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Annual Status Report

For the Period

March 1, 1987 - March 31, 1988

NASA Grant NAG 5-842

Intraplate Deformation, Stress in the Lithosphere and the Driving Mechanism for Plate Motions

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(NASA-CR-183121) INTRAPLATE DEFORMATION, STRESS IN THE LITHOSPHERE AND THE DRIVING MECHANISM FOR PLATE MOTIONS Annual Status Report, 1 Mar. 1987 - 31 Mar. 1988 (California Inst. of Tech.) 42 p CSCL 08G G3/46
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This status report is for the extended (13 month) period March 1, 1987 to March 31, 1988 in order to place the status report cycle in phase with the funding cycle. It incorporates the two semi annual reports for the period March 1, 1987 - September 30, 1987 and October 1, 1987 - March 31, 1988. Future status reports will be issued semiannually covering the periods April 1 - September 30 and October 1 - March.31.

During this period, work was carried out on three fronts relevant to the understanding of intraplate deformation, stress in the lithosphere and the driving mechanism for plate motions: 1) observational constraints, using GPS geodesy on the deformation in the region of the boundary between the Pacific and North American plates in central and southern California; 2) numerical modeling of the effects of temperature dependent lithospheric viscosity on the stress and strain history of extensional regimes; and 3) improvement of estimates of mantle viscosity variation, the long-wavelength density variations in the mantle, and the topography of the core-mantle boundary from modeling of geoid anomalies, nutation, and changes in length of day. These projects are described in more detail below, followed by a discussion of meetings attended and a list of abstracts and papers submitted and/or published.

GPS Geodesy

The mobile VLBI stations established by the Crustal Dynamics Project provide fundamental constraints on deformation in central and southern California on a spatial scale of ~ 100 km. As has been discussed in detail, e.g., by the CDP advisory panel at the Cosmos Club meeting, as well as in many CDP Investigators' Meetings, measurements on an even finer scale are needed, i.e., geodetic "footprints" should be established around these VLBI sites. We have been addressing this need, at least in a limited area, by carrying out GPS geodetic observations in collaboration with investigators at MIT, UCLA, UCSD, JPL, USGS, NGS, and others. The general purpose of this experiment is described in greater detail in Appendix A to this report.

During the period covered by this status report, we engaged in four extensive field campaigns, in May, 1987, October, 1987, early March, 1988, and late March, 1988. Regions occupied included the Channel Islands, the Ventura Basin, the Whittier Narrows region (epicenter of the October, 1987 earthquake), and the Imperial Valley, including the epicentral area of the Superstition Hills earthquake sequence of November, 1987. Because conventional surveys in much of this region extend back up to a century, and because strain rates are relatively high, we were able to obtain rather spectacular results.

In the Ventura Basin, comparison of triangulation and GPS surveys indicate convergence across the basin in the Filmore region (surrounding the CDP VLBI site) of 1 - 3 cm/yr, in agreement with geological estimates. This work was reported at the Spring, 1988 AGU meeting by graduate student Andrea Donnellan and will be discussed at the GPS Chapman Conference in September (see abstracts by Donnellan et al). It suggests that repeated measurements of the Santa Paula VLBI site should be given higher priority by CDP.

Further to the west, comparison of GPS and geodelite surveys from Santa Cruz and Santa Rosa Islands to the mainland indicate convergence of ~ 1 cm/yr. These surveys also help to establish a footprint around the Vandenburg VLBI site. Results were analyzed during this time period that will be discussed at the GPS Chapman conference by graduate student Shawn Larsen (see attached abstract).

Graduate student Frank Webb has compared GPS surveys carried out during this time period to triangulation surveys in the Channel Islands, extending as far offshore as San Nicolas and San Miguel Islands. He also finds significant strain, especially in the Santa Barbara Channel. His results will be discussed at the GPS Chapman Conference (see attached abstract).

Shawn Larsen has also been participating in GPS surveys in the Imperial Valley, in association with Rob Reilinger of MIT. They find substantial deformation, particularly in the epicentral region of the Superstition Hills earthquake sequence. This work will also be discussed at the GPS Chapman conference (see attached abstract).

The occurrence of the Whittier Narrows earthquake during the middle of a GPS experiment made us aware of how important it is to have a solid plan for responding to a major seismic event before the confusing times following the earthquake. After some discussion, we decided to redeploy our receivers to the epicentral area in order to constrain coseismic and postseismic displacements and on the slim chance that a larger event would follow. The data from these surveys has not yet been completely reduced.

Thin Sheet Models of Extensional Tectonics

Postdoctoral Fellow Leslie Sonder continued her investigation of stress and strain in the lithosphere using the thin viscous sheet approximation. While her stipend was supported by a prestigious Weizmann Postdoctoral Fellowship, her research expenses were supported by this grant.

Leslie focussed her attention on understanding the temporal variation in the location of maximum strain rate in extensional regimes. Her models, which include the effects of temperature dependent rheologies, as well as the effects of crustal thickness variations, gave an interesting interpretation of the tectonics of the 1, where the maximum strain rate as revealed by present day seismicity seems to be displaced landward of the location of maximum total accumulated strain, as deduced from crustal thickness variations. Her model predicts that the lithosphere becomes stronger after extension, as the Moho cools following uplift. The weakest part of the lithosphere thus shifts away from the zone where maximum strain (and Moho uplift) has occurred.These models will be tested by upcoming geodetic experiments in this region, including the WEGENER campaign.

Sonder presented her result at the Spring, 1988 CDP meeting, as well as submitting a paper (abstract of the preprint attached).

Models of Large-Scale Mantle Dynamics

For the past several years, we have been developing a global model of mantle flow driven by density contrasts inferred from models of mantle seismic velocity structure determined using seismic tomography. In particular, we have been using the geoid as an additional and very valuable constraint on mantle flow models. The geoid provides a particularly valuable constraint on mantle viscosity structure, as explained Hager and Richards (1988). The abstract of a preprint of this paper is attached.

The basic physics involved is that flow driven by internal density contrasts such as those mapped using seismic tomography leads to dynamically maintained topography of the Earth's surface, the core-mantle boundary, and any other interior compositional boundaries that might exist, such as the top of the D" layer. This dynamically maintained topography has a major effect on the geoid; it is also strongly dependent on the variation of viscosity with depth.

This modeling effort is relevant to CDP for two reasons. First, the density contrasts leading to the geoid are also the major cause of long-wavelength variations in stress in plate interiors. The viscosity structure that so strongly affects the geoid also has a major effect on the lithospheric stresses caused by internal density heterogeneities. When CDP measurements provide reliable determinations of intraplate strain (e.g., by changes in length of baselines within the Pacific plate), these models will provide important constraints on plate rheologies.

Second, the dynamic topography at the core-mantle boundary (CMB) has a major influence on the coupling between motions of the mantle and core. It thus has a major impact on observations of nutation and changes in length of day, measurements carried out by CDP. Most of the work done by us this year in this area was devoted obtaining better models of CMB topography. To briefly summarize work reported in the attached abstracts, we found that the observational constraints provided by CDP measurements of nutation and changes in length of day could be satisfied if the D" layer just above the CMB has a low viscosity, consistent with its being a thermal boundary layer. It may also be chemically distinct.

Meetings attended

Attendance at professional meetings is important to exchange information and ideas and to obtain valuable feedback on one's science. In particular, the CDP meetings are vital to facilitate communication among those making the measurements and those interpreting them in terms of geodynamics. We have placed high priority on fulfilling our responsibilities of CDP meeting attendance, as well as presenting our results at other appropriate forums.

Spring 1987 CDP

Hager presented a talk on the GPS experiments being carried out in central and southern California and their relationship to CDP goals.

IAU Symposium No. 129, Cambridge, MA

Hager gave an invited talk on properties of the core-mantle boundary, including constraints provided by CDP sponsored measurements of nutation and changes in length of day.

Spring 1987 AGU

Hager was involved in three talks related to CDP work, including an invited Union Lecture.

Fall 1987 AGU

In addition to being involved in two CDP related talks, Hager attended the meeting of the U. S. Geodynamics Committee as a Reporter responsible for discussing crustal dynamics and mantle convection. Sonder presented a paper on kinematic evolution of the Big Bend region of the San Andreas fault.

Spring 1988 CDP

Hager presented a talk on the importance of establishing continuously monitored GPS networks. Leslie Sonder spoke about the results of her thin sheet extensional model.

Papers prepared and/or submitted during this period (abstracts attached)

Effects of Long-Wavelength Lateral Viscosity Variations on the Geoid, Mark A. Richards and Bradford H. Hager, submitted *J. Geophys. Res.*.

Long-wavelength variations in Earth's geoid: Physical models and dynamical implications, Bradford H. Hager and Mark A. Richards, submitted to *Phil. Trans. Roy. Soc. Lond. A.*, 1988.

GPS Measurements in Central and Southern California, Duncan Agnew, Yehuda Bock, Bradford H. Hager, David Jackson, Thomas Jordan, and Robert King, submitted to *CSTG Bulletin*, March 1988.

Effects of a temperature-dependent rheology on large-scale continental extension, Leslie Sonder and Philip England, submitted to J. Geophys. Res.

Abstracts prepared, submitted or published during this period (copies attached)

Properties of the core-mantle boundary, B. H. Hager. (Invited.), IAU Symposium No. 129, Cambridge, Massachusetts (May 10-15,1987)

Observational Constraints on Mantle Dynamics, B. H. Hager. (Invited, Union Lecture.), *EOS, Trans. Amer. Geophy. Union, 68,* 1987.

GPS Measurements in Central and Southern California, D. C. Agnew, Y. Bock. T. H. Jordan, R. W. King, T. H. Dixon, B. H. Hager, D. D. Jackson, W. H. Prescott, J. L. Stowell, B. E. Schutz, and W. E. Strange, *EOS, Trans. Amer. Geophy. Union, 68,* 282, 1987.

Monitoring Deformation in the Long Valley Caldera Using GPS-based Geodetic Measurements, T. H. Dixon, D. M. Tralli, G. Blewitt, S. C. Larsen, and B. H. Hager, *EOS, Trans. Amer. Geophy. Union, 68,* 283, 1987.

The Dynamics of D" and the CMB, B. H. Hager (Invited), *EOS, Trans. Amer. Geophy. Union, 68,* 1494, 1987.

Repeating Early Triangulation Surveys in California Using GPS, D. D. Jackson, B. H. Hager, D. Agnew, S. King, Z. Shen, F. Webb, A. Donnellan, and K. Feigl, *EOS, Trans. Amer. Geophy. Union, 68,* 1244, 1987.

Counterclockwise rotation of stresses in the Transverse Ranges, California, *EOS, Trans. Amer. Geophy. Union, 68,* 1507, 1987.

Seismic tomography: Inferences for mantle dynamics, B. H. Hager, Seismic Tomography and Mantle Circulation Meeting, London, England (April 13-14, 1988).

Geodynamical and seismological constraints on mantle stratification, B. H. Hager, *EOS, Trans. Amer. Geophy. Union, 69, 486, 1988.*

Determination of convergence rates across the Ventura basin, Southern California, using GPS and historical triangulation, A. Donnellan,

B. H. Hager, and S. Larsen, *EOS, Trans. Amer. Geophy. Union, 69,* 326, 1988.

Determination of convergence rates across the Ventura basin, Southern California, using GPS and historical triangulation, A. Donnellan, B. H. Hager, and S. Larsen, American Geophysical Union - Chapman Conference: GPS Measurements for Geodynamics, Fort Lauderdale, FL, September 19-23, 1988.

Strain accumulation in the Santa Barbara Channel: 1971-1987, S. Larsen, N. King, D. Agnew, and B. H. Hager American Geophysical Union - Chapman Conference: GPS Measurements for Geodynamics, Fort Lauderdale, FL, September 19-23, 1988.

Comparison of GPS surveys with historical triangulation surveys in the Southern California borderland, F. Webb, B. H. Hager, and D. C. Agnew, American Geophysical Union - Chapman Conference: GPS Measurements for Geodynamics, Fort Lauderdale, FL, September 19-23, 1988.

GPS measurements of deformation associated with the 1987 Superstition Hills earthquake, Imperial Valley, California: Evidence for conjugate faulting, S. Larsen, R. Reilinger, H. Neugebauer, and W. Strange, American Geophysical Union - Chapman Conference: GPS Measurements for Geodynamics, Fort Lauderdale, FL, September 19-23, 1988.

IAU Symp. # 129
may 10-15/87

Properties of the Core-Mantle Boundary

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The core-mantle boundary (CMB), separating the molten metallic core from the overlying solid silicate mantle, marks the largest discontinuity in mechanical properties within the Earth. The ~200 km thick region just above the CMB, named D" by Bullen (1950), is characterized by an anomalous gradient in seismic velocity versus depth. D" was originally interpreted as a region with a strong compositional gradient due to the accumulation of dense material at the base of the mantle. Subsequently, the anomalous gradient was interpreted as the result of a strong temperature gradient in a hot thermal boundary layer at the base of the mantle, an interpretation motivated by the requirement that heat involved in generating the geodynamo must be transported out of the core and through the mantle by convection.

Determining the nature of D" is important to understanding the geochemical evolution of Earth, in addition to understanding mantle and core dynamics. If D" is compositionally distinct from the mantle, it represents a reservoir of material not yet considered in modeling the composition of the mantle. Since direct sampling is impossible, we must resort to indirect methods to determine its properties.

Mapping the topography of the CMB is one way of constraining the nature of D". Due to the high temperature near the CMB, mantle materials respond to stresses by creeping flow; any topographic relief on the CMB must be dynamically maintained by convection in the overlying mantle. If D" were a separately convecting layer, this topography would by much smaller than if D" were the thermal boundary layer of the (entire) convecting lower mantle. CMB topography can be probed in a number of ways. Nutational coupling of the core and mantle depends upon CMB ellipticity. Torques caused by the interaction of fluid flow in the core and CMB topography would cause changes in the length of day. The predicted dynamic topography of the CMB caused by lower mantle density contrasts inferred from seismic tomography can be calculated from fluid mechanical models. The variations in travel times of seismic waves that reflect off or are transmitted through the CMB can be mapped into models of CMB topography.

The results from a number of recent models of CMB topography coming from various branches of geophysics are not in agreement. Nutation and length of day studies indicate CMB topography of order hundreds of meters, while seismic models have topography of over 10 km. Dynamic models which include D" as a chemically distinct layer are in accord with the former estimates.

"Observational Constraints" on Mantle Dynamics

BRADFORD H. HAGER (Seismological Laboratory 252-21,
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Results from a wide range of fields in earth science are providing increasingly useful constraints on the way the earth works. For example, seismology is providing models of velocity variations in the deep interior based on interpretations of travel time anomalies, variations in surface wave velocities and shifts in eigenfrequencies of free oscillations. Geodesy is providing highly accurate maps of the geopotential, the fundamental constraint on the mass anomalies associated with mantle convection; changes in length of day (lod), the fundamental constraint on torques acting on the mantle; and models of core-mantle boundary (CMB) ellipticity from nutation observations. Geomagnetism is providing models of the time variation of the magnetic field from which fluid velocities at the CMB are inferred.

To the extent that these models are correct, they can be used to constrain mantle dynamics. Conversely, the validity of these geophysical models would be supported if they could all be understood in terms of a single model of mantle structure and dynamics. If the viscosity of the mantle increases by about a factor of 300 from the asthenosphere to the top of the lower mantle, then remains essentially constant throughout most of the lower mantle, mass anomalies associated with density contrasts inferred from seismological models and associated dynamic topography can explain ~ 90% of the observed long-wavelength geoid. Such a structure can also explain the state of stress in deep slabs and long-lived isotopic reservoirs. It would lead to sluggish lower mantle convection, with velocities slow compared to plate boundary migration speeds, giving the mantle a "ribbon candy" structure. Nutation and lod changes suggest relatively subdued CMB topography, requiring a low viscosity and perhaps chemically distinct D" layer.

1. 1987 Spring Meeting
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7. 50% at various meetings
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GPS Measurements in Central and Southern California

D. C. AGNEW (IGPP, Univ. of California, La Jolla, CA 92093)
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We report on a series of Global Positioning System (GPS) experiments conducted in central and southern California during December 1986 and January 1987. The scientific objectives of these experiments are threefold: (1) to assess and improve GPS techniques by studying the relative performance of different network configurations, (2) to compare the single-epoch observations made in this experiment with existing triangulation and trilateration data, and (3) to set up a network for long-term monitoring of tectonic deformations along the California margin. For most of the observing interval, the orbits of the GPS satellites were controlled using observations from receivers located at eight fiducial sites distributed across North America: Westford, Algonquin, Austin, Platteville, Owens Valley, Mojave, Ft. Ord, and Vandenberg. The latter four sites constitute a regional fiducial network with 200-500 km baselines, whose performance in controlling orbits will be evaluated relative to the continental-scale network. An array of twenty-one GPS field sites was occupied to measure the deformation across the Coast Ranges and offshore faults; it was specifically designed to identify structures which may be accommodating the "missing motion" between the Pacific and North American plates not accounted for by slip on the San Andreas Fault. Nineteen of these were distributed west of the San Andreas from Piedras Blancas Point (35.67°N) to La Jolla (32.84°N). We also occupied sites on Santa Rosa and Santa Cruz Islands and along the Santa Barbara coastline whose baselines have been measured by previous trilateration and triangulation surveys.

1. 1987 Spring Meeting

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5. (a) Global Positioning System Survey Results
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Monitoring Deformation in the Long Valley Caldera Using GPS-based Geodetic Measurements: The Effect of Varying Fiducial Geometry

T. H. DIXON, D. M. TRALLI, G. BLEWITT (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109)
S. C. LARSEN, B. H. HAGER (Seismological Laboratory, California Institute of Technology, Pasadena, CA 91106)

Geodetic data in the vicinity of the Long Valley Caldera (LVC), Mammoth Lakes, California, are of great geophysical interest, as seismicity and uplift in the region have suggested reinflation of a shallow magma chamber. GPS-based geodetic measurements between LVC and Owens Valley Radio Observatory (OVRO) can supplement conventional geodetic and geophysical methods used to estimate deformation, and provide information referenced to a point well outside the locally deforming zone.

GPS observations of the LVC–OVRO baseline with simultaneous observations at well-located fiducial sites took place in March-April, 1985, November, 1985, and June, 1986. The overall geometry of the fiducial network was constant for these experiments, consisting of Westford, MA, Richmond, FL, Ft. Davis, TX, Mojave, CA, and OVRO. However, subtle changes in the network (e.g. receiver type and performance at a given site) can affect overall system accuracy, possibly introducing systematic errors. The impact of these differences on system accuracy and consequent ability to compare results from different experiments will be discussed using data from the two experiments conducted in 1985.

The Dynamics of D" and the CMB

BRADFORD H. HAGER (Seismological Laboratory 252-21,
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D" has been interpreted as resulting from either (1) a hot thermal boundary layer or (2) a chemically distinct layer of material lying just above the core-mantle boundary (CMB). The expected mechanism of heat transport, the expected topography of the CMB, the expected topography at the top of D", the expected thickness of D", and the expected seismic velocity structure at the base of the mantle depend upon which interpretation is appropriate, as well as upon the material properties (viscosity, thermal diffusivity, etc.) of this region.

Motions of fluid in the molten core exert torques on the mantle through topographic coupling at the CMB. Unless this topography is less than several hundred meters in amplitude, torques exerted by geostrophic models of core flow would exceed those associated with observed changes in length of day (unless "anti-oceans" of a mystery fluid as yet invisible to seismologists buffer this interaction). Such small topography is consistent with (1) if D" has the low viscosity expected of a hot thermal boundary layer, as well as with (2). The seismic structure proposed by Lay and others is consistent with (2), but not with (1), since it is too thick to be stable. Interpretation (2) suggests large lateral variations in the thickness of D", a prediction that should be testable by seismologists. Heat transport arguments (Ahrens and Hager, 1987) suggest that D" is not convecting. It may be unmixed and very heterogeneous.

1. 1987 Fall Meeting
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5. Physics of core-mantle boundary
6. O oral
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8. Invited paper, fees waived. (R. Jeanloz)
9.

G42A-12 1645H

Repeating Early Triangulation Surveys in California using GPS

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We are resurveying century-old triangulation markers to test the hypotheses of significant displacement west of the San Andreas fault and rapid convergence in the Ventura basin. The old surveys had errors on the order of a few ppm, so we can resolve strain rates to better than 0.1 ppm/yr. The most significant problems are correct identification of the original markers, accurate location of surrogates with respect to destroyed original markers, and reliable assessment of local soil instability. We have already made observations at stations equivalent to Lospe, Arguello, Santa Cruz W, Gaviota, and Chaffee. In late 1987 we plan to occupy Castle Mount, Rocky Butte, San Jose, San Luis, Tepusquet, Gaviota, Santa Clara, Laguna, Castro,, San Pedro, Wilson Peak, San Juan, and Santa Cruz E, all described in Bowie(1928). Only a few of the original markers exist, but most stations have well located reference marks. All marks at San Pedro and Wilson Peak have been destroyed; surrogate marks at Vicente Lighthouse and Echo Peak will be used instead. Modern survey markers must be permanent and recoverable if our heirs are to benefit from our present efforts.

T52A-11 1615H

Counterclockwise Rotation of Stresses in the Transverse Ranges, California

LESLIE J. SONDER (Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125)

Observations from earthquake source mechanisms and borehole stress measurements indicate that the directions of the principal horizontal stresses in the Transverse Ranges are rotated by 10°–30° counterclockwise compared with their directions elsewhere in southern California (e.g. Pechmann, 1983; Zoback et al., 1980). Geodetic strain measurements show a similar rotation of the principal horizontal components (e.g. Savage, 1983). I investigate the possibility that this rotation may be produced by the superposition of two sources of stress: 1) a regional stress field reflecting strike-slip deformation associated with Pacific-North America plate motion, and 2) stresses arising locally due to positive or negative buoyancy forces due to topographic, crustal thickness, or lithospheric thickness contrasts between the Transverse Ranges and their surroundings.

A preliminary analysis shows that the amount and sense of rotation of the principal horizontal stresses depend on two parameters. The first is the ratio L/τ, where L is the magnitude of stress arising from buoyancy forces in the Transverse Ranges, and τ is the stress associated with regional strike-slip deformation. The second parameter is the angle between the direction of strike-slip motion and the direction of maximum horizontal compressive or extensional stress associated with the local buoyancy forces. For the Transverse Ranges, counterclockwise rotation of principal horizontal stresses is possible only if the net buoyancy forces are negative. Negative buoyancy forces are consistent with the presence of a dense lithospheric root extending to 250 km depth, indicated by seismic tomography (Humphreys et al., 1984) and with the occurrence of thrust faulting in the Transverse Ranges. The amount of rotation of the principal stresses allows an upper bound to be placed on the ratio L/τ, which for the Transverse Ranges is -1.

Rotation of the principal horizontal stresses implies that the plane of maximum shear stress also rotates, to trend more westerly. This supports the possibility that the 'big bend' in the San Andreas fault may be a consequence of the negative buoyancy forces acting in the Transverse Ranges (Humphreys et al., 1984), and not the cause of Transverse Ranges formation, as has often been assumed.

SEISMIC TOMOGRAPHY AND MANTLE CIRCULATION MEETING
April 13-14, 1988 - London, England

Seismic Tomography: Inferences From Mantle Dynamics

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The seismic velocity anomalies and core-mantle boundary (CMB) topography resolved by seismic tomography are associated with thermal, chemical and density variations in the dynamic Earth. Density variations lead to convective flow and to dynamically maintained topography at the Earth's surface, the CMB, and any interior chemical boundaries that might exist. Dynamic topography is very sensitive to viscosity structure and to chemical stratification. The mass anomalies resulting from dynamic topography have a major effect on the geoid; this places strong constraints on mantle structure. Advective heat transport by the flow driven by the seismically inferred density anomalies also depends on mantle viscosity. About 90% of the variance in the observed geoid can be explained by inferred density anomalies and the resulting dynamic topography predicted for an Earth model with a low viscosity asthenosphere ($\sim 10^{20}$ Pas) overlying a moderate viscosity ($\sim 10^{22.5}$ Pas) lower mantle. This viscosity stratification leads to rapid mixing in the asthenosphere, with little mixing in the lower mantle. Large (~10 km) CMB topography can be reconciled with dynamic considerations and with the relatively weak mechanical coupling between core and mantle inferred from changes in length of day if there is a thin layer of molten silicate at the top of the core. The absence of hundreds of km of dynamic topography at the 670 km discontinuity is inconsistent with chemical stratification at that depth.

GEODYNAMICAL AND SEISMOLOGICAL CONSTRAINTS ON MANTLE STRATIFICATION

Bradford H. Hager

At: (Seismological Laboratory, California Institute of Technology, Pasadena, California 91125)

The density contrasts associated with mantle convection lead to dynamic topography at the surface, the CMB, and any other compositional boundaries that might exist (e.g., top of D", 670 km discontinuity), allowing strong observational tests of the reality of any supposed stratification. For a given chemical and viscosity stratification, the dynamic topography is directly proportional to the interior density contrasts and inversely proportional to the density contrast across a given boundary. The geoid is strongly affected by both interior density contrasts and dynamic topography, providing a strong constraint on acceptable models.

The geoid is consistent with convection penetrating deep below 670 km if the lower mantle has a viscosity several orders of magnitude greater than the asthenosphere. Such a model is also consistent with the well-stirred upper mantle and poorly stirred lower mantle inferred by geochemists. The geoid is also consistent with chemically stratified convection, but only if subducted slabs are made up of a high density phase such as ilmenite and only if several hundred km of dynamic topography exist on the 670 km.

The lack of large topography observed at 670 km and the suggestion of large topography at the top of D" suggest that the mantle is chemically stratified at 2600 km, but not at 670 km. The presence of a substantial geochemical garbage dump in D" would make mass-balance arguments concerning mantle stratification that ignore this reservoir naive and misleading.

1. 1988 Spring Meeting

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5. Chemical Stratification
of the Mantle

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7. 60% Spring 1987 AGU

8. Invited paper, fees
waived (Paul Silver)

9. I (Invited)

DETERMINATION OF CONVERGENCE RATES ACROSS THE VENTURA BASIN, SOUTHERN CALIFORNIA, USING GPS AND HISTORICAL TRIANGULATION

Andrea Donnellan, Bradford H. Hager, and Shawn Larsen

All At: (Seismological Laboratory, California Institute of Technology, Pasadena, California 91125)

Comparison of angles from historical triangulation observations of 1959 and 1975 with Global Positioning System (GPS) measurements taken in 1987 indicates that rapid convergence may be taking place on decade timescales in the central part of the Ventura basin. Changes in angles over this time were analyzed in terms of a model that assumes that the regions to the north and south of the basin, an east-west trending trough bounded by thrust faults, are rigid blocks undergoing relative motion. Inversion of the observed angle changes over the last 28 years for the relative motion vector leads to north-south convergence across the basin of 30 ± 5 mm/yr, with a left lateral component of 10 ± 1 mm/yr in the Fillmore-Santa Paula area in the central part of the basin. The inferred displacements of about 1 meter over this time are large compared to the expected error for either technique (3 ppm for triangulation).

The convergence rate determined by geodetic techniques is consistent with geologic observations in the area. Such large geodetic deformation rates, with no apparent near-surface creep on the major thrust faults in the area, can be understood if these faults become subhorizontal at relatively shallow depths and if the subhorizontal portions of the faults are creeping. An alternative explanation of the large displacement rates might be that the pumping of oil in the vicinity of the benchmarks caused large horizontal motions, although it is unlikely that meter scale horizontal motions are due to oil withdrawal. We are evaluating these and other hypotheses at present in order to better contrain the tectonics of this active region.

1. 1988 Spring Meeting

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5. Combining Historical and
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Strain Accumulation in the Santa Barbara Channel: 1971-1987

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In late 1970 and early 1971 EDM baseline measurements were made between the California coast near Santa Barbara and the offshore islands, Santa Cruz and Santa Rosa. In early 1987 we remeasured these baselines using GPS, as part of a campaign in southern and central California. The 1971 survey (made by Greenwood and Associates), used an AGA Model 8 laser Geodimeter. Corrections for refraction were made using endpoint measurements of pressure, temperature, and humidity, together with records of temperature along the line of sight taken using an airplane. Two doubly-braced quadrilaterals were measured, with line lengths from 18 to 70 km. In the 1987 measurements we reoccupied one of these quadrilaterals with TI-4100 receivers, observing for 3-5 nights in 7-hour sessions.

Fitting a uniform strain model to the observed changes in slope distance gives rms misfits of 5 cm in line length, and errors too large to distinguish nonzero strains. If one particular line is omitted (Gaviota to Santa Rosa) the fit improves markedly (rms misfit 1.6 cm); since this is not true if any other line is omitted, we believe this measurement to have been a blunder. With this line omitted, the best-fit uniform strain rate is $\epsilon_{11} = -0.01 \pm 0.01 \mu\epsilon/\mathrm{yr}$, $\epsilon_{22} = -0.16 \pm 0.01 \mu\epsilon/\mathrm{yr}$, $\epsilon_{12} = 0.05 \pm 0.01 \mu\epsilon/\mathrm{yr}$ (ϵ_{11} axis east, ϵ_{22} axis north). This corresponds to uniaxial compression of $-0.17 \mu\epsilon/\mathrm{yr}$ along an azimuth of N30°E, or about 8 mm/yr of convergence across the Santa Barbara Channel, less than the approximately 20 mm/yr estimated for Quaternary time in the Ventura Basin to the east.

1. 1988 Chapman Conference on GPS Measurements for Geodynamics

2. (A) poster presentation

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Comparison of GPS Surveys with Historical Triangulation Surveys in the Southern California Borderland.

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GPS surveys in the Southern California Borderland conducted in June 1986, December and January 1986-1987, and May 1988 have provided reliable positions for several benchmarks for which historical first order triangulation data exists. The triangulation was performed 35 to 100 years ago. Comparison of spheroidal angles calculated from the GPS positions with the observed triangulation angles indicates angular changes have occurred among some of the stations. However, for many of the stations the angular changes are within the uncertainties associated with the triangulation data. Results from San Nicholas Island north to the Santa Barbara coastline, and from San Nicholas Island east to the Southern California coastline will be discussed.

1. 1988 Chapman Conference on GPS Measurements for Geodynamics

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GPS Measurements of Deformation Associated With the 1987 Superstition Hills Earthquake, Imperial Valley, California: Evidence for Conjugate Faulting

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Measurements of crustal deformation associated with the Superstition Hills earthquake sequence of November 24, 1987 are determined from GPS surveys conducted in the Imperial Valley, California in 1986 and 1988. This is the first occurrence of a large earthquake (M=6.6) within a preexisting GPS network. The two data sets have been processed with the NGS (1986 survey) and Bernese (1988 survey) software packages. Measurements of station displacement are consistent with right-lateral slip along the northwest trending Superstition Hills fault and left-lateral motion along a conjugate northeast trending seismic lineament, recently named the Elmore Ranch fault. The 13 km baseline between L589 (4 km southwest of the Superstition Hills fault) and Kane (100 meters north of the Elmore Ranch fault) was shortened by 70 cm. Calculated station vectors indicate L589 moved about 45 cm to the northwest while Kane was displaced approximately 40 cm to the southwest. 8 additional GPS sites within 20 km of the fault system show significant (~10 cm) movement. A simple (and preliminary) elastic dislocation model with 100 cm right-lateral slip on the Superstition Hills fault and 40 cm left-lateral motion on the Elmore Ranch fault (uniform slip from 0 to 10 km depth) is consistent with the GPS data, although this model is non-unique. In addition to large displacements related to the Superstition Hills earthquake sequence, the GPS measurements show evidence of significant strain accumulation across the Imperial fault, suggesting that a sizable percentage of the Pacific-North American plate motion is concentrated here.

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APPENDIX A.

GPS Measurements in Central and Southern California

INTERIM PROGRESS REPORT

October 22, 1987

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1. Introduction

The San Andreas and related fault systems in California are part of a complex zone of deformation between the North American and Pacific plates. Global models of present-day plate kinematics predict a relative motion of 50-60 mm/yr across this boundary [*Minster and Jordan*, 1978 ; *DeMets et al*, 1987], whereas geodetic and geological observations in California indicate that only about 30-40 mm/yr is localized on the San Andreas [*Lyzenga and Golombek*, 1986]. Recent analyses of this well-known "San Andreas discrepancy" suggest that a significant fraction of the missing motion occurs on faults west of the San Andreas [*Minster and Jordan*, 1984; 1987; *Weldon and Humphreys*, 1986]. From these studies it has been inferred that the integrated deformation rate across the California coastal margin is about 10 mm/yr. If correct, this hypothesis implies that much of the deformation is taken up by infrequent large earthquakes not yet apparent in the historical record. Evaluating it is therefore crucial to understanding the seismogenic potential of faults on the highly populated California margin, as well as having intrinsic scientific interest.

Several models have been advanced to account for deformation west of the San Andreas Fault. *Bird and Rosenstock* [1984] take the view that the region west of the San Andreas is fairly well coupled to the Pacific Plate; this implies convergence across the whole of the Transverse Ranges, with any motion on the San Gregorio fault stepping over to the San Andreas and San Jacinto faults. *Weldon and Humphreys* [1986] propose instead that the southern California plate boundary is actually two active zones, with the area between the San Andreas and offshore faults rotating so as to move parallel to the trend of the San Andreas in the "Big Bend" and further south. The motion between this area and the Pacific plate then has to be taken up by strike-slip faults north and south of the Transverse Ranges, and by thrusting within the Ranges, particularly their western parts.

These models can be tested directly by geodetic methods. Terrestrial triangulation and trilateration surveys have already provided important constraints on strain in the vicinity of the San Andreas and other major faults [*Savage*, 1983]. Observations by very long baseline interferometry (VLBI) and satellite laser ranging (SLR) have established a strong control network for the region and confirmed the relative motions of several of the crustal blocks. Surveying using signals from the Global Positioning System satellites now provides the means to bridge the gap between the terrestrial surveys and the VLBI/SLR measurements. The current capabilities of GPS technology allow measurements of 1 part in 10^7 without the terrain limitations of terrestrial methods or the cost and logistical constraints of VLBI and SLR.

In December 1986 we began a series of GPS experiments in central and southern California (Figure 1) with three primary objectives:

(1) To assess and improve the accuracy of GPS measurements for studying crustal deformation;
(2) To compare the GPS measurements with existing triangulation and trilateration data; and
(3) To establish a network for long-term monitoring of deformations along the California plate margin.

(Some of us had previously participated in an experiment in June, 1986, organized by the Jet Propulsion Laboratory (JPL) and in conjunction with the National Geodetic Survey (NGS) and the U.S. Geological Survey (USGS), pursuing these objectives in the southern Channel Islands. The sites observed in this earlier experiment are also included in this report for completeness.)

In Section 2, we discuss briefly the scientific rationale underlying each of these objectives. We then describe in Section 3 our initial experiments and, in Section 4, our plans for future observations.

These experiments have been carried out in cooperation with several government agencies and researchers at other universities. GPS receivers and field crews have been provided by the University Navstar Consortium (UNAVCO), USGS, and NGS. An additional receiver was provided by the Navy Pacific Missile Test Center (PMTC) and operated by personnel from JPL. Orbital tracking data were collected by NGS, the University of Texas, the Texas Highway Department, the University of Colorado, and the Geodetic Survey of Canada (GSC). Logistical support and field crews were provided by JPL and Colorado. University funding for the field work and data analysis has been provided by NSF, NASA, and USGS.

Nine graduate students at the four universities are engaged in analysis and interpretation of the data from this project: Andrea Donnellan, Shawn Larsen, and Frank Webb at Caltech; Kurt Feigl and Mark Murray at MIT; Zheng-Kang Shen and Li-Yu Sung at UCLA; Nancy King and Kristine Larson at UCSD. Thirty-two other students have assisted with the observations and received training in the operation of GPS receivers.

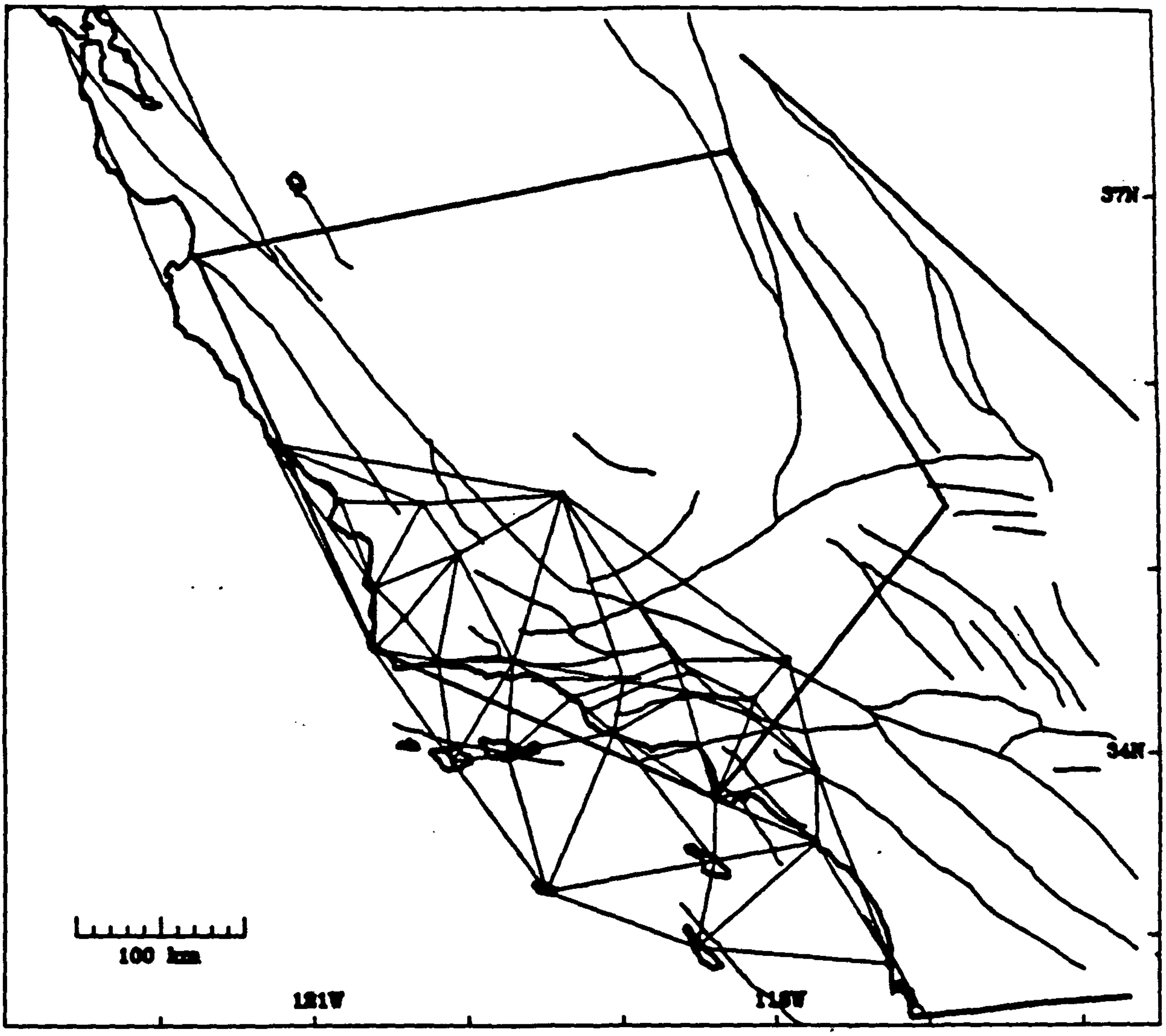

Figure 1. Network of sites occupied during our initial experiments in June 1986, December 1986, and January 1987. The large pentagon outlines the "fiducial" sites whose coordinates are well-known from VLBI and/or SLR observations.

2. Scientific Objectives

2.1 Development of Improved GPS Techniques

The dominant sources of error in precise relative-position measurements using GPS are the satellite orbits (ephemerides), the troposphere (primarily the wet component), and signal multipath. Ionospheric effects can be rendered negligible by combining observations at the two GPS frequencies, but the ionosphere must still be considered in resolving phase observation ambiguities. The relative importance of the sources of error depends on the length of the baseline, availability of orbital tracking data, tropospheric and ionospheric conditions, availability of independent measurements of the tropospheric delay, and antenna design.

High-precision orbits of the GPS satellites have been computed by several investigators over the last two years, from which baseline accuracies of 1 part in 10^7 or better have been obtained. Two methods of orbital analysis have been primarily used: the "fiducial" concept approach in which coordinates of stations determined from VLBI and SLR measurements are constrained [*King et al., 1984; Thornton et al., 1984*], and the "free-network" approach in which a combination of station and satellite coordinates are allowed to vary simultaneously [*Beutler et al., 1985*]. However, for GPS studies of regional crustal deformation, the optimal network configuration for the determination of orbital parameters and station coordinates is not well established. During our December 1986 and January 1987 experiments, up to seventeen GPS receivers were deployed across North America, enabling us to perform orbit determination using a dense regional network and/or fiducial networks on three scales: (1) 200-500 km in the region of prime interest, (2) 1000-2000 km, and (3) 3000-4000 km. The large number and distribution of receivers allows a comprehensive study of different orbital analysis techniques, particularly those that use short satellite arcs. In addition, the ability to construct networks of different scales and geometries allows us to differentiate between orbital errors and other sources of error such as propagation medium and multipath.

For both orbit determination and baseline measurements, the tropospheric delay in the signal path is an important source of error. Several methods of accounting for this delay are available to the analyst of GPS data: (1) modeling the delay using measurements of surface meteorological quantities; (2) estimating the delay from the GPS data along with the parameters of geodetic interest; and (3) using radiometric measurements of the atmospheric microwave emission to estimate the water-vapor component of the delay (when such measurements are available). An important objective of our research is to develop techniques for using methods (1) and (2) in a network analysis, accounting for the effect of intersite distance on unmodeled tropospheric fluctuations [*Davis et al.*, 1987].

Compact antennas of the type used by the TI 4100 receivers employed in our initial experiments are subject to signal multipath, which may amount to several centimeters of equivalent pathlength in phase observations. The magnitude of these errors is a strong function of antenna design and of the nature of the reflecting surfaces below and around the antenna. The signature of multipath tends to repeat from day to day, since the satellite geometry repeats. As long as the observing schedule remains the same, the repeatability of the baseline determination is not affected by multipath. However, the accuracy is affected, and the repeatability may also be significantly affected if hardware failures, meteorological conditions, or changes in the satellite constellation cause changes in the observing schedule. In order to assess and reduce multipath effects, we plan to study different configurations for the TI 4100 antenna and, if possible, to test other antenna designs, such as the crossed-dipole with ground plane used by the Macrometer II™, which are less affected by multipath [*Counselman and Gourevitch*, 1981]

An important factor in the accuracy of GPS relative-position measurements is the ability to resolve the integer-cycle ambiguities in phase observations. For single-frequency observations, ambiguity resolution is straight-forward but is limited to intersite distances of a few tens of kilometers by the effects of the ionosphere, which is usually the largest source of error (see, e.g., *Bock et al.*, 1985). The ionospheric delay can be rendered negligible by using a particular combination of the two (L-band) GPS frequencies, but when this combination is formed, the effective ambiguity spacing is smaller than the 19-cm wavelength of the L1 signal. By appropriately constraining the ionospheric delay in the analysis [*Bender and Larden*, 1985; *Ladd et al.*, 1986; *Bock et al.*, 1986a], it is possible to resolve the phase ambiguities for dual-frequency observations over much longer baselines than for single-frequency observations. If tropospheric and orbital errors have been minimized, the most important variable affecting ambiguity resolution is the time of day of the observations, since gradients in the ionospheric delay are 5-10 times larger in the daytime (particularly near sunrise) than at night. Hence, our plan for future occupations (see Section 4) includes observations at three different times of the day.

Evidence from our analyses of observations from previous GPS campaign suggests that troposphere, multipath, and orbits are all important sources of error in measuring regional networks, and that the orbital error currently dominates only for distances greater than about 200 km [*Bock et al.*, 1986b]. In our results for which the phase ambiguities were resolved, the uncertainties in the means of four baseline determinations closely spaced in time were 5-15 mm in the horizontal components, and 15-30 mm in the vertical components. These uncertainties imply that we can determine horizontal deformation rates with an uncertainty of 3-7 mm/yr (one-sigma) using a 3-year span of observations. For baselines 200-300 km long, the phase ambiguities could not always be resolved, and the uncertainties were up to 25 mm in the east components. These uncertainties are probably larger than those which can now be obtained with VLBI or SLR, but the measurement of the east component of the longer baselines will be valuable in assessing the effect of errors in the satellite orbits (on the short as well as long baseline determinations) and in providing a better assessment of accuracy through comparisons with VLBI and SLR measurements. One goal of our research is to improve the accuracy of GPS measurements for the longer baselines by achieving better orbit determination and easier resolution of the phase ambiguities.

2.2 Comparisons with Historical Triangulation and Trilateration Data

Relatively high quality triangulation surveys of coastal California were carried out over a century ago [*Bowie*, 1928]. Further surveys were carrried out about 60, 50, and 30 years ago. A high quality trilateration survey was carried out between Santa Cruz and Santa Rosa Islands and the mainland 15 years ago [*Willot et al.*, 1971; A. G. Sylvester, private communication, 1986]. Although the conventional surveys are less accurate than GPS measurements, the long timespans involved allow them to be used in conjunction with recent GPS measurements to provide meaningful tests of tectonic models.

The first order triangulation carried out in the 1870's and subsequently has a standard deviation (σ) in angles of less than 0.7" (about 3 ppm). The expected error in angular strain rate when an N-angle triangulation survey performed T years ago is compared to a precise modern survey is $2\sigma/(N^{1/2}\ T)$ [*Savage*, 1983]. For a typical region, $N^{1/2} = 4$, so errors in angular strain are expected to be about $(2/T) \times 10^{-6}$/yr, or as low as 2×10^{-8}/yr for the oldest triangulation data. Typical strain rates in California tectonic regions are about 10^{-7}/yr .

For the trilateration survey of 1971, the uncertainty is estimated to be ± 2 cm on baselines of length about 50 km, only slightly greater than the expected GPS uncertainty. Strain rates should be recoverable with an uncertainty of about 2×10^{-8}/yr by comparison with our GPS measurements, giving comparable sensitivity to the triangulation measurements as well as determining areal strain.

For perspective, the 20 mm/yr convergence rate predicted by *Weldon and Humphreys* [1986] and *Yeats* [1983] across the Ventura Basin, if it extends to the west through the Santa Barbara Channel, predicts strain rates about 5×10^{-7}/yr. Comparison of initial-epoch GPS measurements with historical surveys would give results of immediate importance and interest for testing models of deformation in the Borderlands.

Triangulation stations from the late 1800's onward are shown in Figure 2, and the 1971 trilateration survey is shown in Figure 3. Tables 1 and 2 list each of the stations and indicate whether it has been recovered (R) and observed by GPS (G). (In some cases, only reference marks have been recovered, but these are generally adequate for our purposes.)

Unfortunately, a number of historical monuments have been destroyed. For some of these, sufficient surveys have been made locally to make possible a direct tie to another site, while for others we have not yet determined if the historical data are recoverable. Stations marked S have been destroyed but have been tied sufficiently well to a local net that they can be effectively recovered using "surrogate" sites. A question mark for the status of a site indicates either that it has not been visited or has been found destroyed but offers the possibility of recovery through a local survey. Enough historical monuments have been recovered to make our comparison promising. Securing ties to our main GPS network will be accomplished as soon as possible within the resources available. Some sites are part of our GPS network while others will be tied in using local surveys performed with a combination of GPS and conventional techniques.

Table 1. Triangulation Stations

Station	Name	Lat. (N)	Long. (W)	Observed	Status
ROKY	Rocky Butte	35.60	121.06	1884, 1923	G
CSTL	Castle Mount	35.94	120.34	1885, 1923	G
SLUI	San Luis	35.28	120.56	1883, 1923	G
SJOS	San Jose	35.32	120.27	1884, 1923	G
LOSP	Lospe 1875	34.89	120.61	1875, 1923	G
TEPU	Tepusquet 1875	34.91	120.19	1875, 1923	G
ARGU	Arguello 1875	34.58	120.56	1875, 1910, '23,'24,'51,'56	S
GAVI	Gaviota 1873	34.57	120.20	1875, 1924, '25, '51, '56	G
SBA2	Santa Barbara 1956	34.40	119.71	1956, '59	G
	Santa Barbara 1857	34.40	119.71	1898, 1923, '24, '25, '29', '41	S
NSNM	New San Miguel 1873	34.04	120.39	1873, 1924	?
SAN4	San Miguel 4 1951	34.03	120.36	1951	?
SNRI	Soledad 1872, Santa Rosa Is.	33.95	120.10	1951, 1959	G
SCRW	Santa Cruz W 1874	34.07	119.92	1874, 1924, '56	G
DEVL	Devils Peak 1951, Santa Cruz Is	34.03	119.78	1951, '59	G
SCRE	Santa Cruz E 1857	34.05	119.56	1898, 1924	G
HIGH	High 1951, Santa Cruz. Is.	34.02	119.58	1951, 1959	R
CHAF	Chaffee 2 1923	34.30	119.33	1923, '41, '51', '56	G
	Chaffee 1867	34.30	119.33	1867, 1923	S
SCLA	Santa Clara 1898	34.33	119.04	1898, 1923, '41, '59	G
LAGU	Laguna 2 1951	34.11	119.06	1951, '56, '59, '64, '71	S
	Laguna 1857	34.11	119.06	1898, 1923	S
CATO	Castro 1898	34.09	118.78	1898, 1923, '51, '59	G
SAFE	San Fernando 1898	34.33	118.60	1898, 1923	G
LOVE	Loma Verde	34.50	118.67	1923	G
HAPY	Happy 1959	34.36	118.85	1959	G
HOPP	Hopper 1941	34.48	118.87	1941, '59, '63	G
SNP2	Santa Paula 1941	34.44	119.01	1941, '59, '63	G
SANP	San Pedro 1853	33.75	118.34	1878, '98, 1923, '51, '56	S
WILP	Wilson Peak 1890	34.22	118.06	1890, 1923	S
SJUA	San Juan	33.91	117.74	1886, 1923	G
SANT	Santiago	33.71	117.53	1899, 1923, '29, '56	G
NIGU	Niguel 1884	33.51	117.73	1898, 1923, '51, '56	S
CATW	West Peak 1875, Catalina Is.	33.46	118.57	1940, '51	G
CATP	Catalina Peak 1875	33.39	118.40	1878, 1940, '51	?
SBIS	Santa Barbara I 2 1940	33.64	119.03	1940, 1951	?
JACK	Jackson, San Nicolas Is.	33.24	119.51	1951	R
HARB	Harbor, San Clemente Is.	33.00	118.56	1877, 1940, '51	R
BOUL	Boulder 1862, San Clemente Is.	32.90	118.47	1877, 1940, '51	G
SNJA	San Jacinto	33.81	116.68	1898, 1923	?
CUYA	Cuyamaca	32.95	116.61	1898, 1923	G
SOLE	Soledad 1887, La Jolla	32.84	117.25	1951	G

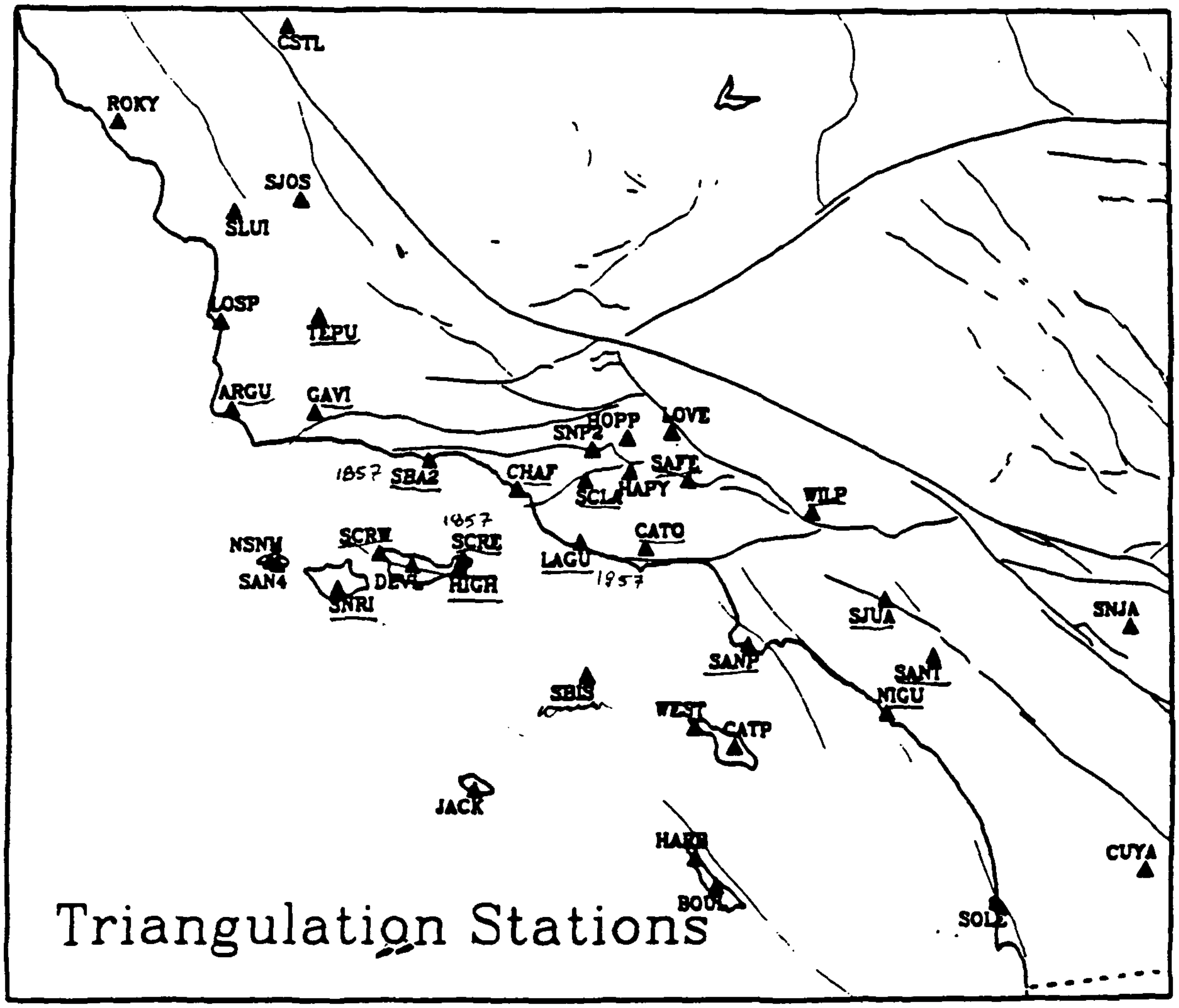

Figure 2. Triangulation stations surveyed between 1874 and 1971.

Table 2. 1971 Trilateration Stations

Station	Name	Lat. (N)	Long. (W)	Status
SNRI	Soledad 1872, Santa Rosa Is.	33.95	120.10	G
GAVI	Gaviota 1873	34.57	120.20	G
DEVL	Devils Peak 1951	34.03	119.78	G
HIMT	High Mount	34.03	119.58	R
LACU	La Cumbre Peak	34.50	119.71	G
CHAF	Chaffee 2 1923	34.30	119.33	G

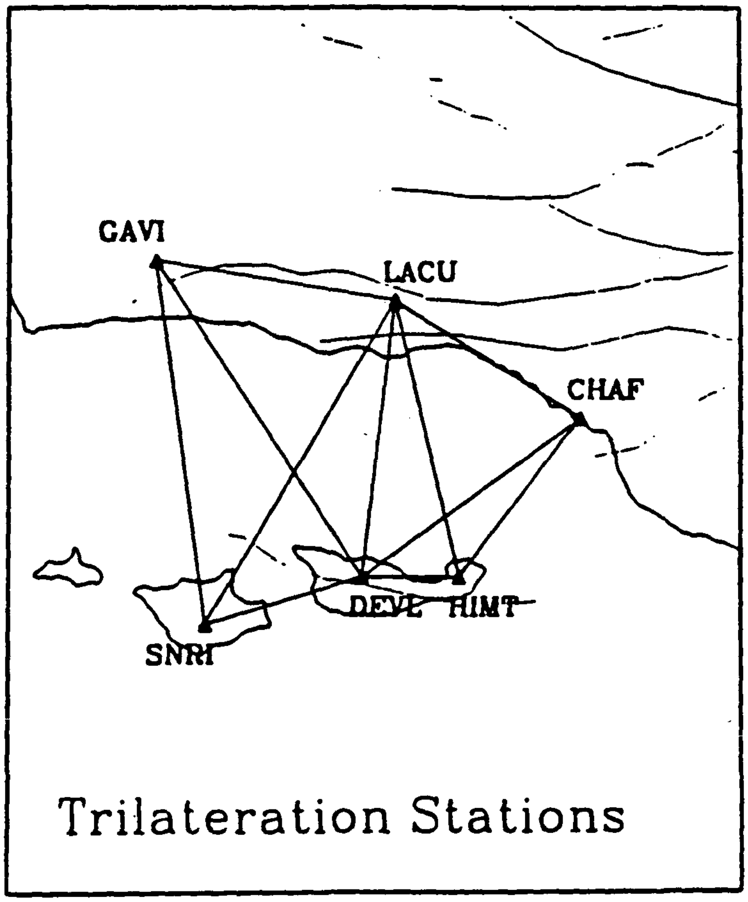

Figure 3. Stations included in the 1971 trilateration survey of *Willot et al.* [1972].

2.3 A Deformation Monitoring Network for the California Margin

The design of a long-term network for monitoring crustal deformation demands a careful consideration of both the scientific objectives and the practical aspects of the surveying technique. Sites used historically for trilateration and triangulation surveys had to meet two very restrictive criteria: intervisibility and proximity with respect to other sites in the network. GPS surveys do not have these restrictions. We are free to employ greater intersite distances if they satisfy the scientific objectives, and we can choose low-elevation sites which are more accessible than those used for terrestrial surveys.

In selecting sites for our December and January experiments, we considered first our scientific objectives, both in technique development and geophysical studies. We then applied four other criteria which are important for GPS observations: a clear sky view to 20^o elevation in all directions; existence of permanent monumentation; accessibility by vehicle or easily by foot in all weather conditions; and absence of antennas which might be a source of radio-frequency interference. We have made extensive use of sites being occupied by VLBI and SLR systems under the NASA Crustal Dynamics Project, sites monumented and observed by the USGS, and sites selected by the NGS for the National Crustal Motion Network (NCMN). Prior to the recent observation campaigns, we carried out extensive reconnaisance of sites to determine the condition of existing monumentation and the suitability of the site for GPS occupation. Not all of the sites selected met all of our criteria as well as we would have liked, but we have determined a minimal usable set for repeat observations. We have prepared (in a separate document) extensive descriptions of these sites, as well as the triangulation and trilateration sites we have occupied since June 1986.

The complete network for southern and central California is listed in Table 3 and shown in Figure 4 . The regional fiducial sites (Vandenberg, Fort Ord, Owens Valley, Mojave, and Palos Verdes) are all measured repeatedly with VLBI and/or SLR systems and, consequently, establish a reference frame for GPS measurements. If the satellite orbits are determined using fiducial sites outside of California, the relative positions estimated for the regional fiducial sites can be compared with VLBI and SLR determinations to help in the assessment of measurement errors.

The southernmost sites in the network (Santa Paula, JPL, Palos Verdes, La Jolla, and San Nicholas, San Clemente, and Santa Catalina Islands) were first occupied during the June 1986. Measurements between these sites provide a measure of strike-slip on the San Clemente and other offshore faults in the southern Borderlands. Similarly, measurements from Santa Cruz Island to Cotar, La Cumbre, and Vandenberg constrain deformation across the Santa Barbara Channel.

The Black Hill and Blancas sites are situated to the east of the Hosgri fault zone on the Salinian block. The Madre and Pozo sites are also on the Salinian block northeast of the Santa Maria Basin. Measurements between these sites provide a test of the hypothesis that motion along the Hosgri fault system is transferred to faults in the Santa Barbara Channel by deformation within the Santa Maria Basin north and east of Vandenberg (see *Hall*, [1975; 1981]). These baselines can also be used to estimate the compressive deformation perpendicular to the San Andreas indicated by the kinematical model of the San Andreas discrepancy [*Minster and Jordan*, 1984; 1987] and directly by geological observations [*Crouch et al*, 1984]. The Pozo-Black Hill baseline tests the stability of the southern end of the Salinian block. Measurements from these sites to Fibre, east of the San Andreas Fault, provide an anchor for the network on the North American plate and complement the trilateration measurements in the USGS Carrizo and San Luis Obispo networks.

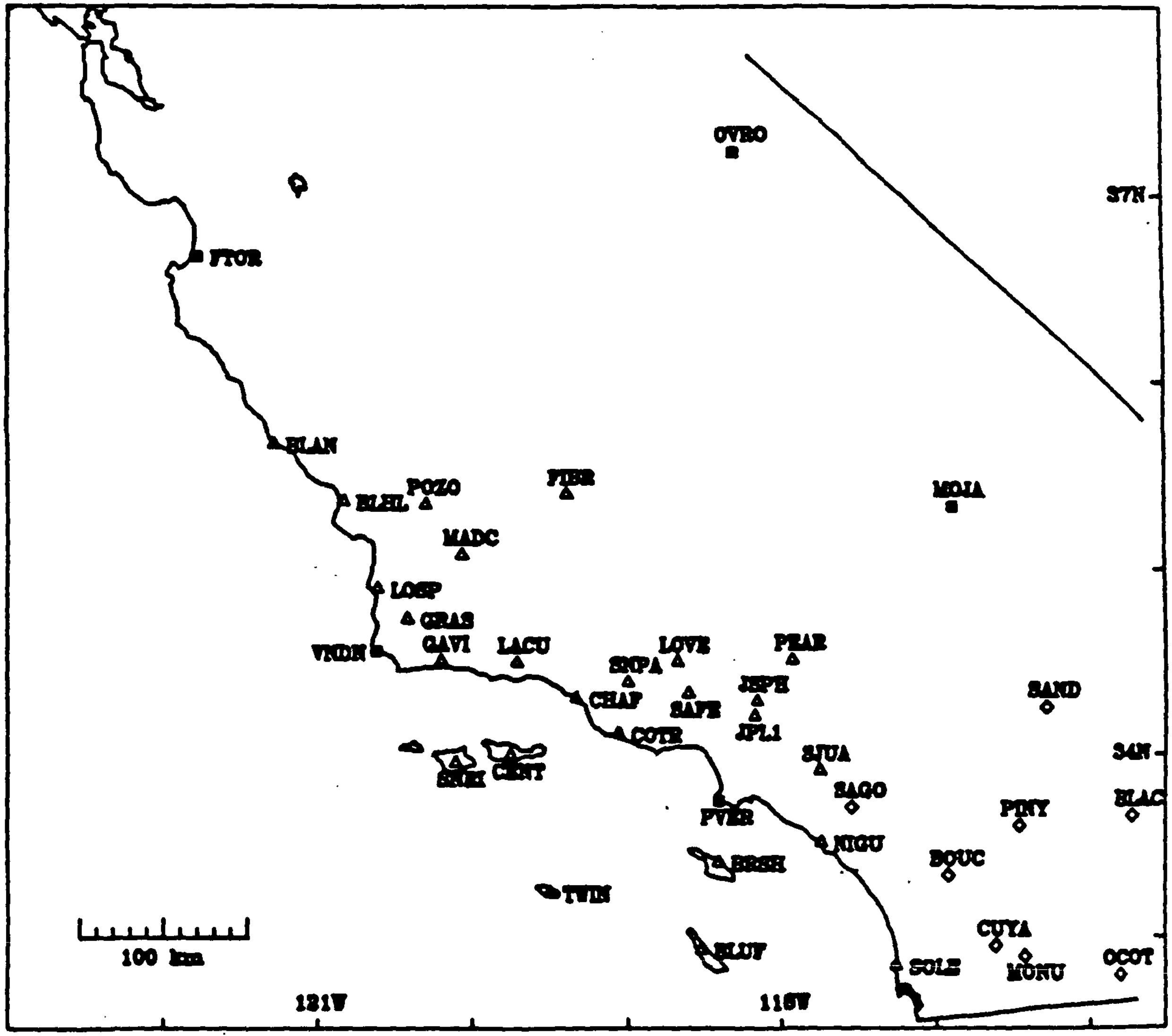

Figure 4. GPS network for central and southern California, showing regional fiducial sites (▪), sites of the primary network (Δ), and VLBI sites observed by the NGS (◊).

Table 3. Central and Southern California Crustal Deformation Network Sites

Station	Name	Approximate Coordinates Lat. (N)	Long. (W)	Elev. (m)	Other Networks
OVRO	Owens Valley	37.233	118.291	1200.	VLBI
FTOR	Ft. Ord	36.670	121.772	24.	VLBI
BLAN	Piedras Blancas LH	35.666	121.282	16.	
BLHL	Black Hill	35.358	120.826	202.	USGS (San Luis)
FIBR	Fibre (Buttonwillow)	35.399	119.393	88.	
POZO	Pozo	35.35	120.30	800.	
MOJA	Mojave	35.332	116.887	899.	VLBI
MADC	Madre	35.076	120.066	992.	USGS (Carrizo)
LOSP	Lospe (Vandenberg N.)	34.894	120.605	499.	NGS, DMA
GRAS	Grassy	34.731	120.413	365.	DMA
VNDN	Vandenberg	34.556	120.615	24.	VLBI
GAVI	Gaviota	34.502	120.198	749.	NGS
PEAR	Pearblossom	34.512	117.921	900.	VLBI
LOVE	Loma Verde	34.496	118.668	760.	NGS
LACU	La Cumbre	34.495	119.712	1216.	
SNPA	Santa Paula	34.388	118.998	190.	VLBI
SAFE	San Fernando	34.330	118.600	1137.	NGS
CHAF	Chaffee	34.301	119.33	343.	NGS
JSPH	Josephine Peak	34.285	118.153	1635.	NGS
JPL1	JPL, Pasadena	34.205	118.170	474.	VLBI
COTR	Cotar	34.1	119.06	1.	PMTC
CENT	Center, Santa Cruz Is.	33.995	119.753	425.	
SNRI	Soledad, Santa Rosa Is.	33.951	120.105	495.	NGS
SJUA	San Juan	33.914	117.757	543.	NGS
PVER	Palos Verdes	33.744	118.403	78.	VLBI
NIGU	Niguel	33.513	117.733	288.	NGS, USGS (Anza)
BRUS	Brush, Catalina Is.	33.407	118.404	485.	
TWIN	Twin, San Nicholas Is.	33.232	119.478	237.	
BLUF	Bluff, San Clemente Is.	32.927	118.518	335.	
SOLE	Soledad, La Jolla	32.840	117.252	555.	NGS

Other networks: NGS = Triangulation, USGS (network) = Trilateration

3. Description of the 1986 and 1987 Campaigns

Offers by the NGS and USGS of TI 4100 receivers for use over the 1986-87 holiday period provided a unique opportunity for us to begin our investigation with first- (or in a few cases, second-) epoch measurements far more extensive than any of us had envisioned. Between December 16 and January 30 over 200 site-days of observations were collected, involving 30 different sites in California. Each of the four universities contributed at least 60 person-days to the observations.

The plan for the campaign divides conveniently into six "experiments", distinguished by their time, personnel, receiver deployment, and (to some extent) scientific objectives. Experiment 1 lasted 5 days, December 16-20, and employed eight field receivers in California: five provided by the USGS, two by UNAVCO, and one by the Navy PMTC. The permanent tracking receiver operated by the University of Texas and NGS at Mojave provided an additional California fiducial site for this and all the other experiments. The Texas Highway Department permanent tracker in Austin observed during this period, and the University of Colorado operated the third UNAVCO receiver as a fiducial tracker at Platteville. Experiment 1 was preceded by a one-day organizational and training session at Caltech, conducted by the investigators and Will Prescott of the USGS. USGS field crews accompanied their receivers for all five days of the experiment and provided valuable training for the university operators. The scientific objectives of Experiment 1 were to tie the VLBI sites at Vandenberg, Santa Paula, and Palos Verdes to the NGS triangulation site on north Vandenberg (Lospe), to the Pozo site, and to the USGS triangulation site at Black Hill. In conjunction with Experiment 2, it provided first-epoch data for studying tectonic deformation across the Santa Maria Basin.

Experiments 2 and 3 were the most comprehensive of the campaign since they employed twelve receivers in California (including Mojave) and six receivers at other sites in North America. In addition to the five USGS, two UNAVCO, and one PMTC receivers, we used three NGS receivers at California sites. (These experiments were also the most ambitious since they required university crews to man all eleven of the field receivers.) Data from the permanent trackers at Austin, Mojave, and Westford, and a UNAVCO receiver at Platteville were available, and the Geodetic Survey of Canada operated receivers at the Algonquin VLBI site and a field site at Churchill, Manitoba. Each experiment lasted five days: Experiment 2; December 29-January 2; Experiment 3, January 3-7. The objectives of these experiments were to extend the network to the north, and to measure deformation across the Santa Barbara Channel by re-occupying trilateration and triangulation sites. Experiment 2 provided the most widely distributed observations, with sites as far north as San Simeon (Blancas Lighthouse), one site (Fibre) east of the San Andreas, and a site on Santa Cruz Island (Center). Two of the sites (Black Hill and Madre) are included in trilateration networks established by the USGS. In Experiment 3, triangulation and trilateration sites on Santa Rosa Island (Soledad), Santa Cruz Island (Devil's Peak), and Santa Catalina Island (Brush), and at several coastal sites (La Cumbre, Gaviota, and Chaffee) were occupied.

Experiments 4, 5, and 6 involved cooperation between three of the universities (Caltech, UCLA, and UCSD), JPL, and NGS to use three UNAVCO and three NGS receivers to support the NGS campagin to re-occupy (mostly) VLBI sites in southern California, and our objectives to obtain measurements between coastal and island sites. NGS crews operated their receivers during all of this period. Between January 13 and 23 (Experiments 4 and 5) sites at Ocotillo, Monument Peak, Black Butte, Owens Valley, Pinyon Flat, Palos Verdes, Deadman Lake (Sand Hill) and JPL (Aries 1), were occupied for four days each, and Pearblossum, Santa Paula, and Niguel for two days each. Sites at Boucher and Josephine Peak were occupied for one day. In Experiment 6, sites on San Clemente Island (Bluff), Santa Cruz Island (Center), and Santa Catalina Island (Brush) were occupied together with La Cumbre, La Jolla (Soledad), and Palos Verdes, thus completing the tie between the southern islands and the remainder of our long-term crustal deformation network.

The field data from Experiments 1-3, plus the Canadian data, have been transcribed from cassette to 9-track tape at MIT and distributed to JPL, NGS, GSC, the University of Colorado, and the University of Texas in ARL FICA format. Data from Platteville have been transcribed by Colorado and sent to MIT for further distribution. Data from Mojave and Austin have been transcribed (from disk) by Texas and sent to MIT (via USGS) for further distribution. Data from Experiments 6 have been transcribed by Colorado and data from Experiments 4-5 have been transcribed and archived by NGS.

For 5 days each in May and September 1987 we cooperated with the USGS in reoccupying the regional fiducial (VLBI) sites, shown by squares in Figure 4, plus Black Hill and Santa Cruz Center, each about 70 km from Vandenberg. (In May we could not occupy Ft. Ord due to the last minute loss of one receiver; in September two additional receivers were provided by the Geodetic Survey Squadron of the Defense Mapping Agency.) As in the December and January campaigns, the observations at Mojave were obtained by NGS using the University of Texas' permanently deployed receiver. These experiments (7 and 8) were designed to study sources of error in our observations and to increase confidence in their reliability. Since the window of satellite observability advances by 2 hours each month, the 4-month interval between campaigns allows us observe at different times of day, thus sampling different ionospheric and tropospheric conditions. The mid-winter observations were entirely at night, the May observations in the afternoon and evening, and the September observations from sunrise to mid-afternoon, the time of peak ionospheric gradients. The effect of the ionosphere can be removed from the observations using a particular combination of the two (L1 and L2) GPS signals, but its magnitude significantly affects the analyst's ability to resolve phase ambiguities and thus to obtain the most accurate estimates of site coordinates.

During Experiments 8 (22-26 September) and 9 (27 September - 11 October) we used two UNAVCO receivers, two from the Geodetic Survey Squadron, and two from the Polar Institute at the Ohio State University to obtain GPS observations at 13 of the historical sites. For these measurements we observed at each site for only two days and often used satellite scenarios of 4-5 hours instead of our usual 7-8 hours. The magnitude 6 Whittier Narrows Earthquake of October 1, 1987, occured during our scheduled observations but on a day when our receivers were deployed over 100 km to the north. Based on the small but non-negligible probability (1-5 %) that this earthquake might have been a foreshock of a larger event (*Jones*, 1985; *Kagan and Knopoff*, 1987), we revised our observing schedule somewhat. We occupied the Mt. Wilson (ECHO) and San Juan (SJUA) sites earlier than originally planned, and we added the triangulation sites Workman Hill (WORK), near the region of maximum coseismic destruction, and San Tuze (SNTZ), which had been part of a triangulation survey with ECHO and SJUA. Our observations, coupled with the earlier triangulation surveys may allow measurement of coseismic displacement.

4. Data Analysis

Most of the observations from Experiments 1,2, and 3 have analyzed in at least a preliminary fashion. Table 4 gives a summary of successful observations for each of our primary sites. Shown are the days of occupation and an indication whether the observations were successful (1), unsuccessful (0), or not yet analyzed (C or ?).

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Table 4. Observations of the California GPS Network and Fiducial Sites December 1986-September 1987

	EXPERIMENT NUMBER	1					2					3					4				5				6					7					8					
	DAY NUMBER	350	351	352	353	354	363	364	365	001	002	003	004	005	006	007	013	014	015	016	020	021	022	023	026	027	028	029	030	144	145	146	147	148	265	266	267	268	269	270
	YEAR	1986								1987																														
	MONTH	December								January																				May					September					
	DATE	16	17	18	19	20	29	30	31	1	2	3	4	5	6	7	13	14	15	16	20	21	22	23	26	27	28	29	30	24	25	26	27	28	22	23	24	25	26	27
	CONTINENTAL FIDUCIAL																																							
ALGO	Algonquin Park, ONT	.	.	.	.	.	1	1	1	1	1	1	1	1	1	0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
AUST	Austin, TX	0	0	1	.	.	0	0	0	0	0	0	0	0	0	1	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
CHUR	Churchill, Manitoba	.	.	.	.	.	.	1	1	1	1	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	C	C	C	C	C
MOJA	Mojave, CA	0	1	1	1	0	.	1	1	1	.	.	.	1	1	1	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
PLAT	Platteville, CO	1	1	.	1	1	1	1	1	1	1	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	C	C	C	C	.
WSFD	Westford, MA	0	0	0	.	.	0	1	1	1	1	1	1	1	1	0	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
YKNF	Yellowknife, NWT	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	?	?	?	?	?	?	?	?	?	?	?
	REGIONAL FIDUCIAL																																							
FTOR	Fort Ord	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	C	C	C	C	C	.
OVRO	Owens Valley	1	1	1	1	1	1	.	1	1	1	1	1	1	1	1	0	1	.	.	.	.	.	.	.	.	.	.	.	1	1	1	1	1	C	C	C	C	C	.
PVER	Palos Verdes	1	1	1	1	1	.	.	.	.	.	1	1	1	1	1	.	.	.	.	1	1	0	1	1	1	1	1	.	C	C	C	C	C	C	C	C	C	C	.
VNDN	Vandenberg	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	C	C	C	C	C	C	C	C	C	C	.
	DEFORMATION NETWORK																																							
BLAN	Piedras Blancas	.	.	.	.	.	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
BLHL	Black Hill	1	1	1	1	1	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	1	1	1	C	C	C	C	C	.
BLUF	Bluff S. Clemente I.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.
BRSH	Brush S. Catalina I.	.	.	.	.	.	.	.	.	.	.	1	1	1	1	1	.	.	.	.	.	.	.	.	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.
CENT	Center, S. Cruz I.	.	.	.	.	.	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	1	1	.	1	1	1	1	1	C	C	C	C	C	C
CHAF	Chaffee (A = SOLI)	.	.	.	.	.	.	.	.	.	.	1	A	A	A	A	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
COTR	Cotar	.	.	.	.	.	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
FIBR	Fibre, Buttonwillow	.	.	.	.	.	1	1	1	1	1	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
GAVI	Gaviota	.	.	.	.	.	.	.	.	.	.	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
JPL1	JPL Aries 1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0	1	1	1	0	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
JSPH	Josephine Peak	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
LACU	La Cumbre	.	.	.	.	.	.	1	1	1	1	1	1	1	1	1	.	.	.	.	.	.	.	.	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.
MADC	Madre	.	.	.	.	.	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
NIGU	Niguel	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
POZO	Pozo Summit	.	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
SNPA	Santa Paula	0	.	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
SOLE	Soledad, La Jolla	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	1	1	0	.	.	.	.	.	.	.	.	.	.	.
SNRI	Santa Rosa Island	.	.	.	.	.	.	.	.	.	.	1	1	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

LEGEND:

1	More than 3/4 of scenario useable.
0	Less than 3/4
C	Collected, not yet read
?	Not yet known
A	Alternative site occupied

We have analyzed the observations from Experiments 2 and 3 using orbits determined from a 4-station continental network (Ft. Ord, Platteville, Churchill, and Algonquin). The repeatabilities obtained in our estimates for baseline components are typically 1 part in 10^7 or better. The results for four representative baselines, varying in length from 80 to 200 km, are shown in Table 5.

Table 5. Repeatability of Baseline Estimates from 4-6 Days of Observations in January 1987

		rms (mm)		
Baseline	Length (km)	North	East	Vertical
Vandenberg - La Cumbre	80	3	23	16
Vandenberg - Santa Cruz Is.	100	8	5	14
Vandenberg - Buttonwillow	150	5	14	14
Vandenberg - Ft Ord	200	13	12	19

In addition to general processing [*Agnew et al.*, 1987; *Murray et al.*, 1987], several specialized studies are being carried out. These include preliminary comparison of GPS baselines with the results of historical surveys [*Jackson et al.*, 1987], the use of regional fiducial stations alone for orbit control [*King et al.*, 1987], the effect of ionospheric constraints on phase-ambiguity resolution [*Bock et al.*, 1986a; *Bock and King*, 1987], the use of tropospheric constraints for improved estimates of the vertical component [*Davis et al.*, 1987; *Murray et al.*, 1987], and comparison of analyses from several different software packages [*Webb, Larson, and Larsen,* 1987].

5. Future Plans

We plan to re-occupy all of the sites of our network at 1-2 year intervals at least over the 5-year duration of our NSF investigations. In 1988 most, if not all, of our observations will be carried out in March, when we are scheduled to use the three UNAVCO receivers and have arranged joint observations with the USGS and NGS. During the next two months, we will evaluate the results of our 1987 observations in order to set priorities for reoccupation of sites during the March campaign.

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