number:** 06HQAG0125

**Investigator:** Kathy G. Troost, University of Washington, Department of Earth and Space Sciences, Box 351310, Seattle, WA 98195-1310

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**NEHRP Element:** I, Pacific Northwest region
**Keywords**: Geologic Mapping, Surficial Deposits, Tectonic Structures, Urban Geology

Many engineering applications in urban areas are impacted by the spatial distribution of geologic materials. This project is developing a detailed understanding and representation of the three-dimensional distribution of geologic materials beneath Seattle and the surrounding region, with a focus on the major earthquake-generating structures of the central Puget Lowland. To date, we have acquired and organized 86,600 items of geologic information, representing a substantial fraction of the vast amount of existing data; in combination with our ongoing field investigations, we are preparing and publishing the geologic maps to display this information for scientists, agencies, and the public.

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## GEOLOGIC MAPS

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