to 3 mm/yr of changes in height. We discuss the possible origin of this change with emphasis on the effects of the GPS-satellite phase-center models, including the position of the phase-center with respect to the center of mass of the satellite, and that the apparently systematic changes in scale are due to the slow evolution of the GPS constellation from Block I to Block II, IIA and currently block IIR generations of satellites.

G31D-08 1035h

Bringing Tide Gauges Into the Terrestrial Reference Frame: GPS Results to Support Calibration of the Emerging Altimetric Sea-level Record.

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The Topex/Poseidon (T/P) era of altimetry (1992–present) has fortuitously coincided with the emergence of GPS as an invaluable scientific tool in both the geodetic and atmospheric sciences. Many of the observations from terrestrial GPS stations (e.g., vertical land motion, water vapor abundance, total electron content) bear directly on the interpretation of the emerging record of global mean sea level from altimetry. Combined with the rapid growth of the numbers of permanent GPS stations–most notably at coastal and island locations–this has significantly enhanced the potential for exploiting terrestrial GPS as a multi-faceted altimeter calibration tool.

In this paper, we present new determinations of the vertical positions and velocities of tide gauge sites in the International Terrestrial Reference Frame (ITRF2000). We first review the latest results from the Harvest platform experiment off the coast of Central California. In its capacity as a dedicated T/P calibration site, Harvest has hosted a GPS receiver and tide gauges since 1992. We present estimates of the platform vertical motion and local sea level from nearly a decade of continuous monitoring, and discuss implications on the altimeter calibration estimates. In addition, we present results from selected other GPS/tide gauge collocations that support the determination of the stability of the T/P measurement system. The time series of GPS vertical position estimates generally show evidence of annual and longer-term systematic variations. We will discuss potential sources of these signals, including various loading and thermal effects as well as manifestations of GPS measurement errors. Included in our characterization of the latter will be the effects of water vapor delays, and the impact of equipment swaps (e.g., receiver and radome changes).

G31D-09 1050h INVITED

BIFROST project: 3-D site motion inferred from 2500 days of continuous GPS in Fennoscandia and implications for regional changes of sea level

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Beginning in 1993 the BIFROST project has been compiling a large data base of geodetic positions using permanent networks of GPS receivers in Sweden and Finland, SWEPOS and FinnRef, respectively. The continuous GPS observation has provided a total of about 2500 daily solutions.

From this data rates of change of, for instance, vertical position or intraplate deformation can be inferred. Removing, from the data, crustal deformation predictions determined from a glacial isostatic adjustment (GIA) model gives normalised χ^2 values of order 10, showing that GIA dominates the observed deformation field.

Another wealth of data can be found in relative sea level observations obtained from a dense network of tide gauges that has been in operation since typically 50 and, in the case of Stockholm, 220 years. The uncertainties for the relative sea level rates and for the GPS-based land-surface rates have become comparable, 0.2 and 0.4 mm/yr, respectively. Thus, we explore the two data sets in order to infer regional changes of sea level. The tide gauges are approximately colocated with the GPS array and the majority are sampling the Baltic Sea and its sub-basins; hence a regionally constant sea level term is expected to correlate primarily with a change of the North Atlantic level at the North Sea-Skagerak-Kattegat. We are currently exploring deviations from a constant term, which might be indicative of long-wavelength or far-field perturbations of the geopotential. In this regard, we are considering the regional Fennoscandian signal that would arise from a suite of ongoing mass loading/unloading scenarios.

G31D-10 1105h INVITED

Tide Gauge Data and the Geometry of Present-Day Sea-Level Rise

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It has long been recognized that ongoing mass flux of ice sheets and glaciers will cause a geographically non-uniform sea-level rise. Indeed, in the vicinity of a melting ice complex sea level will fall, while in the far-field of this ice sheet sea level will rise at a rate which exceeds the so-called eustatic value (i.e., the value expected under the assumption of a globally uniform sea-level change). The departure from eustasy arises primarily from the effects of self-gravitation, but loading and rotational signals also contribute. Thus, mass flux associated with any ice center (including major polar ice complexes or mountain glaciers and ice sheets) will be characterized by a unique pattern, or 'fingerprint', of sea-level change.

Tide gauge records of sea-level rates exhibit significant geographic variations, even after correction for the ongoing signal due to glacial isostatic adjustment. However, the potential for rather extreme non-uniformity in sea-level change associated with present-day changes in the global ice budget has not, until recently, been embraced in analyses of these tide gauge data. Indeed, previous analyses have generally ignored the geographic variation by taking a simple average of the tide gauge rates to obtain a global value for sea-level rise. We recently reported on an attempt to separate the unique patterns of sea-level change using an independently published subset of tide gauge rates [Mitrovica et al., *Nature*, 2001; see also Plag and Jüttner, 2001], and demonstrated that several previously identified anomalies in the global tide gauge record could be reconciled using an appropriate weighting of sea-level patterns. In this talk we extend this work to incorporate global patterns of sea-level change due to the steric effect of ocean thermal expansion. These patterns are derived, in part, from the output of coupled atmosphere-ocean general circulation models, and they are characterized by a broad suite of geometries. Accordingly, we focus on the sensitivity of our inferences of ice sheet mass balances to the variation reflected in these geometries.

G31D-11 1120h

Inverting Relative Sea Level Trends for Contributions From Different Climate-Related Processes

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Present-day changes in ice sheets and glaciers, post-glacial rebound and thermal expansion of the ocean are among the processes contributing significantly to local relative sea level trends at many tide gauges. Local relative sea level trends determined from carefully processed tide gauge records can be used to invert for the different processes, if models are available to describe these contributions. The contribution from ice sheets can be parametrised on the basis of the so-called sea level equation. Geophysical models can be used to account for postglacial rebound. Climate models provide information on the pattern of steric expansion. An analysis of the contribution of these three processes to trends observed at globally distributed tide gauges will be presented and the significance of model parameters determined in an inversion of local relative sea level trends will be discussed.

G31D-12 1135h

A Comparison of two methods of gravity inversion and their impact on predictions of Ice Mass Balance

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One of the challenges of using a budgetary approach to measuring sea level rise and ice mass balance are the large uncertainties inherent in measuring the Earth's gravity field and calculating the components of the geopotential. For example, the non-steric portion of sea surface height may make a contribution to the low degree zonal coefficients as large as that as polar ice. We will present two methods of gravity inversion, one that uses a template that fixes the shape of the regions in the ice sheets that are used to find ice thicness, and one that uses an iterative procedure that makes no assumptions about the shape of the thickness profile over polar ice. This analysis gives an estimate of the uncertainties in ice thickness that result from the non-uniqueness of any mass balance inversion from the geopotential. We expect to show that these uncertainties are generally smaller than either the measurement uncertainties of those associated with components of the global gravity budget.

G32A MC: 121 Wednesday 1330h

The Terrestrial Reference Frame: Definition, Long-Term Stability, and Limitations I *(joint with H, OS, S, T, DI)*

Presiding: **K Larson,** University of Colorado at Boulder**; Z Altamimi,** ENSG/LAREG

G32A-01 1330h

The International Terrestrial Reference System. An overview of its background and its future.

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The International Earth Rotation Service (IERS) is in charge of the realization of the International Terrestrial Reference System (ITRS) since its establishment in 1988. An overview of its developments is presented both on technical and organizational aspects, focusing on the quality issues in the broad sense (accuracy, availability...). After the presently available realization (ITRF2000), new challenges are on the spot. A review of some of them is threfore given, investigating how IERS can face them: densification, improvement of site consistency, improved model for ITRS and possible refinement of its definition...

G32A-02 1345h

Review and Progress of the ITRF Datum Definition: New Results From ITRF2000

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Since 1988, the ITRF has sustained successive improvements in data analysis strategy in terms of constraint handling, weighting of the individual solutions as well as datum definition. This latter is one of the most critical aspects, since it should endow the frame with all its full geodetic and geophysical significance. Starting with diagonal weighting using the initial individual solution uncertainties, other empirical schemes were used and, currently, estimation of the variance components is applied, favored by SINEX format which contains full variance covariance information. Analysis strategy improvements both by IERS Analysis Centers and ITRF combination as well as their mutual interaction allowed to establish the ITRF2000 that is free from any external constraint. Minimum constraints approach is used, in a consistent geodetic way, solely to implement the datum in terms of origin, scale, orientation and time evolution. The paper will outline the ITRF progress in the three aspects mentioned above, emphasizing on the particular case of ITRF2000 whose datum definition was deeply reviewed. New results from the ITRF2000 will be presented and in particular estimated tectonic motions of six major plates which differ from those predicted by NUVEL-1A model. Implications of these new results on the ITRF datum definition will be discussed.

URL: http://lareg.ensg.ign.fr/ITRF/ITRF2000

G32A-03 1400h

Featured Presentation: Plate Velocities in Hotspot Reference Frame

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There is no abstract available for this presentation.

G32A-04 1415h INVITED

Some Recent Results for Geologically Instantaneous Plate Motions

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Geologically "instantaneous" plate motions, i.e., those averaged over the past few Myr, provide a fundamental constraint on the terrestrial reference frame. In this talk I review some recent results for geologically instantaneous plate motion, which indicate that the motion of some plates differ significantly from those of the NNR-NUVEL1A set of angular velocities, which are currently incorporated into the international terrestrial reference frame.

The set of relative angular velocities for plate motions in the Indian Ocean have been revised in many ways since the construction of the NUVEL-1 and NUVEL-1A angular velocities. The Indo-Australian composite plate is now interpreted as three component plates (Indian, Capricorn, and Australian) with multiple diffuse plate boundaries rather than merely two component plates [Royer and Gordon 1997]. The African composite plate, which was treated as a single plate in NUVEL-1 is now treated as two component plates (Nubian and Somalian) with an intervening diffuse plate boundary [Chu and Gordon 1999; Horner-Johnson et al., this meeting]. The motion of India relative to Eurasia has also been significantly revised (slower and more clockwise) because of new plate motion data in the Indian Ocean, the revised geometry of African and Indian Ocean plates, and a re-weighting of data from the Atlantic [Argus and Gordon 1999]. These results change not only the relative plate angular velocities but also the motion of all plates relative to the no-net-rotation reference frame.

Modifications to the no-net-rotation reference frame are tiny compared with the differences between the no-net-rotation frame and the hotspot frame, however. Gripp and Gordon [in press] recently constructed a new set of data from the young traces of hotspot tracks and combined it with NUVEL-1A to obtain a set of angular velocities of the plates relative to the hotspots, which they call HS3-NUVEL1A. The angular velocity of any plate relative to the NNR-NUVEL1A no-net-rotation reference frame differs significantly from the corresponding angular velocity relative to the hotspots specified in HS3-NUVEL1A. Thus, the lithosphere has a net rotation relative to the hotspots of $0.44 \pm 0.11^{\circ}$ per Myr (95% confidence level) about a pole at 56S, 70E. This net rotation will be compared with that predicted from models for plate driving forces.

G32A-05 1430h INVITED

Plate Motions from Space Geodesy

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We determine GEODVEL (GEODesy VELocity model), a model of the angular velocities among 9 major plates, using observations from the global positioning system (GPS), very long baseline interferometry (VLBI), and satellite laser ranging (SLR). We assign sites to plates on the basis of geological observations: the distribution of major faults, the locations of large and historical earthquakes, other seismicity, and the distribution of high topographic relief generated by active deformation. We aim to address three sets of outstanding questions: (1) How rigid are the plates? How big is the viscous response of the solid earth to the unloading of the late Pleistocene ice sheets? (2) Where are the limits of the plate interiors? Do these limits coincide with the distribution of earthquakes, Holocene faulting, and topography? (3) What are the best estimates of the motions among the plates? Do estimates of plate motion from geodesy differ significantly from those estimates from seafloor spreading rates and transform azimuths? In particular, where are differences between GEODVEL and geologic plate motion model NUVEL-1A the biggest?

G32A-06 1445h

A No-Net-Rotation Model of Present-Day Surface Motions

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A significant portion of the Earth's surface consists of zones of diffuse deformation. The interior regions of these diffuse zones of deformation move at distinctly different velocities from that of adjacent plates, and, because of their complexities, have been ignored in previous no-net-rotation (NNR) models (e.g., NNR-NUVEL1A). We have calculated a new NNR model from a continuous velocity field that incorporates both rigid plate motion and velocity gradients within plate boundary zones. The velocity field is obtained through a bi-cubic Bessel interpolation of almost 3000 geodetic velocities and strain rates inferred from Quaternary faults. The geodetic velocities are taken from about 50 different, mainly published, studies. For each study we have not adopted the original reference frame. Instead, we have solved for a rigid body rotation for each study that rotate the vectors of each study into a model reference frame in the process of satisfying a least-squares fit between model and observed velocities and model and observed strain rates. When compared with earlier NNR models we find significantly different angular velocities for many plates in our model. Differences between the NNR model presented here and earlier NNR models can be attributed to both the effect of including velocity gradients in diffuse plate boundary zones, as well as actual differences between geodetically derived, present-day, surface motions and geologic estimates. We find that for the Indian, Arabian, Nazca, Cocos, Philippine Sea, and the Caribbean plate the differences between our model and the NNR-NUVEL1A model are mainly due to differences between geodetic and geologic plate velocities. For the Eurasian plate the discrepancy that we find between our result and NNR-NUVEL1A model can not only be ascribed to the difference between geodetic and geologic velocities, but also to the significant effect of including plate boundary zones. The significantly different NNR rotation vectors that we find for the majority of plates suggests that caution is warranted when using the NNR-NUVEL1A model to change from an ITRF to a tectonic reference frame. Our new NNR results indicate that such practice may result in significant discrepancies in crustal velocities with respect to the chosen reference plate. Finally, similar to earlier NNR models, we find a significant difference between the NNR velocities and velocities with respect to hotspots.

URL: http://geophysics.geo.sunysb.edu

G32A-07 1520h INVITED

A New Global Mode of Earth Deformation: Reference Frame Implications

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Precise positioning of GPS sites distributed worldwide reveals a global mode of Earth deformation predicted by theory. We have identify this pattern as the degree-one spherical harmonic response of an elastic Earth to increased winter loading of soil moisture, snow cover, and atmosphere (see abstract in session G05). Here we discuss implications for the Terrestrial Reference Frame (TRF). The first problem is on locating the TRF origin with respect to geodetic stations considering that we now understand that the degree-one response is more than a simple translation with respect to the origin. The second problem is on how a Terrestrial Reference System (TRS) might accommodate 3-D station displacements caused by predictable variations in the degree-one response.

On the first problem, we show how the 3-D surface deformation field can be expressed as coordinate displacements in the center of figure frame (the frame of no-net 3-D translation of the surface). Furthermore, we show how the 3-D surface displacement field is related to the translation of the center of figure frame ("geocenter" displacement) with respect to the TRF origin (the center of mass of the entire Earth system). Therefore, rigorous analysis should account for this deformation field when estimating geocenter displacements, which affects the realization of the TRF origin. For example, the "dynamic" method of using satellite orbit residuals to estimate geocenter offsets would be incorrect if ground station positions were constrained (e.g., assuming constant velocities). Not taking the degree-one deformation into account would generate biased satellite orbits, upon which realization of the origin depend. A less biased (but possibly noisy) approach is the "geometric" method of deriving the geocenter time series from the application of Helmert transformations to global free-network epoch solutions. Here we derive a geocenter estimation approach using the degree-one (translation plus deformation) model of station coordinate displacement relative to the Earth system center of mass.

On the second problem, our data show an annual oscillation of station coordinates in the center of figure frame with amplitude 3 mm, which appears to be forced by seasonal redistribution of surface mass (see abstract in G05). These oscillations might, for example, bias the interpretation of station motion for tectonics. We present an empirical predictive model as an example of how the TRS might account for this phenomenon.

G

G32A-08 1535h

TRF Accuracy Improvement from Better Atmosphere Modeling for VLBI and GPS

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Significant improvements in the Terrestrial Reference Frame (TRF) have been attained through better modeling of the atmosphere. Each advance in mapping function for the azimuthally symmetric component of the troposphere has resulted in better definition of the local vertical component of the geodetic measurements and thus in the scale of the TRF. Studies of the azimuthally asymmetric contribution of the atmosphere to the delay model have indicated the need to estimate the magnitude and direction of such an effect. Incorporation of a gradient model has improved the accuracy of the horizontal component of site positions and has reduced systematic declination-dependent errors in the Celestial Reference Frame.

A major step in modeling the azimuthally symmetric atmosphere was the separation into hydrostatic and wet components, based on recognition that the different vertical distributions require different mapping functions for the best modeling accuracy. Implementation of such a model is possible because the hydrostatic zenith delay can be calculated accurately apriori from

surface pressure measurements, leaving the wet delay to be estimated.

As the precision of geodetic GPS and VLBI measurements has improved, so has the need for better modeling of the azimuthally asymmetric contribution of the atmosphere. We have developed a means of correcting for the hydrostatic gradient using information from a global numeric weather model, thus allowing the estimation of the wet gradient with its significantly different mapping function. The data set required for the hydrostatic gradient information is the same as that to be used for a new time- and site-dependent azimuthally symmetric hydrostatic mapping function.

We will describe the derivation and give the results of testing the new hydrostatic gradient model with VLBI data. The use of a re-analysis of the global weather data (e.g., by the Goddard Space Flight Center Data Assimilation Office) will ensure that the atmosphere model contribution to the TRF is consistent over the entire span of VLBI data.

G32A-09 1550h

Re-Analysis of a Decade of Continuous GPS Data at the Scripps Orbit and Permanent Array Center: Implications for Terrestrial Reference Frame Stability

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The Scripps Orbit and Permanent Array Center serves as a global archive and analysis center for the International GPS Service, since it inception. Recently, we have completed a re-analysis of our entire archive of continuous GPS data spanning more than a decade in a consistent manner with the GAMIT/GLOBK software suite. We have produced new orbital solutions, EOP parameters, site coordinates, and SINEX files in the ITRF97 reference frame which have replaced our (inconsistently-analyzed) long-term operational products on the SOPAC Web Site. The terrestrial reference frame is realized by the adoption of a set of epoch coordinates and velocities for a set ot global tracking stations. We describe a time series analysis of the site coordinate solutions that provides insight into the long-term stability of the terrestrial reference frame defined by GPS. In particular, we characterize the noise in the time series, identify periodic signals, and investigate non-linear effects that complicate the assignment of a velocity and a velocity uncertainty for global tracking sites.

URL: http://sopac.ucsd.edu

G32A-10 1605h

Comparison of ITRF2000 With a GPS Defined Reference Frame

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It is now possible to define a global terrestrial reference frame using the GPS satellite constellation. The GPS reference frame has an origin definined as the center of mass about which the satellites orbit. The scale or unit of measurement is the meter which is defined by light travel times from the satellites to receivers on the ground. Orientation of the frame is defined for alignment with historical Earth orientation estimates and no net drift with respect to the NNR-NUVEL1A plate motion model. Offsets and drifts between the ITRF2000 and GPS reference frames will be quantified and discussed.

G32A-11 1620h

The Terrestrial Reference Frame Derived from VLBI

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The TRF derived from VLBI observations since 1979 includes precise positions and velocities for 80 points on the globe as well as positions at the observing epoch for 50 other points. Although the VLBI terrestrial and celestial reference frames along with the intervening Earth orientation parameters provide a uniquely complete set of measurements, the VLBI TRF differs substantially in construction from TRFs based on satellite observations. The long time span of the data, the intrinsic precision of individual 24-hr measurements, the accuracy of the TRF scale, and the consistency of modeling over the data set are some of the strong points. On the other side the relatively small size of most 24-hr networks, the temporal and spatial inhomogeneity of the data, cessation of observations at some sites, and finite capacity/funding of the VLBI correlator facilities place some limitations on VLBI for certain applications. The analysis of VLBI data, moreover, has been optimized for particular uses, and the best overall analysis for fully integrating TRF, CRF and EOP is the subject of continuing study.

G32A-12 1635h

Realization of the International Terrestrial Reference Frame by DGFI Analysis Center

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The realization of the International Terrestrial Reference Frame (ITRF) is done by a combination of station position and velocity coordinates from individual space geodetic technique's solutions. A major problem of the combination is the reduction of the a priori datum constraints which normally are included in the solutions. In general, individual solutions are declared to be unconstraint, minimum constraint, loosely constraint, or removable constraint. DGFI checked the declarations of solutions submitted for the ITRF2000 realization and found remarkable contradictions. In particular the solutions declared as loosely or minimum constraint include often tremendous constrains. If one neglects these constrains, one gets significant biases in the combination result. Another problem is the combination of different solutions of the same technique. All these solutions are based on the same observations, i.e., they are highly correlated. Therefore, the combination procedure has firstly to combine the individual solutions of each one technique. After that, the technique solutions have to be combined to the final ITRF. For velocity estimates, the kinematic datum plays an important role. The current solutions are generally referring to the NNR NUVEL-1A plate kinematic model. This geophysical model, however, does not fulfill the no net rotation condition, because it does not provide present day, but geological motions. Furthermore it does only include the rigid plates and not the extended plate boundary deformation zones. The DGFI solution is based on a geodetically determined actual plate kinematic and crustal deformation model (APKIM) with a globally integrated no net rotation constrain. The paper presents the DGFI computation of an ITRF based on the input data (solutions) submitted for the ITRF2000. The results are analyzed and compared with the official ITRF2000 solution. In general, there is a good agreement, but there are considerable discrepancies in some station coordinates and velocities. A proposal is made for the requirements on solutions submitted for future ITRF realizations.

G41A MC: Hall D Thursday 0830h

Crustal Deformation: New Results II

(joint with S, T, V, DI)

Presiding: **J T Freymueller,** University of Alaska, Fairbanks**; A Tikku,** Lamont-Doherty Earth Observatory of Columbia University

G41A-0188 0830h POSTER

A Least-Squares Approach for Long-Term Analysis of Deformations With SAR Interferometry.

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An new approach for the retrieval of long-term deformations from a set of differential interferograms is presented. Except for the case of desert areas, single interferograms spanning intervals of more years are usually heavily affected by temporal decorrelation, making it practically impossible to retrieve unambiguous information. The result is that for the majority of the areas slow deformations, like those caused by land subsidence, which would request long time spans in order to be detected, fall outside the range of applicability of this technique. For the same reasons, long term monitoring of hazardous areas, subject for example to frequent seismic activity, is also only partially feasible.

The time range of applicability of INSAR can however be extended by using a newly developed analysis technique. The method uses a database of interferograms spanning different, long- and short-term intervals within the time span of interest. The interferograms are first combined linearly with an iterative procedure to assess the presence of biases. Subsequently, they are merged in a least squares sense to determine the terrain deformations as a chronological sequence.

The presented approach has several advantages. The combination of several interferograms not only results in an increased signal-to-noise ratio, but allows to reduce the effects of interferometric processing errors. Moreover, decorrelation patches in the long term interferograms can in this way if not totally, at least partially, be filled with information from shorter term interferograms. Finally, solving all the deformations as a unique least-squares problem provides a chronologically ordered sequence, i.e. a picture of the development of the deformation pattern in time, even if no direct interferograms between subsequent dates are available, either because the area has not been imaged or because the baseline is too large.

The least-squares approach has been applied in the Phlegrean Fields (Naples, Italy). The result is a time series of deformation figures describing the evolution in time of the subsidence from 1993 to 1999.

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Locking State of the Northern Cascadia Megathrust Fault Inferred From Inversion of GPS Velocities

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In order to assess the state of interseismic locking of the plate boundary fault between the Juan de Fuca (JDF) plate and the North American plate in the northern Cascadia subduction zone (CSZ), we invert GPS horizontal velocities using a method based on Akaike's Bayesian Information Criterion (ABIC). We model the interseismic locking, represented by back slip, along the 3-D curved upper surface of the subducting JDF plate using a 420 $\times$ 210 km source region within a purely elastic half-space. GPS velocities from 37 continuous and campaign stations in Western Canada and 5 continuous stations in northern Washington are inverted to determine the back-slip distribution. The observed velocities are characterized by a northeastward motion and a landward decrease away from the CSZ. The reference station at Penticton has little motion relative