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NASA-CR-201836

July 26, 1996

Ms. Gloria Blanchard
Grants Officer
NASA/Goddard Space Flight Center
Code 286.1
Greenbelt, Maryland 20771

Dear Ms. Blanchard:

I am pleased to submit the following progress report for your records:

(1) Title: UNAVCO Facility Support of NASA Dynamics of the Solid Earth (DOSE) GPS Investigation for years 1995-1996

(2) Type of report: Annual Progress Report

(3) Principal Investigator: Dr. Randolph Ware

(4) Period covered by report: August 1, 1995 - August 1, 1996

(5) Name and address of institution:
University Corporation for Atmospheric Research (UCAR)
University Navstar Consortium (UNAVCO)
P.O. Box 3000
Boulder, Colorado 80307-3000

(6) Grant number: NAG 5-3035

This report consists of the following sections:

(1) List of NASA DOSE Program Global Positioning System (GPS)-based campaigns supported by the UNAVCO Boulder Facility (Enclosure (1)).

(2) List of NASA DOSE GPS permanent site installations supported by the UNAVCO Boulder Facility (Enclosure (2)).

Wayne S. Shiver
Deputy Director

(3) Example science snapshots indicating the research projects supported with equipment and technical support available to DOSE Principal Investigators via the UNAVCO Boulder Facility (Enclosure (3)).

As can be seen from these documents, the UNAVCO Facility has supported a large number of DOSE projects which in turn have resulted in considerable scientific output by the project Principal Investigators. Certainly, a more extensive publication list resulting from research conducted with UNAVCO support will be available in the near future as the results of the DOSE field campaigns and permanent site installations are translated into scientific findings.

If you have questions regarding this report, please contact me at (303) 497-8005 or by e-mail at shiver@ucar.edu.

Sincerely,

Wayne S. Shiver

Wayne S. Shiver
UNAVCO Deputy Director

Enclosures

cc: B. Bills, NASA/GSFC
NASA CASI

Enclosure (1)

DOSE Campaigns
August 1995 through September 1996

Project Name/Location	Field Dates	P.I.	Institution	Sponsor
		1995		
Parkfield	23 Apr-16 May	Hurst	JPL	DOSE
Alaska USGS	10 May-1 Aug	Savage	USGS	DOSE
Alaska GSFC Training		Sauber	GSFC	DOSE
Alaska GSFC		Sauber	GSFC	DOSE
Alaska LDEO		Beavan	LDEO	DOSE
Tien Shan	May 95-May 96	Reilinger	MIT	NSF-EAR/DOSE
		Hager	MIT	
		Hamburger	Indiana	
		Molnar	MIT	
Seafloor Geodesy	1Aug-5 Oct	Young	JPL	DOSE/NSF
		Spiess	Scripps	
Mojave/Mammoth	11 Sept - 13 Oct	Dixon	U. Miami	DOSE
		Miller	CWU	
		Humphreys	Oregon	
Northern Baja**	15 Oct-15 Nov	Dixon	U. Miami	DOSE
		Humphreys	Oregon	
		Miller	CWU	
		Suarez	CICESE	
		1996		
CASA	5 Jan-1 May	Kellogg	USC	NSF-EAR
		Dixon	U. Miami	
Costa Rica	5 Jan - 10 Mar	Lundgren	JPL	DOSE
Parkfield**	7 Apr-7 May	Hurst	JPL	DOSE
SNAPP**	12 May-15 July	Stein	NW	Y2 DOSE
		Sacks	Carnegie Inst.	
		Dixon	U.Miami	
Seafloor Geodesy**	Aug-Oct	Young	JPL	DOSE
		Spiess	Scripps	
Scandinavia	16 Aug-mid Sept	Davis	Harvard/Smiths.	DOSE
Norwegian Network	20 Aug-mid Sept	Harsson	Statens Kartverk	Norw.Mapping Ag.
		Engen	Statens Kartverk	
Mojave	Sept	Miller	Cent.Wash. Univ.	DOSE
Irkutsk	Sept		ITR	DOSE
Basin & Range	15 Sept-Oct	Thatcher	USGS	DOSE

7/26/96

DOSE Permanent Sites
August 1995 through September 1996

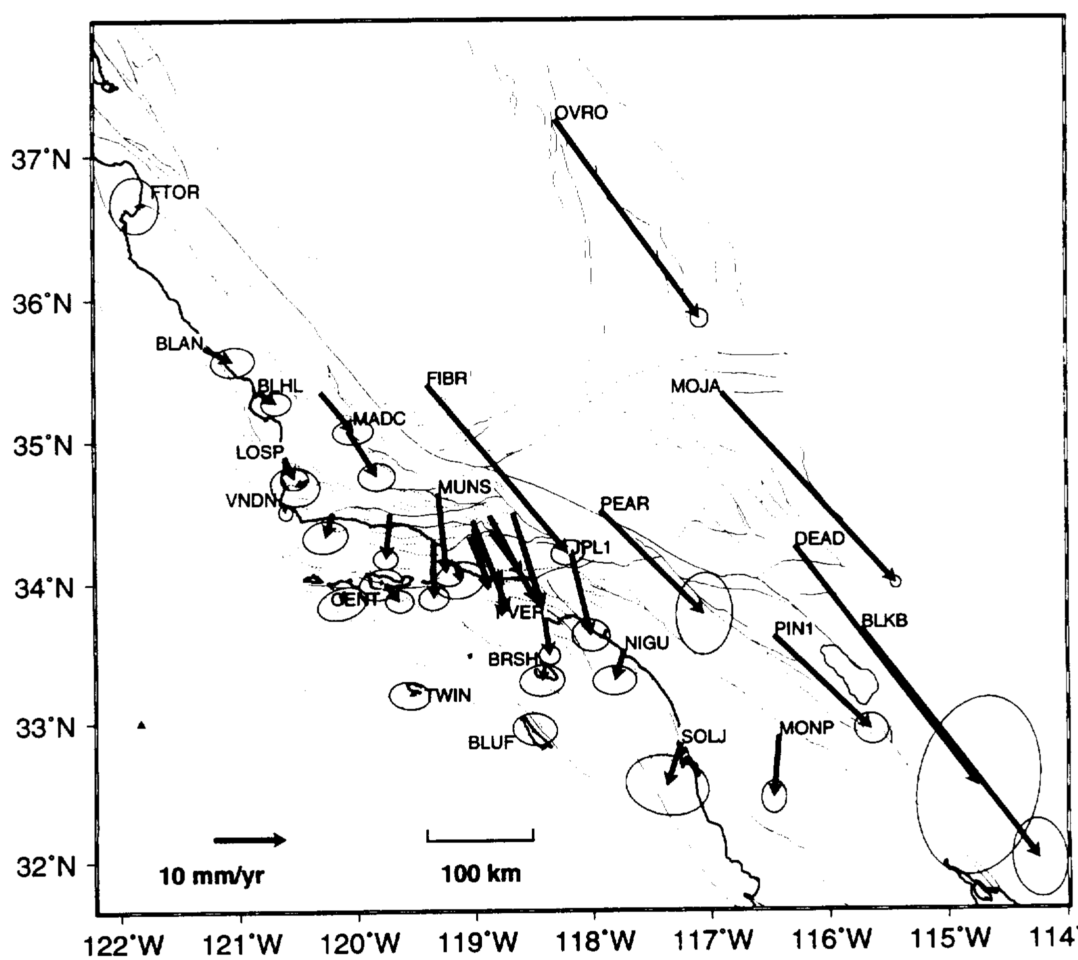
Project Name/Location	Field Dates	P.I.	Institution	Sponsor
		1995		
Tien Shan	May 95-May 96	Reilinger	MIT	NSF-EAR/DOSE
		Hager	MIT	
		Hamburger	Indiana	
		Molnar	MIT	
Costa Rica DOSE (Arenal Volcano)	11 June-30 June	Lundgren	JPL	DOSE
India, Bangalore Sta.	Sept. 6-20	Guar	CMMACS	DOSE
Xi'an, China	8-Sep	MA	JPL/Shaanxi Obs.	DOSE
Popo	1-18 Mar	Dixon	U. Miami	DOSE
		1996		
CASA (Rio Bamba)	5 Jan - 1 May	Kellogg	USC	NSF-EAR
		Dixon	U.Miami	DOSE

Space-geodetic measurements of crustal motion in central and southern California

D. Agnew[1], Y. Bock[1], D. Dong[2], A. Donnellan[2], K. Feigl[3], B. Hager[4], T. Herring[4], D. Jackson[5], R. King[4], S. Larsen[6], K. Larson[7], M. Murray[8], Z. Shen[5], and F. Webb[2]
[1]Scripps Institute of Oceanography; [2]Jet Propulsion Laboratory; [3]Observatoire Midi-Pyrenes; [4]Massachusetts Institute of Technology; [5]University of California at Los Angeles; [6]Lawrence Livermore National Laboratory; [7]University of Colorado; [8]Stanford University

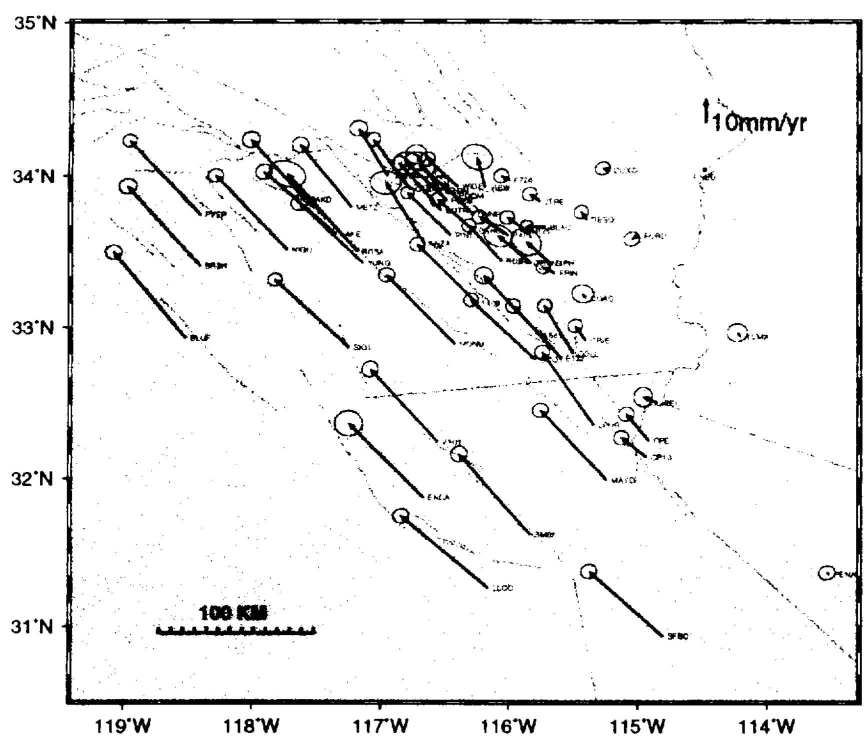
PI's from several universities (Caltech, MIT, Scripps, and UCLA) began making GPS measurements in Central and Southern California in late 1986--some of the first GPS data collected in this region. A succession of 26 GPS campaigns (most with UNAVCO equipment) over the next 6 years produced the velocity field shown in the figure: the first measurement of crustal velocities with a relatively high spatial density. These measurements, combined with VLBI data, confirmed the usual picture of distributed motion across this plate boundary, with most of the deformation related to the San Andreas system of faults--but also added some new features. Most notably, the data showed high rates of contraction across the Ventura Basin--a result whose significance was emphasized soon after its publication by the occurrence of the Northridge earthquake. These measurements also provided the first good evidence for rates of deformation offshore of the southern California mainland, and of rotations of crustal blocks. These results provided the first good estimate of the rate of contraction across the Los Angeles basin, a quantity of great importance in evaluating the seismic hazard of this area.

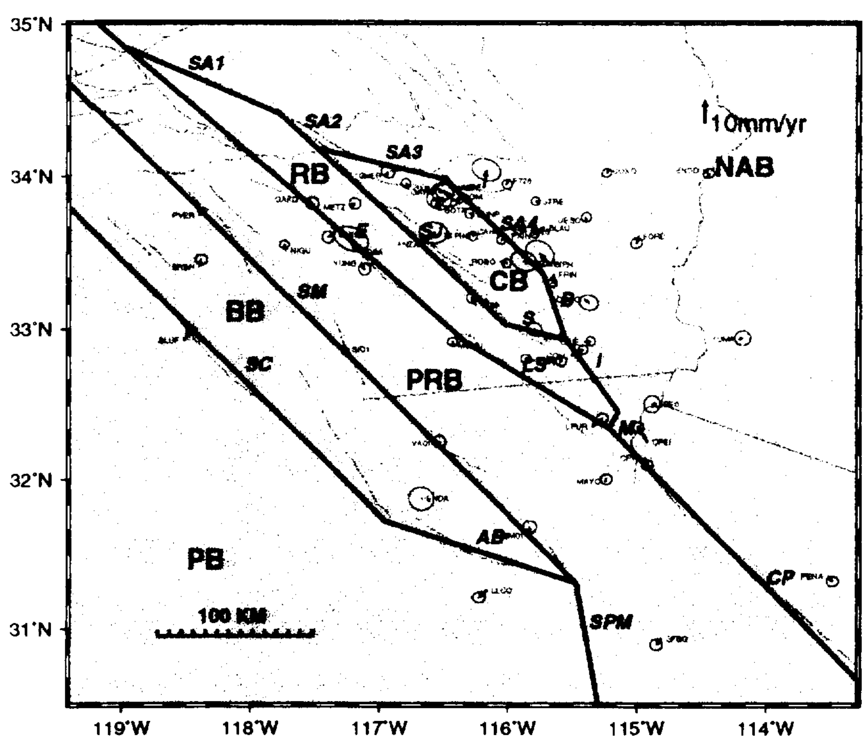
These results have continued to guide further, much expanded studies of crustal motion in southern California, including the installation of permanent GPS stations. Just as importantly, the working relationships developed through this collaboration have continued (most recently through the Southern California Earthquake Center), with the interactions providing a more complete view of the geodetic and geodynamic issues involved.



GPS constraints on fault slip rates in Southern California and Northern Baja, Mexico

R. Bennett[1], W. Rodi[1], R. Reilinger[1], and J. Gonzalez[2]
[1]Massachusetts Institute of Technology; [2]CICESE, Baja, Mexico





We use GPS estimates of horizontal site velocity for the period 1986-1995 (Figure 1) to constrain slip rates on faults comprising the Pacific-North America plate boundary in southern California and northern Mexico. We enlist a simple elastic block model (Figure 2) to parameterize the distribution and sum of deformation within and across the plate boundary. We estimate a Pacific-North America relative plate motion rate of 49 +/- 3 mm/yr, consistent with NUVEL-1A estimates. We are able to resolve robust slip rate estimates for the southernmost San Andreas, San Jacinto, and Elsinore faults (26 +/- 2 mm/yr, 9 +/- 2 mm/yr, and 6 +/- 2 mm/yr, respectively) and for the Imperial and Cerro Prieto faults (35 +/- 2 mm/yr and 42 +/- 1 mm/yr, respectively), accounting for about 86% of the total plate motion. The remaining 14% appears to be accommodated to the west of these fault systems, probably via slip along the San Clemente fault and/or the San Miguel, Vallecitos, Rose Canyon, and Newport-Inglewood fault systems. These results are highly consistent with paleoseismic estimates for slip rates implying that off-fault strain accumulation within the deforming zone of the plate boundary is largely elastic. We estimate that the seismically quiescent, southernmost San Andreas fault has incurred about 8.2 meters of slip deficit over the last few hundred years, presumably to be recovered during a future large earthquake.

Figure 1 (top). GPS velocities and their 95% confidence ellipses in a (approximately) N. America-fixed reference frame.

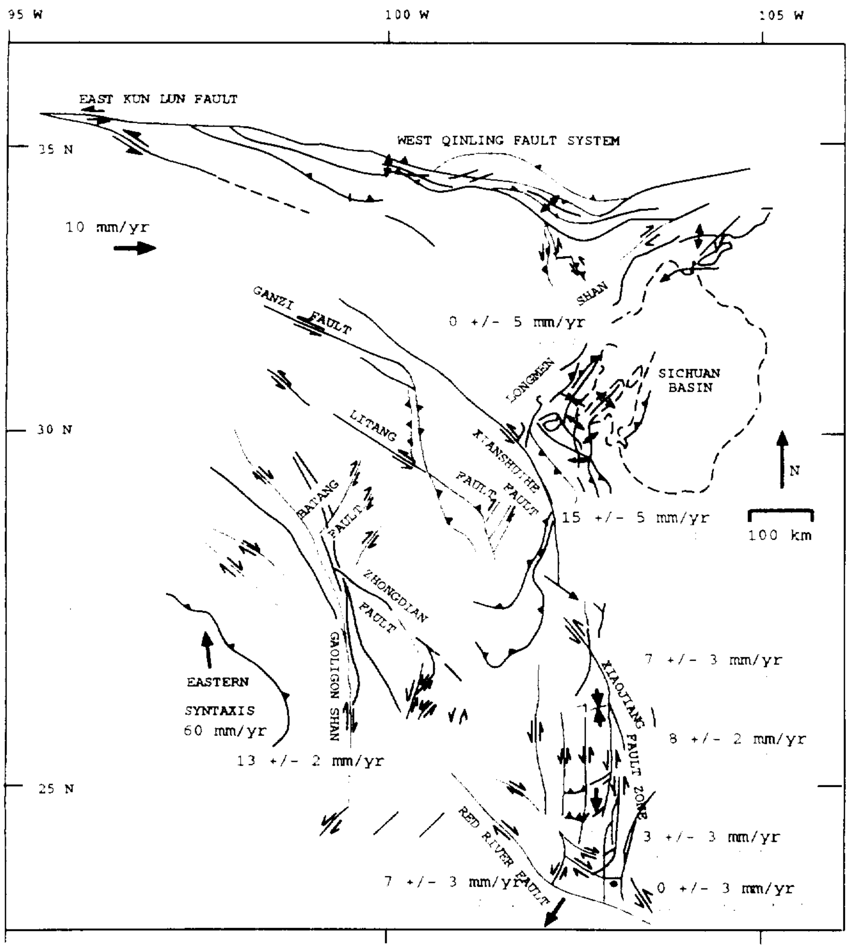
Figure 2 (bottom). Block model for S. California/N. Mexico deformation and residual motions (i.e., motions not accounted for by the model).

Geological, geodetic, and geophysical study of southwest China: A test of Cenozoic tectonic models for Eurasia

B. C. Burchfield[1], R. W. King[1], L. H. Royden[1], and Z. Chen[2]

[1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA; [2]Chengdu Insitute of Geology and Mineral Resources, Chengdu, Sichuan, China

The eastern margin of the Tibetan plateau lies within the center of the broadest and most active area of intracontinental deformation on earth and serves as a natural laboratory to study the processes by which continents deform. The diverse structural features of this region are generally accepted to be the result of collision and continued north-south convergence between a more rigid Indian plate and a more ductile Eurasian plate over the past 45 million years. During this time the Tibetan plateau has been elevated from sea-level to more than 4 km and the continental crust beneath the plateau has been thickened to nearly twice normal thickness. A wide range of hypotheses have been proposed to explain this crustal thickening and the partition of deformation east of Tibet. We are testing these hypotheses by a combination of geological mapping of Cenozoic structures, GPS measurement of a present-day crustal motion, and three-dimensional numerical modeling of deformation within the crust.



Simplied tectonic map of the central and southern part of the Tibetan plateau and region of lower topography to the east. Major young and active structures are show in color: left-slip (blue) and right-slip (red) faults; shortening (green) and extensional (yellow) structures. Arrows and upper values show the short-term rates, relative to the Sichuan basin, determined by GPS surveys; lower italicized values indicate the geologically inferred rates for the same area.

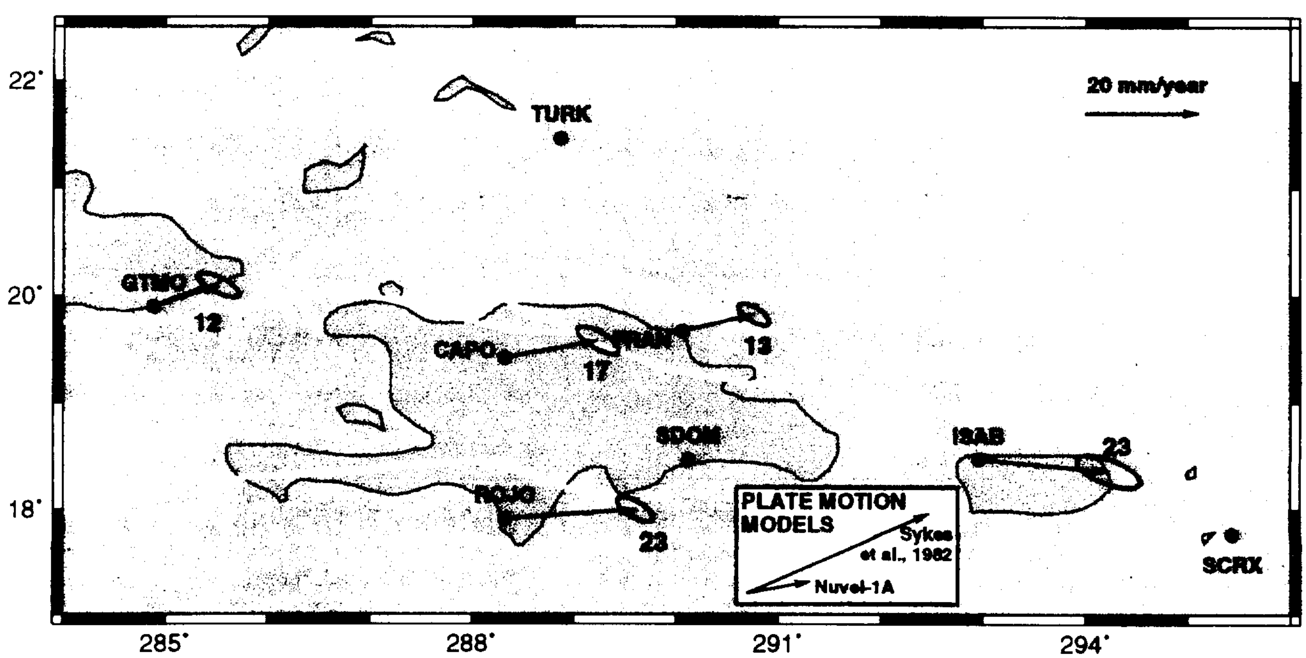
We have completed geological mapping of most regions of high topography within Sichuan and Yunnan provinces [Burchfiel et al., 1995; Wang et al., 1995]. We find little evidence of recent deformation in the Longmen Shan, previously thought to absorb significant shortening from the eastward extrusion of crust from Tibet. GPS measurements between 1991 and 1995 confirm this result, showing less than 5 mm/yr of motion [King et al., 1996]. By contrast the Xianshuihe/Xiaojiang fault system indicates 60 km of left-lateral displacement during Pliocene/Quaternary time, with deformation on the northern segments confined to a narrow width and deformation in the south transferred through a region of complex oblique convergence accommodated by slip on at least five faults. GPS measurements for this region are available for only a 2-yr span but show good agreement with the geological results. If we assume that the velocity of regions east of the Xianshuihe/Xiaojiang fault system is small relative to the Sichuan Basin, then the GPS observations imply a displacement rate of 12 to 15 mm/yr on the fault system. If the deformation has not changed significantly over the past few million years, then these geodetically observed rates, coupled with the geological observations, allow us to date the onset of activity at about 4 Ma.

GPS measurements across the Northern Caribbean plate boundary zone

T. Dixon[1], F. Farina[1], C. Demets[2], P. Jansma[3], P. Mann[4], and E. Calais[5]

[1]University of Miami; [2]University of Wisconsin, Madison; [3]University of Puerto Rico, Mayaguez; [4]University of Texas, Austin; [5]University of California, San Diego

Relative motion of the Caribbean plate with respect to the North American plate is accommodated across a 3000 km-long, complexly deforming zone that connects the Lesser Antilles and Middle America trenches.The relative motion between these two plates is poorly defined in global plate motion models because transform fault azimuths, earthquake slip vectors and seafloor spreading rates are poorly defined, complex, and sparse or non-existent along much of their common boundary. Not surprisingly, the distribution of strain within this complex plate boundary is likewise poorly defined. For example, although Late Quaternary activity is recognized for both the Septentrional fault and the Enriquillo fault zones in the Dominican Republic, the present-day slip rates are unknown. Significant submarine seismicity north and south of these active faults further suggests that onshore faults accommodate only part of the relative plate motion. In 1986, a network of geodetic sites was occupied by GPS receivers as part of a NASA program to test and validate this new technology in a humid tropical environment [Dixon et al., 1991]. This network was occupied in 1994 and 1995 as part of a joint NSF-sponsored project between UW-Madison, the University of Miami, UT-Austin, and the University of Puerto Rico at Mayaguez. Site velocities derived from the 1986, 1994, and 1995 GPS measurements are shown in the figure. The results suggest that the Caribbean plate moves east relative to the North American plate at 23-+2 mm/yr, nearly twice the rate predicted by the NUVEL-1Amodel [Demets et al.,1994]. Elastic strain modeling of site velocities from the Dominican Republic suggests that the Septentrional fault carries ~40-60% of Caribbean-North America motion, and further implies that significant motion occurs offshore to the north. The Enriquillo fault in the southern Dominican Republic accommodates few mm/yr at most. We are presently investigating the implications for strain partitioning and for circum-Caribbean tectonics.



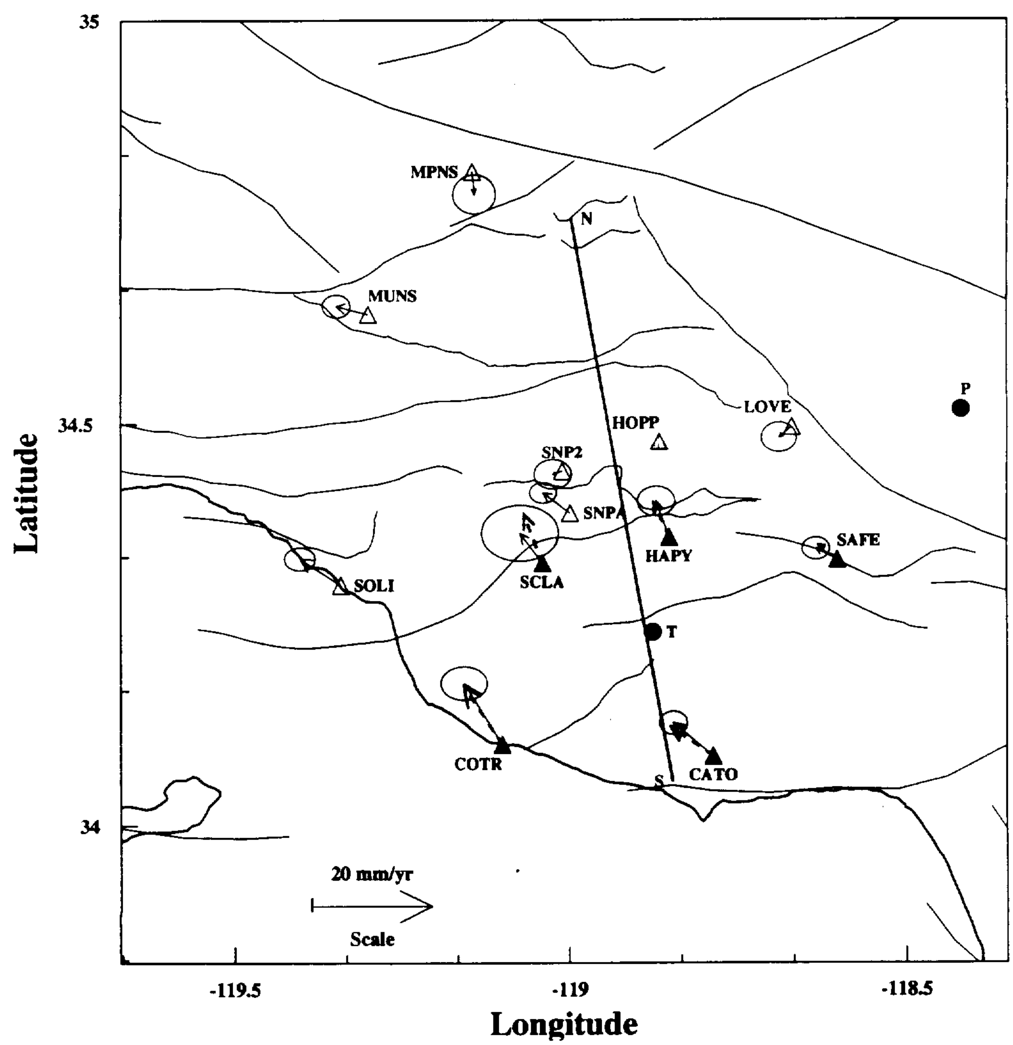
Site velocities relative to TURK.

Discrepancy between geological estimates and GPS measurements of convergence rates across the Ventura basin

A. Donnellan[1], B.H. Hager[2], and R. W. King[2]

[1]Jet Propulsion Laboratory; [2]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institution of Technology

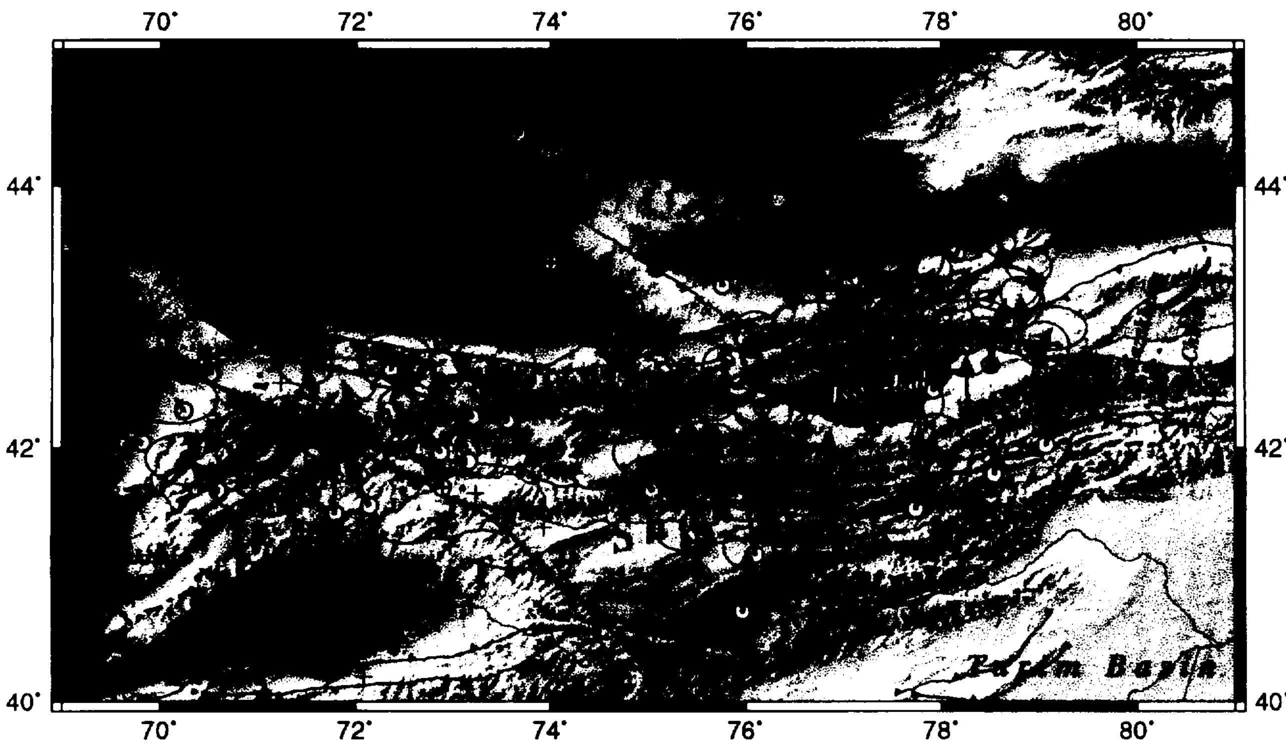
GPS provides a new tool for measuring active tectonic deformation which, when combined with geological and geophysical models and observations, can be used to infer rates and styles of deformation. Geological estimates of the convergence rate across the Ventura basin in the Transverse Ranges of southern California were 20 - 25 mm/yr – rapid enough to be tested using GPS measurements over a few years. Our measured velocities (shown as solid vectors, relative to site HOPP to the north of the basin) give convergence rates of 7 - 10 mm/yr across the basin, and only 11 3 mm/yr of regional convergence. This discrepancy has resulted in revision of the geological models. The maximum shear strain rate within the basin is 60% greater than that measured across the San Andreas fault north of the basin, and the dilatational strain rate across the basin is unusually large, suggesting significant seismogenic potential. This suggestion was born out by the 1994 Northridge earthquake, which ruptured the region to the southwest of site SAFE. The motion of the region to the south of the basin occurs with negligible deformation – velocities (dashed vectors in figure) predicted by rigid body rotation about point P at 8 / Myr match the observed velocities to within their 95% confidence ellipses, while most of the deformation to the north of the basin can be attributed strain accumulation from the San Andreas. Viewed in this way, the region south of the basin appears as a nearly rigid block pivoting about an axis near the eastern end, squeezing the basin like a nut in a nutcracker.



A GPS Study of the Tien Shan of Kyrgyzstan and Kazakhstan

M. W. Hamburger[1], B. Hagar[2], T.A. Herring[2], P. Molnar[2], and R. Reilinger[2]
[1]Indiana University; [2]Massachusetts Institute of Technology

The high mountains of the Tien Shan of Kyrgyzstan, Kazakhstan, and China, located some 1000-2000 km distant from the collisional boundary of the Indian and Eurasian plates, offers an outstanding laboratory for the study of tectonics of intracontinental mountain belts. The Tien Shan, considered to be a modern analog to the Laramide Rocky Mountains and the Transverse Ranges of southern California, is characterized by high rates of crustal deformation and seismic activity, and offers the opportunity to study geodynamics of an active intracontinental mountain belt. Our GPS project in the Tien Shan is the product of a four-year-old multinational collaboration involving ten scientific organizations in the U.S., Russia, Kyrgyzstan, and Kazakhstan. Our principal collaborators include the Institute of High Temperatures (Russian Academy of Sciences) the Kyrgyz national geodetic agency, and the Kazakh national geodetic agency. The Tien Shan GPS network, developed in collaboration with local scientific and geodetic agencies, now includes over 150 sites distributed over an area of 350 x 700 km, roughly half the size of the state of California. The project has become a successful pilot area for the application of the "MOST" strategy, which involves acquiring GPS measurements through a mixture of continuous, semi-continuous, and roving field stations. The observed velocity field reveals consistent north-south shortening across the Tien Shan, between the stable Kazakh platform on the north and sites near the southern edge of Kyrgyzstan, close to the Chinese border. We measured a shortening rate across the entire network of 12 +/- 2 mm/yr, in a direction nearly coincident with the India-Eurasia convergence vector. Because our network does not cross the entire range, this rate underestimates the total convergence rate across the Tien Shan. Combining geologic evidence for rapid shortening across the southern margin of the Tien Shan with our GPS- based estimate suggests a total convergence rate across the orogen of roughly 20 mm/yr. This estimate of shortening across the western Tien Shan accounts for nearly half of India's present-day convergence with Eurasia, despite the Tien Shan's modest area and distance from the collision front. The observed shortening appears to be distributed as nearly uniform strain across much of the network. Future surveys are expected to quantify the degree to which strain is non-uniform. In particular, the western part of the network is designed to determine the complexities of strain partitioning near the end of a major strike-slip fault, the Talas-Ferghana.



This figure shows the network of GPS sites and observed deformation rates in the Tien Shan. GPS sites are shown by the following symbols: stars = continuous sites (installed in 1995); red and yellow circles = sites installed in 1992 and 1993, respectively; triangles = sites remeasured in 1994; crosses = sites established by the GFZ and our local collaborators. Black lines show inferred faults, with hachures indicating thrust or reverse faulting. The large NW-SW trending black line shows the trace of the Talas-Ferghana fault. Shading shows relief, with green areas lowest and brown to white shading showing highest areas. Measured deformation rates, with respect to the station AZOK, near the northern edge of the network, are shown by red arrows, with ellipses defining 95% confidence intervals.

Arc-continent collision and oblique subduction in the north Andes

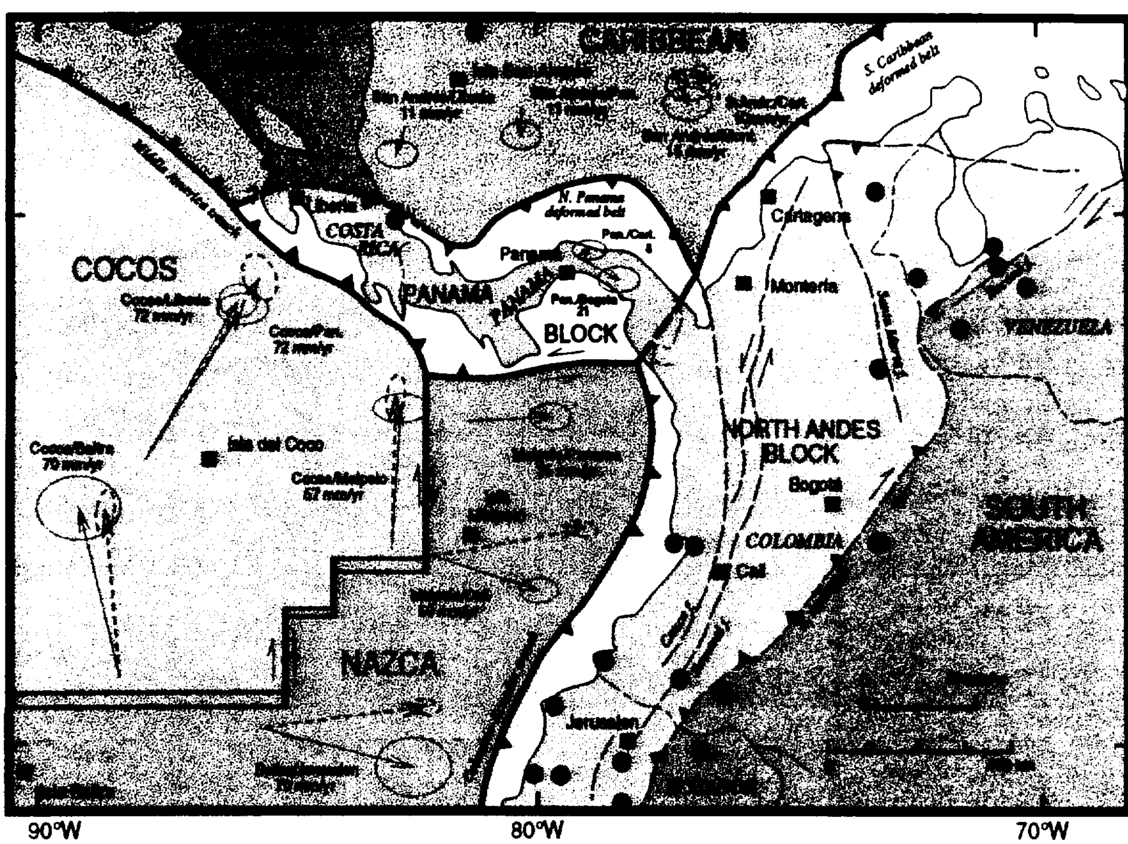
J. Kellogg[1], H. Mora[2], R. Trenkamp[1], J. Freymueller[3], and T. Dixon[4]
[1]University of South Carolina; [2]Ingeominas, Colombia; [3]University of Alaska at Fairbanks; [4]University of Miami

Displacement rates have been determined for the wide plate boundary in Central And South America (CASA) from GPS measurement campaigns in 1988, 1990, 1991, and 1994. GPS measurements suggest the existence of a rigid Panama arc microplate. The Panama arc is colliding eastward with the Northern Andes at about 20 mm/yr. The GPS measurements also show that the Panama arc is moving northward relative to the stable Caribbean plate. About 6 to 12 Ma the Panama arc arrived at the northwestern margin of South America. The arc-continent collision eventually formed a land bridge between the Americas, and closed the Pacific-Caribbean seaway. Features of the active arc-continent collision include seismicity, crustal thickening, and shortening distributed across a wide plate boundary. Shortening normal to the suture zone extends 500 km into the continental crust. Over 150 km of collision-related crustal shortening formed the Eastern Cordillera of Colombia.

Rapid subduction is taking place at the Ecuador (70 mm/yr) and Colombia (>50 mm/yr) trenches. The relative motions of the larger plates are in agreement with the predictions of the NUVEL-1 global model. However, deformation in the plate boundary zone is not addressed by global models. Earthquake focal mechanisms, offset glacial moraines and Quaternary thrust faults suggest that the oblique Nazca-South America convergence at the Colombia-Ecuador Andean margin is partitioned into components of right-lateral slip parallel to the margin and crustal shortening perpendicular to the margin. GPS measurements show that the North Andean block is moving approximately 6 mm/yr northeastward relative to stable South America. This right-lateral shear is taking place on northeast-trending faults which originate in the Gulf of Guayaquil.

Slow amagmatic Caribbean subduction beneath the Northern Andes, inferred from active folding in the South Caribbean deformed belt (SCDB), a southeast-dipping Wadati-Benioff zone, and seismic tomography, is supported by GPS measurements (10-15 mm/yr). Measurements also show significant Caribbean convergence at the 95% confidence level with Costa Rica (11 mm/yr) and Panama (11 mm/yr).

Unresolved problems include apparent locking of the subduction zones in Ecuador, Middle America trench (Costa Rica), and South Caribbean deformed belt (Colombia). Also unresolved are the details of deformation within the North Andes and the placing of significant constraints on the partitioning of slip on major faults. The on-going 1996 measurements will densify the network to address these problems.



Kinematics of the New Zealand plate boundary

C. Meertens[1], R. Walcott[2], T. VanHove[1], and J. Beavan[3]
[1]University Corporation for Atmospheric Research/University Navstar Consortium; [2]Victoria University, Wellington New Zealand; [3]Institute of Geological and Nuclear Sciences, New Zealand

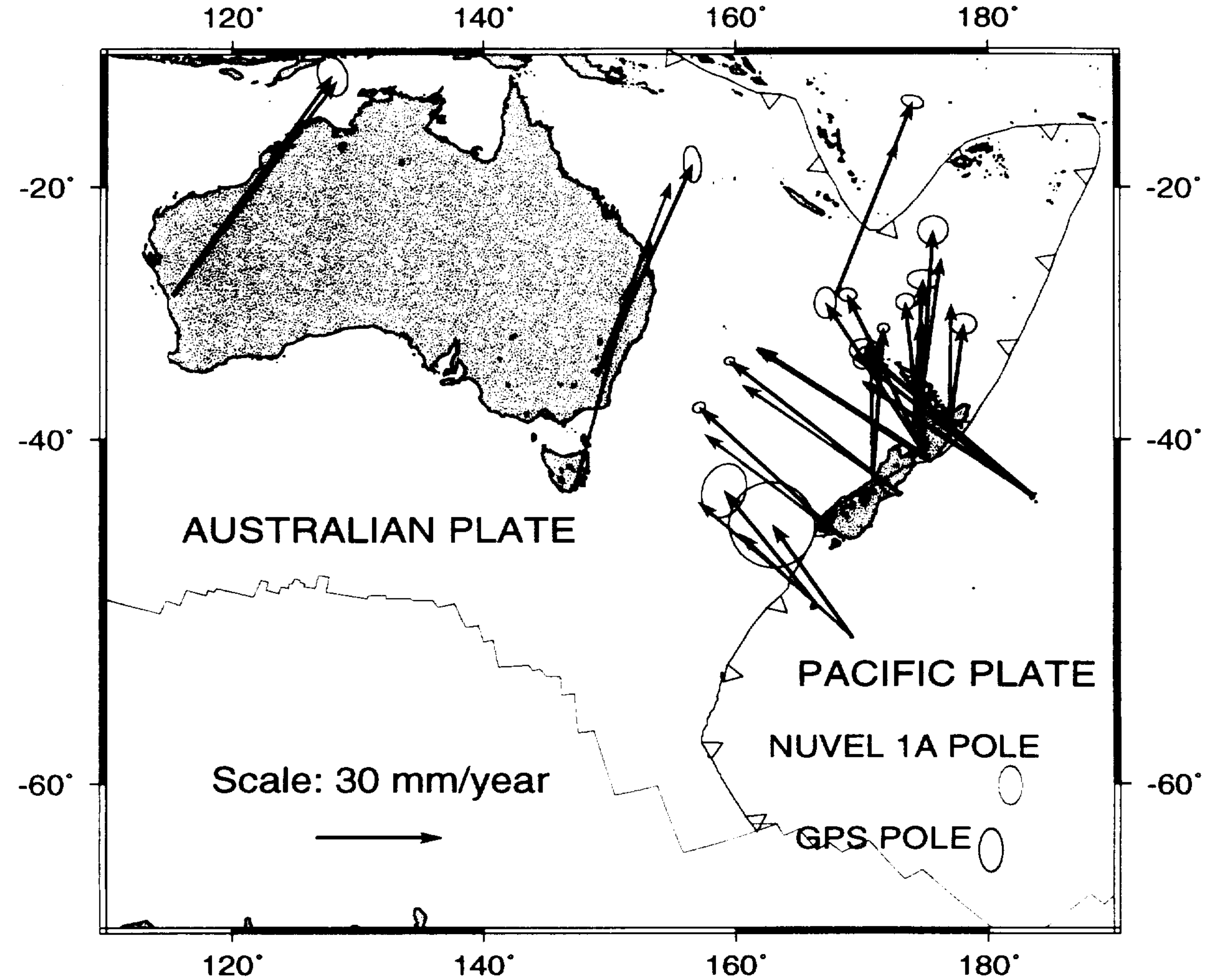


Figure 1. GPS-determined velocities (small arrows with one-sigma error ellipses in black) compared with NNR-NUVEL1A model based on geologic and earthquake slip vectors (red arrows) across the Australian-Pacific plate boundary. GPS data were acquired in 1992 and 1995 field campaigns. The Euler pole of rotation determined in this study is plotted with the NNR-NUVEL1A pole.

One of the remarkable findings from space geodetic observations over the last two decades has been the general agreement of contemporary plate motions with those predicted from time-averaged plate tectonic models derived from a global inversion of sea-floor spreading directions and rates, strikes of transform faults and slip vectors orientations from earthquakes.

In order to test the most recent plate model, NUVEL-1A, at the Australian-Pacific plate boundary and the possibility of a change in the rate or position of the Euler plate motion pole over time, a regional cooperative GPS survey was conducted on the islands in and around New Zealand (see figure). The plate boundary here is of particular interest because since it is a non-spreading boundary and there are complications in interpreting the earthquake slip vectors, the Australian-Pacific Euler vector is predicted only indirectly from a circuit of data from other plate boundary pairs. This pole is therefore inherently less well constrained than other major poles in NUVEL-1A.

The resulting GPS velocities are compared with NNR-NUVEL1A vectors in the figure. A fit of the GPS velocities gives an Euler vector of -62.9±1.0 N, 180.2±1.0 E with angular velocity of 1.09±0.05 degrees/Myr (see figure, lower right). This GPS-derived pole is comparable in Longitude and rate, but several degrees south of the NNR-NUVEL1A pole. This regional estimate is also 4 degrees west of recent estimates from global space geodetic observations at more distant and widely separated global sites. These results suggest a southward migration of the Australian-Pacific pole of rotation over the past few million years. In order to refine future plate motion estimates of the Pacific plate and to improve global tracking, permanent GPS stations were installed at the Chatham Islands and at Auckland as part of this project.

Kinematics and dynamics of continental lithosphere in the eastern California shear zone: Constraints from GPS geodesy and geophysical modeling

M. Miller[1], E. Humphreys[2], R. Dokka[3], and F. Webb[4]

[1]Central Washington University; [2]University of Oregon; [3]Louisiana State University; [4]Jet Propulsion Laboratory

In 1991, a high precision GPS geodetic network was installed to measure transform-related deformation partitioned from the Pacific - North America plate boundary northeastward through the Mojave Desert via the Eastern California shear zone to the Walker Lane. The onset of the Mw=3D7.3 June 28, 1992, Landers, California earthquake sequence within this network poses unique opportunities for continued monitoring of regional surface deformation related to the culmination of a major seismic cycle and characterization of the dynamic behavior of continental lithosphere during the seismic sequence and post-seismic transient deformation. Continued geodetic measurements will further allow characterization of secular strain in the Eastern California shear zone and its role in the kinematics of a continental transform.

We use integrated GPS geodetic and geologic studies to characterize deformation in the Mojave Desert region and related structural domains to the north, and geophysical modeling of lithospheric behavior constrained by these and continued measurements. Continued measurements will provide much needed data on far-field strain accumulation across the region and on the dynamic behavior of continental lithosphere during and following a large earthquake, forming the basis for kinematic and dynamic modeling of secular and seismic cycle deformation.

GPS results from the western Walker Lane belt constrain motions within the northern part of the Eastern California shear zone and the Sierra Nevada block. Data from 1991-1993 indicate approximately 25+/-4 mm/yr of west-northwestward displacement between the Funeral Mountains and the western Sierra Nevada. Nearly 24 mm/yr are in the direction of Pacific-North America relative plate motion. Results for the 1993-1994 epoch are somewhat slower, accounting for 15+/- 5 mm/yr across the same baseline.

The velocity field in this region during both epochs records displacements that lie counterclockwise from the generally NNW striking faults, indicating a dilational component that is geologically expressed as Basin and Range topography. During 1991-1993, approximately 8+/-4 mm/yr of relative displacement occurred on faults of the Death Valley - Furnace Creek fault zone or elsewhere in Death Valley, agreeing with the long term geological estimates of 5 to 10 mm/yr. Approximately 6+/-6 mm/yr occurred between the Panamint Range and the Darwin Plateau, presumably on the Panamint/Hunter Mountain fault. Another 11+/-6 mm/yr occurred within Owens Valley, along the Owens Valley and Sierra Nevada range front fault systems. Rates for 1991-1993 may have been anomalously high due to transient deformation in the wake of the 1992 Landers earthquake. The rates on these shorter baselines were proportionally smaller during 1993-1994, at 1, 7, and 8 mm/yr respectively. These results differ magnitude, but not direction, from previous estimates of cumulative slip across the region that are based on geological data and VLBI.

The most important conclusions from this modeling are that Basin and Range extension is confined only to the Walker Lane Belt in the Owens Valley region, that the Garlock fault is less active than the 7 mm/yr commonly assumed (less than 4 mm/yr), the southern extension of the Owens Valley fault into the China Lake region is more active than commonly thought, and that most of the eastern California Shear zone trends across the Mojave east of the MOJAVE geodetic site. This work is producing well-resolved maps of the regional tectonic patterns, and is providing the far-field constraint needed for dynamic modeling.

Dynamics of inter-earthquake deformation. The visco-elastic relaxation response of the Landers earthquake is the best (and only strike-slip) earthquake with enough geodetic data available to model the coupling between the elastic upper crust and visco-elastic lower crust. We have extended our code recently to handle the gravitational effects (e.g., bulge suppression) and are testing this code against cases for which analytical solutions exist. Between now and the end of summer we will be modeling observed geodetic displacement functions excited by the well-constrained Landers slip function. Both a short-duration relaxation signal (seen in the data) and a long-duration relaxation (required by the long repeat time) presents information that is anticipated to limit greatly the range of admissible Earth structures.

Geodetic measurements across the Pacific - North American plate boundary in Alaska

J. Sauber[1], T. Clark[1], and S. Nerem[2]

[1]National Aeronautics Space Administration, Goddard Space Flight Center; [2]University of Texas, Austin

Among the clues critical to understanding the dynamics of the subduction zone process is a knowledge of the rate and orientation of ongoing distortion in the overriding tectonic plate. These parameters can be inferred from topography and stress release in earthquakes. We can measure such distortion directly using repeated, precise, space-based measurements of position. The Alaska-Aleutian subduction zone has a significant portion of the overriding plate accessible for geodetic measurements in southern Alaska. Since subduction of the Pacific plate beneath the North American plate occurs by variable styles in different regions of Alaska it provides a natural laboratory to study the subduction zone process.

GPS measurements were made in Alaska in June of 1993 and 1995 (See Figure). These measurements build upon the earlier geodetic VLBI (very-long-baseline-interferometry) measurements made between 1984 and 1990 as part of the NASA's Crustal Dynamics Project. The GPS measurements were made at approximately 25 sites across the oblique subduction plate boundary zone in southern Alaska and across Kodiak Island (white diamonds in the Figure). Southern Alaska has not had a large earthquake since 1899 and is thought to have the potential for a large earthquake in the next 20 years. The Kodiak Island segment of the plate boundary has had large earthquakes, on average approximately every 60 years, and this segment ruptured in the great 1964 Prince William Sound earthquake. Earlier geodetic, geologic, and tsunami data have been used to invert for a detailed fault slip model for the 1964 earthquake [Holdahl and Sauber, 1993; Johnson et al., 1996]. Also, the offset of the VLBI Cape Yakataga site has been used to estimate the average slip during the 1987-1988 Gulf of Alaska earthquakes (M=6.9, 7.6, 7.6) [Sauber et al., 1993].

Rates of deformation (1984-1993) have been estimated from a combination of VLBI and GPS data in southern Alaska [Sauber et al., 1994] and are given for two sites in the figure. These results have been used to test alternative tectonic models. With the denser station distribution we will be able to constrain tectonic models in the future. The results of this study will provide important input to evaluate seismic hazard in Alaska.

Southern Alaska topography and sites surveyed with GPS in June 1993 and June 1995. The GPS sites are shown by thewhite diamonds. The faults of southern Alaska are shown by solid red lines. The sites that were previously occuppied with VLBI are labeled in yellow and are YAKA=Cape Yakataga, KODI=Kodiak Island, SOUR=Sourdough, GILC=Gilcreek. The rate of deformation at YAKA is 37 mm/yr at N34W and at Kodiak it is 9 mm/yr at N56W.

GPS geodesy using sea floor monuments

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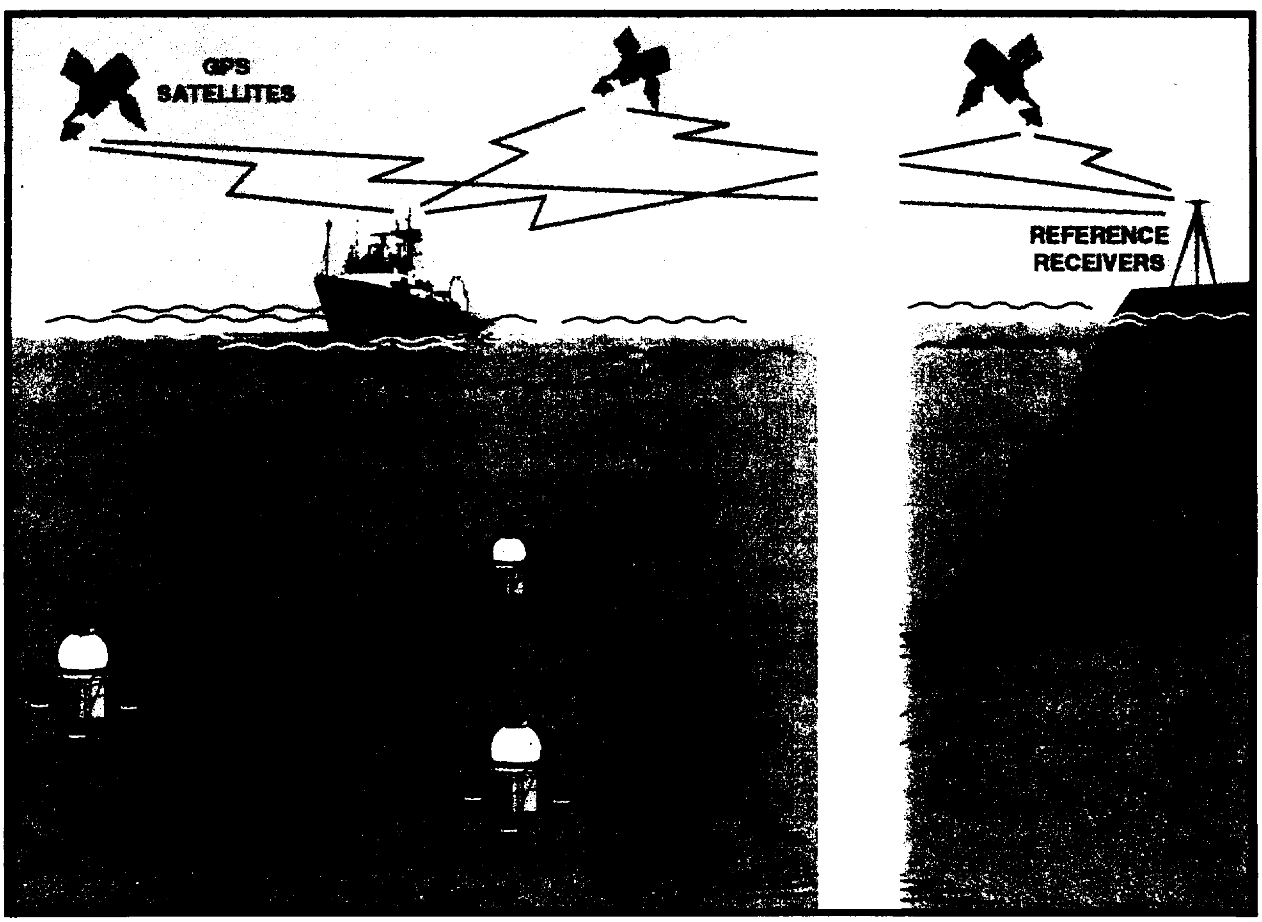
[1]Scripps Institution of Oceanography; [2]Geologic Survey of Canada; [3]Jet Propulsion Laboratory

Creation and destruction of the Earth's crust takes place on mid-ocean ridges and seafloor trenches. Until now, studies of these processes have not been amenable to global geodetic measurements. We have been developing a method for using the extensive range and centimeter-level precision of GPS techniques in conjunction with precise acoustic ranges to measure the motion of seafloor reference marks.

Seafloor arrays of precision acoustic transponders (PXP's) provide the primary reference points on the ocean floor (see Figure). Array internal geometries are determined by near bottom surveys. GPS data are recorded once per second at the three antennas on the ship, and at one or more reference stations ashore, while the PXP's are interrogated from the hull-mounted transducer. Several hours of GPS and acoustic ranging data suffice to determine the horizontal location of the center of the PXP array with cm-level precision. As long as the ship remains near the center of the array, changes in sound speed affect all the measured ranges in the same way and have little effect on the estimates of the horizontal coordinates of the array center [Spiess, 1985].

Since 1991, with support from NASA's DOSE Program and the Pacific Geoscience Centre, we have maintained an array of at least four PXP's just seaward of the Cascadia Subduction Zone (48-11N, 127-11W). In 1994, with additional support from NSF, we began observations on the Juan de Fuca Ridge (44-40N, 130-22W) with three PXP's on the Pacific plate and three on the Juan de Fuca plate. Initial analyses show a spread in the residuals between individual observed and modeled data are +/- 5 cm at any instant, but with a superposed +/- 20 cm coherent variation at internal wave periods [Spiess, et al., 1994]. With introduction of Kalman filtering to allow modeling of the sound velocity variations as time-varying functions, and additional scheduled observation epochs, this approach should produce useful measurements of seafloor deformation.



Catching earthquakes with GPS

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Most GPS networks installed to date by the geophysical community have been designed to study plate motions or plate boundary processes, rather than specifically to measure earthquake displacements. However, it is in the nature of plate boundaries that geodetic stations will sometimes be close enough to earthquakes that coseismic displacements will be detected.

The 1992 Landers and 1994 Northridge earthquakes in California represent the best examples of the ability of GPS to detect coseismic motion. However, there have been many other cases worldwide, some leading to far-reaching conclusions. These events can be both a bonus in providing coseismic and postseismic phenomena for study, and also a bane in that they affect, at least for several years, the interseismic strain accumulation that the network was originally designed to measure.

In the case of the 1993 Mw 7.8 Guam earthquake, GPS data from 14 sites on Guam was used to demonstrate that the quake was an interplate thrust event [Beavan et al., 1993, 1994]. This result has been subsequently supported by seismological studies [Campos et al., in press]. The occurrence of the Guam earthquake indicates that the southern end of the Marianas subduction zone is strongly seismically coupled. This observation has led to a new model for the dynamics of subduction zones that describes more than 80% of subduction zones worldwide [Scholz and Campos, 1995].

In another study, GPS data together with a partial analysis of the aftershocks of the 1994 Mw 6.9 Arthurs Pass earthquake in New Zealand, suggested that this earthquake occurred on a left-lateral "cross-fault", the first well-documented such event in New Zealand [Robinson et al., 1995; Arnadottir et al., 1995], and similar to the many left-lateral cross-faults in southern California. More recently, body-wave and surface-wave inversions have suggested a rather simple pure-thrusting event. Work is ongoing to reconcile these apparently incongruous results. This study provides an excellent example of how geodetic and seismological studies must work side by side to obtain the fullest understanding of earthquake sources [Abercrombie et al., 1996].

In the case of the Arthurs Pass earthquake, which occurred within a zone of transition between a predominantly strike-slip regime to the north and a largely continental collision regime to the south, the correct interpretation of the quake will probably be of great importance to our understanding of this transition zone and of the mechanisms responsible for the uplift of the Southern Alps.

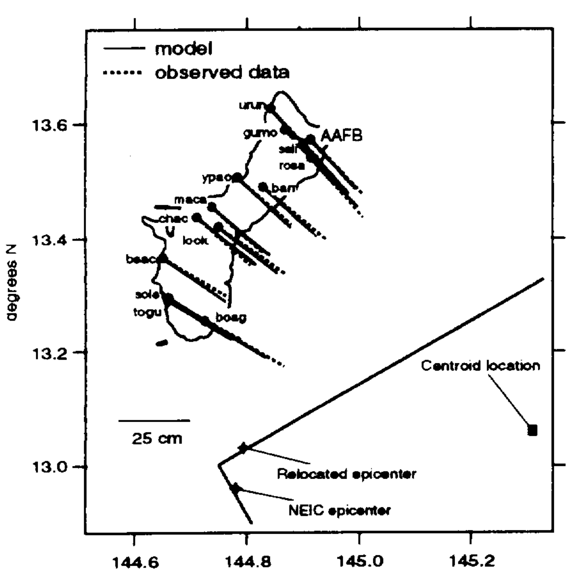

Figure 1. Guam earthquake observed (blue) and modelled (red) displacements for shallow-dipping plate interface thrust whose surface projection is outlined in green.

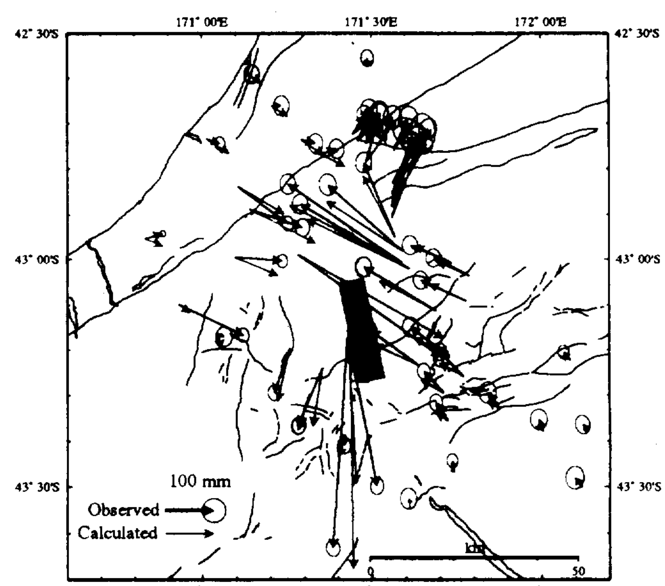

Figure 2. Observed and calculated coseismic displacements 1992 - 1995. Observed (blue) and modelled (red) displacements for Arthur's Pass earthquake with surface projection of model fault shown in yellow and green. The fault consists of roughly equal thrust and left-lateral components with about 90% of the moment release in the northern third (yellow shading). Figure courtesy of T. Arnadottir.

GPS and the potential for great subduction zone earthquakes: New Zealand

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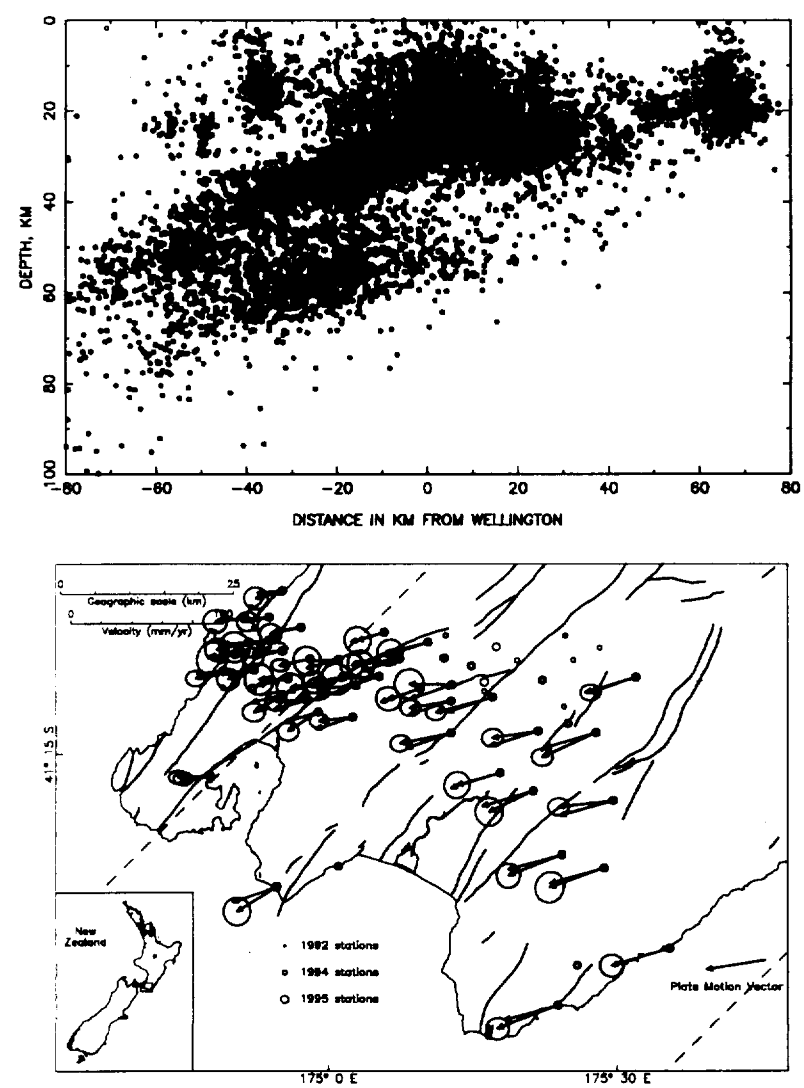
GPS networks in subduction environments allow us to understand strian buildup in thrust boundary zones. This knowledge contributes both towards a basic understanding of the kinematics and dynamics of the subduction process as well as towards our ability to assess seismic hazard.

In New Zealand the Pacific plate subducts obliquely beneath the North Island and the northern South Island along the Hikurangi margin - the southern continuation of the Tonga-Kermadec subduction zone. In the absence of large historical subduction interface events the state of coupling and the resulting seismic hazard due to this type of event has been unknown, though there is well-documented palaeoseismic information on a series of right-lateral strike slip faults that accommodate at least part of the transcurrent motion within the overriding plate. Whether slip on the subduction interface was involved in the great 1855 Wairarapa earthquake that broke one of these strike slip faults remains an open question. We have made repeat GPS measurements across the southern end of the North Island to address the state of coupling of the Hikurangi subduction interface in the vicinity of Wellington, New Zealand's capital city. Initial inversion of the 1994-95 deformation data by non-linear least squares techniques (see Figure) suggests that the interface is strongly coupled and that the potential for major subduction events in the Wellington region is real [Darby et al., 1996].



The top figure shows the seismicity profile. Lower figure shows observed velocity (with 1 sigma error ellipses) measured by GPS over a 1-year interval, compared with model. With the dip and depth of the locked zone constrained in the inversion by microseismicity information, the surface projection of the locked zone is shown by the dashed lines.

GPS and the potential for great subduction zone earthquakes: Alaska

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Because it is usually impossible to make geodetic measurements immediately seaward of a subduction zone, GPS can be used to monitor strain induced in the overriding plate caused by the coupling of the colliding plates at the subduction interface. The GPS data allow us to discriminate between the elastic models used to describe the interseismic strain accumulation.

The Shumagin seismic gap in the western Alaska Peninsula is one of the few gaps in the set of great earthquakes that ruptured the Alaska-Aleutian subduction boundary between 1938 and 1965. There has been ongoing discussion over the past 20 years as to whether this gap represents a zone almost ready to break in a major earthquake or a zone where subduction proceeds either aseismically or with only moderate earthquakes. Geodetic work by Lamont-Doherty, and particularly by the USGS, in the 1980s demonstrated that the latter seems to be the case - strains in the overriding plate are almost an order of magnitude smaller than predicted by fully coupled plate interface models [Lisowski et al., 1988; Larson & Lisowski, 1994]. To investigate whether this phenomenon continues to the northeast and southwest we measured two additional profiles (Figure 1) with GPS in 1993 and 1995 [Beavan, 1995]. The results, shown in Figure 2 in terms of modelled and observed horizontal velocities perpendicular to the trench, show clearly that in the northeastern network strain is accumulating in accord with a fully coupled interface model, while in the southwest the contractional strain rates are even lower than in the Shumagins. The region of apparent low seismic coupling therefore extends at least a couple of hundred km southwest of the Shumagins, more or less throughout the region that did not break in the 1938-1965 series of quakes.

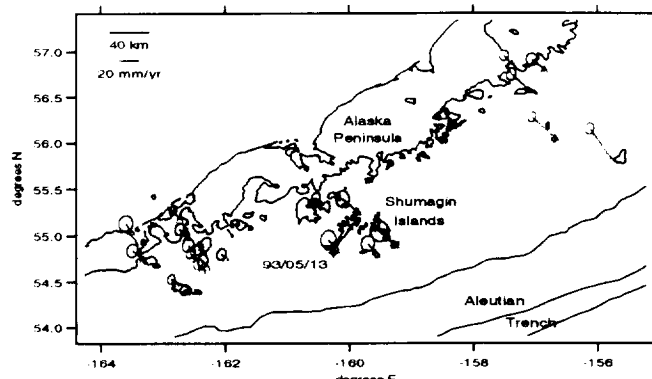

Figure 1. Location of Shumagin GPS transect, with Semidi transect to the NE and Sanak transect to the SW.

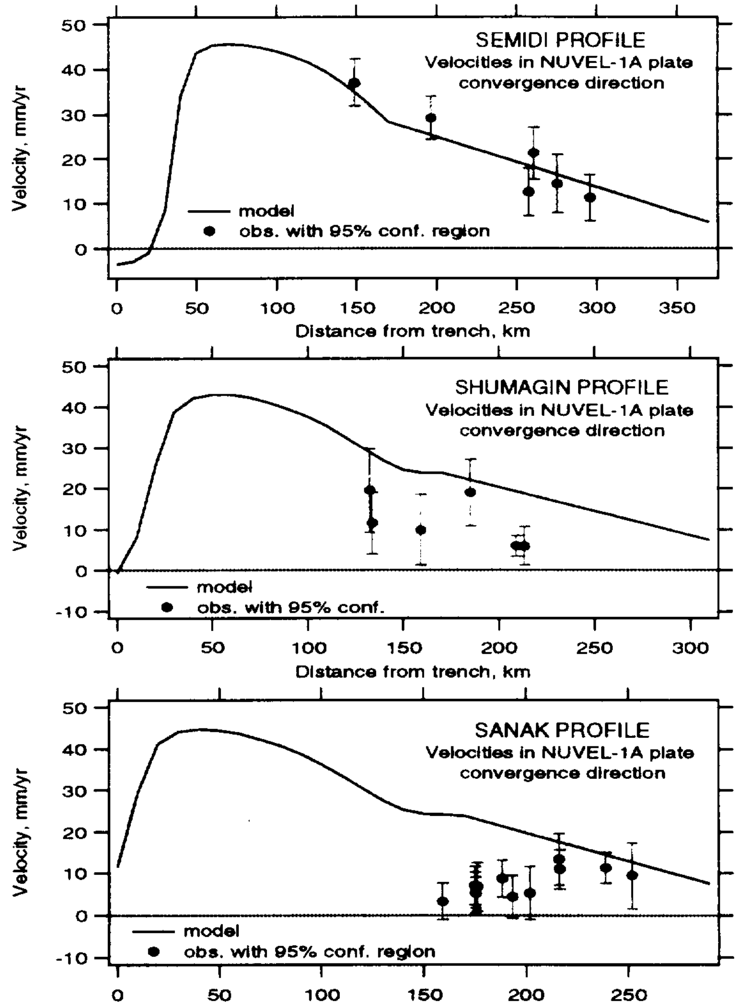

Figure 2. Observed horizontal velocities parallel to plate motion direction compared with model assuming fully coupled plate interface.The Semidi area (a) appears fully coupled, while the Shumagin area (b) is partly coupled and the Sanak area (c) appears completely uncoupled, with apparent extensional strain in the overriding plate.

Strain rates in the India-Eurasian collision zone

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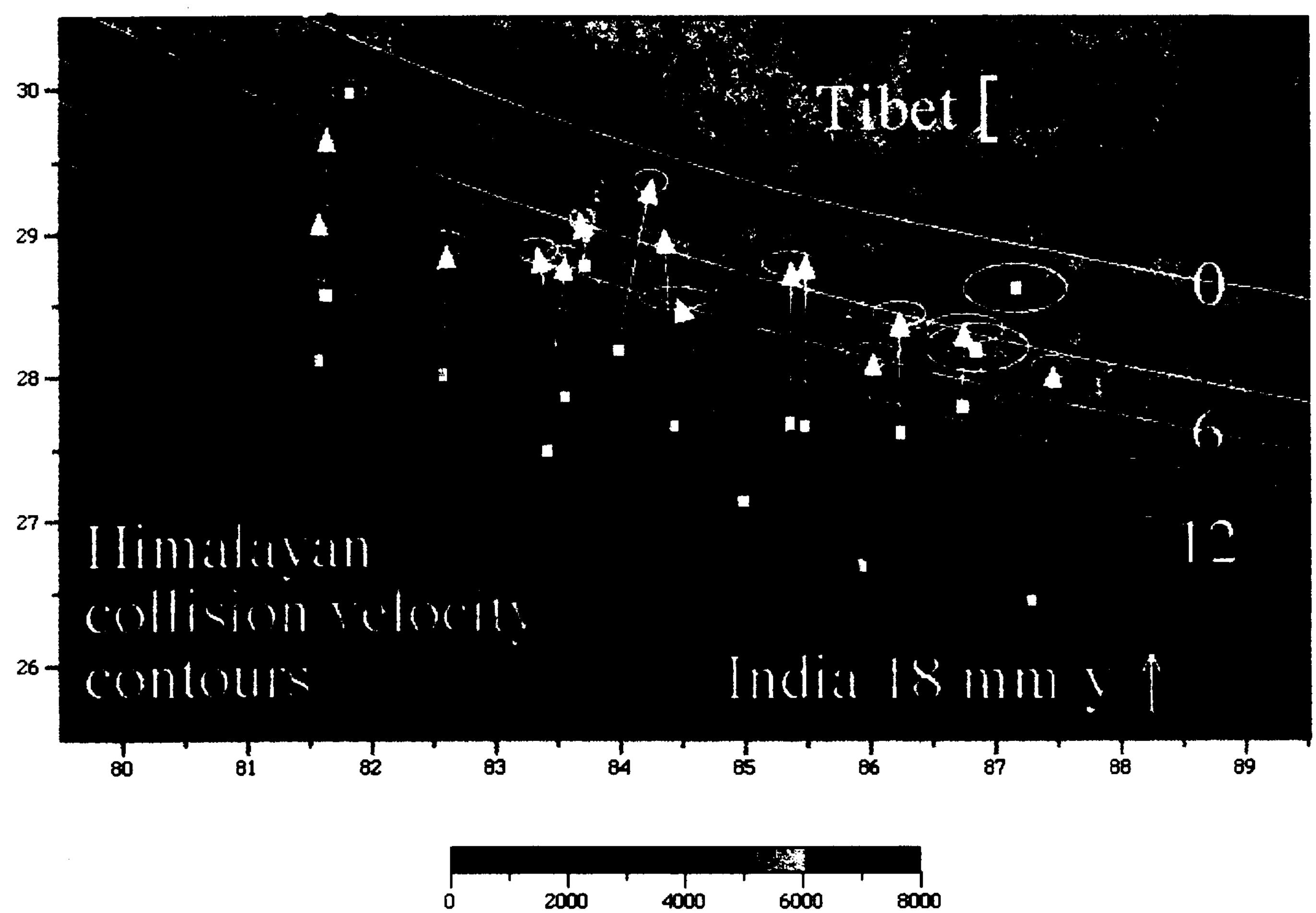
For the past 25 million years, India has been colliding with Asia. The collision has consumed an entire ocean, several island arcs and an unknown fragment of the continent of India, resulting in the elevation of the Tibetan Plateau to an average height of 5 km. The instantaneous rate of collision holds the clue both to the stability of the Tibetan plateau and to the recurrence intervals of great earthquakes in the Himalaya. Hitherto, the collision rate has been poorly known.

In order to determine the collision rate, we began GPS measurements in Nepal and Tibet in 1991. We remeasured parts of the array in 1992, and 1994, and remeasured all points in November 1995 collaborating with French scientists and the Nepalese Survey Dept. We have also collected GPS data throughout India, collaborating with scientists in Bangalore led by Vinod Gaur.

Shown below are surface velocity estimates holding Tibet fixed. The error ellipses are 95% confidence regions. North-south convergence is evident over the 200 km north-south span of the network, although 80% of the convergence occurs within a 100 km wide zone centered 30 km south of the Greater Himalaya. Maximum surface strain rates are 0.2 micorstrains per year. Subsurface convergence is approximately north-south at a rate of 21+/-2 mm/yr based on sibple elastic models of the collision. The apparent north-south narrowness of the velocity field in E. Nepal requires creep beneath the southern edge of the Tibetan Plateau at 10-15 km depth.

In order to study this tectonic region more accurately, we are now introducing permanent tracking systems in Nepal. The data are stored continuously and are periodically downloaded (daily or weekly via telemetry and internet). The first is in position near Kathmandu and a second was installed at Namche near Mt. Everest in April 1996. More permanent sites are planned to constrain the subsurface geometry of the collision process.



Postseismic GPS observations of the Northridge earthquake

A. Donnellan[1] and G. Lyzenga[2]
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The moment magnitude 6.7 Northridge earthquake occurred in the San Fernando Valley, southern California on January 17, 1994 [Jones et al., 1994]. The earthquake was a thrust event on a south-dipping fault that ruptured from about 20 km to 5 km depth on an 18x24 km plane [Wald et al, 1996]. GPS measurements were collected in the region prior to the earthquake, providing both pre-seismic velocities and co-seismic displacements from the earthquake [Donnellan et al., 1993a,b; Feigl et al., 1993; Hudnut et al., 1996]. The maximum observed uplift from the earthquake was 42 cm and the maximum horizontal displacement was 22 cm [Hudnut et al., 1996]. Sites in the Ventura basin GPS network, which has been intermittently occupied since 1987, and additional stations have been reoccupied several times following the Northridge earthquake between January 1994 and August 1995.

We find that, in general, stations within 2 fault dimensions of the rupture plane have continued to move in the same direction as their co-seismic sense of displacement. Stations north of the rupture plane have continued to move north (e.g. Figure 2), while stations to the south have continued to move southward. Stations east and west move eastward and westward respectively while stations on the nodal plane show no post-seismic motion. We have subtracted the pre-seismic station velocities (Southern California Earthquake Center, unpublished data) from the time series and attribute the residual observations to post-seismic motion. We also find significant uplift on the order of several centimeters (3-8) near the upper edge of the rupture plane.

The timescale of decay of an exponential fit to the observations is less than one year and is about 8 months at the station Castro Peak located southwest of the epicenter. We are unable to attribute post-seismic motions on this time scale to relaxation of a viscoelastic lower crust. A stiff lower crust is required to match the pre-seismic velocity field which is inconsistent with the rapid timescale of decay following the earthquake [Hager et al., manuscript in preparation]. Possible explanations for the rapid post-seismic motions include slip on either the rupture plane or downdip extension of the plane, nonlinear relaxation of the lower crust, or relaxation of a soft sediment layer in the upper crust.

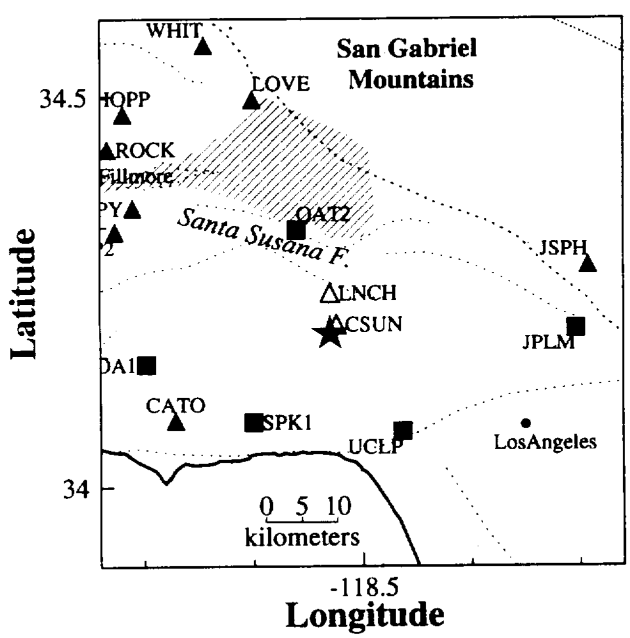

Figure 1. Location map showing the epicenter of the Northridge earthquake (star), epoch measurement GPS stations established prior to the earthquake (black triangles), epoch measurement GPS stations established following the earthquake (open triangles), and continuous GPS stations (squares). The hatched region marks the Ventura basin.

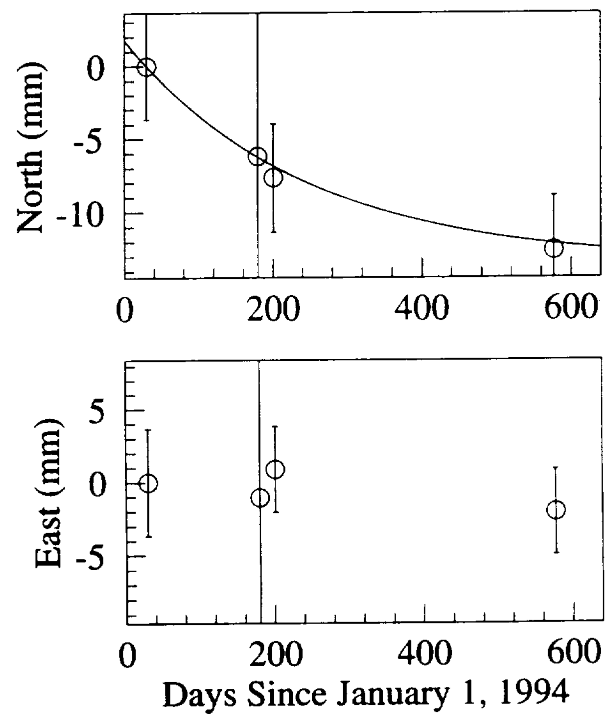

Figure 2. Residual time series of the Jet Propulsion Laboratory (JPLM) relative to Castro Peak (CATO). The predicted station positions based on the pre-Northridge velocities have been removed from the time series. Error ellipses are 95% confidence. The solid line on the upper plot shows the best fit exponential, which has a time constant of decay of 8 months (243 days). The sense of motion in the plot shows JPL moving south relative to Castro Peak.

Strain accumulation and shortening in the Central Andes

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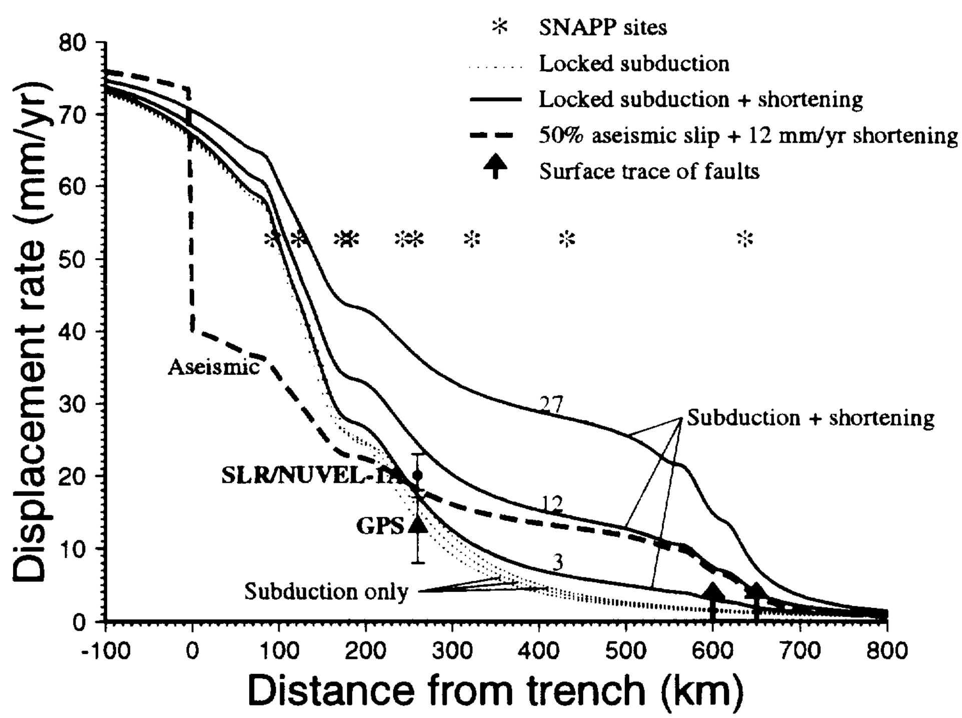
[1]University of Miami; [2]Northwestern University; [3]Memphis State University; [4]Carnegie Institution; [5]Instituto Geofisico Del Peru

Data from four permanent GPS sites in South America have been used to constrain models of Andean deformation: Arequipa (Peru), and three sites in stable South America: Fortaleza and Brasilia (Brazil) and Kourou (French Guiana) [Leffler et al., 1996]. We defined a stable South America reference frame by minimizing in a least squares sense the velocities of Fortaleza, Kourou, and Brasilia. The velocity of Arequipa relative to this stable South America reference frame is 13+/-5 mm/yr (all uncertainties are twice the standard error) in a direction N78+/-7E. This velocity reflects a combination of elastic strain accumulation associated with a locked Nazca-South America subduction zone, presumably to be released in a future earthquake, and crustal shortening across the fold and thrust belt on the eastern margin of the Andes. To separate these effects, we modeled the locked subduction zone as three segments with progressively steeper dips: 10 degrees to a depth of 15 km, 18 degrees from 15-35 km, and 26 degrees from 35 km to the maximum locking depth, using the boundary element modeling progam "3D-DEF" [Gomberg and Ellis, 1994] and the approach of Savage [1983]. By constructing models of elastic strain accumulation for both a fully locked and partly locked subduction zone, we can constrain the amount of Arequipa's motion that is due to shortening in the fold and thrust belt (see Figure). For a fully locked subduction zone, we found that shortening in the eastern Andes is constrained to 0-10 mm/yr, consistent with seismic moment release estimates of shortening. For a subduction zone with 50% aseismic slip, we found 0-18 mm/yr of shortening, consistent with seismic estimates and with some geologic estimates from cross section balancing but precluding one high rate (27 mm/yr) geologic estimate. With just one station (Arequipa) for constraint, we are unable to eliminate a no shortening model for the central Eastern Andes. Sites closer to the subduction zone and closer to the fold and thrust belt respectively will help constrain both the amount of aseismic slip at the subduction zone and the amount of shortening in the fold and thrust belt. The figure shows the relative location of sites in the NASA supported SNAPP (South America Nazca Plate Motion) GPS experiment that will help characterize the deformation along this part of the Nazca-South America plate boundary zone. The next campaign is scheduled for July 1996.



GPS and SLR/NUVEL-1A velocity data for Arequipa and two standard errors, compared to elastic half-space models for surface displacement. "Subduction only" refers to models for elastic strain accumulation on a locked subduction zone (locking depths 46, 50, and 54 km), convergence rate from NUVEL-1A (78 mm/yr) and all plate motion accommodated at the subduction zone. "Subduction + Shortening" assumes elastic strain accumulation as above locked to 50 km but with total slip partitioned between trench and two west-dipping thrust faults in the eastern Andes with surface traces 600 and 650 km from the trench each accommodating half the geologic shortening, taken as 3, 12 or 27 mm/yr. "Aseismic" is similar to the subduction with shortening model with 12 mm/yr shortening but with 50% of subduction zone slip accommodated aseismically. Asterisks are locations of GPS sites from SNAPP, a regional campaign supported by UNAVCO.

GPS monitoring of the earthquake cycle in Costa Rica

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[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena; [2]OVSICORI, Universidad Nacional, Heredia, Costa Rica; [3]University Corporation for Atmospheric Research/University Navstar Consortium

The Costa Rica GPS project (Figure 1) is monitoring the deformation of the crust due to active faults at differing stages of the earthquake cycle. In 1991 a very large (M 7.7) earthquake occurred beneath the Caribbean side of Costa Rica in an area little appreciated for its seismic hazard. GPS measurements to determine the 3-dimensional and relative positions of geodetic sites were made 2 months prior to this event and were remeasured immediately after the earthquake to recover their coseismic displacements (Figure 2). These high precision GPS measurements in 3-D allowed for numerical models of the earthquake to be generated. Given the early success of the project, a program was developed to measure the deformation during the earthquake cycle in Costa Rica. Why Costa Rica? Costa Rica lies at a prime tectonic setting to observe seismic deformation. Off the western Pacific coast the Cocos Plate is diving beneath the Caribbean Plate (where Costa Rica lies) at among the highest rates in the world of 92 mm/yr. In addition the subduction of the Cocos ridge off the southern end of Costa Rica and the active thrusting associated with the large 1991 earthquake on the Caribbean side lend a richness in tectonic deformation uncommon to such a small area. Specifically, the Costa Rica GPS Monitoring project has a number of objectives:

- Quantify strain rates adjacent to Middle America Trench to define seismic deformation and hazard.
- Measure postseismic deformation across the Caribbean coastal region following the 1991 M 7.7 eq.
- In the context of defining the earthquake related strain a detailed understanding of the long-term motion of the Cocos Plate - Caribbean Plate - Panama Block (southern half of Costa Rica).
- Use continuously operating GPS receivers to monitor time-varying crustal strain.

Measurements to date include: 6 sites, 1991; 24 sites, 1994; 25 sites, 1996. In 1996 2 permanent sites were installed. A second permanent site on Pacific coast will be established in April 1996.

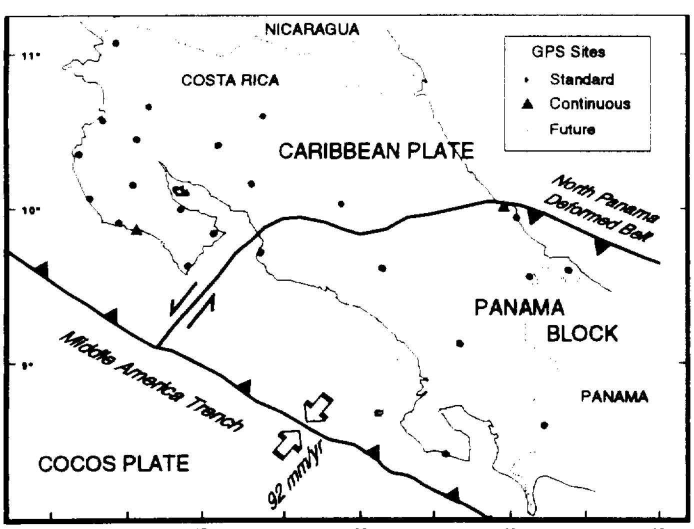


Figure 1. Tectonic map of Costa Rica with GPS sites.

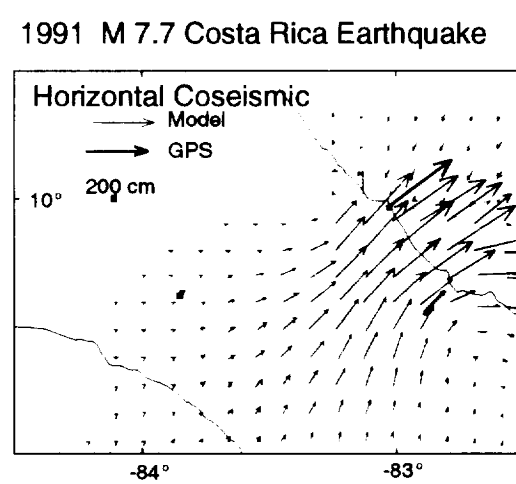


Figure 2. Horizontal GPS coseismic displacements and elastic model based on Harvard CMT focal mechanism for 1991 earthquake.

Expected geodetic deformation from blind thrust faults in the Los Angeles basin

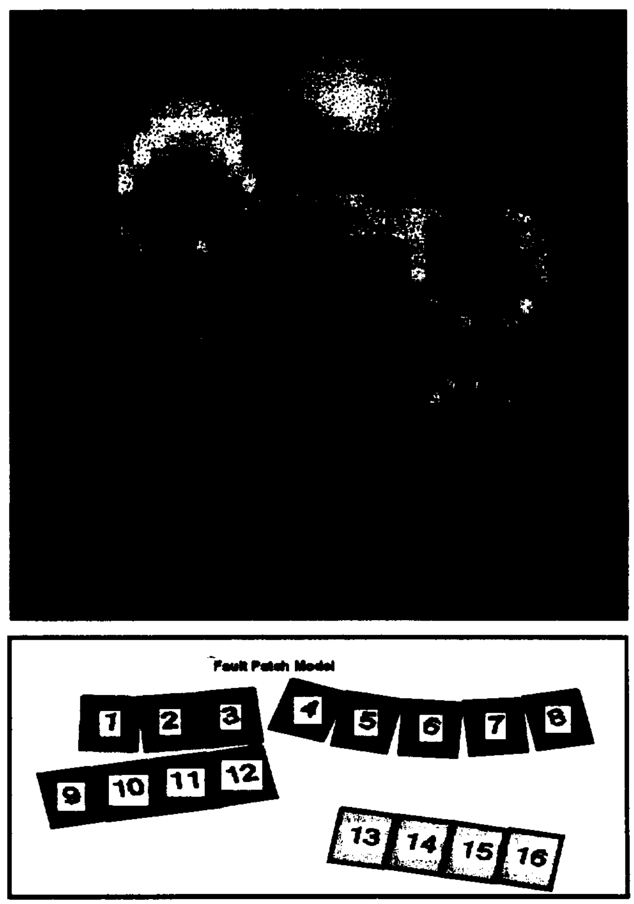
G. A. Lyzenga[1] and A. Donnellan[2]

[1]Harvey Mudd College; [2]Jet Propulsion Laboratory, California Institute of Technology

The distribution and activity of blind thrust faults and related tectonic structures in the vicinity of the Los Angeles basin have been the focus of much research on seismic hazard and the seismotectonic problem of how strain in southern California is accommodated in space and time. Understanding these problems is cited as a major motivation for continuous monitoring of a dense GPS geodetic array in the region. While detection of transient deformation events is a natural goal of such continuous monitoring, a potentially equally important product is a high-resolution "snapshot" picture of the spatial distribution of surface deformation.

Knowledge of the amplitudes, wavelengths and locations of fluctuations in the regional velocity field may provide insight into the history and distribution of slip on the faults that underlie and bound the basin. The expected geodetic signature of postseismic relaxation from hypothetical earthquake sequences are the subject of numerical modeling in this study. An assumed realistic distribution of blind thrust faults with specified characteristic rupture dimensions and repeat times are modeled in an elastic-viscoelastic half space. (The problem is inherently three-dimensional; equivalent elastic dislocation displacements derived from related two-dimensional viscoelastic finite element calculations are employed.) The figure shows typical results of one such model, which predicts fluctuation amplitudes of order 1 mm/yr with wavelengths comparable to the characteristic rupture dimension. While this level of residual motion is near the threshold of what is possible to detect with GPS, alternative models produce amplitudes and scales that vary over a wide range.

The required level of geodetic precision is important in order to reliably "see" plausible fluctuations and make geophysical inferences from them. These determinations will influence decisions regarding monument design stability, network density and other GPS design and processing issues. Given the required robustness of velocity field determination, the combined GPS and modeling results will potentially allow examination of: (a) characteristic spatial wavelengths of subsurface sources, (b) statistical estimates of viscoelastic relaxation times versus earthquake repeat time, (c) regions of aseismic and/or recent seismic slippage, (d) possible heterogeneities in crustal rheological properties.



Perturbations in the regional N-S velocity field caused by segmented fault activity. In this scenario, postseismic relaxation has a 100 year characteristic time, and fault segments have randomly distributed times to last failure between 0 and 1000 years. In the illustrated model, fault segment 15 moved most recently (22 years ago), segments 10 and 11 moved 90 years ago and segment 4 (just visible) moved 150 years ago. The velocity scale (red to violet) is +0.5 mm/yr. Bottom panel shows the relative locations of the fault patches.

Monitoring active volcanoes with continuous GPS measurements

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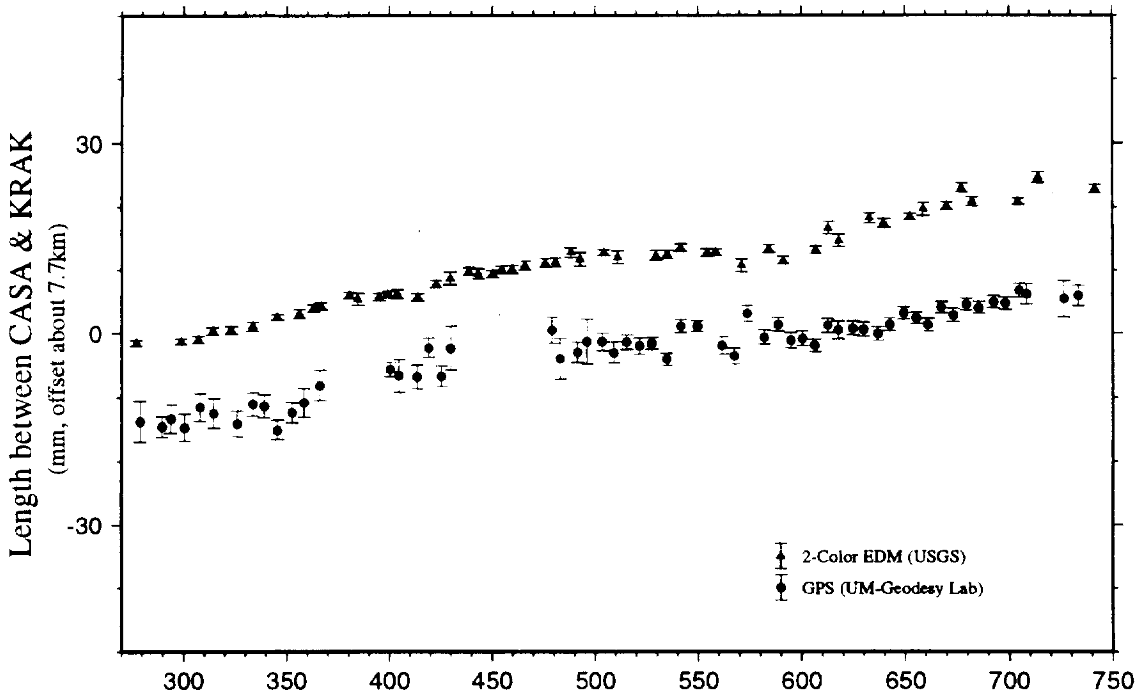
[1]University of Miami; [2]U. S. Geological Survey, Menlo Park, CA; [3]University of California, Santa Cruz; [4]OVSICORI-UNA, Costa Rica



GPS and two color EDM data from Long Valley Caldera. X-axis represents the days after Jan 1, 1994.

Measurement of surface deformation on active volcanoes may yield important information on magmatic processes at depth. In addition, since changes in surface strain rate near active volcanoes may precede volcanic eruptions by days to months, monitoring surface deformation may allow assessment of volcanic hazard. Geodesy is therefore a critical component of any monitoring program designed to understand magmatic processes, assess volcanic hazard, and perhaps predict eruptions at active volcanoes.

Continuous GPS measurements at Long Valley Caldera, an active volcanic region in east-central California, have been made on the south side of the resurgent dome within the caldera beginning in 1993. A site about 7.7 km away on the north side of the dome was added in late 1994. The data record ongoing volcanic deformation consistent with uplift and expansion of the surface above a shallow magma chamber. Measurement precisions (one standard error) are about 3-4 mm/yr in the vertical component and 2 mm/yr in horizontal components averaged over a given 12 month period. Three dimensional vector data from the two GPS stations define the depth (4.6+/-1.1 km) and location of the major center of inflation on the west side of the resurgent dome, in agreement with other geodetic techniques, and near the top of the seismically defined magma chamber. The figure shows the five day mean length between the two GPS stations based on analysis at the University of Miami, compared to the two-color laser measurements obtained by USGS from stations that are within a few tens of meters of the GPS marks. A slow down in the rate of expansion between days 500-600 (mid-May to mid-August, 1995) is apparent in both data sets.

Two continuously operating GPS stations were recently installed at Arenal volcano, an actively erupting volcano in Costa Rica with UNAVCO assistance. Seven months of preliminary data indicate rapid subsidence but small horizontal motions at two sites located several kilometers north and south of the summit. The large vertical and relatively small horizontal motions suggest the presence of both a deep (> 6 km) magma reservoir undergoing depletion and a shallow magma reservoir or dikes that may be expanding.

GPS and absolute gravity observations of crustal motion in Greenland

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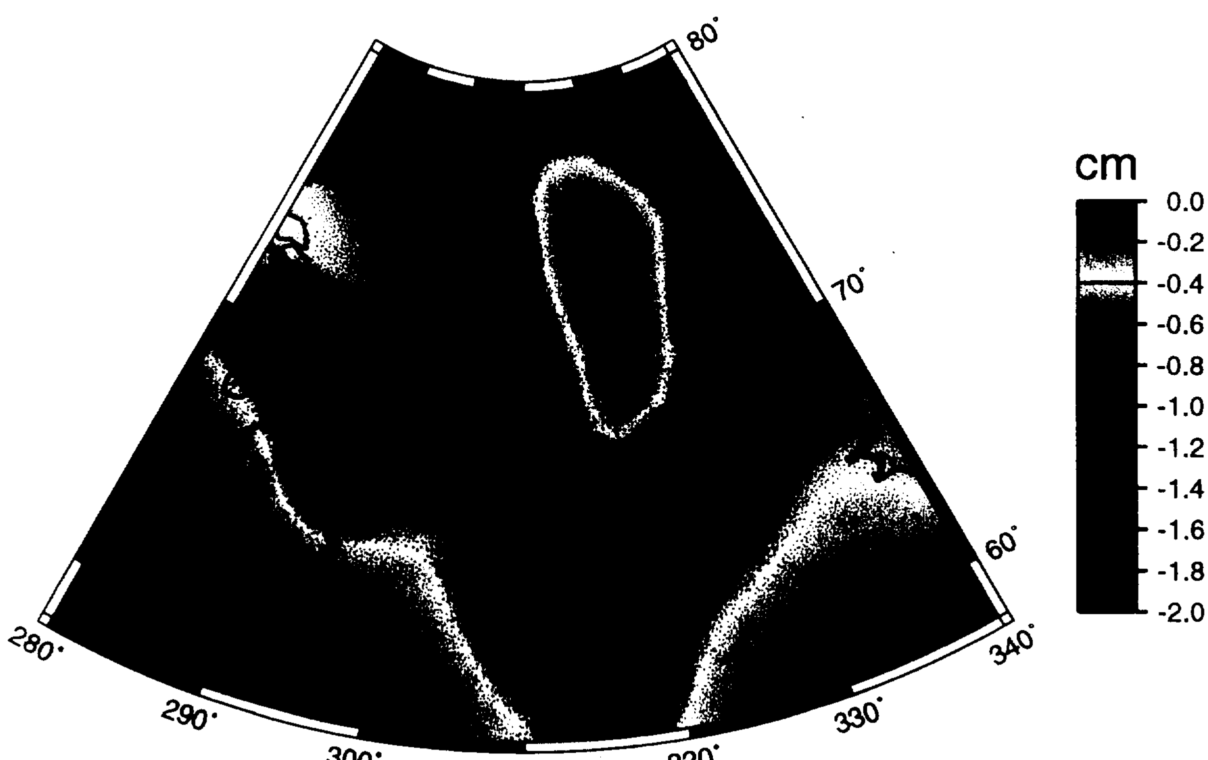
Tide gauge data indicate that global sea level has been increasing at a rate of about 1.5-2.0 mm/yr during this century. The effects of thermal expansion of the ocean, of melting continental glaciers, and of direct anthropogenic sources (eg. dams, groundwater extraction, etc.) are imperfectly known, but estimates of these effects suggest there must be some additional mechanism causing sea level to rise by anywhere from several tenths of a mm/yr to more than 1 mm/yr. Conceivably the source of this additional water is the decreasing volume of the Greenland and Antarctic ice sheets. But direct measurements of the mass balance of those ice sheets are inconclusive. For example, the most recent IPCC report [Warrick et al., 1995] concludes that the sea level rise from Antarctic ice could be anywhere between -1.4 mm/yr and +1.4 mm/yr, whereas that from Greenland is likely to be between +-0.4 mm/yr.

One possible means of constraining changes in polar ice is to make geodetic measurements of crustal uplift along the edges of the ice caps. Any change in the ice will load and deform the earth, with results that could be evident in observations of crustal displacements or of surface gravity. Our models suggest that uplift along the edge of either ice sheet could be up to 2-3 mm/yr or more in places. Seasonal fluctuations in grounded ice, which are of considerable interest to glaciologists, could cause seasonal signals in vertical crustal displacements with amplitudes as large as 10 mm around the edge of the southern third of Greenland.

In an effort to begin looking for these displacements, we established a permanent GPS site on the grounds of the SRI International facility near Kangerlussuaq, on the west coast of Greenland, in July 1995. Data are being retrieved across an internet connection to the SRI facility, and are being archived at NOAA. Absolute gravity measurements were also taken at the site during a two week period in July 1995. We plan to re-occupy the site with the absolute meter at regular intervals in the future. By combining the gravity and GPS measurements, we hope to be able to separate the effects of ongoing changes in ice, from the effects of the earth's visco-elastic response to past loading - including that from the Holocene de-glaciation [see Wahr, et al, 1995]. We plan to establish a similar GPS/absolute gravity site in Kulusuk, on the east Greenland coast directly across the ice from Kangerlussuaq, during the summer of 1996.



Greenland seasonal loading effect.

UNAVCO and the international GPS service: possibilities for collaboration and cooperation

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The International GPS Service (IGS) is an international infrastructure thatprovides services, data and products from continuous GPS stations to support geodetic and geophysical research activities, as well as government and civilian applications worldwide. (A map of current IGS sites is shown in the Figure.) The estimated 60-75 new fixed GPS sites being planned for installation over the next three years by UNAVCO community members represents a significant potential contribution to the global Earth science infrastructure. We encourage the UNAVCO community to help foster a closer, cooperative relationship with the IGS and to carefully consider how the UNAVCO facilities and member institutions can organize to contribute to the IGS infrastructure and activities.

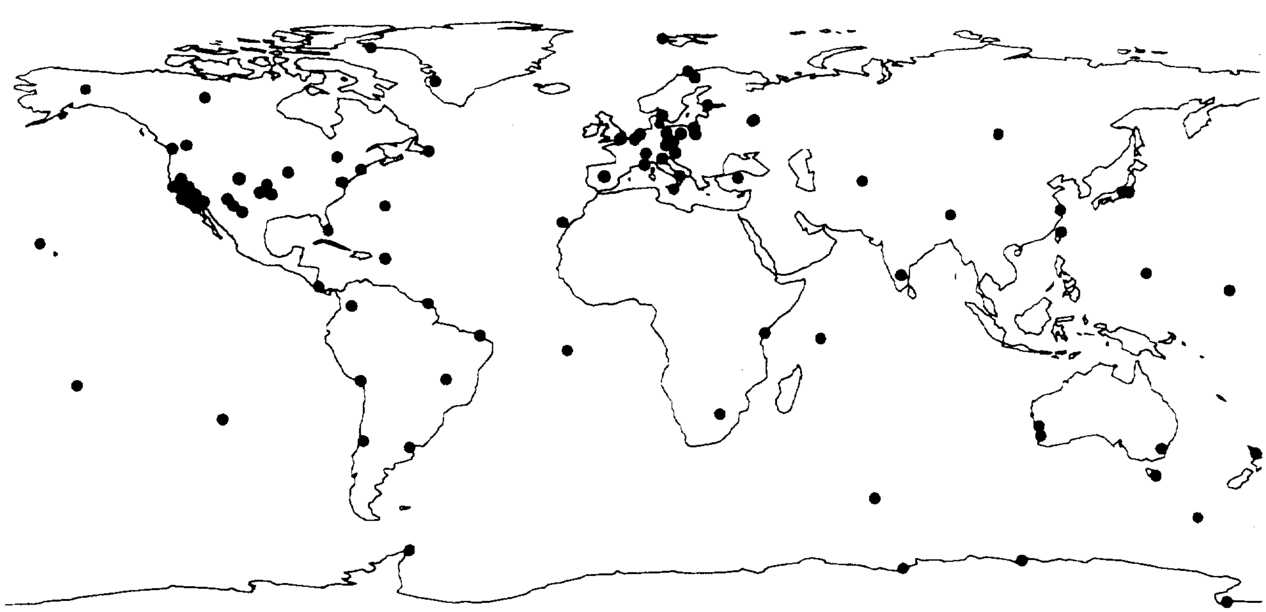
UNAVCO members and facilities are already very involved with the IGS in various capacities. The Scripps Orbit and Permanent Array Center (SOPAC), in addition to providing tracking data from Southern California sites, is one of the three Global Data Centers and one of the seven Analysis Centers of the IGS. The Boulder facility, in support of NASA activities, has assisted with the implementation of 14 tracking stations to date and continues to assist with the operation and maintenance of those stations. Additionally, many of the UNAVCO community members regularly contribute to the IGS through participation in governance, meetings, data sharing and other activities. The IGS Governing Board recognizes the important role that UNAVCO has played within the US scientific community and would encourage the UNAVCO community to strengthen its contribution to the global infrastructure by developing a cohesive approach to collaboration. A few examples of potential functions yet to be fulfilled by UNAVCO facilities and/or members include the following:

1) Operational Center(s) - UNAVCO facilities or member institutions install and directly operate fixed GPS stations or arrays and provide standardized data and operational information to the IGS.

2) Regional Data Center - UNAVCO facilities collect the GPS tracking data from Operational Centers, provide local archive and transmit appropriate data to the Global Data Centers, as well as promote and support the development of Operational Centers within the UNAVCO community.

3) Associate Analysis Center - UNAVCO facilities serve as an IGS Analysis Center for special projects (e.g., densification of the ITRF with regional measurements, address antenna and site calibration issues, etc.).

The UNAVCO community is encouraged to take steps toward formalizing its position within the IGS by sending a letter of intent outlining the roles and desired responsibilites to the IGS Governing Board.



Global Stations of the IGS Network

Antenna height effects in high-accuracy GPS observations

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In order to determine the effect of antenna height on GPS observation accuracy, we measured baseline length and height solutions for combinations of high (150 cm) and low (25 cm) antenna mounts. Antennas were positioned over monuments separated by 5 m at the Table Mountain site in Colorado. The site is located on flat alluvium and is free from obstructions above 5 degrees elevation.

We observed with low-low, low-high, high-low, and high-high antenna height combinations using Trimble SST antennas and Trimble SSE receivers. Antenna cut-off angles were 15 degrees. We computed ionosphere free daily solutions with and without tropospheric delays estimated every hour using Bernese software version 3.5. The tests are described in detail on the home page *www.unavco.ucar.edu.*

We found *plus* 14.9 mm vertical error for the high-low solution when tropospheric delays were estimated. The true baseline height and length were determined to an accuracy of 1 mm using optical and metal tape surveys. All GPS baseline length measurements were found to be accurate within 1 mm. Precisions of the GPS vertical and length measurements were less than 1 mm rms in all cases. Observed errors are listed in the table.

Changing the antenna heights from high-low to low-high changed the vertical error to *minus* 14.5 mm. Thus, vertical offsets in repeat surveys as large as 30 mm could result if inconsistent high-low antenna combinations were used.

We simulated the phase and amplitude of ground scattered multipath for 25 and 150 cm antenna heights. Near 15 degrees elevation we found 60 minute phase and amplitude modulation for low mounts, and 9 minute modulation for high mounts. Observed amplitude modulations in signal-to-noise ratios (SNR) recorded by the receivers were similar to the simulation results. This confirms that the vertical surveying error was generated by ground scattered multipath.

We also modeled the effect of tropospheric delays. We found that ground-scattered multipath and tropospheric delay are coherent over certain time intervals. This coherence is strongest for low antennas at low observation angles.

In separate tests, we found that ground-scattered multipath can be reduced by roughly 50% using 35-cm diameter choke ring antennas sold by geodetic GPS receiver vendors. These antennas have reduced gain at low and back angles.

In summary, ground scattered multipath from a combination of high and low antennas can cause vertical surveying errors as large as ±15 mm. Fortunately, vertical accuracy at the several mm level can be achieved using low-low or high-high antenna combinations.

For the highest GPS surveying accuracy and precision, high antenna mounts, choke ring antennas, and consistent antenna heights for repeat surveys should be used.

Observed GPS surveying errors using high (150 cm) and low (25 cm) antenna combinations with and without one hour tropospheric delay estimation.

Antenna heights	Number of days of observations	Without tropospheric estimation		With tropospheric estimation	
		vertical	length	vertical	length
low-low	3	-0.6	0.1	2.5	-0.1
low-high	4	1.3	-0.1	-14.5	0.8
high-low	4	-0.3	0.2	14.9	0.1
high-high	5	-0.6	0.2	1.9	0.6