NEHRP
Final Technical Report: Project 00HQGR0056

1. Regional Panel Designation: PN

2. Project Title: Enhancing PANGA for Seismic Risk Assessment: Collaborative Research Central Washington University, Oregon State University, and University of Washington.

3. Principal Investigator:

Chris Goldfinger (PI)
COAS
Oregon State University
104 Ocean Admin Bldg.
Corvallis, OR 97331-5503
(541) 737-5214
(541) 737-2064 (fax)
email: gold@oce.orst.edu

4. Authorized Institutional Representatives:

Mark A. Abbott, Dean of College of Oceanic and Atmospheric Sciences
(541) 737-5195, (541) 737-2064 Fax
email gbd@oce.orst.edu
Wilson C. Hayes, Vice Provost for Research
Oregon State University
(541) 737-3437, (541) 737-3093 Fax
wilson.hayes@orst.edu

5. Element Designation: Elements I, II

6. Key Words: GPS-Continuous, Regional Modeling, Neotectonics, Seismotectonics

7. Amount Funded: FY 2000: $ 20,000

8. Proposed Start Date: May. 1, 2000

9. Duration: 12 months

Abstract

Final Technical Report: Project 00HQGR0056

Project Title: Enhancing PANGA for Seismic Risk Assessment: Collaborative Research Central Washington University, Oregon State University, and University of Washington.

Principal Investigator:
Chris Goldfinger (PI)
COAS
Oregon State University
104 Ocean Admin Bldg.
Corvallis, OR 97331-5503
(541) 737-5214
(541) 737-2064 (fax)
email: gold@oce.orst.edu

The primary goal of PANGA is to measure deformation that will constrain the kinematics and dynamics of continental lithosphere and the forces that drive it, using integrated GPS geodetic, geologic and geophysical studies of lithospheric behavior. This PANGA project focuses on seismic risk assessment in the urban corridor of the Puget-Willamette lowland. Detailed evaluation of the map pattern of interplate coupling, particularly in northwestern Oregon and southwestern Washington, will directly address strain accumulation in those parts of the forearc that affect seismic hazards in the Seattle and Portland metropolitan areas.

The 2000 meeting was held in Corvallis at Oregon State University, Chaired by Chris Goldfinger. The list of participants is included below. This project supported travel and lodging for some of the participants. Organization was assisted by staff at Oregon State University, supported by this project.

Under NEHRP funding, which was considerably reduced from that requested, three operations were conducted: The Panga Annual Meeting; Routing operation of two permanent sites; and a field campaign.

The 2000 PANGA Annual meeting was held in Corvallis at Oregon State University, Chaired by Chris Goldfinger. The list of participants is included below. This project supported travel and lodging for some of the participants. Organization was assisted by staff at Oregon State University, supported by this project. One highly productive outcome of this workshop was a PANGA science plan for the upcoming Plate Boundary Observatory component of the Earthscope project. This plan is incorportated into the current Earthscope proposal, currently on the President's desk for signature (as of April 2002). This proposal may support as many as 50 continuous GPS sites in the Pacific Northwest to be installed over the next several years.

Two permanent stations on Oregon, at Newport and Corvallis were supported by NEHRP funding under this award.

The Corvallis and Newport continuous sites were operated through FY 2000 without significant problems. The two stations had new UNAVCO radomes installed, and other normal maintenance including firmware upgrades. The data are and site logs are now available from the Active Tectonics web site at http://coas.activetectonics.oregonstate.edu. The Newport site was reconfigured to log data at 1 Hz for June as part of a Scripps seafloor Geodesy experiment by David Chadwell and John Hildebrandt.

In FY 2000, we decided to use what funds were anticipated to remain after normal network maintenance was anticipated and station upgrades performed to augment NSF funds to run an unscheduled campaign in Oregon. Previous recent results strongly suggested that eastern Oregon was rotating about a pole along the eastern Oregon-eastern Washington border. Sparse data east of the Cascades did not allow

definition of this block with any detail however. Piggybacking on an existing NSF project, we ran a campaign and occupied 120 sites covering 2/3 of Oregon.

SIGNIFICANCE OF THE PROJECT

Comparison of subduction zones around the world first focused attention on the great seismic potential of the Cascadia subduction zone (Figure 1) [Heaton and Kanamori, 1984]. Since this suggestion, many geologic studies have provided local evidence for the occurrence of great earthquakes along the plate boundary (e.g., Atwater, 1987; Atwater, 1992; Atwater and Yamaguchi, 1991; Darienzo, 1990], and crustal faults within the deforming continental plate margin. PANGA, the Pacific Northwest Geodetic Array, provides first order constraints on the distribution and processes of active deformation in the Pacific Northwest, using a permanent array of Global Positioning System (GPS) receivers. The paleoseismologic work has characterized past great earthquakes, and continues to refine this important line of evidence. The current strain field in Cascadia will tell us about the coming event. GPS (and other conventional geodetic techniques) measures accumulation of elastic strain above the Cascadia subduction zone as a monitor of subduction zone dynamics. Additionally, GPS also records details of Pacific-North America plate margin deformation accompanied by crustal faulting across the arc and back-arc region. Together with sister permanent GPS arrays throughout the circum-Pacific, PANGA provides high precision resolution of crustal kinematics at unprecedented temporal scales that are simply not achievable using conventional geodesy [Bock et al., 1997; Donnellan and Webb, 1998; Heflin et al., 1998; Miller et al., 1998; Wdowinski et al., 1997]. These studies present strong evidence of rapid surface motions and temporally variable deformation rates that have not been detected by any other means, although the continuous GPS measurements are broadly confirmed by INSAR and VLBI results (e.g., Massonnet et al., 1996; Murakami et al., 1996; Ozawa et al., 1997). GPS surface velocities can be used to constrain seismic hazards associated with large crustal and plate boundary faults. In a subduction system such as Cascadia, coupling between the slab and upper plate generate surface displacements (horizontal and vertical) in the upper plate measurable with GPS. The velocity field in the upper plate is a first order indicator of the coupling processes on the megathrust. The details of whether this interaction is elastic, visco-elastic, or some other rheologic type are not entirely known, however the efficacy of using surface velocities to model plate interactions is well accepted. In general, coupling along the megathrust produces a bulge of vertical displacement centered over the downdip end of the coupled zone. Horizontal velocities also have a peak that lags behind (trenchward of) the vertical peak. We can use both the vertical and horizontal surface displacements as recorded by GPS to model the location of the coupled interface, using elastic and visco-elastic modeling techniques. The ability to establish the map pattern of interplate coupling is revolutionizing the analysis of hazards from the Cascadia plate interface in the Pacific Northwest. These models, in coming years, will allow much more realistic analysis of scenario earthquakes, which presently are modeled in a highly subjective way. With established likely source zones, planners and engineers will be able to model site, local, basin and regional ground responses in urban areas in a meaningful way that is simply out of reach at present. Tsunami modelers will likewise be able to improve tsunami hazard analysis with a better model for the source of strain release.

The primary goal of PANGA is to measure deformation that will constrain the kinematics and dynamics of continental lithosphere and the forces that drive it, using integrated GPS geodetic, geologic and geophysical studies of lithospheric behavior. This PANGA project focuses on seismic risk assessment in the urban corridor of the Puget-Willamette lowland. Detailed evaluation of the map pattern of interplate coupling, particularly in northwestern Oregon and southwestern Washington, will directly address strain accumulation in those parts of the forearc that affect seismic hazards in the Seattle and Portland metropolitan areas.

PANGA Meeting and Workshop

As the GPS velocity estimates mature, other workers will model PANGA results under the umbrella of NEHRP and other funding sources, as part of companion proposals to this one and as part of future initiatives. To date, this growing PANGA community has had six annual. Until 1998 these meetings have not been funded, and have necessarily been short (1 day) workshops focused on coordination. As resources have become available to this community, the need for a longer (2 or 3 day) meeting with sessions on site prioritization, evolving design standards, maintenance and operations issues, presentation of results, and plans for future monitoring and modeling efforts is increasingly necessary. Since 1998 these meetings have been funded by NEHRP.

The 2000 meeting was held in Corvallis at Oregon State University, Chaired by Chris Goldfinger. The list of participants is included below. This project supported travel and lodging for some of the participants. Organization was assisted by staff at Oregon State University, supported by this project.

One highly productive outcome of this workshop was a PANGA science plan for the upcoming Plate Boundary Observatory component of the Earthscope project. This plan is incorportated into the current Earthscope proposal, currently on the President's desk for signature (as of April 2002). This proposal may support as many as 50 continuous GPS sites in the Pacific Northwest to be installed over the next several years.

CORV and NEWP Station Operation, Data Collection, Processing and Archiving

Two permanent stations on Oregon, at Newport and Corvallis were supported by NEHRP funding under this award. The two stations had new UNAVCO radomes installed, and other normal maintenance including firmware upgrades. The data are and site logs are now available from the Active Tectonics web site at http://coas.activetectonics.oregonstate.edu The data are downloaded rinexed and archived daily, and are available to other institutions and the public 24 hours after collection. The data are routinely downloaded by NOAA, NGS, other PANGA members, and by Unavco and Scripps, where they are also archived.
The results of 2000 operations of the two permanent stations operated under NEHRP funding were reported at the 2000 PANGA meeting in October, 2000 at Oregon State University, and at the San Francisco Fall AGU meeting. The CORS data were combined with campaign data and older USGS data to produce an updated and much more extensive (than in 1999) velocity field for the central Oregon study corridor. Data processing was done by R. McCaffrey. Elastic dislocation models and a joint inversion for the pole of rotation were done from the 1992-1999 velocity field. The results of that modeling were reported in a GRL paper listed below.

The Newport site was reconfigured to log data at 1 Hz for June as part of a Scripps seafloor Geodesy experiment by David Chadwell and John Hildebrandt.

FY 2000 Field Campaign

In FY 2000, we decided to use what funds were anticipated to remain after normal network maintenance was anticipated and station upgrades performed to augment NSF funds to run an unscheduled campaign in Oregon. Recent results strongly suggested that eastern Oregon was rotating about a pole along the eastern Oregon-eastern Washington border. Sparse data east of the Cascades did not allow definition of this block with any detail however. Piggybacking on an existing NSF project, we ran a campaign with the following objectives and preliminary results.

Objectives:

-- Densifying network on the Oregon rotating block
-- Test the rigidity of the block
-- Identifying block boundaries and sites of internal deformation

Field Campaign:

-- 120 sites occupied, 8 teams using 9 receivers over three weeks covering 2/3 of Oregon
-- Average occupation time > 20 hours
-- 10 new sites installed or HARN/USGS sites replaced

Appendix A Publications

R. McCaffrey, M. Long, C. Goldfinger, J. Nabelek, C. Johnson, P. Zwick and C. Smith, 2000, Rotation and plate locking at the southern Cascadia subduction zone v. 27, p. p. 3117-3120

Rotation and Plate Locking along the Central
Cascadia Subduction Zone - An Update
PANGA Annual Meeting
Oregon State University
Corvallis, Oregon State University
October, 2000

Chris Goldfinger
College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis OR

McCaffrey et al (2000) use Global Positioning System and surface tilt measurements to simultaneously invert for both secular plate motion relative to stable North America and elastic plate locking on the central Cascadia subduction interface. GPS measurements are from campaign and continuous measurements made between 1996 and 1999 by RPI and OSU, and incorporate campaign measurements between 1992 and 1998 by the US Geological Survey, Cascades Volcano Observatory, and the National Geodetic Survey.

McCaffrey et al. (2000) calculate a rotation pole for stations east of the Cascades, which approximate a rigid body rotation, and where plate locking is assumed to be negligible. The simultaneous inversion calculates the rotation pole and best-fitting coupling model through many iterations to minimize misfit. The rotation is then applied to all of Oregon. McCaffrey et al. (2000) infer that clockwise rotation of a relatively rigid Oregon block may be driven by collapse of the Basin and Range, the northward migration of the Sierra Nevada block, and resisted by shortening in NW Washington State. The rotation pole lies along the Olympic–Wallowa lineament and explains the predominance of extension south of the pole and contraction north of it. The rotation pole is in good agreement with that proposed by Wells et al. (1998) based on geologic and paleomagnetic evidence. The collision with a weaker western Washington is supported by both seismicity and observed contractional structures in the Puget Willamette lowland. The rotation about a pole in eastern Oregon can also explain the "fanning" of the fold axes of the Yakima fold belt. These active folds are responding to north-south compression, but also fan westward in map view. The fold axes project to a convergence at the computed Oregon rotation pole, consistent with the predicted strain field.
Plate locking at the Cascadia thrust is anomalous in that the model resolves two coupled zones, one offshore, and a second deep zone beneath the western Cascades. While the existence of deeper coupling may not be real, the model tries to resolve anomalous east velocities observed in the western Cascades in this way. In the Puget-Willamette lowland, little east component is observed. The anomalous western Cascades vectors could represent dextral shear along the Cascade Arc (not incorporated in the model) or other crustal deformation superimposed on a deep viscous coupling signal. More observations are needed in the Western Cascades to verify and characterize the velocity field in this area.

Appendix B

PANGA 2000 Meeting Participants

Name	affiliation	email
Chris Goldfinger	Oregon State University	gold@oce.orst.edu
Joel Johnson	Oregon State University	jjohnson@oce.orst.edu
Meghan Miller	Central Washington University	meghan@geology.cwu.edu

William Elliot	Oregon Seismic Safety Commission	elliottllc@earthlink.net
Sean Gulick	University of Texas Institute for Geophysics	sean@ig.utexas.edu
Andrew Meigs	Oregon State University	meigsa@geo.orst.edu
John Oldow	Univeristy of Idaho	oldow@uidaho.edu
Herb Dragert	Pacific Geoscience Centre	dragert@pgc.nrcan.gc.ca
Sean Willett	University of Washington	swillett@u.washington.edu
Roy Hyndman	Pacific Geoscience Centre	hyndman@pgc.nrcan.gc.ca
Ian Madin	DOGAMI	Ian.P.Madin@state.or.us
George Priest	DOGAMI	george.priest@dogami.state.or.us
Zhenming Wang	DOGAMI	zhenming.wang@dogami.state.or.us
Anne Trehu	Oregon State University	nabelek@oce.orst.edu
John Nabelek	Oregon State University	trehu@oce.orst.edu
Sam VanLaningham	Oregon State University	samvan@geo.orst.edu
Gary Peraso	National Geodetic Survey	perassg@wsdot.wa.gov
Wayne Thatcher	USGS	thatcher@usgs.gov
Mike Lisowski	USGS	mlisowski@usgs.gov
Mark Murray	Stanford University	mhmurray@stanford.edu
Eugene Y. Iwatsubo	USGS/Cascades Volcano Observatory	Ewatsu@usgs.gov
Tim Melbourne	Central Washington University	tim@geology.cwu.edu
Mark Hemphill-Haley	URS Greiner Woodward-Clyde	mark@newberry.uoregon.edu
Ray Wells	USGS	rwells@usgs.gov
Stephanie Mazzotti	Pacific Geoscience Centre	smazzotti@pgc-gsc.nrcan.gc.ca
Todd Williams	Humboldt State University	twb3@humboldt.edu
R. Ning	University of Washington	
Tony Qamar	University of Washington	tony@geophys.washington.edu
Joe Henton	PGC/University of Victoria	henton@pgc.nrcan.gc.ca
Dan Dzursin	USGS/Cascades Volcano Observatory	dzursin@usgs.gov
Dan Johnson	Central Washington University	johnson@geology.cwu.edu
Ken Austin	Central Washington University	

Rotation and Plate Locking along the Central Cascadia Subduction Zone - An Update

Chris Goldfinger
College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis OR

McCaffrey et al (2000) use Global Positioning System and surface tilt measurements to simultaneously invert for both secular plate motion relative to stable North America and elastic plate locking on the central Cascadia subduction interface. GPS measurements are from campaign and continuous measurements made between 1996 and 1999 by RPI and OSU, and incorporate campaign measurements between 1992 and 1998 by the US Geological Survey, Cascades Volcano Observatory, and the National Geodetic Survey.

McCaffrey et al. (2000) calculate a rotation pole for stations east of the Cascades, which approximate a rigid body rotation, and where plate locking is assumed to be negligible. The simultaneous inversion calculates the rotation pole and best-fitting coupling model through many iterations to minimize misfit. The rotation is then applied to all of Oregon. McCaffrey et al. (2000) infer that clockwise rotation of a relatively rigid Oregon block may be driven by collapse of the Basin and Range, the northward migration of the Sierra Nevada block, and resisted by shortening in NW Washington State. The rotation pole lies along the Olympic–Wallowa lineament and explains the predominance of extension south of the pole and contraction north of it. The rotation pole is in good agreement with that proposed by Wells et al. (1998) based on geologic and paleomagnetic evidence. The collision with a weaker western Washington is supported by both seismicity and observed contractional structures in the Puget Willamette lowland. The rotation about a pole in eastern Oregon can also explain the "fanning" of the fold axes of the Yakima fold belt. These active folds are responding to north-south compression, but also fan westward in map view. The fold axes project to a convergence at the computed Oregon rotation pole, consistent with the predicted strain field.

Plate locking at the Cascadia thrust is anomalous in that the model resolves two coupled zones, one offshore, and a second deep zone beneath the western Cascades. While the existence of deeper coupling may not be real, the model tries to resolve anomalous east velocities observed in the western Cascades in this way. In the Puget-Willamette lowland, little east component is observed. The anomalous western Cascades vectors could represent dextral shear along the Cascade Arc (not incorporated in the model) or other crustal deformation superimposed on a deep viscous coupling signal. More observations are needed in the Western Cascades to verify and characterize the velocity field in this area.

References

Adams, J., Paleoseismicity of the Cascadia subduction zone: Evidence from turbidites off the Oregon-Washington margin, Tectonics, 9, 569-583, 1990.

Argus, D.F., and R.G. Gordon, Current Sierra Nevada-North America motion from Very Long Baseline Interferometry: Implications for the kinematics of the western United States, Geology, 19, 1085-1088, 1991.

Argus, D.F., and M.B. Heflin, Plate motion and crustal deformation estimated with geodetic data from the Global Positioning System, Geophysical Research Letters, 22, 1973-1976, 1995.

Atwater, B.F., Evidence for great Holocene earthquakes along the outer coast of Washington state, Science, 236, 942-944, 1987.

Atwater, B.F., Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington, Journal of Geophysical Research, 97, 1901-1919, 1992.

Atwater, B.F., and f. others, Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone, Earthquake Spectra, II (1), 1-18, 1995.

Atwater, B.F., and D. Yamaguchi, Sudden, probably coseismic submergence of Holocene trees and grass in coastal Washington state, Geology, 19 (7), 706-709, 1991.

Atwater, T., Implications of plate tectonics for the Cenozoic tectonic evolution of western North America, Bulletin of the Geological Society of America, 81, 3513-3536, 1970.

Bock, Y., S. Wdowinski, P. Fang, J. Zhang, S. Williams, and e. al., Southern California Permanent GPS Geodetic Array: Continuous measurements of regional crustal deformation between the 1992 Landers earthquake and 1994 Northridge earthquake, Jour Geophys Res, 102, 18,013-18,033, 1997.

Calais, E., and J. Minster, GPS detection of ionospheric perturbations following the January 17, 1994, Northridge earthquake, Geophys Res Lett, 22, 1,045-1,048, 1995.

Clarke, S.H., and G.A. Carver, Late Holocene tectonics and seismicity , southern Cascadia subduction zone, Science, 255, 188-192, 1992.

Crosson, R.S., and T.J. Owens, Slab geometry of the Cascadia subduction zone beneath Washington from earthquake hypocenters and teleseimic converted waves., Geophysical Research Letters, 14, 824-827, 1987.

Darienzo, M.E., and C.D. Peterson, Magnitude and frequency of subduction-zone earthquakes along the northern Oregon coast in the past 3,000 years, Oregon Geology, 57, 3-12, 1995.

Darienzo, M.E.P., C.D., Episodic tectonic subsidence of late Holocene salt marshes, northern Oregon central Cascadia margin, Tectonics, 9, 1-22, 1990.

DeMets, C., R.G. Gordon, D.F. Argus, and S. Stein, Effect of recent revisions to the geomagnetic reversal time-scale on estimates of current plate motions, Geophysical Research Letters, 21, 2191-2194, 1994.

Donnellan, A., and F. Webb, Geodetic observations of the M=5.1 January 29, 1994 Northridge aftershock, Geophys Res Lett, 25, 667-670, 1998.

Dragert, H., and R.D. Hyndman, Continuous GPS monitoring of elastic strain in the Northern Cascadia subduction zone, Geophysical Research Letters, 22, 755-758, 1995.

Dragert, H., R.D. Hyndman, G.C. Rogers, and K. Wang, Current deformation and the width of the seismogenic zone of the northern Cascadia subduction thrust, Journal of Geophysical Research, 99, 653-668, 1994.

Duan, J., M. Bevis, P. Fang, Y. Bock, S. Chiswell, and e. al., GPS Meteorology - Direct estimation of the absolute value of precipitable water, Jour. Appl. Meteor., 35, 830-838, 1996.

Flück, P., Hyndman, R.D., and Wang, K., 1997, 3-D dislocation model for great earthquakes of the Cascadia subduction zone: Journal of Geophysical Research, v. 102, P. 20,539-20,550.

Goldfinger, C., Kulm, L.D., Yeats, R.S., Appelgate, B., MacKay, M., and Moore, G.F., 1992, Transverse structural trends along the Oregon convergent margin: implications for Cascadia earthquake potential: Geology, v. 20, 141-144.

Goldfinger, C., Kulm, L.D., Yeats, R.S., McNeill, L.C., and Hummon, C., 1997, Oblique strike-slip faulting of the central Cascadia submarine forearc: Journal of Geophysical Research, v. 102, p. 8217-8243.

Goldfinger, C., McCaffrey, R., Murray, M., Zwick, P., Nabelek, J., Smith, C., and Johnson, C., 1999, GPS Constraints on Plate Coupling in central Western Oregon: Seismological Research Letters, v. 70, p. 224-225.

Heaton, T.H., and S.H. Hartzell, Earthquake hazards on the Cascadia subduction zone, Science, 236, 162-168, 1987.

Heaton, T.H., and H. Kanamori, Seismic potential associated with subduction earthquakes in the northwestern United States, Seismological Society of America Bulletin, 74, 933-941, 1984.

Heflin, M., D. Dong, A. Donnellan, K. Hurst, D. Jefferson, and e. al., Rate change observed at JPLM after the Northridge earthquake, Geophys Res Lett, 25, 93-96, 1998.

Humphreys, E.D., and K.G. Dueker, Western United States upper mantle structure, Jour. Geophys. Res., 99, 9,615-9,634, 1994.

Hyndman, R., and K. Wang, The rupture zone of Cascadia great earthquakes from current deformation and the thermal regime, Jour. Geophys. Res., 100, 22,133-22,154, 1995.

Hyndman, R.D., and K. Wang, Thermal constraints on the zone of major thrust earthquake failure: The Cascadia subduction zone, Journal of Geophysical Research, 98, 2039-2060, 1993.

Jackson, D., Z. Shen, D. Potter, X. Ge, and L. Sung, Southern California Deformation, Science, 277, 1621-1622, 1997.

Kelsey, H.M., D.C. Engebretson, C.E. Mitchell, and R.L. Ticknor, Topographic form of the coast ranges of the Cascadia margin in relation to coastal uplift rates and plate subduction, Journal of Geophysical Research Solid Earth, 99 (B6), 12245-12255, 1994.

Kelsey, H.M., R.L. Ticknor, J.G. Bockheim, and C.E. Mitchell, Quaternary upper plate deformation in coastal Oregon, Geological Society of America Bulletin, 108, 843-860, 1996.

Kelsey, H.M., R.C. Witter, and E. Hemphill-Haley, Response of a small Oregon estuary to coseismic subsidence and postseismic uplift in the past 300 years, Geology, 26, 231-234, 1998.

Ludwin, R.S., C.S. Weaver, and R.S. Crosson, Seismicity of Washington and Oregon, in Neotectonics of North America, edited by D.B. Slemmons, E.R. Engdahl, D. Blackwell, and D. Schwartz, pp. 77-98, Geological Society of America, Boulder, Co., 1991.

Massonnet, D., K. Feigl, H. Vadon, and M. Rossi, Coseismic deformation field of the M=6.7 Northridge, California earthquake recorded by 2 radar satellites using interferometry, Geophys Res Lett, 23, 969-972, 1996.

McCaffrey, R., and Goldfinger, C., 1995, Forearc deformation and great earthquakes: Implications for Cascadia earthquake potential: v. 267, p. 856-859.

McCaffrey, R., Goldfinger, C., Murray, M., Zwick, P., Nabelek, J., Smith, C., and Johnson, C., 1998, GPS Constraints on Forearc Sliver Motion, Plate Coupling, and Strain Partitioning in Northwestern Oregon: EOS, Transactions of the American Geophysical Union, Fall Supplement.

McCrory, P.A., Evolution of a trench-slope basin within the Cascadia subduction margin - The Neogene Humboldt Basin, California, Sedimentology, 42 (2), 223-247, 1995.

Miller, M.M., H. Dragert, E. Endo, C. Goldfinger, E.D. Humphreys, D.J. Johnson, R. McCaffrey, A. Qamar, and C.M. Rubin, Precise Measurements Help Gauge Pacific Northwest's Earthquake Potential, Eos - Article, in press., 1998.

Mitchell, C.E., P. Vincent, R.J. Weldon, and M.A. Richards, Present day vertical deformation of the Cascadia margin, Pacific Northwest, United States, Journal of Geophysical Research Solid Earth, 99 (B6), 12257-12277, 1994.

Murakami, M., M. Tobita, S. Fujiwara, T. Saito, and H. Masaharu, Coseismic crustal deformations of 1994 Northridge, California, earthquake detected by interferometric JERS-1 synthetic aperture radar, Jour Geophys Res, 101, 8605-8614, 1996.

Nelson, A.R., Atwater, B.F., Brobowski, P.T., Bradley, L., Clague, J.L., Carver, G.A., Darienzo, M.A., Grant, W.C., Krueger, H.W., Sparks, R., Stafford, T., and Stuiver, M., 1995, Radiocarbon evidence for extensive plate boundary rupture about 300 years ago at the Cascadia subduction zone: Nature, v. 378, p. 371-374.

Oldow, J.S., Late Cenozoic displacement partitioning in the northwestern Great Basin, in Structure, tectonics, and mineralization of the Walker Lane, edited by S.D. Craig, pp. 17-52, Geological Society of Nevada Symposium Proceedings Volume, Reno, Nevada, 1992.

Ozawa, S., M. Murakami, S. Fujiwara, and M. Tobita, Synthetic aperture radar interferogram of the 1995 Kobe earthquake and its geodetic inversion, Geophys Res Lett, 24, 2,327-2,330, 1997.

Pezzopane, S.K., Active faults and earthquake ground motions in Oregon, Ph. D. dissertation thesis, University of Oregon, Eugene, 1993.

Pezzopane, S.K., and R. Weldon, Tectonic role of active faulting in central Oregon, Tectonics, 12 (5), 1140-1169, 1993.

Prawirodirdjo, L., Bock, Y., McCaffrey, R., Genrich, J., Calais, E., Stevens, C., Puntodewo, S.S.O., Subarya, C., and Rais, J., 1997, Geodetic observations of interseismic strain segmentation at the Sumatra subduction zone: Geophysical Research Letters, v. 24, 2601-2604.

Qamar, A., and Khazaradze, G., 1999, Earthquake hazards in Western Washington: What have we learned from continuous GPS measurements: Seismological Research Letters, v. 70, p. 225.

Rasmussen, J., and E. Humphreys, Tomographic image of the Juan de Fuca plate beneath Washington and western Oregon using teleseismic P-wave travel times, Geophys. Res. Lett., 15, 1417-1420, 1988.

Riddihough, C.R., Recent movements of the Juan de Fuca plate system, J. Geophys. Res., 89, 6980-6994, 1984.

Rielinger, R.E., and J. Adams, Geodetic evidence for active landward tilting of the Oregon and Washington coastal ranges, Geophysical Research Letters, 9, 401-403, 1982.

Ryan, J., and C. Ma, NASA Space Geodesy Program - VLBI Annual Report 1995., 1995.

Satake, K., K. Shimizaki, Y. Tsuji, and K. Ueda, Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700, Nature, 379, 246-249, 1996.

Sauber, J., W. Thatcher, S.C. Solomon, and M. Lisowski, Geodetic slip rate for the eastern California shear zone and the recurrence time of Mojave desert earthquakes, Nature, 367 (January 20, 1994), 264-266, 1994.

Savage, J.C., and M. Lisowski, Strain measurements and potential for a great subduction earthquake off Oregon and Washington, Science, 252, 101-103, 1991.

Savage, J.C., M. Lisowski, and W.H. Prescott, Geodetic strain measurements in Washington, Journal of Geophysical Research, 86, 4929-4940, 1981.

Trehu, A., I. Asudeh, T. Brocher, J. Luetgert, W. Mooney, J. Nabelek, and Y. Nakamura, Crustal architecture of the Cascadia fore-arc, Science, 266 (5183) (1994 Oct 14), 237-243, 1994.

Unruh, J.R., J.R. Humphrey, and W.D. Page, Northwest continuation of the greater Walker Lane belt and counterclockwise rotation of the Sierra Nevada microplate, northeastern California, Geological Society of America Abstracts with Programs, 28, 119, 1996.

Velasco, A.A., C.J. Ammon, and T. Lay, Recent large earthquakes near Cape Mendocino and in the Gorda Plate - broad-band source time functions, fault orientations, and rupture complexities, Journal of Geophysical Research Solid Earth, 99 (B1), 711-728, 1994.

Verdonck, D., Three-dimensional model of vertical deformation at the southern Cascadia subduction zone, western United States, Geology, 23 (3), 261-264, 1995.

Wagner, D.L., G.J. Saucedo, and T.L.T. Grose, The Honey Lake fault zone, northeastern California, its nature, age, and displacement, Eos, Transactions of the Amer. Geophys. Union, 70, 1,358, 1989.

Wallace, R.E., Fault scarp formed during the earthquakes of October 2, 1915, in Pleasant Valley, Nevada, and some tectonic implications, U.S. Geol. Surv. Prof. Pap., A1-A33, 1984.

Wang, K.L., H. Dragert, and H.J. Melosh, Finite-element study of uplift and strain across Vancouver-Island, Canadian Journal of Earth Sciences, 31 (10), 1510-1522, 1994.

Wang, K.L., and G.C. Rogers, An explanation for the double seismic layers north of the Mendocino triple junction, Geophysical Research Letters, 21 (2), 121-124, 1994.

Ward, S. N., 1998, On the consistency of earthquake moment rates, geological fault data, and space geodetic strain: the United States, Geophysical Journal Int., 134, p. 172-186.

Wdowinski, S., Y. Bock, J. Zhang, P. Fang, and J. Genrich, Southern California Permanent GPS Geodetic Array: Spatial filtering of daily positions for estimating coseismic and postseismic displacements induced by the Landers earthquake, Jour Geol Res, 102, 18,057-18,070, 1997.

Weaver, C.S., and G.E. Baker, Geometry of the Juan de Fuca plate beneath Washington and northern Oregon from seismicity, Bull. Seismol. Soc. Am., 78, 264-275, 1988.

Webb, F.H., and J.F. Zumberge, An introduction to GIPSY/OASIS-II: Precision software for the analysis of data from the Global Positioning System, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Ca, 1995.

Wells, R.E., Paleomagnetic rotations and the Cenozoic tectonics of the Cascade Arc, Washington, Oregon, and California, Journal of Geophysical Research Solid Earth and Planets, 95 (B12), 19409-19417, 1990.

Wells, R.E., Tectonic segmentation of Cascadia, GSA Abstracts With Programs, 26 (7), A-456, 1994.

Wells, R.E., and P.E. Heller, The relative contribution of accretion, shear, and extension in Cenozoic tectonic rotation in the Pacific Northwest, Geological Society of America Bulletin, 100, 325-338, 1988.

Wells, R.E., C.S. Weaver, and R.J. Blakely, Crustal block motions in the Pacific Northwest: Implications for the earthquake potential of the Cascadia forearc, Geological Society of America Abstracts with Programs, 28, 123, 1996.

Wells, R.E., Weaver, C.S., and Blakely, R.J., 1998, Fore-arc migration in Cascadia and its neotectonic significance: Geology, 26, 759-762.

Wilson, D.S., Confidence-intervals for motion and deformation of the Juan-de-Fuca plate, Journal of Geophysical Research, 98 (B9), 16053-16071, 1993.

Wyatt, F., and D. Agnew, Secular strain accumulation at high resolution: Results from a year of strainmeter measurements on the southern San Andreas fault, Eos, Transactions, American Geophysical Union, 76 (46), F155, 1995.

Zhang, J., Y. Bock, H. Johnson, P. Fang, S. Williams, S. Wdowinski, J. Behr, and J.F. Genrich, Southern California permanent GPS geodetic array: Error analysis of daily position estimates and site velocities, Journal of Geophysical Research, 102, 18,035-18,055, 1997.

PROJECT PERSONNEL

Curriculum Vitae

Chris Goldfinger
Assistant Professor, (Senior Research)
College of Oceanic & Atmospheric Sciences, Oregon State University
104 Ocean Admin. Building, Corvallis, OR 97331-5503
e-mail: gold@oce.orst.edu

Born: January 10, 1956

Education:

• B.A. (Geology)	Humboldt State University	1980
• B.S. (Oceanography)	Humboldt State University	1980
• M.S. (Geology)	Oregon State University	1990
• Ph.D. (Structural Geology)	Oregon State University	1994

Research Work Experience:

• Research Assistant, Oregon State University	4/89-3/94
• Post-Doctoral Research Associate, Oregon State University	3/94-4/95
• Consultant (Earthquake Hazards)	4/94-present
• Assistant Professor of Oceanography (Senior Research)	4-95-present

Professional Service:

- Consulting Panel, Oregon Department of Transportation, Seismic Design Mapping Project. Geomatrix Consultants, 1994-95
- Panel Member, USGS National Earthquake Hazards Reduction Program review panel, 1995, 1997
- Invited Panelist, NURP-sponsored Gulf of Alaska (GASS) Initiative Workshop. Anchorage, Alaska March 1996
- Invited Panelist, 5 Year Planning Workshop, USGS National Earthquake Hazards Reduction Program, 1997
- Invited Panelist, SEIZE Seismogenic Zone Experiment Workshop, Kona HI, 6/97

Relevant Experience:

- Co-Investigator, with Robert McCaffrey (RPI) and John Nabelek (OSU). PANGA: A Pacific Northwest Geodetic Array. Continuous and MOST GPS measurement of crustal strain. 1996-1999
- Chief Scientist, 7 Cascadia subduction zone cruises, all earthquake related.

Publications:

1992 Transverse structural trends along the Oregon convergent margin: Implications for Cascadia earthquake potential and crustal rotations, Geology, v. 20, p. 141-144 (Goldfinger, C., Kulm, L.D., Yeats, R.S., Appelgate, B., MacKay, M.E., and Moore, G.F.)

1992 A left-lateral strike-slip fault seaward of the Oregon convergent margin, Tectonics, v. 11, p. 465-477 (Appelgate, B., Goldfinger, C., MacKay, M.E., Kulm, L.D., Fox, C.G., Embley, R.W., and Meis, P.J.)

1992 Neotectonic map of the Oregon continental margin and adjacent abyssal plain, Oregon Department of Geology and Mineral Industries, OFR 0-92-4, 17 pages and 2 map sheets. (Goldfinger, C., Kulm, L.D., Yeats, R.S., Mitchell, C., Weldon, R. J., II, Peterson, C., Darienzo, M., Grant, W., and Priest, G.R.)

1994 Active deformation of the Cascadia forearc: Implications for great earthquake potential in Oregon and Washington [PhD Thesis]: Oregon State University, Corvallis, OR, 202 p. (Goldfinger, C.)

1995 Forearc deformation and great subduction earthquakes: Implications for Cascadia offshore earthquake potential: Science, v. 267, p. 856-859 (McCaffrey, R., and Goldfinger, C.)

1995 A seismic reflection profile across the Cascadia subduction zone offshore central Oregon: New constraints on methane distribution and crustal structure: Journal of Geophysical Research, v. 100, p. 15,101-15,116 (Tréhu, A., Lin, G., Maxwell, E., and Goldfinger, C.).

1996 Oblique strike-slip faulting of the Cascadia submarine forearc: The Daisy Bank fault zone off central Oregon: Subduction Top to Bottom, AGU Geophysical Monograph, p. 65-74 (Goldfinger, C., Kulm, L.D., Yeats, R.S., Hummon, C., Huftile, G.J., Niem, A.R., Fox, C.G., and McNeill, L.C.)

1996 Active strike-slip faulting and folding of the Cascadia plate boundary and forearc in central and northern Oregon. U.S.G.S. Professional Paper 1560, Earthquake Hazards in the Pacific Northwest, Rogers, et al., eds., p. 223-256 (Goldfinger, C., Kulm, L., Yeats, R., Appelgate, B., MacKay, M., and Cochrane, G.)

1997 Oblique strike-slip faulting of the central Cascadia submarine forearc: Journal of Geophysical Research, Journal of Geophysical Research, v. 102, p. 8217-8243, (Goldfinger, C., Kulm, L.D., Yeats, R.S., McNeill, L.C., and Hummon, C.)

1997 Case study of GIS data integration and visualization in marine tectonics: The Cascadia subduction zone, Marine Geodesy, v. 20, p. 267-289. (Goldfinger, C. and McNeill, L.C.)

1997 McNeill, L.C., Piper, K.A., Goldfinger, C., Kulm, L.D., and Yeats, R.S., Listric normal faulting on the Cascadia continental shelf: Journal of Geophysical Research, v. 102, p. 12,123-12,138, 1997.

1998 Stonewall anticline: An active fold on the Oregon continental shelf: GSA Bulletin, v. 110, p. 572-587 (Yeats, R.S., Kulm, L.D., Goldfinger, C., and McNeill, L.C.)

1999 The Effects of Upper Plate Deformation on Records of Prehistoric Cascadia Subduction Zone Earthquakes, *in* Vita-Finzi, C., and Stewart, I., eds., Coastal Tectonics: Geological Society Special Publication 146, p. 319-342 (McNeill, L.C., Goldfinger, C., Yeats, R.S., Kulm, L.D.)

1999 Active Tectonics: Data Acquisition and Analysis with Marine GIS Systems, C. Goldfinger, Wright, D., and Bartlett, D. eds., Marine GIS, Taylor and Francis, in press.

1998 Precise measurements help gauge Pacific Northwest's Earthquake potential: EOS, v. 79, p. 269-275. (Miller, M., Dragert, H., Endo, E., Freymueller, J.T., Goldfinger, C., Kelsey, H.M., Humphreys, E.D., Johnson, D.J., McCaffrey, R.M., Oldow, J.S., Qamar, A., and Rubin, C.M.)

1999 Super-Scale slumping of the southern Oregon continental margin: in Pure and Applied Geophysics Special Volume on Landslides, B. Keating and C. Waythomas, eds. (Goldfinger, C., Kulm, L. D., McNeill, L.C. and Watts, P.)

1999 In Prep. Cascadia Paleoseismicity: Turbidite Pathway Analysis of the Astoria Channel (preliminary title): U.S.G.S Open File Report: (Nelson, C.H., Goldfinger, C., Wolf, S.)

1999 In Prep. Active Deformation of Pleistocene Low-Stand Shorelines on the Oregon Continental Margin: Tectonic Erosion during Frontal Accretion: Chris Goldfinger, Robert W. Embley, Charles Hutto, Robert S. Yeats, L. C. McNeill, LaVerne D. Kulm.

INSTITUTIONAL QUALIFICATIONS

Central Washington University will administer the collaborative effort, and brings considerable resources and experience in GPS studies (detailed in Management Plan). The NSF supported PANGA Data Analysis Facility, CWU routinely performs GPS data analysis using GIPSY/OASIS II software developed by the Jet Propulsion Laboratory [Webb and Zumberge, 1995], in conformance with IGS standards. Dr. Dan Johnson coordinates this effort. At CWU, Dr. Dan Johnson routinely performs GPS daily solutions of permanent array data on a Sun workstation using GIPSY/OASIS II software developed by Jet Propulsion Laboratory. CWU further supports this effort by providing 50% of Johnson's salary as match to the grant that funds the Data Analysis Facility, and guarantees his continued support as a CWU employee at the end of the three year NSF project. Routine analysis of the datastream for existing Pacific Northwest sites is now in place and results are posted at http://www.panga.cwu.edu/. We are currently seeking approval as an IGS (International GPS Service for Geodynamics) Regional Associate Analysis Center. Under the IGS umbrella, processing protocols, data product formats, and distribution and archiving of products are standardized for use by the geophysical community. CWU also supports a computer systems administrator whose time is fully devoted to Geology and GIS computer labs. Under the NSF initiative, CWU Grants and Contracts, with the PI's, have developed bid specifications for GPS monumentation and managed the contract for UW and CWU installations by EarthSafe during the summer of 1997-98. These monuments were constructed in conformance with the Wyatt drilled braced monument design. All new monuments proposed here will be constructed to meet IGS standards, and will be constructed under a single coordinated bid request administered through CWU. The combination of this experience, the advantage of a single contract, and cost savings achieved by indirect agreements make this a cost effective strategy.

The University of Washington has operated the first PANGA continuous GPS stations at Neah Bay and Seattle since 1995, and has added four more sites with deeply anchored drilled braced monuments in 1997-8. UW has been processing GPS data using GIPSY since 1995. UW has developed computer scripts to automatically download data from many GPS sites in the Pacific Northwest and process the data on a daily basis. Data from its GPS stations are available at http://www.geophys.washington.edu/GPS/.

Oregon State University has operated two permanent GPS sites at Newport and Corvallis, OR since 1996. These sites were developed and installed in conjunction with PI's at Rensselaer Polytechnic Institute who have provided expertise and loaned equipment to initiate continuous GPS measurements in Oregon. OSU and RPI have developed downloading software that recovers site data each day, and performs automatic error checking for missing data, runs quality control scripts, and archives the data at mirror sites at RPI and OSU. (see http://pandora.oce.orst.edu). The Active Tectonics lab at OSU's College of Oceanic and Atmospheric Sciences is equipped with a wide range of parallel computers, workstations and small computers with which to carryout geologic and geodynamic modeling. RPI performs data processing of a subset of PANGA data using MIT's GAMIT and GLOBK software. Independent processing with different methods and software serves as a crosscheck on the overall PANGA velocity field. OSU will initiate data processing during 1999, and process permanent and campaign sites using a network adjustment strategy similar to RPI.

CWU, RPI, and UW collectively own and operate more than 30 GPS receivers, most with Dorne-Margolin choke ring antennas, which are deployed in a variety of permanent and regional campaign modes. In addition, some of us have historically had access to UNAVCO-administered pools of NSF and NASA receivers to support campaign efforts.

PROJECT MANAGEMENT PLAN

Dr. Meghan Miller is the Principal Investigator and is responsible for the successful execution of the proposed research and coordination between institutions. She is jointly appointed at Central Washington University and NASA's Jet Propulsion Laboratory, and has extensive experience in field GPS campaigns including eight years work on a 19 site network in eastern California, and design and field operations expertise in four other GPS networks (Loma Prieta response GPS array, northern Baja California network, Landers post-seismic studies, and Mammoth network installations and operations). She is currently funded under the UNAVCO NSF-ARI initiative, NSF-Geophysics, NSF Instrumentation and Facilities, and NASA Dynamics of the Solid Earth programs for GPS related work. Dr. Charles Rubin's expertise in paleoseismology and active tectonics is critical to network design. In addition, he has expertise in permit negotiations and monument design, including participation in a NASA-sponsored workshop on the proposed dense array in southern California and overseeing the EarthSafe drilling contract and installations in 1997-98. He will provide technical expertise to the project, and assure that monumentation subcontractor meets IGS requirements for monument construction. Dr. Dan Johnson conducts data analysis; he holds a Ph.D. in Geophysics from the University of Hawaii and manages the CWU GPS Data Analysis Center. Dr. Johnson is routinely processing and archiving continuous and campaign GPS data using GIPSY/OASIS II with JPL products such as fiducial free precise orbits and precise clocks. His effort comes at no cost to this project as he is funded by the NSF initiative (50%) and CWU (50%). The incremental effort of processing the five additional proposed sites is small. Dr. Anthony Qamar is the Washington State Seismologist and has installed a number of permanent GPS sites. Qamar seeks ongoing support for maintenance and operation of three sites, and will be responsible for the two new sites in Washington. Dr. Chris Goldfinger at Oregon State University has participated in annual GPS campaigns and permanent site installation in Cascadia since 1996. He is operating two PANGA sites, and is responsible for downloads, quality control, and archiving of data from these sites. He is engaged in elastic modeling of PANGA data and working with hazard planners to integrate new interpretations into future hazard analyses. He will plan the Tillamook, McMinnville, and

Portland Oregon sites, and supervise follow up on upgrades at existing sites Newport and Corvallis. He will be responsible for planning of and hosting the PANGA Community Meeting during this project period. He is engaged in marine geologic investigations of the Cascadia forearc that bear on the updip position of the coupled megathrust, and is studying turbidite occurrence and distribution to address periodicity and spatial distribution of Holocene great Earthquakes in Cascadia. McCaffrey (RPI), Goldfinger (OSU), Dragert (PGC) and Qamar (UW) are funded by NSF co conduct a major margin-wide campaign in 2000.

CURRENT AND PENDING SUPPORT

(p. 25)