The February 28, 2001 Nisqually earthquake:
GPS Geodesy and quantifying seismic hazard.

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Topic: *Life in the Subduction Zone: The recent Nisqually Earthquake and Federal Efforts to Reduce Earthquake Hazards*

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Tectonic setting of the Nisqually Earthquake:

The February 28, 2001, Mw=6.8 Nisqually earthquake broke within the subducting Juan de Fuca slab, the oceanic plate that is being thrust under the western edge of North America. GPS geodesy can measure Earth deformation at the millimeter level. The Nisqually earthquake was the first in the Pacific Northwest to be detected with GPS geodesy.

There are three types of earthquakes that pose seismic risk in the Pacific Northwest: those, like the Nisqually, that break the down going oceanic plate, those along shallow faults within the North America plate, and the potentially much larger but also less frequent ruptures along the subduction zone fault that separates the two plates. Each of these types has expected characteristic seismic hazard. The deep earthquakes, common during the last century, are strong and widely felt but on the whole less damaging at a particular magnitude because of their depth. Forecasting size and frequency of such earthquakes are perhaps the most difficult using current methods. The potential size and frequency distributions of shallow earthquakes can be much better known as geodetic constraints improve, in studies that are currently underway and planned. Finally, the subduction zone fault poses special hazard, despite its largely offshore location, because the likely magnitude is greater than 8 and may well be close to 9, exceeding even the 1906 San Francisco earthquake and would be comparable in size to the Great 1964 Alaska earthquake. Such earthquakes also generate large tsunamis.

1) How significant were the effects of the Nisqually earthquake on the Puget Sound region? How are these effects assessed?

The Nisqually earthquake was widely felt. Two of the major geologic effects of the earthquake were widespread landslides and liquefaction. The USGS led a major scientific effort that involved members of the academic scientific community to map and assess the damage resulting from these processes. Urban development on unconsolidated materials such as landfill are particularly vulnerable to liquefaction. Developments on unstable hill slopes are most susceptible to landslides.

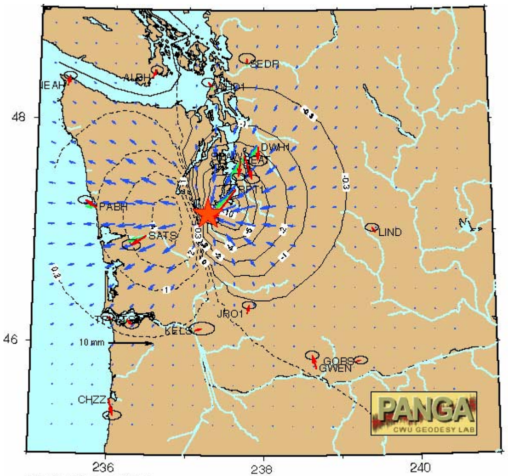
The co-seismic deformation (the change in the position of the ground after the earthquake fault has slipped) that accompanied this earthquake was also significant, and was the first to be observed using continuous GPS geodesy in the Pacific Northwest. These observations give us constraints on the physics of earthquakes and the parameters, such as rigidity, that control how the earth responds to earthquakes. These in turn have implications for seismic risk assessment and planning.

2) To what extent did buildings and land behave differently than expected in this earthquake? To what extent should codes, earthquake preparations and the research agenda be altered as a result?

The Pacific Northwest is recognized as an area where the engineering community has taken seriously the sometimes abstract determinations of the scientific community, and has systematically worked to strengthen seismic zoning in the urban corridor from Seattle, Washington, to Portland, Oregon. Nevertheless, as the body of scientific information continues to grow, this collaboration continues to be important, especially as urban growth places increased pressure on remaining hill slope properties that may not be suitable for development from the standpoint of seismic risk and periods of intense rainfall.

The co-seismic geodetic deformation that we observed in this earthquake was somewhat smaller than we expected from seismic parameters. This pattern has emerged from several recent earthquakes such as large earthquakes in the California desert during the 1990s. This growing database leads us to reassess our working models for earthquake physics.

The national research agenda needs to be strengthened in this area. All the elements from basic research to risk mitigation are the targets of ongoing efforts by the scientific and engineering communities. As new advances in geodesy (such as GPS and strain meters) and seismology become available, responsive federal support is needed to implement state of the art research programs.

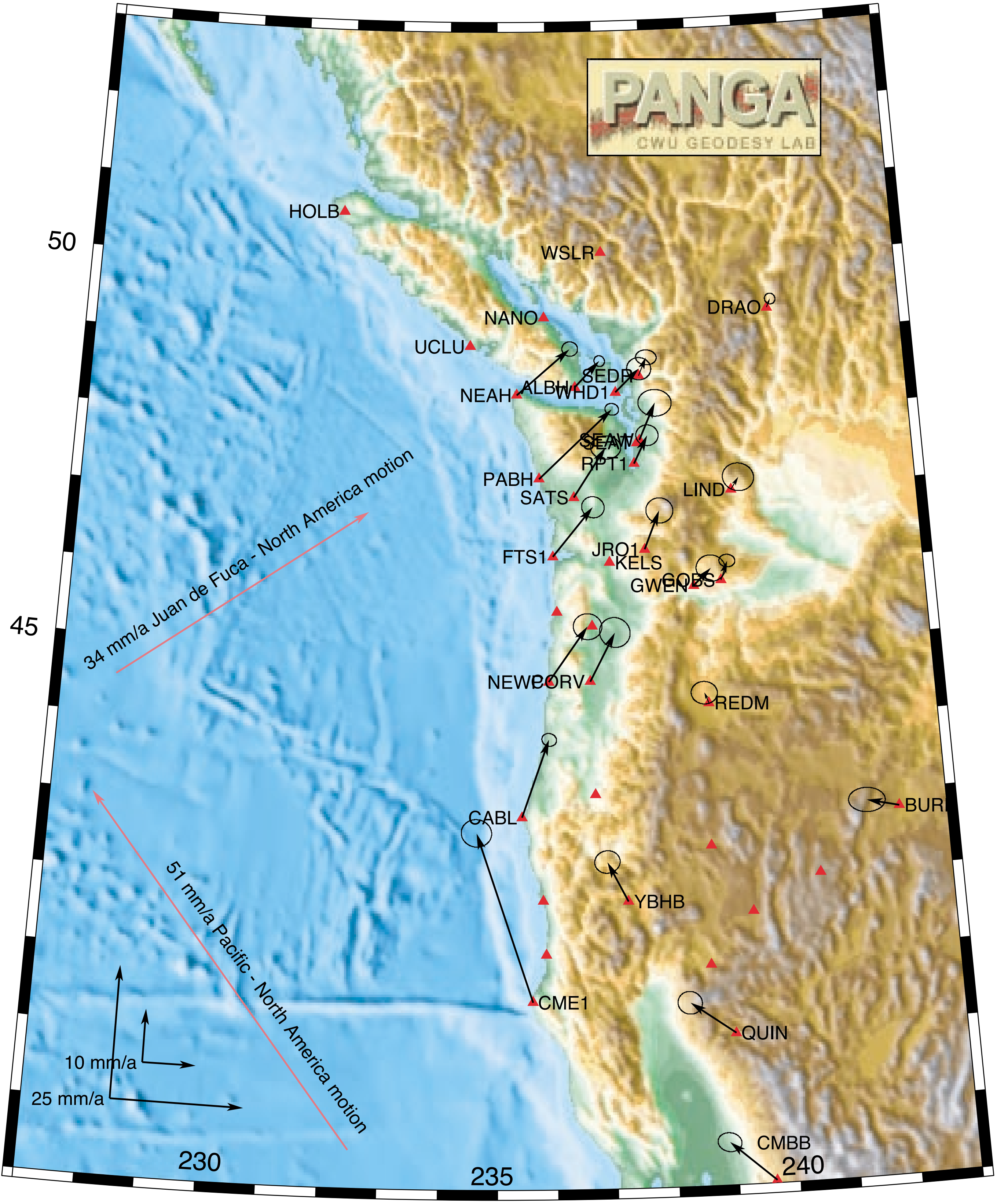


Model Parameters:
30 km strike length, 1.1 m displacement, depth 52.4 km
Mw = 6.8, Strike 347°, dip 77° east, slip -104
Blue & green arrows show predicted surface displacements
Red arrows show geodetic observations by PANGA

Preliminary dislocation model for the February 28, 2001, M=6.8 Nisqually earthquake.
Developed by Kenneth E. Austin and M. Meghan Miller using 3ddef code from Gomberg and Ellis [1994]. Contours show uplift in mm.

3) What is the current depth of our understanding about earthquakes in the Pacific Northwest and elsewhere, and where should we focus future research efforts.

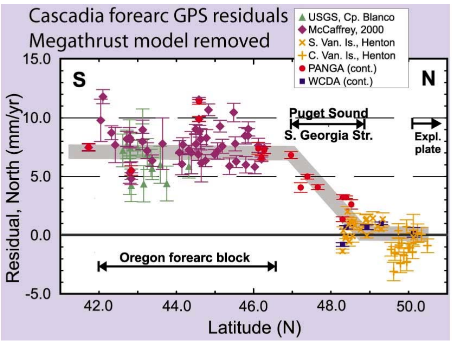
The last decade has been a period of great vitality in Pacific Northwest active tectonics research. New technology and new geologic approaches have rap-



GPS-determined velocity field, Pacific Northwest Geodetic Array (PANGA). This velocity field is plotted relative to North America, as defined by 11 GPS stations in the continental interior and Atlantic passive margin. Two to six years of data from continuously operating GPS stations yield PANGA station velocities; red triangle without velocities show stations with time series less than two years. Error ellipses show two-dimensional 95% confidence regions. Seafloor topography from Smith and Sandwell [1997]. From Miller et al., 2001.

idly advanced our understanding, yet a tremendous amount of work remains to be done in order to quantify the regional seismic hazard.

Several factors concentrate Pacific Northwest seismic hazard in the Puget Sound and Olympic Peninsula region. Seismicity along deep faults such as the Nisqually earthquake fault, and along shallow faults in the Puget Lowlands, is regionally concentrated in this area. This is a result of arching of the slab underneath western Washington, where it is breaking up in response to this arching. Earthquakes on the shallower faults result from a concentration of north-south shortening as the Oregon-southern Washington coastal block drives into Vancouver Island and is absorbed through earthquake faulting. Finally the locked or seismogenic part of the subduction zone fault is very wide under western Washington, implying greater energy release in that area during infrequent but great earthquakes.



The northward migration of central Oregon results compression across Puget Sound. This creates shallow crustal faults.

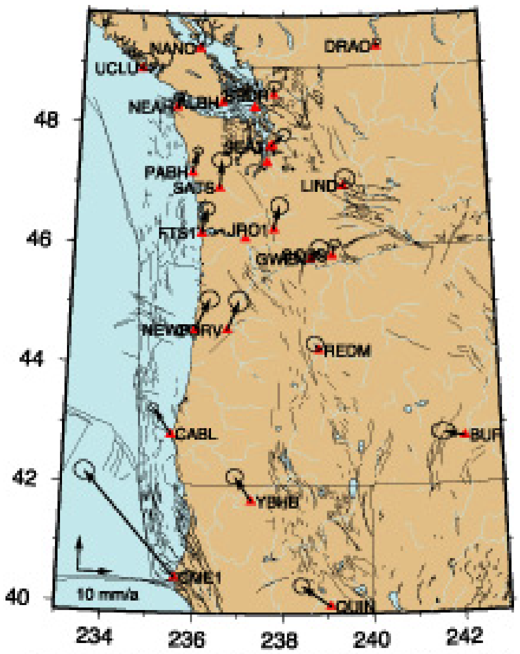
Advancing Seismic Risk Assessment and Hazards Planning in Puget Sound:

GPS geodesy demonstrates that the coastal region from central Oregon to central Washington is a coherent block that is driving into a rigid backstop, Vancouver Island. Approximately 5 mm (about one quarter of an inch) of shortening occurs each year across the Olympic Mountains and Puget Sound. This background deformation will ultimately be released through earthquakes and related processes. The deformation is similar in magnitude to the annual shortening across the Los Angeles Basin. The Seattle fault, oriented east-west under West Seattle, is the strongest among several candidates for carrying much of this deformation and could rupture in an earthquake at least as large as magnitude 7.5, or in more numerous smaller events. Because of its proximity to urban corridor, such events could rival or exceed the Northridge earthquake for damage and casualties.

Seattle ought not to be lulled into a false sense of security, having sustained so little damage in the Mw 6.8 Nisqually earthquake. The depth of this earthquake greatly reduced the amplitude of shaking experienced in the metropolitan region. A shallow event of that size, or larger, which is expected on the shallow faults, would not be so kind to the older buildings and perhaps modern structures throughout the urban area.

Denser distribution of continuous GPS stations in the Puget Lowlands will characterize which faults pose seismic hazard. The GPS-determined parameters have a direct impact on seismic zoning and building code development: How much strain is accumulating? Where it is accumulating? Which faults are being loaded with seismic deformation? How wide are the down-dip rupture patches on shallow faults? These findings will constrain the likely size, location, and frequency of earthquakes on active faults in Puget Sound. Because the Seattle, Tacoma Narrows, Southern Whidbey Island and other similar faults are shallow (likely seismic sources at 10 - 15 km depth), they pose much graver seismic risk than the fault ruptured in the Nisqually earthquake.

Mitigation strategies, community preparedness, and response planning depend on the accuracy of fault parameter determinations. GPS geodesy is a new technology that is rapidly advancing our ability to set scientific constraints on these parameters.



Using a computer model to remove the annual effects of subduction zone deformation, these residual vectors show how the rigid block that makes up coastal Oregon and southern Washington is driving into Vancouver Island. This results in shallow faults localized in Puget Sound and the Olympic Peninsula.

GPS geodesy and the Nisqually earthquake:

Central Washington University received NSF support to densify the PANGA continuous GPS network in the Puget Lowlands in order to address critical questions regarding the Nisqually earthquake and future Pacific Northwest earthquakes. Partners in this effort include the Southern California Earthquake Center, the U.S. Geological Survey, and UNAVCO (the University NAVSTAR Consortium).

1. How is the budget of north-south shortening (5 mm) that accumulates each year between coastal central Washington and Vancouver Island relieved? The budget is comparable in size to that across the Los Angeles Basin. Should we expect a flurry of earthquakes on the Seattle, Tacoma Narrows or Whidbey Island fault, like those in the last 15 years in Los Angeles which followed a long period of dormancy?
2. Is the series of deep earthquakes recorded in 1939, 1946 and 1949 a typical sequence? Are we entering another period of such events, beginning with the 1999 Grays Harbor and the 2001 Nisqually earthquakes, to be followed by some near-term future event(s)?
3. Do earthquakes relieve all of the strain in the Puget Lowlands or do other processes play a role?
4. Can these deep earthquakes and trigger earthquakes on shallow faults, as suggested by recent patterns of earthquakes in southern Alaska and El Salvador? The December 1999 Kodiak earthquake is similar to the Nisqually earthquake in that both ruptured the slab although the style of faulting is different . The January 2001 El Salvador event is probably more similar to the Seattle event, but with about 3 times the energy release. That earthquake was also followed by a complex aftershock sequence that included faulting in the upper plate. It is clear from the Kodiak and El Salvador examples that these slab events can be followed by aftershocks or triggered events in the upper plate. This may

be explained by static stress changes, or by patterns of deformation that are temporarily perturbed after such a large earthquake.

Nisqually earthquake response deployment:

We have undertaken an immediate deployment of seven continuous GPS stations in the Puget Lowlands in order to quantify the distribution of slip on active faults in the metropolitan region. We currently have four teams in the field finding suitable sites for installation, negotiating permits, and making the installations. These seven stations will add to the more widely spaced existing network of 40 stations, which spans the region from northern California to the international border, and from the coast as far east as Idaho and Nevada.

PANGA (the Pacific Northwest Geodetic Array)

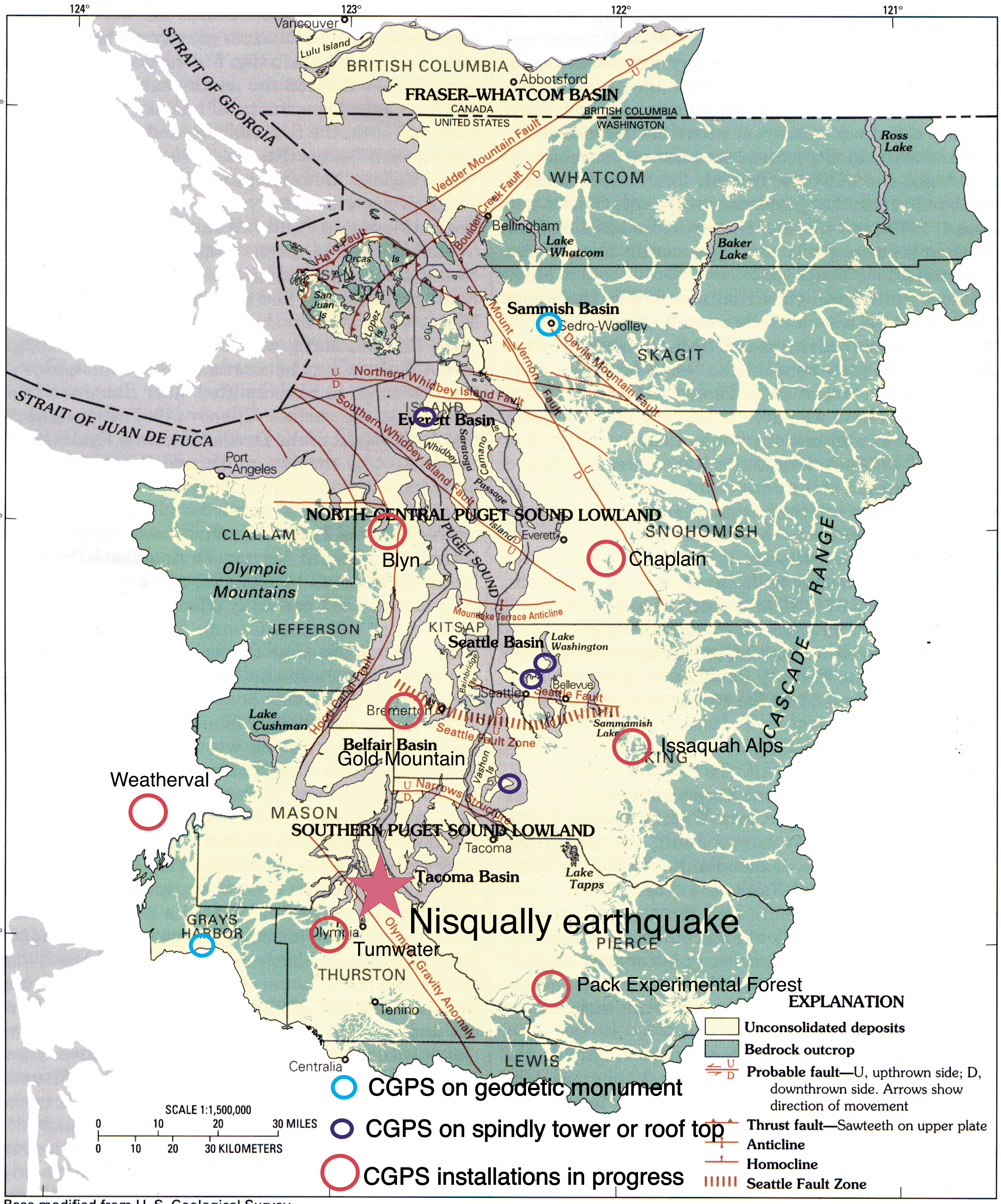
The Pacific Northwest Geodetic Array (PANGA) is an international consortium of institutions committed to using continuous GPS geodesy to further understanding of Earth deformation in the Pacific Northwest, including seismic hazard assessment. Central Washington University coordinates PANGA. Institutions that participate in funded PANGA projects include Central Washington University, the Geological Survey of Canada, the U.S. Geological Survey, University of Washington, University of Oregon, Oregon State University, and University of Alaska. Many other academic institutions and government agencies participate in annual PANGA Investigator Community Meetings. Data analysis is performed at the PANGA Data Analysis Facility in the Geodesy Laboratory at Central Washington University, an NSF facility.

The core projects that have established PANGA and supported the PANGA Data Analysis Facility at Central Washington University since 1997 have been funded by the National Science Foundation, through the Earth Sciences Research programs. Supplementary funding has come from the U.S. Geological Survey – National Earthquake Hazards Research Program (External Research), the National Aeronautics and Space Administration, and private gifts from Sun Microsystems.

Translating Scientific Results into Benefits to Society:

An essential element of long-term earthquake hazard mitigation is the establishment and refinement of hazard maps. The data from these GPS stations will be used as input to probabilistic seismic hazard analysis to refine future versions of these hazard maps. By better defining areas most susceptible to strong shaking, future land use planning can take this into account, thereby improving seismic risk mitigation in this rapidly developing urban and suburban region. Furthermore, data from the PANGA network will rapidly provide earthquake information that will be useful to emergency responders, helping them to target and prioritize their response efforts.

Precise location data provided by GPS is of much broader utility than PANGA’s scientific goals. This network of GPS base stations will be widely used by federal, state, county, city and private parties for routine surveying applications. These uses support damage reparations, landslide and liquefaction mapping, road repair, life line and damage mapping and reparation, GIS applications for urban and seismic planning in-



Base modified from U. S. Geological Survey
digital data, 1:2,000,000, 1972

Nisqually earthquake response continuous GPS site installations. The stations are constrained to be on bedrock from the standpoint of monument design. Bedrock map from M. A. Jones, USGS Professional Paper 1424-C. (map updated 3/18/01 8:15 a.m.)

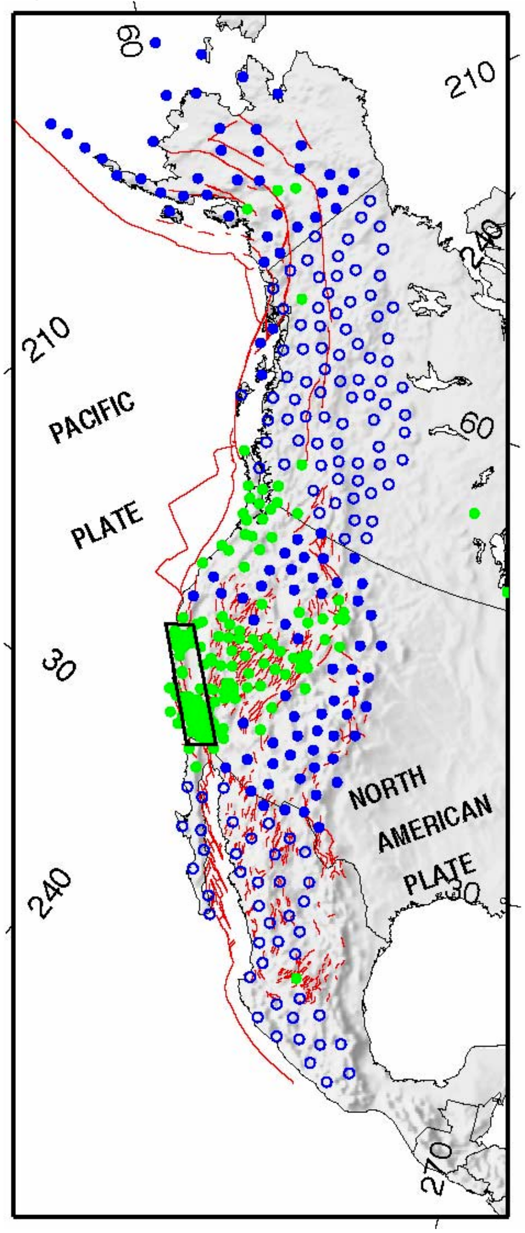
cluding HAZUS, road reparations and hill slope stability planning, and other geotechnical needs directly related to mitigation.

The Future: Earthscope

The existing PANGA network, as well as its in-progress enhancement following the Nisqually earthquake, forms a critical first step towards understanding the processes that cause earthquakes in the Pacific Northwest. The nascent GPS technology promises enormous results if implemented more broadly. Each time the scientific community has attempted to learn something about how the Earth deforms using GPS as a tool, we discover far more than we set out to measure and we must reformulate the questions in light of results that exceed our expectations. The Earth is a complex and intriguing laboratory, sometimes messy, but always rewarding. GPS is an unprecedented tool for characterizing the Earth's dynamics.

The scientific community is poised to expand these observations in a manner that will support a systematic accounting of seismic hazard in many vulnerable states: through the Earthscope initiative. This initiative from the scientific community has NSF's National Science Board approval and is awaiting congressional support. It is a multi-agency collaboration between the NSF, USGS, NASA, and DOE.

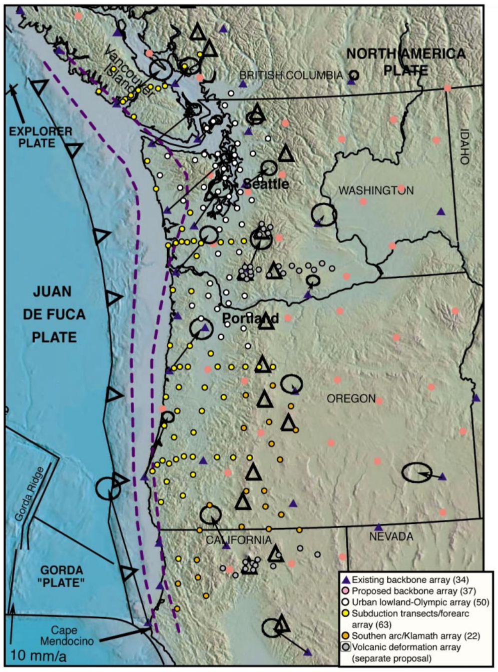
PANGA is one of a few continuous GPS networks in the western United States. The scientific community has recognized the potential synergy of combining GPS observations throughout the country, with concentrated "clusters" of geodetic instrumentation in areas that are known to experience many earthquakes. This planned Earthscope network, termed the Plate Boundary Observatory or PBO, has three levels of deployment: (1) a sparse network of GPS stations that covers the stable continental interior and provides key constraint for understanding the deforming regions, (2) a backbone of GPS stations through all the areas from the Rocky Mountain westward at 200 km spacing to provide even, systematic characterization of the active mountain building regions, and (3) clusters that focus on



Earthscope PBO backbone network

areas where deformation is caused by either earthquake faulting or volcanic activity occur. The Pacific Northwest has been targeted for such clusters that will constrain earthquake faulting and volcano deformation.

The PBO is one of several components of Earthscope. It provides a perspective that is unique among the elements of Earthscope, setting seismological and other observations within the context of how the Earth deforms through time. Together the elements of Earthscope provide a state of the art characterization of the actively deforming continent on which we live.



Cascadia GPS Cluster proposed for Earthscope.

International Aspects and Global Uniqueness of Earthscope

Earthscope has two international components: (1) partnerships with Canada and Mexico and (2) similar initiatives in Japan and Taiwan. The scientific community is committed to developing international partnerships with Canada and Mexico that would complete the picture of the deforming continent beyond our national boundaries.

Japan has implemented a similar project of 1000 GPS sites within their small country. The U.S. has provided scientific expertise to this project. In the wake of the 1999 Chi-Chi earthquake, Taiwan is planning to implement a PBO modeled after the U. S. plan, and is seeking the experience and expertise of our scientific community to support this effort.

The U.S. scientific community is poised to implement the Earthscope initiative that would provide urgently needed observations on a global scale. The investigator community is very strong, and practiced in interdisciplinary studies. Furthermore, we dwell on a varied active plate boundary that includes microcosms of each of Earth’s major tectonic environments: subduction zones of two important types in Cascadia and Alaska, a the textbook example of a transform boundary in the San Andreas fault, and rifting by extension in the Great Basin of Nevada, Utah, and adjacent states. No similar projects boast this wealth of tectonic environments.

Summary

Because of dramatic growth in our understanding of seismicity in the Pacific Northwest over the last decade or more, scientists were not surprised by the February 28, 2001, Mw = 6.8 Nisqually earthquake. Continued integration of scientific results into urban planning and risk mitigation requires enhanced support for the new technologies that can help scientists map the likely locations, size and frequency of future earthquakes on shallower faults, which pose much more serious risk to life and property.

Recent technological advances include the use of GPS to study how the planet Earth's tectonic plates deform in real time. With NSF, NASA, USGS, and Sun Microsystems support, the Pacific Northwest Geodetic Array (PANGA) has piloted applications of this technology in the Pacific Northwest. PANGA has responded to the Nisqually earthquake by initiating installation of seven new stations in the Puget Lowlands region. This has been undertaken with NSF support and in partnership with the geodetic investigator community including the Southern California Earthquake Center, UNAVCO, and the U.S. Geological Survey.

The scientific community is poised to dramatically extend our knowledge base by implementing these technologies at an unprecedented scale in the planned projects that make up Earthscope, which has been approved by the National Science Board. Through Earthscope, the scientific community will provide meaningful constraints for urban planning and emergency response measures, in addition to advancing our basic research in the areas of earthquake physics, the physics of deforming volcanoes, and the forces that drive plate tectonics and mountain building within the continents.

Recommendation:

Federal funding of earthquake sciences needs to be strengthened to support the growth of technology such as GPS geodesy. This includes Earthscope, which has been approved by the National Science Board, funding to earthquake response agencies, and basic research initiatives implemented through the research programs of the NSF.