FINAL TECHNICAL REPORT

Project period January 1, 2001 – June 30, 2006

Title: THE QUATERNARY GEOLOGIC FRAMEWORK FOR THE CITY OF SEATTLE AND THE SEATTLE-TACOMA URBAN CORRIDOR

Cooperative Agreement Number: 01HQAG0017

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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 01HQAG0017. 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.

ABSTRACT

The overall focus of this project has been to understand the architecture and map the distribution of Quaternary deposits in the central Puget Lowland to provide critical support of ongoing research into fault locations and history, and the effects of ground shaking from earthquakes, across this region. These deposits are primary determinants of the magnitude and location of strong ground shaking, and so knowledge of the thickness, geometry, and density variations of these deposits is critical to the ongoing seismic evaluations. 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. To date, we have acquired and organized more than 70,000 items of geologic information, representing a substantial fraction of the vast amount of existing data, and have made this information fully available to agencies, researchers, and the general public. In combination with ongoing field investigations, we have also prepared and are publishing the geologic maps to display this information and its geologic interpretation (5 published, 9 in press, and one in review at scales of 1:12,000–1:100,000).

INTRODUCTION

The cities of the Puget Lowland region (Figure 1) have been built atop a complex sequence of deposits with widely varying engineering strengths and an irregular bedrock surface at depth. They lie in one of the most seismically active regions of North America, with moderate earthquakes virtually assured during the lifetime of any structure, most recently the Nisqually earthquake of 2001. Many contain steep hillslopes that are marginally stable in wet weather; because of shallow water tables, underlying sandy deposits are particularly susceptible to liquefaction during strong ground shaking. As the center of both population and economic activity of the Pacific Northwest, geologic events of even moderate intensity can and do result in substantial human and economic losses. Seattle was recognized by Federal Emergency Management Agency (FEMA) in 2000 as the city with the seventh-highest annualized earthquake loss in the United States, and the highest outside of California. At the state level, Washington has the second highest risk (2nd only to California) of suffering economic loss due to earthquakes.

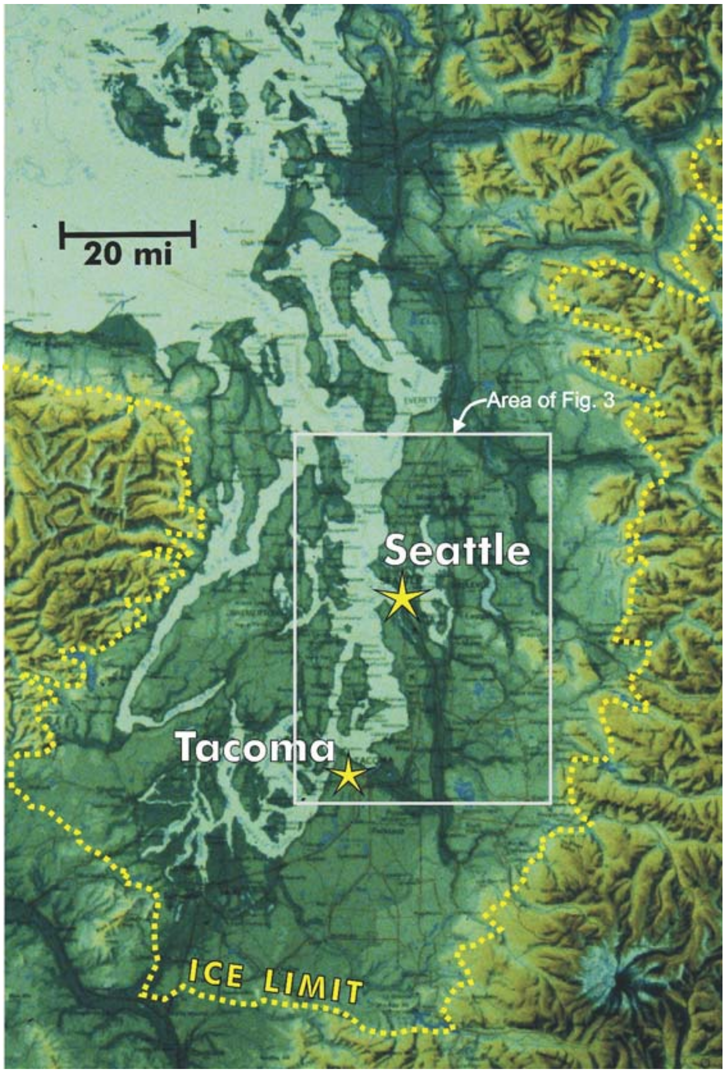


Figure 1. Location map of the Puget Lowland region, showing the southern extent of the Puget lobe of the Cordilleran ice sheet about 16,000 calendar years ago (dashed line; Booth and others, 2004).

Geoscientists and engineers recognize that the Quaternary deposits of the Puget Lowland are primary determinants of the magnitude and location of strong ground shaking. Knowledge of the geometry and variability of these deposits—the *geologic framework*—is critical to the support of ongoing seismic evaluations across this region, which will ultimately determine the necessary measures, and the cost, of adequate preparation and hazard mitigation. Such a framework comprises a detailed representation of the sequence, chronology, structural history, distribution, lateral lithologic variability, and geotechnical properties (such as strength and permeability) of geological materials.

The Pacific Northwest Center for Geologic Mapping Studies (http://geomapnw.ess.washington.edu) is a collaborative effort to develop new data and greater understanding of the geology of the central Puget Lowland. The project was initiated in 1998 through collaboration with the U.S. Geological Survey, the University of Washington, and the City of Seattle to provide state-of-the-art geologic data to support geologic hazard mitigation in the City. Since that beginning, its scope has broadened to include other geographic areas and a broadened range of research topics. The project goals are to acquire existing geologic data and create new geologic information; to conduct geologic research and produce new geologic maps; and to support the wide variety of additional research, hazard assessments, and land-use applications of other scientists, organizations, and agencies throughout the region.

Our efforts to improve the regional understanding of western Washington's geologic framework consist of several interrelated elements:

- A subsurface database of existing geologic data, built to include new geographic areas and accept new data fields as the needs arise;
- Surficial geologic maps across the central Puget Lowland, replacing preliminary documents that are locally almost 50 years old and establishing a new standard of consistency and geologic mapping for the region;
- Scientific studies of the regional geologic framework, including determinations of the age and identification of geologic materials to help understand the history of crustal deformation and develop standardized nomenclature for all geologists working in the central Puget Lowland;
- Public access to geologic data via web-based interfaces for both subsurface geologic data and geologic maps; and
- Outreach to varied audiences, particularly the technical and planning community, and research scientists.

SUBSURFACE GEOLOGIC DATABASE OF THE GREATER SEATTLE AREA

Geologic investigations in urban areas, regardless of location, all face the same quandary—the value and potential applicability of the data are high, but the same human infrastructure that makes these data so valuable also obscures the very source of that information. Fortunately, that infrastructure also creates some of the most valuable geologic data to be found in urban areas, namely subsurface explorations. Although abundant, most of these exploration data are widely scattered and poorly organized in building and utility departments, transportation agencies, and private consulting firms. To be able to take full advantage of these data, we have developed and are continuing to populate a GIS-based relational database to efficiently store, manipulate, and display the vast amount of subsurface geologic data available for the Seattle area. Geologic data from tens of thousands of field explorations, exposures, and excavations have been entered into the database and are now accessible and available to a much wider audience than ever anticipated.

Partnerships have been formed with a number of local public agencies (such as building departments, public utilities, port authorities, transportation agencies, and natural resource departments) both to acquire the raw data from geologic and geotechnical studies and to return the populated database and GIS interface to those agencies and the public. As a result of continued partnerships over the past seven years, we have developed and streamlined processes for identifying and acquiring geologic data from a variety of sources, with our data largely obtained from public-agency, reports, permit files, and other records.

A basic three-level structure was adopted for the database to provide a common framework for all data and to allow for future expansion (Figure 2). Information about the *document* (i.e. the physical report for a property, a structure, or other type of project) that contains the geologic data and its spatial coverage are stored at the first level (Figure 2, in the GEOTECH_DOC table). Within that document, the attributes and location of subsurface *explorations*, of which there may be just one or many, and which may range from shallow test pits to deep water wells, are stored at the second level (EXPLORATION table). For each exploration point, all the related subsurface *layers* described in each exploration log are stored at the third level. Any additional layer-based information, either comments made on the original logs or subsequent geologic interpretations of the individual layers themselves, are stored at this level as well. The structure of the database and the fields were designed to accommodate geologic data from a variety of sources and formats, to create a common interface for entering and displaying data, and to support current and future scientific and engineering studies.

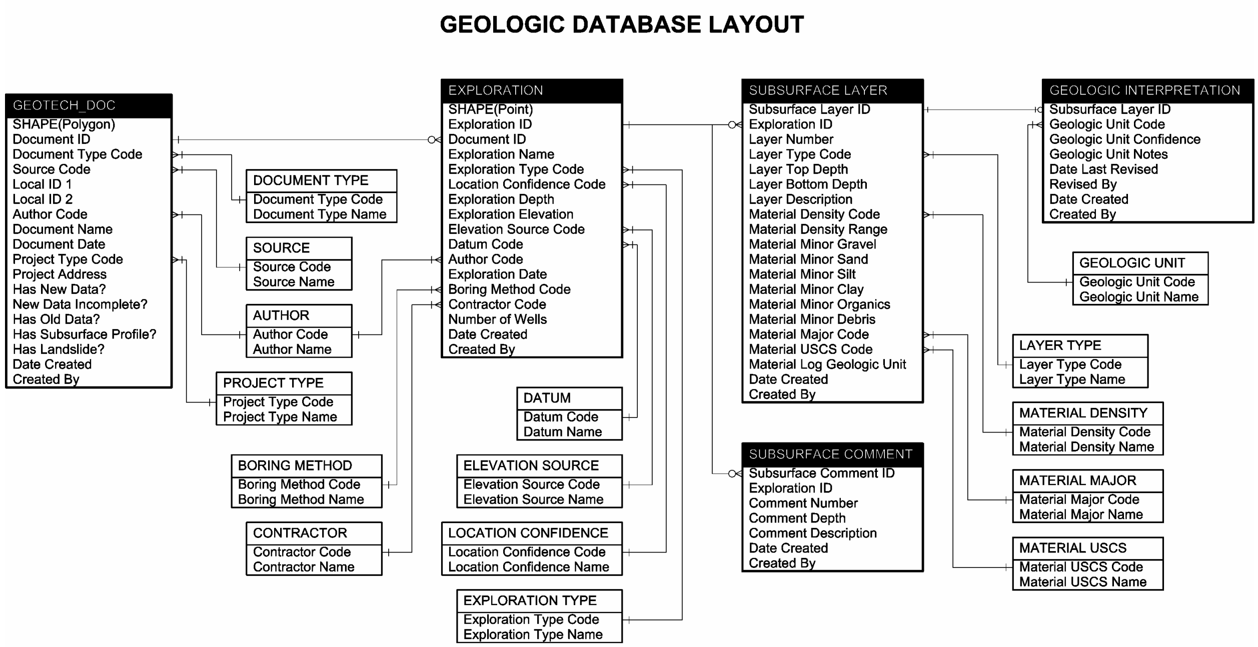


Figure 2. Three-level database structure, showing the data fields and their relationships for the spatial data (GEOTECH_DOC and EXPLORATION) and the nonspatial data (SUBSURFACE LAYER, SUBSURFACE COMMENT, AND GEOLOGIC INTERPRETATION).

Data are entered through customized GIS and database interfaces. Spatial data, namely the area covered by a document and the data points representing the explorations, are entered through a GIS interface along with their associated attributes; the nonspatial data (i.e. the subsurface geologic layer data associated with a specific exploration data point, together with any comment or interpretation) are entered through customized database forms.

Guidelines have been developed to ensure that the data are entered in a uniform and consistent manner. These guidelines provide normalization of data collected from boring logs, test pits, and other exploration types that were prepared by many different consultants and agencies under a variety of classification systems and protocols. Geologic layer-entry guidelines were developed to facilitate translation from the logs to the database. Similar guidelines exist for document and exploration point entry. The guidelines define the fields, give default values, and describe what to do if data are missing from the log.

The database contains “raw” data, in particular the verbatim transcription of the original on-site geologist’s or well-driller’s description of each layer. This information is then parsed manually into fields for density, major and minor materials, and the presence of organics and debris in order to facilitate future database queries. Fields are also available for geologic interpretation, the metadata on original source documents, and anticipated accuracy of point locations.

Since 1998, we have populated the main database tables with a significant amount of data:

TOTAL STUDY AREA (as of 8/06)	
Geotechnical Documents	15,420
Exploration Points	73,523
Subsurface Layers	305,388

Because there are no fixed limits on the prospective area of database coverage, we cannot estimate an ultimate magnitude of data acquisition. Mainly by increasing the geographic area, 1300–2800 documents per year have been added to the database. Within the city of Seattle, where we have been working steadily since the project’s inception, we have an ongoing program to add new data as it is received by the City; for example, nearly 200 new documents were added there alone in 2005.

The geographic areas covered by subsurface information are illustrated in Figure 3.

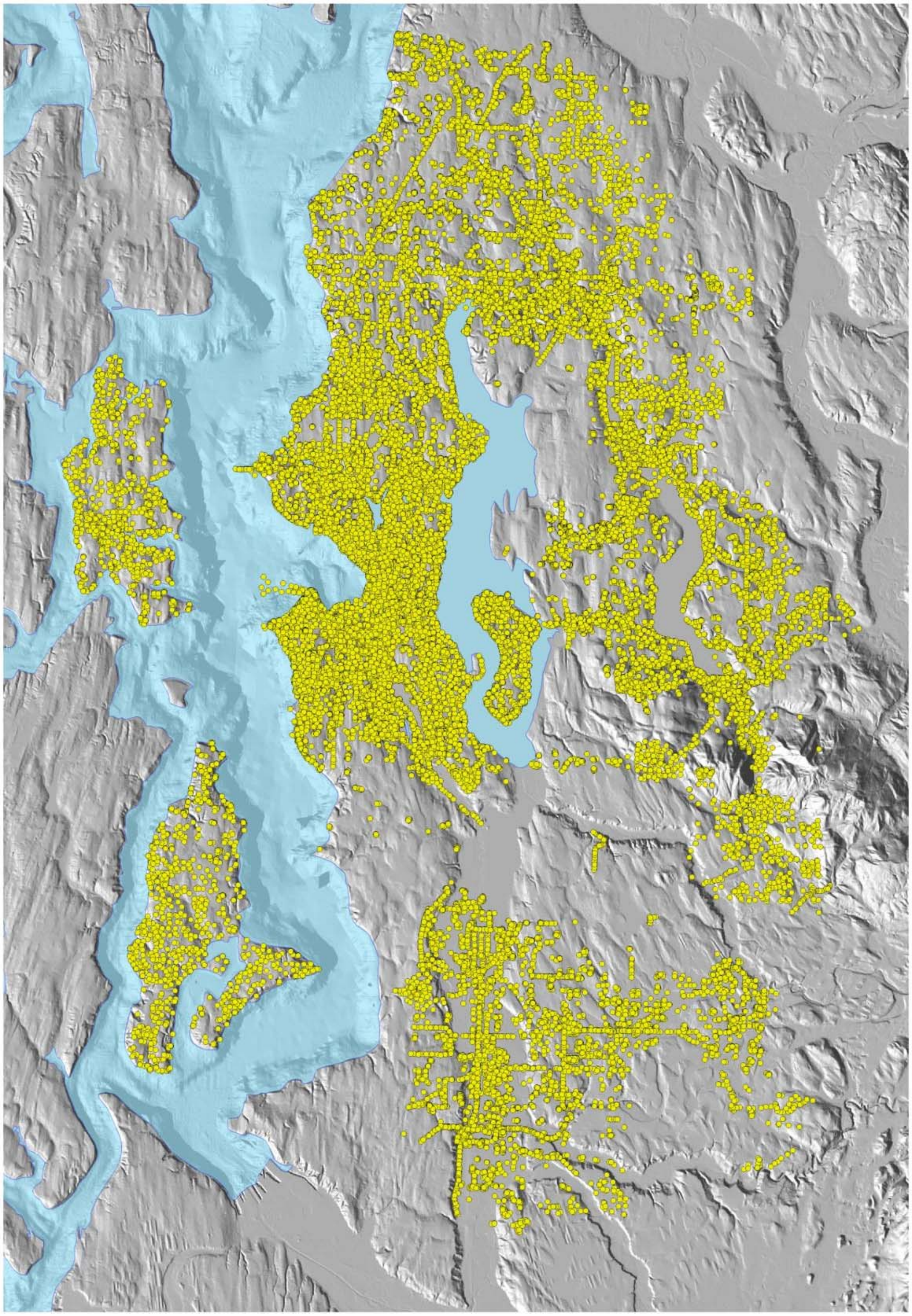


Figure 3. Database coverage currently available, as indicated by the distribution of exploration points (light-colored circles).

When we began the project, data were entered into the database through customized ArcView and Microsoft Access interfaces to take advantage of readily available software and to simplify interactions between multiple (mainly municipal) users, nearly all of whom had access to these software tools but not to anything more sophisticated. The spatial data (document areas and exploration data points) were entered through an ArcView interface along with their associated attributes. Once the spatial data were recorded, nonspatial data (layer data and associated comments) were entered through customized Microsoft Access forms. The two phases of the data-entry process corresponded to the two main components of the database: the spatial data, stored in ArcView shapefile format, and the nonspatial data, stored in a Microsoft Access file. This approach was chosen to take advantage of the relational database capabilities of Microsoft Access while keeping the spatial data in a common format.

Increasing volumes of data, the desire to accommodate multiple simultaneous users, and concerns for fail-safe back-up led us to our present system, whereby the database and corresponding GIS are stored in ESRI's geodatabase format employing ArcSDE with an Oracle database backend. ArcSDE was chosen for its ability to accommodate a multiuser editing environment for spatial data using multiversioning, and for its ability to efficiently store and deliver geospatial datasets. Access to the data stored in the geodatabase is available through a number of application program interfaces (API's) so that customized applications and services can be developed on a variety of computer platforms. Full access to the data is also available to native Oracle objects such as views, functions, and stored procedures, making it possible to programmatically query and analyze the data efficiently. The previous customized tools for entering, analyzing, and viewing data were converted for use within ArcMap by using Visual Basic and object model component technology. Our municipal partners, however, have generally required conversion of data to ESRI shapefile and dBASE dbf file formats to maintain compatibility with their ArcView systems. The database and corresponding GIS are currently stored on a Linux server and are accessed by several Windows workstations through a gigabit network.

SURFICIAL GEOLOGIC MAPS

One of the primary direct applications of the subsurface geologic database has been to support the preparation of new geologic maps. To date, the area where we first began our compilation (the City of Seattle) has been completely remapped at 1:12,000 scale; a preliminary compilation is available (Troost, and others, 2005a), with its four constituent quadrangles in various stages of USGS technical review and publication (Booth and others, 2005; Troost and others, in review a,b; Booth and others, in review a). These maps represent a dramatic increase in both the detail and quality of geologic information for the city relative to the only previously available map (Waldron and others,1962, scale 1:31,680; see Figure 4).

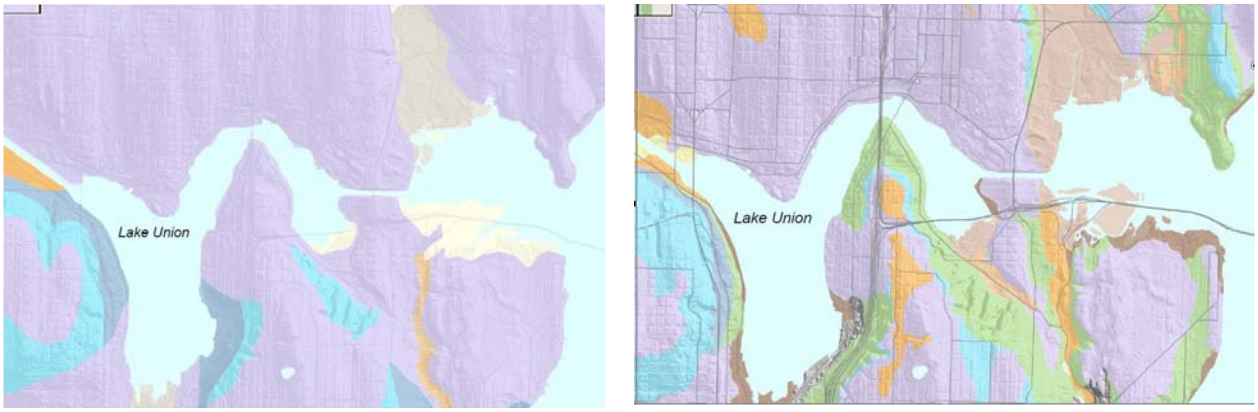


Figure 4. Comparison of old and new geologic maps of Seattle (differences only evident in online color version; printed version available only in grayscale). A portion of the geologic map of Seattle from Waldron and others (1962; left), and from Troost and others (2005a; right).

In areas where both local-agency concerns and regional geologic questions have warranted intensive study, and where funding was provided, this database has been applied to the development of new geologic maps. These include the westward and eastward extension of the Seattle fault (Haugerud, 2005; Booth and others, in review b; Troost and others, in prep.) and planned expansion areas of the regional wastewater-treatment system, particularly just north and east of Seattle. Additional geologic maps have been developed that, in total, span most of the urban core of the central Puget Lowland (Figure 5).

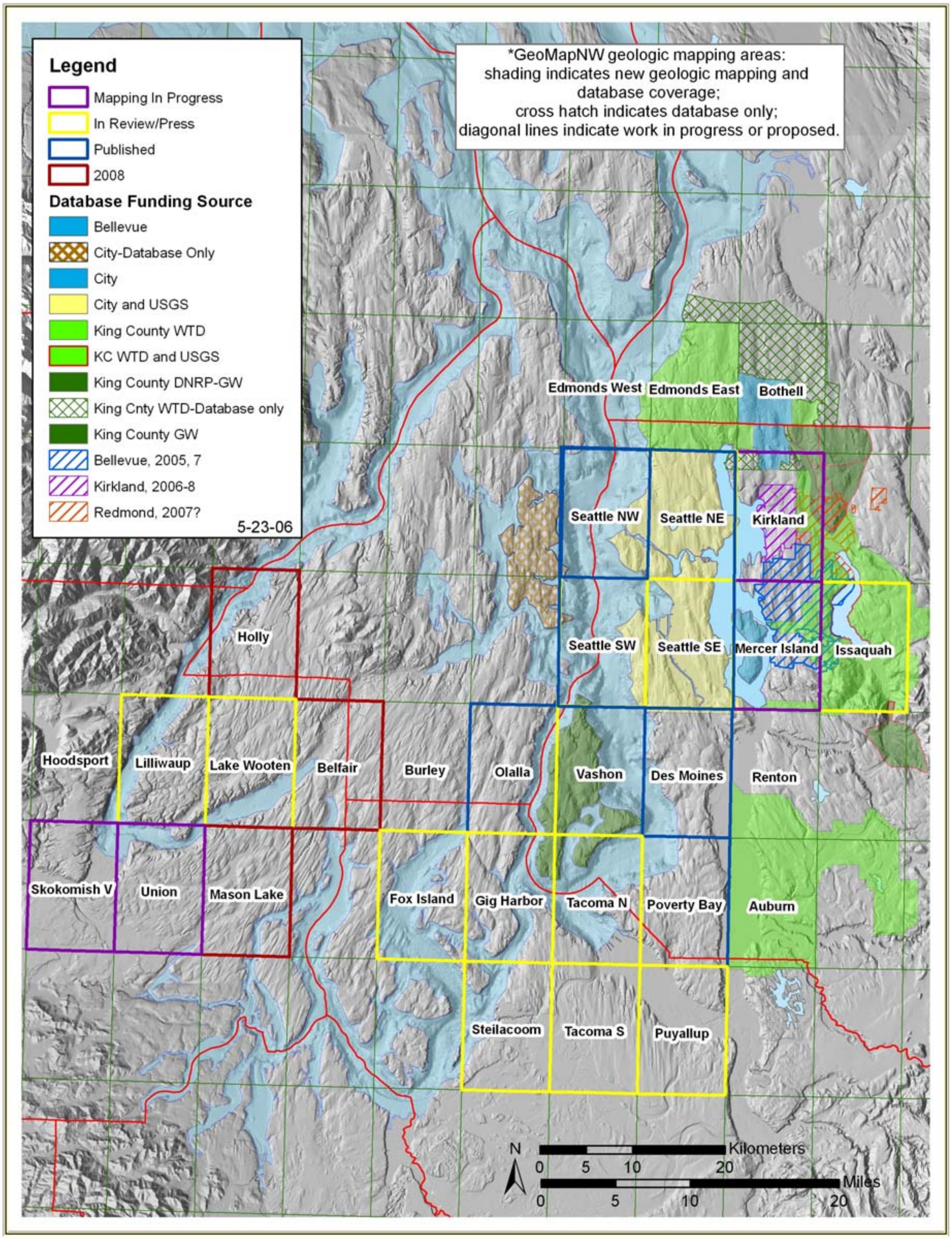


Figure 5. Extent and status of geologic mapping and subsurface database in the central Puget Lowland. Individual map references are listed at the end of this report; colored shading references agency collaborators. Note that the quadrangles in the western part of the area are being mapped collaboratively but have not been supported directly by this project.

REGIONAL GEOLOGIC FRAMEWORK

In addition to the focused acquisition of data and development of very large-scale geologic maps, we are developing a chronological and lithologic context for the complex sequence of glacial and nonglacial deposits in the central Puget Lowland, one that can be used to evaluate the distribution, correlation, and deformation of individual geologic units across the region. As a result of the mapping and stratigraphic and chronologic work being done for our geologic maps, we have established a regional stratigraphic nomenclature and updated timescale. Fundamental errors of stratigraphic (mis-) assignment in the southern Puget Lowland have been recognized over the last two decades, reflecting profound differences between stratigraphic sections exposed in the southeastern (Crandell, 1963) and northern Puget Lowland (e.g., Easterbrook and others, 1981; Blunt and others, 1987). Regional mapping and chronologic efforts (e.g., Hagstrum and others, 2002; Mahan and others, 2003; Figure 6) are now beginning to reconciling these differences (see also Booth and others, 2004).

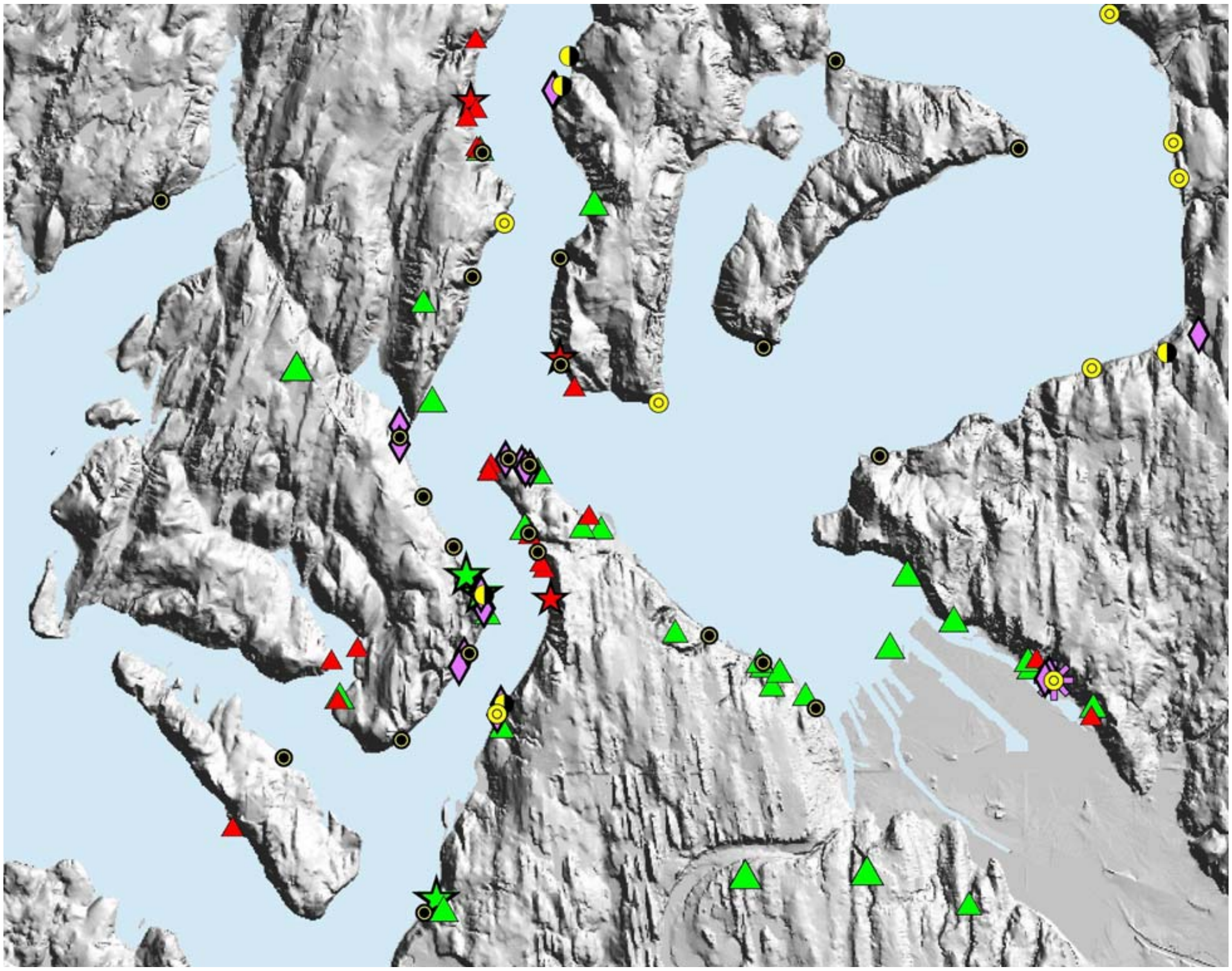


Figure 6. Map of analytic samples of Quaternary sediments collected, dated, and/or compiled by the project. Key: circles = paleomagnetic samples; diamonds = IRSL age samples; triangles and stars = ^{14}C age samples; snowflake = fission-track age sample.

Through collaboration with USGS scientists, we have also shown that the stratigraphic units identified at type sections on Whidbey Island (Easterbrook, 1986), 40 km north of Seattle, can be identified more than 70 km south in the Tacoma area using absolute age control (Troost and others, in press), and we have identified deposits from mid-Pleistocene climatic stages previously undocumented anywhere in the Puget Lowland. A summary of these findings, as a result of our work and others, is compiled in Figure 7.

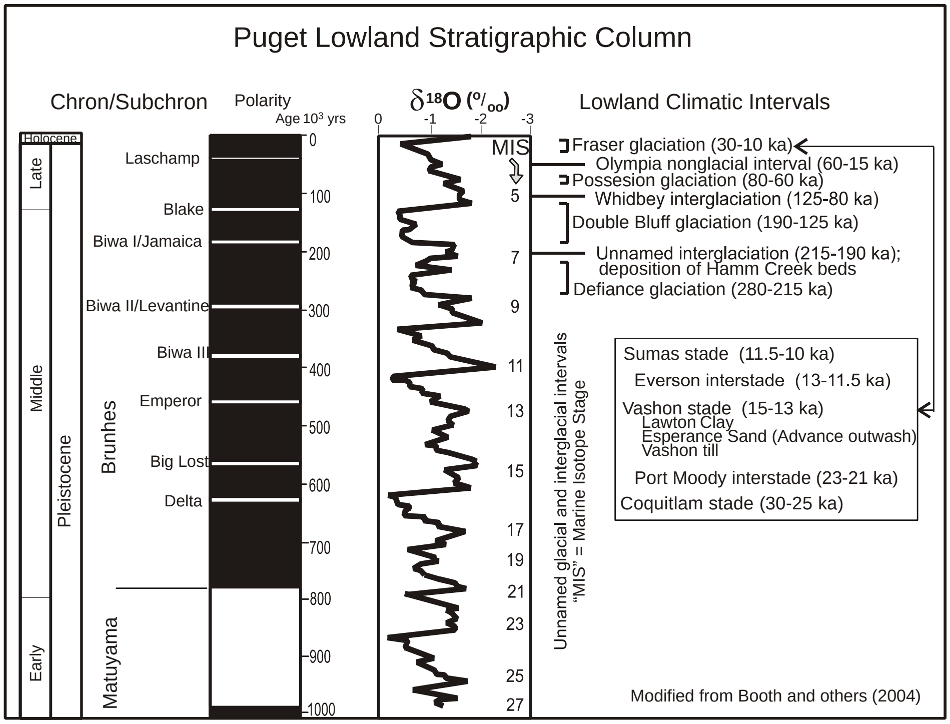


Figure 7. Comparison of the marine oxygen-isotope curve stages (MIS) using the deep-sea oxygen-isotope data for ODP677 from Shackleton and others (1990), global magnetic polarity curve (Mankinnen and Dalrymple, 1979; Barendregt, 1995; Cande and Kent, 1995), and ages of climatic intervals in the Puget and Fraser lowlands. Ages for deposits of the Possession glaciation through Double Bluff glaciation from Easterbrook and others (1981), Easterbrook (1986), Blunt and others (1987), and Easterbrook (1994). Ages for the Olympia nonglacial interval from Armstrong and others (1965), Mullineaux and others (1965), Pessl and others (1989), and Troost (1999). Ages for the Coquitlam stade from Hicock and Armstrong (1985); ages for the Port Moody interstade from Hicock and Armstrong (1981). Ages for the Vashon stade from Armstrong and others (1965) and Porter and Swanson (1998). Ages for the Everson interstade from Dethier and others (1995) and Kovanen and Easterbrook (2001). Ages for the Sumas stade from Clague and others (1997), Kovanen and Easterbrook (2001), and Kovanen (2002).

OUTREACH AND ACCESS TO DATA

The manner of data distribution outside of our immediate research group has been guided by the individual users. For those public agencies that have provided us with sources of data and, commonly, funding as well, we have been delivering quarterly (static) updates of the database, generally as ESRI shapefiles of the documents and exploration points and dBASE dbf files for subsurface layers and comments. The agencies, in turn, load these data onto their intranets, to be available to staff (Figure 8). Actual use of the data, however, is almost certainly quite variable. In the City of Seattle, for example, where our interaction and funding spans seven years, engineering and building departments use the database regularly and we maintain a systematic program of adding new information and delivering it to the City. For some of the smaller cities, however, usage by staff is probably less common; in addition, many of these smaller jurisdictions were only contacted by us during a single interval of data collection, and so the one-time digital compilation of geologic explorations will drift inexorably more and more out-of-date. We have not yet solved the logistical and financial problem of maintaining a truly “current” data set in each of the areas once visited for data acquisition.

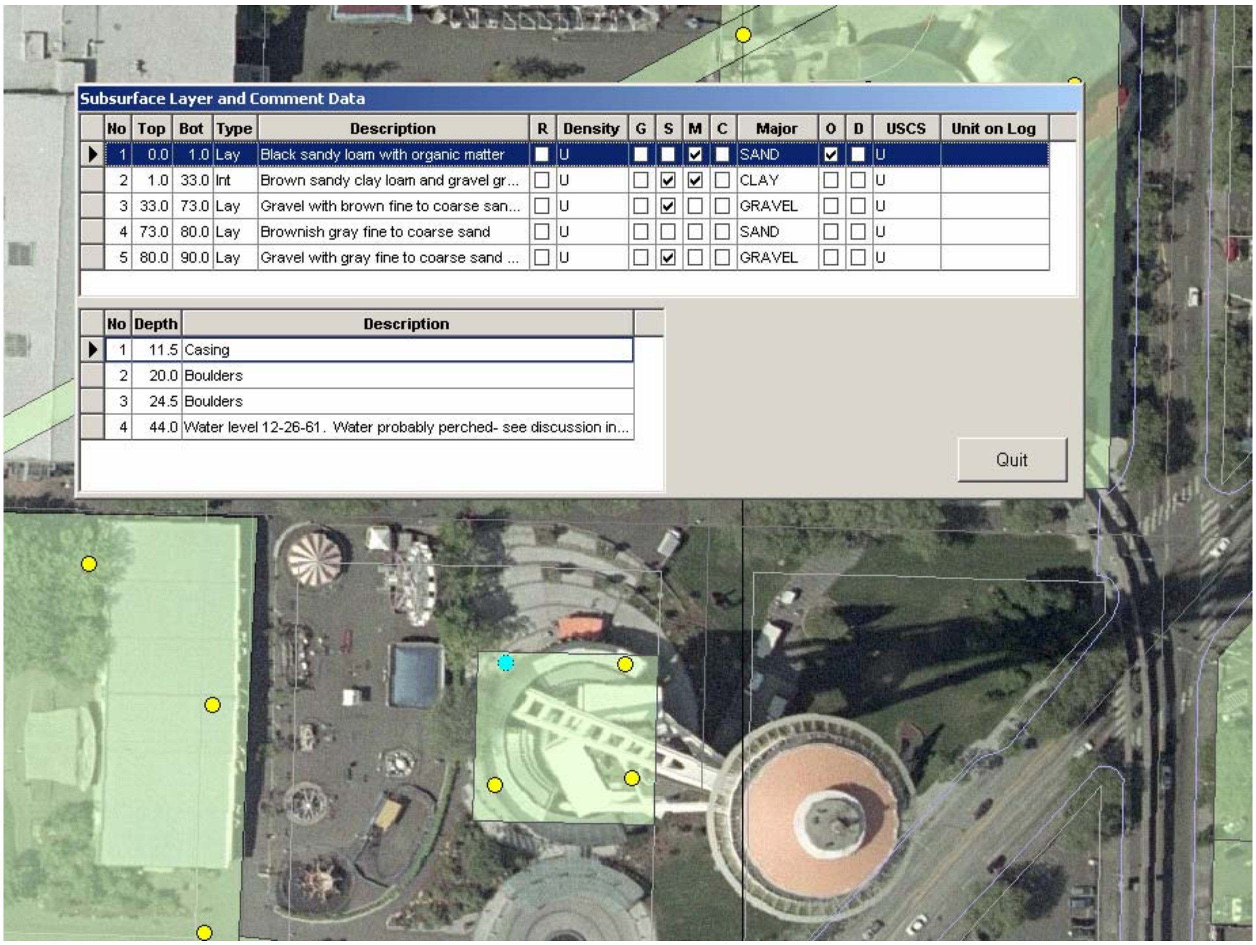
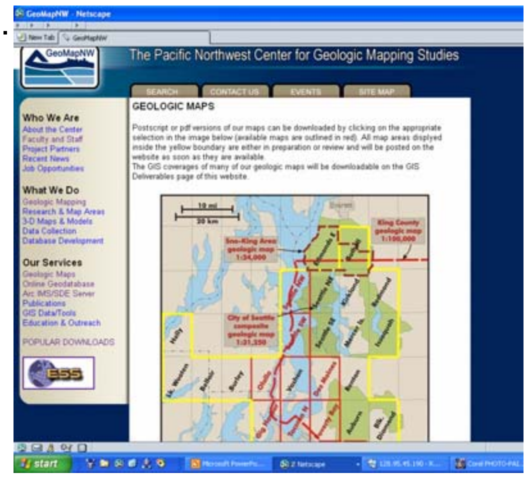


Figure 8. Example of an ArcView data query screen. The base aerial photograph is of the Space Needle; document areas are shaded (green in color online version). Of the four explorations originally drilled for the Space Needle foundation, that in the upper left-hand corner of the Needle footprint (turquoise highlight in online version) has been selected; the pop-up window shows the description of the five geologic layers in the exploration log and the dominant and secondary grain sizes as parsed from the layer description (upper table), and any comments (lower table).

We also provide a point of public access to our data, in part to satisfy our funders’ goal of public data access, and in part to provide a broader service to the geotechnical and engineering community without making undue demands on our time. Access is through the Center website, http://geomapnw.ess.washington.edu (Figure 9a); the most heavily used links are those for downloading of publications and geologic maps (Figure 9b) and for individual queries of the geologic database (Figure 9c and d), for which we upload a static update on a roughly quarterly basis. Typical rates of access for the first half of 2005 have been about 700 unique visits per week, with 75 downloads/week of reports and maps and about 300 queries/week of individual exploration logs. At the continuing request of colleagues in the consulting community, we are in the process of scanning all of our borehole data and posting those scanned images on the web as pdf files. Currently almost two-thirds of our files are scanned and available.

A.

B.



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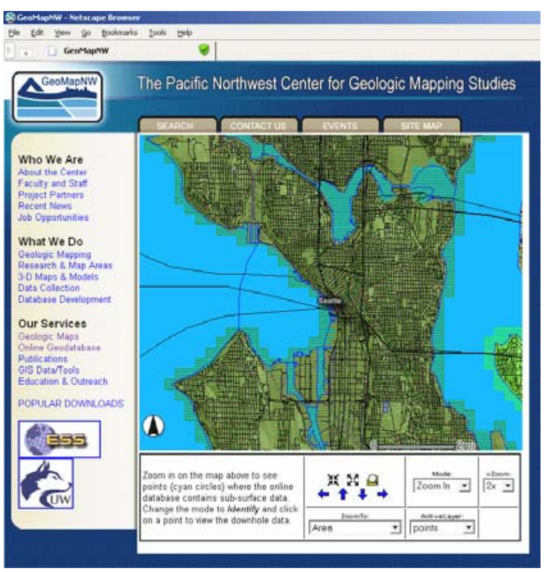
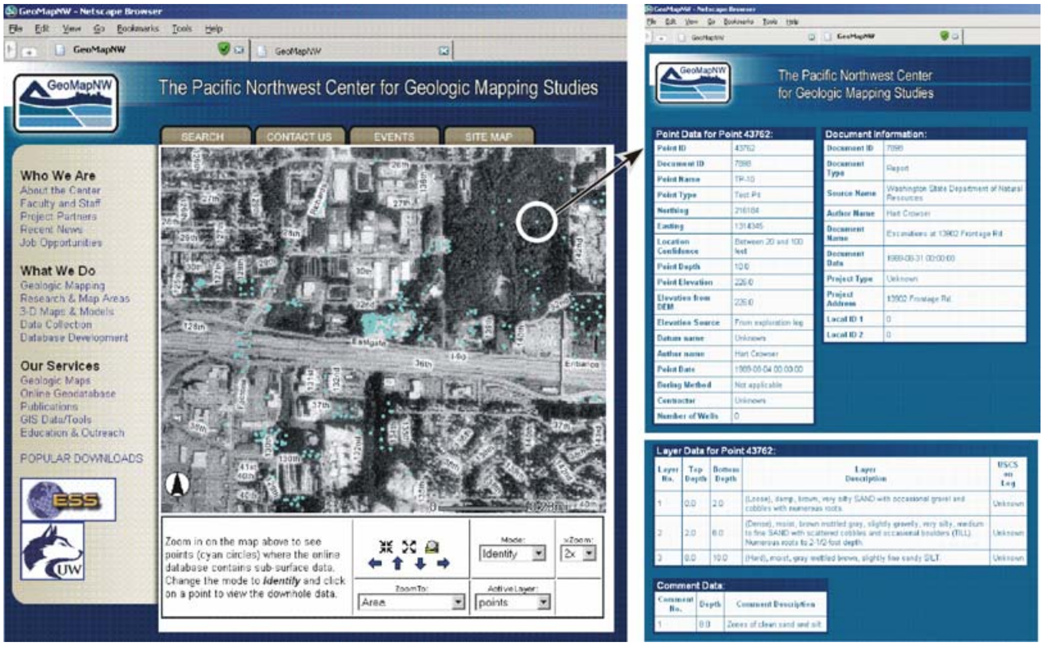


Figure 9. Screenshots of the types of data access available from our website. (A), Center home page (http://geomapnw.ess.washington.edu). (B), view of index screen for downloading geologic maps. Queries for those maps available only in draft form are served in .pdf format from this site directly; queries for those maps that are already published by the USGS are redirected to the corresponding USGS page. (C) view of part of central Seattle in the ArcIMS window used to view and select explorations in map view. Zooming in to a local area (D, below) allows selection of an individual point (highlighted in white circle), which opens windows for the point's layer information and for the metadata on the data point and the source document.

D.



EDUCATION AND TECHNICAL OUTREACH

We have actively participated in and led seminars, field trips, professional short courses, and workshops, to educate the scientific and nontechnical community about the baseline geologic setting of the Seattle and Tacoma areas. This acknowledges a critical emphasis in urban-area geology, namely bridging the gap between research and consulting geology. This is an ongoing effort with steadily increasing attention and influence. It also requires a significant expenditure of time, but one that we feel is critical to the long-term viability and value of our work.

To further support this outreach, a technical advisory group was established early in our first year to enhance communication between this project and the end users of the products, especially consultants and agency representatives. The group’s membership, several dozen in number, emphasizes senior members of the region’s geologic, geotechnical, hydrogeologic, and engineering consulting firms, and also includes representatives from state, city, and local agencies who are both the major users and the major contributors of data.

Our partnerships have permitted the digital archiving of some of the very best data—closely spaced, deep, linear transects of continuously sampled borings—provided by large capital projects. Together with new field mapping and the many additional sites of prior study by both public agencies and private individuals, these data are now starting to provide excellent opportunities to learn about the region’s geology. They are also forming the basis for the new, detailed, large-scale geologic maps of the region’s urban and urbanizing areas that are now being prepared and published.

FUTURE PLANS AND ISSUES

Although the project in its current form has demonstrated the value of detailed data compilation within the framework of regional scientific investigations, the full range of this approach to geospatial data has been explored only modestly. We recognize several additional areas in which this work could expand to the greater benefit of current and future users:

1. Creating a data model for incorporating other types of spatial information, emphasizing widely available base data that is available not only across all of the Puget Lowland but also nationwide.
2. Expanding the existing geologic data compilation, both spatially and thematically, to achieve spatially contiguous coverage over our region of interest and to incorporate geospatial data types not part of our current data model into a relational database structure.
3. Integrating these disparate data types into a single access interface.
4. Expanding how users, both members of the project team and the broader public, can view, query, and analyze the data for scientific, engineering, and educational applications, emphasizing web-accessed map-based interfaces.
5. Developing a systematized approach to data delivery and outreach to known and potential users.
6. Creating new geologic products, particularly subsurface visualizations and 3-D representations of surfaces and stratigraphic layers.

Although these future plans would expand the value of detailed geologic information, the *current* costs of the present effort are already quite substantial: for example, a detailed, digital, USGS-published 7.5' geologic quadrangle map based on new field work and a subsurface database has averaged $250,000 at 1:24,000-scale and about twice that amount at 1:12,000 scale (i.e. across the City of Seattle). Derivative maps are not nearly as expensive, but they too add an incremental expense. In an urban area such as Seattle, the cost of detailed geologic mapping and a subsurface database is more palatable when expressed as a function of population density, with rates of about $1.75 to $2.00 per person (Troost and others, 2005b). Ultimately, however, the value of detailed mapping and geologic data must be quantified wherever we try to initiate or continue support for them. The question we therefore face is whether these new geologic products are worth their cost; and even if they are, can we find funding agencies with the foresight to recognize that value and to bear the expense?

REFERENCES

Armstrong, J.E., Crandell, D.R., Easterbrook, D.J., and Noble, J.B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geological Society of America Bulletin, v. 76, p. 321–330.

Barendregt, R.W., 1995, Paleomagnetic dating methods, in Rutter, N.W., and Catto, N.R., Dating methods for Quaternary deposits: Geological Association of Canada, GEOtext2, 308 p.

Blunt, D.J., Easterbrook, D.J., and Rutter, N.W., 1987, Chronology of Pleistocene sediments in the Puget Lowland, Washington, in Schuster, J.E., editor, Selected papers on the geology of Washington: Washington Division of Geology and Earth Resources Bulletin 77, p. 321-353.

Booth, D.B., K.G. Troost, K.G. and Shimel, S.A., in review a, Geologic map of the Seattle NE quadrangle: U.S. Geological Survey Scientific Investigation Map, scale 1:12,000.

Booth, D.B., Troost, K.G., and Walsh, T.J., in review b, Geologic map of the Issaquah quadrangle: U.S. Geological Survey Scientific Investigation Map, scale 1:24,000.

Booth, D.B., Troost, K.G., and, Shimel, S.A., 2005, Geologic map of northwestern Seattle (part of the Seattle North 7.5' x 15' quadrangle), King County, Washington: U.S. Geological Survey Scientific Investigations Map 2903, 1:12,000 (available at http://pubs.usgs.gov/sim/2005/2903/).

Booth, D.B., Troost, K.G., Clague, J.J., and Waitt, R.B., 2004, The Cordilleran ice sheet: Chapter 2, in Gillespie, A., Porter, S.C., and Atwater, B., eds., The Quaternary Period in the United States: International Union for Quaternary Research, Elsevier Press, p. 17-43.

Cande, S.C., and Kent, D.V., 1995, Revised calibration of the geomagnetic polarity time scale for the late Cretaceous and Cenozoic: J. Geophys. Res., v. 100, p. 6093–6095.

Clague, J.J., Mathewes, R.W., Guilbault, J.P., Hutchinson, I., and Ricketts, B.D., 1997, Pre-Younger Dryas resurgence of the southwestern margin of the Cordilleran ice sheet, British Columbia, Canada: Boreas, v. 26, p. 261–278.

Crandell, D.R., 1963, Surficial geology and geomorphology of the Lake Tapps quadrangle, Washington: U.S. Geological Survey Professional Paper 388-A, 84 p., 2 plates.

Dethier, D.P., Pessl, F., Jr., Keuler, R.F., Balzarini, M.A., and Pevear, D.R., 1995, Late Wisconsinan glaciomarine deposition and isostatic rebound, northern Puget Lowland, Washington: Geological Society of America Bulletin, v. 107, p. 1288–1303.

Easterbrook, D.J., 1986, Stratigraphy and chronology of Quaternary deposits of the Puget Lowland and Olympic Mountains of Washington and the Cascade mountains of Washington and Oregon: Quaternary Science Reviews, v. 5, p. 145-159.

Easterbrook, D.J., 1994, Chronology of pre-late Wisconsin Pleistocene sediments in the Puget Lowland, Washington, *in* Lasmanis, R., and Cheney, E.S., conveners, Regional geology of Washington State: Washington Division of Geology and Earth Resources Bulletin 80, p. 191-206.

Easterbrook, D.J., Briggs, N.D., Westgate, J.A., and Gorton, M.P., 1981, Age of the Salmon Springs glaciation in Washington: Geology, v. 9, no. 2, p. 87-93.

Hagstrum, J.T., Booth, D.B.,, Troost, K.G., and Blakely, R.J., 2002, Magnetostratigraphy, paleomagnetic correlation, and deformation of Pleistocene deposits in the south-central Puget Lowland, Washington: Journal of Geophysical Research–Solid Earth 107 (B4): art. no. 2079, Apr. 10, 2002.

Haugerud, R., 2005, Preliminary geologic map of Bainbridge Island, Washington: U.S. Geological Survey Open-File Report 2005-1387, scale 1:24,000 (available at http://pubs.usgs.gov/of/2005/1387/).

Hicock, S.R., and Armstrong, J.E., 1981, Coquitlam Drift—a pre-Vashon Fraser glacial formation in the Fraser Lowland, British Columbia: Canadian Journal of Earth Sciences, v. 18, p. 1443–1451.

Hicock, S.R., and Armstrong, J.E., 1985, Vashon drift—definition of the formation in the Georgia Depression, southwest British Columbia: Canadian Journal of Earth Sciences, v. 22, p. 748–757.

Kovanen, D.J., 2002, Morphologic and stratigraphic evidence for Allerod and Younger Dryas age glacier fluctuations of the Cordilleran Ice Sheet, British Columbia, Canada, and northwest Washington, U.S.A.: Boreas v. 31, p. 163–184.

Kovanen, D.J., and Easterbrook, D.J., 2001, Late Pleistocene, post-Vashon, alpine glaciation of the Nooksack drainage, North Cascades, Washington: Geological Society of America Bulletin, v. 113, p. 274–288.

Mahan, S.A., Troost, K.G., and Booth, D.B., 2003, Dating sediments older than 100 ka in the Seattle-Tacoma urban corridor: A test for infrared stimulated luminescence and thermoluminescence on fine grain deposits: Geological Society of America, Abstracts with Programs, Annual Meeting, v. 35.

Mankinnen, E.A., and Dalrymple, G.B., 1979, Revised geomagnetic polarity time scale for the interval 0–5 m.y. b.p.: Journal of Geophysical Research, v. 84, p. 615–626.

Mullineaux, D.R., Waldron, H.H., and Rubin, M., 1965, Stratigraphy and chronology of late interglacial and early Vashon time in the Seattle area, Washington: U.S. Geological Survey Bulletin 1194-O, p. O1–O10.

Pessl, F., Jr., Dethier, D.P., Booth, D.B., and Minard, J.P., 1989, Surficial geology of the Port Townsend 1:100,000 quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Map I-1198F.

Porter, S.C., and Swanson, T.W., 1998, Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation: Quaternary Research, v. 50, p. 205–213.

Shackleton, N.J., Berger, A., and Peltier, W.R., 1990, An alternative astronomical calibration of the lower Pleistocene time-scale based on ODP site 677: Transactions of the Royal Society of Edinburgh, Earth Sciences, v. 81, p. 251–261.

Troost, K.G., 1999, The Olympia nonglacial interval in the southcentral Puget Lowland, Washington [M.S. thesis]: Seattle, University of Washington, 123 p.

Troost, K.G., Booth, D.B., and Wells, R.E., in press, Geologic map of the Gig Harbor 7.5-minute quadrangle, Washington: U.S. Geological Survey Scientific Investigation Map, scale 1:24,000.

Troost, K.G., Booth, D.B., and Wisher, A.P., in preparation, Geologic map of the Mercer Island quadrangle: U.S. Geological Survey Scientific Investigation Map, scale 1:24,000.

Troost, K.G., Booth, D.B., Shimel, S.A., Blakely, R.J. , and Wells, R.E., in review a, Geologic map of the Seattle SW quadrangle: U.S. Geological Survey Scientific Investigation Map, scale 1:12,000.

Troost, K.G., Booth, D.B., and Shimel, S.A., in review b, Geologic map of the Seattle SE quadrangle: U.S. Geological Survey Scientific Investigation Map, scale 1:12,000.

Troost, K.G., Booth, D.B., Wisher, A.P., and Shimel, S.A., 2005a, The geologic map of Seattle – a progress report: U.S. Geological Survey Open-File Report 2005-1252, scale 1:24,000 (available at http://pubs.usgs.gov/of/2005/1252/).

Troost, K.G., Booth, D.B., Shimel, S.A., Wisher, A.P., and O'Neal, M., 2005b, Detailed geologic mapping—is it worth the cost? Applications of a geodatabase of the Seattle, Washington area: Geological Society of America, Abstracts with Programs, Annual Meeting, v. 37.

Waldron, H.H., Liesch, B.A., Mullineaux, D.R., and Crandell, D.R., 1962, Preliminary geologic map of Seattle and vicinity, Washington: U.S. Geological Survey Miscellaneous Investigations Map I-354, scale 1:31,680.

REPORTS PUBLISHED

Manuscripts:

Booth, D.B., Troost, K.G., and Hagstrum, J.T., 2004, Deformation of Quaternary strata and its relationship to crustal folds and faults, central Puget Lowland, Washington: Geology, v-32(6).

Booth, D.B., Troost, K.G., S.A. Shimel, M.A. O'Neal, and A. P. Wisher, in press, New geologic mapping and geologic database for the urbanized Puget Lowland, western Washington State, USA: Proceedings, AASG/USGS 2005 Workshop on Digital Mapping Techniques.

Booth, D.B., Wells, R.E., Givler, R., 2004, Chimney damage along the margin of the Seattle Basin during the 2001 Nisqually earthquake; Bulletin of the Seismological Society of America.

Abstracts:

Troost, K.G. and Booth, D.B., 2004, Applications of a Geologic Database of the Greater Seattle Area, Western Washington, Program with Abstracts, 2004 Annual Meeting, Association of Engineering Geologists, Dearborn, Michigan, September 26-October 2, 2004, Changes to Program with Abstracts p. 5.

Troost, K.G., Booth, D.B., Haugerud, R.A., and Barnett, E.A., 2002, Status and findings from 1:24,000 scale geologic mapping in the Puget Lowland, WA: Geological Society of America, Abstracts with Program, vol. 34, no. 5, Cordilleran Section Meeting, Corvallis, OR, May 13-15, 2002.

Troost, K.G., Booth, D.B., Mahan, S.A., and Hagstrum, J.T., 2003, Presence of mid-Pleistocene deposits (MIS4 through 8) in the Tacoma area: Did the Possession glacier make it to Tacoma?: Abstracts with Program, Geological Society of America, Annual Meeting, Seattle, November 2-5, 2003, p. 215.

Troost, K.G., Booth, D.B., O'Neal, M.A., Shimel, S.A., and Wisher, A.P., 2004, Improved aquifer susceptibility and infiltration mapping, Puget Sound, Washington, Abstracts with Program, 2004 Annual Meeting, The Geological Society of America, Denver, Colorado, November 7-10, 2004, p. A-578.

Troost, K.G.; Booth, D.B.; Shimel, S.A.; Frankel, A.D., 2002, Geologic controls on site response and ground failures in Seattle during the 2001 Nisqually earthquake [abstract]: Seismological Research Letters, v. 73, no. 2, p. 214.

Troost, K.G., Booth, D.B., Shimel, S.A., Haugerud, R.A., Kramer, S.L., Kayen, R.E., and Barnhardt, W.A., 2001, Geologic controls on ground failures in Seattle and vicinity during the 2001 Nisqually earthquake, Seismological Research Letters, v. 72, no. 3, p. 393.

Troost, K. G., Booth, Derek B., Shimel, S., Wisher, A, and O'Neal, M., 2005, Detailed geologic mapping—is it worth the cost? Applications of a geodatabase of the Seattle, Washington area: Geological Society of America, Abstracts with Programs, Annual Meeting, v. 37.

Troost, K. G., Booth, Derek B., Shimel, S., Wisher, A, and O'Neal, M., 2005, Is new, detailed 1:12,000-scale geologic mapping worth the cost? Hydrogeologic applications of a geologic database of the Seattle area, Washington: Abstract volume, 5th Symposium on the Hydrogeology of Washington State, Tacoma, Washington, April 12-14, 2005, p. 114.

Troost, K.G., Haugerud, R.A., Walsh, T.J., Harp, E.L., Booth, D.B., Steele, W.P., Wegmann, K.W., Pratt, T.L., Sherrod, B.S., and Kramer, S.L., 2001, Ground failures produced by the Nisqually earthquake, Seismological Research Letters, v. 72, no. 3, p. 396.

Troost, K. G., Johnson, K. H., Booth, Derek B., Ogier, S., and Wisher, A, 2005, Aquifer susceptibility mapping of Vashon-Maury Island, King County, Washington: Abstract volume, 5th Symposium on the Hydrogeology of Washington State, Tacoma, Washington, April 12-14, 2005, p. 113.

Weaver, C. S., Troost, K. G., Booth, D. B., Frankel, A., Wells, R. E., Mullen, J., and Nolan, T., 1999, The Seattle urban seismic hazard mapping project: a USGS contribution to Seattle's Project Impact: Seismological Research Letters, v. 70, no. 2, p. 256.

GEOLOGIC MAPS

Published

Booth, D.B., and Troost, K.G., 2005, Geologic map of the Olalla 7.5-minute quadrangle, Washington: U.S. Geological Survey Scientific Investigations Map 2903, scale 1:24,000.

Booth, D.B., Troost, K.G., and Shimel, S.A., 2005, Geologic map of the Seattle NW quadrangle: U.S. Geological Survey Scientific Investigations Map 2902, scale 1:12,000.

Booth, D.B. and Waldron, H.H., 2004, Geologic map of the Des Moines 7.5-minute quadrangle, Washington: U.S. Geological Survey Scientific Investigations Map 2855, scale 1:24,000.

Booth, D.B., Waldron, H.H. and Troost, K.G., 2004, Geologic map of the Poverty Bay 7.5-minute quadrangle, Washington: U.S. Geological Survey, Scientific Investigations Map 2854, scale 1:24,000.

Troost, K.G., Booth, D.B., Wisher, A.P., and Shimel, S.A., 2005, The geologic map of Seattle: U.S. Geological Survey Open-File Report 2005-1252, scale 1:24,000.

In press/reviews completed

Booth, D.B., and Troost, K.G., in press, Geologic map of the Vashon quadrangle: U.S. Geological Survey Scientific Investigations Map, scale 1:24,000.

Booth, D.B., Troost, K.G., and Shimel, S.A., in press, Geologic map of the Seattle NE quadrangle: U.S. Geological Survey Scientific Investigations Map, scale 1:12,000.

Booth, D.B., Walsh, T.J., and Troost, K.G., in press, Geologic map of the Issaquah quadrangle: U.S. Geological Survey Scientific Investigations Map, scale 1:24,000.

Troost, K.G., in press, Geologic map of the Puyallup 7.5-minute quadrangle, Washington: U.S. Geological Survey Scientific Investigations Map, scale 1:24,000.

Troost, K.G., in press, Geologic map of the Tacoma South 7.5-minute quadrangle, Washington: U.S. Geological Survey Scientific Investigations Map, scale 1:24,000.

Troost, K.G. and Booth, D.B., in press, Geologic map of the Steilacoom 7.5-minute quadrangle, Washington: U.S. Geological Survey Scientific Investigations Map, scale 1:24,000.

Troost, K.G., Booth, D.B., and Borden, R.K., in press, Geologic map of the Tacoma North 7.5-minute quadrangle, Washington: U.S. Geological Survey Scientific Investigations Map, scale 1:24,000.

Troost, K.G., D.B. Booth, S.A. Shimel, R.J. Blakely, and R.E. Wells, in press, Geologic map of the Seattle SW quadrangle: U.S. Geological Survey Scientific Investigation Map, scale 1:12,000.

Troost, K.G., Booth, D.B., and Wells, R.E., in press, Geologic map of the Gig Harbor 7.5-minute quadrangle, Washington: U.S. Geological Survey Scientific Investigations Map, scale 1:24,000.

Troost, K.G., Booth, D.B., Wisher, A.P., and Shimel, S.A., in press, Geologic map of the Seattle SE quadrangle: U.S. Geological Survey Scientific Investigations Map, scale 1:12,000.

In review

Booth, D.B., Haugerud, R.A., and Sacket, J., in review, Geologic map of King County, Washington: U.S. Geological Survey Open-File Report, scale 1:100,000.

In preparation

Troost, K.G., Wisher, A.P., and Booth, D.B., in prep., Geologic map of the Mercer Island quadrangle: U.S. Geological Survey SIM series, scale 1:24,000.

Troost, K.G., Wisher, A.P., Booth, D.B., and Shimel, S.A., in prep, Geologic map of the Kent and Auburn Areas: U.S. Geological Survey Open-File Report, scale 1:24,000.

FINANCIAL NOTE

This project successfully leveraged the contribution of the USGS NEHRP funds at a 3:1 ratio (other:NEHRP) through additional financial and in-kind support from other programs of the USGS and from local governments. Some of that support was used to cover the initial shortfall of funds for the originally scoped NEHRP project (namely, the geologic map of the City of Seattle), some was used to develop the scientific framework for Quaternary geologic investigations in the region (Component 1 of this project), and some was used to expand the geographic scope of the effort into populated areas to the north, south, and east. Funding amounts are tabulated below.

Project Funding 2000-2005:

SOURCE	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*
USGS: NEHRP	$160,000	$170,000	$170,000	$125,000	$100,000	$75,000
USGS: NCGMP	$38,332	$12,450	$31,617	$36,975	$37,425	$25,000
City of Seattle: DCLU	$60,000	$60,000	$60,000	$60,000	$40,000	$30,000
City of Seattle: SPU	$50,000	$25,000	$25,000	$25,000	$25,000	$25,000
King Co. Groundwater			$25,000		$75,000	$82,000
Mercer Island					$50,000	$102,304
City of Bellevue						$50,000
WSDOT						$21,000
King Co. DDES						$20,000
Univ. of WA: CWWS	$20,000	$10,000	$10,000	$10,000	$10,000	
King Co. Wastewater		$327,449	$216,600	$278,420	$100,000	
Seattle Monorail				$20,000	$40,000	
Bainbridge Island					$75,444	
City of Bothell			$15,000			
	$328,332	**$604,899**	**$538,217**	**$555,395**	**$552,869**	**$430,304**

TOTAL PROJECT FUNDS, USGS NEHRP: $ 800,000

TOTAL PROJECT FUNDS, ALL SOURCES: $ 3,010,016