

G62A-0977 1330h POSTER

Using a Numerical Weather Model to Improve Geodesy

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The delay of the radio waves by the neutral atmosphere continues to be a significant source of error for geodetic measurements by VLBI and GPS. A numerical weather model (NWM) provides the best global information on the state of the atmosphere along the entire path traversed by the signal from the satellite or extragalactic radio source. Mapping functions for the hydrostatic and wet components of the atmosphere based on a NWM have demonstrated a substantial improvement in repeatability of baseline lengths, corresponding to a reduction in the atmosphere contribution to vertical error of about 4 mm, for a two-week high quality VLBI data set. The mapping functions, designated IMF, have now been implemented in the SOLVE VLBI estimation package using the NCEP numerical weather analysis results. Initial tests on the full VLBI data set (1979-2002 August) and on selected subsets confirm that use of the NWM improves the results of both. Further evaluation, including the impact on seasonal and diurnal signals, will be reported.

G62A-0978 1330h POSTER

An Integrated Bathymetric and Topographic Digital Terrain Model of the Canadian Arctic Archipelago

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Currently, the International Bathymetric Chart of the Arctic Ocean (IBCAO) (Jakobsson et al. 2000), contains the most up-to-date digital bathymetric model of the entire Canadian Arctic Archipelago. IBCAO is a seamless bathymetric/topographic Digital Terrain Model (DTM) that incorporates three primary data sets: all available bathymetric data at the time of compilation; the US Geological Survey GTOPO30 topographic data; and the World Vector Shoreline for coastline representation. The horizontal grid cell size is 2.5 x 2.5 km on a Polar Stereographic projection, which is adequate for regional visualization and analysis, but which may not be sufficient for certain geoscientific and oceanographic applications. However, the database that was constructed during the IBCAO project holds bathymetric data of a high quality throughout most of the Canadian Arctic Archipelago, justifying a compilation resolution that is better than 2.5 x 2.5 km. This data is primarily from historical hydrographic surveys that were carried out by the Canadian Hydrographic Survey (CHS).

The construction of a higher resolution bathymetry/topography DTM of the Canadian Arctic Archipelago (complete with an error estimation of interpolated grid cells) requires a consideration of historical metadata which contains detailed descriptions of horizontal and vertical datums, positioning systems, and the depth sounding systems that were deployed during individual surveys. A significant portion of this metadata does not exist in digital form; it was not available during the IBCAO compilation, although due to the relatively low resolution of the original DTM (2.5 x 2.5 km), its absence was considered a lesser problem.

We have performed "data detective" work and have extracted some of the more crucial metadata from CHS archives and are thus able to present a preliminary version of a seamless Digital Terrain Model of the Canadian Arctic Archipelago. This represents a significant improvement over the original IBCAO DTM in this area. The use of a merged seamless bathymetry/topography model substantially facilitates the overlay and incorporation of other spatially referenced geological and geophysical datasets. For example, one intended use of the model is to merge the results from the mapping of regional glacial morphology

features, in order to further address the glacial history of the region.

Jakobsson, M., Cherkis, N., Woodward, J., Coakley, B., and Macnab, R., 2000. A new grid of Arctic bathymetry: A significant resource for scientists and mappers, EOS Transactions, American Geophysical Union, v. 81, no. 9, p. 89, 93, 96.

G61A MCC: Hall C Saturday 0830h

Slow Earthquakes in Subduction Zones Posters (joint with S, T)

Presiding: T Melbourne, Central

Washington University; M M Miller, Central Washington University

G61A-0963 0830h POSTER

Aseismic Deformation, Plate Subduction and Stress Localization in Kanto-Tokai (Central Japan) Revealed by GPS

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Aseismic deformation detected by GPS (Global Positioning System) at subduction zones reveals that a large proportion of strain energy associated with plate subduction during an interseismic period is released through aseismic slip. The aseismic slip to some extent controls the pattern of stress at a subduction zone, as evidenced by the transient deformation and stress change associated with episodic slip or slow earthquakes. Previous analysis of GPS observations mainly focused on the pattern of deformation or strain, and did not attempt to assess stress change associated with plate subduction. While the studies revealed the first-order features of plate coupling, they do not fully include the effect of the major plate driving forces acting at a subduction zone such as the slab pull, ridge push and drag force. Since stress concentration/localization is indicative of where earthquakes could occur, a quantitative assessment of stress change is crucial for a better understanding of the stress accumulation process at a subduction zone. In this study, using the surface deformation determined by the Japan permanent GPS array and the depth distribution of earthquakes in the Kanto-Tokai region as quantitative constraints, we construct a three-dimensional model to simulate the subduction of the Philippine Sea plate at the Suruga and Sagami troughs and the Pacific plate at the Japan trench. The model incorporating the effect of major plate driving forces (ridge push, slab pull and drag force) provides an overall fit to the horizontal deformation observed by GPS during 2001 in the Kanto-Tokai region. After extracting the regional deformation associated with subduction of the Philippine Sea and the Pacific plates from the GPS observations through an inversion analysis, a distinct boundary is revealed between two types of motion trend in the region, which provides a strong support for the presence of the North American plate in central Japan. Further, a large band of stress concentration (0.6 bar/yr at a depth of 15 km) is found around the Suruga trough with the largest stress change at the joint of the Suruga and Sagami troughs, which corresponds well with the locations of the most recent interplate earthquakes. Our results indicate that the pattern of stress localization is mainly controlled by the characteristics of subducted slabs (geometry and slip distribution) and the persistent stress concentration is responsible for repeated large inter-plate earthquakes in the region.

G61A-0964 0830h INVITED POSTER

Partitioning between seismogenic and aseismic slip as highlighted from slow slip events in Japan

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1. Introduction

It has been recognized that fault slip in a subduction zone takes place with a source duration varying from seconds (ordinary earthquakes) to even years (slow fault slip). Such a slow fault slip must readjust the stress distribution in the seismogenic zone to control the occurrence of a future large earthquake. In this study, we present a numerical method to analyze the GPS data, and examine slow fault-slips in Hyuga-nada and Sanriku-oki, Japan.

2. Data

The time interval analyzed is from 1996 June to 1998 December for Hyuga-nada region where the Philippine Sea plate subducts northwest beneath the Eurasian Plate, and from 1994 December to 1995 March for Sanriku-oki region where the Pacific plate subducts west beneath the northeastern Japan island arc. The GPS data of Hirosaki University is also used for Sanriku-oki region.

3. Method

We take a fault model region on the plate boundary considering the fault plane of previous earthquakes and seismicity, and divide it into many sub-faults. The slip-rate function at each sub-fault is modeled by a series of isosceles. Neglecting the source duration of ordinary earthquakes, the coseismic fault slip is described by Heaviside step function. To get better resolution for co-seismic and aseismic slip distribution, we imposed a weak constraint of a priori information due to co-seismic slip determined by seismic wave analysis.

4. Results

In Hyuga-nada, after two large earthquakes in 1996, a slow fault-slip expanded from the source area to the north and then triggered another slow event with characteristic source duration of about one year. The aseismic slip has increasingly highlighted a particular site where little slow fault-slip takes place but where the subducting plate drags the overriding plate. It is noteworthy that the highlighted area is just the site of a past large earthquake: the 1968 Hyuga-nada earthquake (Mw7.5). We propose that this area is a possible site for a future large earthquake.

In Sanriku-oki, the co-seismic and post-seismic slip of 1994 Sanriku-haruka-oki earthquake do not overlap, but share a plate boundary region. The post-seismic slip was triggered in an area surrounding the fault plane of the main shock. It rapidly developed a shear stress concentration at an edge of its slip area, and triggered the largest aftershocks.

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G61A-0965 0830h POSTER

Chilean Analog for 17th-Century Uplift Along the Southern Kuril Trench

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What caused a meter or so of widespread uplift in eastern Hokkaido in the last decades of the 17th century A.D.? Coasts along the Kamchatka, Kuril, and Japan Trenches lack documented modern analogs for uplift this large and geologically fast. But a meter of uplift, in 1960-1990, raised shorelines inland from the seismic rupture plane of the 1960 Chile earthquake. By this Chilean analogy, Hokkaido's 17th-century uplift may have occurred aseismically-during minutes of precursory slip and also during decades of postseismic creep, all down-dip from the seismic rupture surface.

Hokkaido's area of 17th-century uplift extends at least 50 km along the southern Kuril Trench. It includes the estuaries Akkeshi-ko and Hichirippu, on the Pacific coast, and Furen-ko and Onneto, on the Okhotsk Sea. At each estuary, intertidal and subtidal flats rose with respect to tide level; wetland plants colonized the emerging land; and peaty wetland deposits thereby covered mud and sand of the former flats. Such evidence for uplift was first reported by Sawai and coworkers, who identified at least three uplift events from the past 2500 years at Akkeshi-ko (Quat. Res. 56, 231-241, 2001). The youngest of the uplift events probably began in the 1660s or 1670s, as dated by tephra layers. The uplift probably exceeded 1/2 m (inferred from paleoecology) without far exceeding 1 m (estimated by comparing early descriptions of Akkeshi-ko).

Though this evidence permits the Hokkaido uplift to have been coseismic or aseismic or both, depths to the subducting Pacific plate probably preclude seismic rupture of the plate boundary directly beneath the uplifted area. These depths exceed 50 km and also exceed depths of seismic coupling inferred from continuous GPS (Mazzotti et al., JGR 105, 13159-13177, 2000; Ito et al., EPSL 176, 117-130, 2000). When Hokkaido's plate boundary ruptured in earthquakes of Mw 8.1 (in 1952) and 7.8 (1973), the ruptures occurred offshore at depths less than 50 km, and the adjoining coast either subsided several centimeters or failed to change level.

Perhaps more appropriate to eastern Hokkaido is analogy with the preseismic and postseismic uplift that occurred above forearc mantle, inland from the seismic rupture surface of the 1960 Chile earthquake of Mw 9.5. This uplift began in 1960 as an inner upward many tens of kilometers wide and up to 1 m in amplitude [GSA Bull. 81, 1001-1030, 1970]. It caused shoreline changes that residents associated with the mainshock but may have resulted instead from a slow precursory earthquake downdip from the mainshock [Linde & Silver, GRL 16, 1305-1308, 1989]. For decades since 1960, uplift has been accumulating at 2-4 cm/yr in Chile's inner upward and at its boundary with the coseismic downwarp [Barrientos et al., GRL 19, 701-704, 1992].

This Chilean analogy may clarify the earthquake hazard implied by 20th-century subsidence in eastern Hokkaido. The subsidence, which averaged 5-10 mm/yr, probably represents strain accumulation; the subducting Pacific plate is dragging eastern Hokkaido downward. In that case, why did the offshore ruptures in 1952 and 1973 fail to reverse the subsidence [Kasahara & Kato, Pageoph 119, 392-403, 1981]? Perhaps their rupture areas and displacements were too small to allow large aseismic slip downdip from the seismic rupture surface. In that case, the 17th-century uplift entailed a Hokkaido earthquake larger than those in 1952 and 1973.

G61A-0966 0830h POSTER

An Investigation of slow earthquakes on the San Andreas Fault using InSAR

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The ubiquity of slow earthquakes (SEQs) on faults (both dip-slip and strike-slip) throughout the world indicates that they are a fundamental mode of strain release. The fact that they characteristically occur in the transition region between steadily slipping and locked faults, may allow us to draw general conclusions about the mechanism by which faults transition between locked and creeping. A sequence of three slow earthquakes (M_w 4.8-5.1) was observed between 1992 and 1998, at the northern end of the creeping section of the San Andreas Fault (SAF), using strain- and creep-meter records. Their shallow depth and compact size (relative to subduction zone SEQs), provides the opportunity to apply the high spatial resolution and good precision of InSAR to observing the deformation pattern of SEQs.

The challenge in using InSAR in the central SAF region lies in overcoming significant amounts of decorrelation noise, resulting in a loss of connectivity between patches of coherent phase. From 130 interferograms processed using data from the ERS 1 & 2 satellites (track 299, frame 2861), 10 have been selected for in-depth analysis. To connect discrete phase patches, we have employed campaign GPS measurements from a 25+ station network along the SAF with observations from 1989-2002. We present the results of this analysis and a model of the 1998 SEQ as a dislocation in an elastic half-space. These are compared to the results of previous studies based on creep- and strain-meter records.

URL: <http://www.seismo.berkeley.edu/~ingrid>

G61A-0967 0830h INVITED POSTER

Transient subduction slip episodes in Japan observed by the nationwide GPS array

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We observe slow thrust slip events along the Suruga-Nankai Trough where the Philippine Sea plate is subducting beneath the Japanese Islands. The first event initiated around 1997.0 at the Bungo Channel, following two successive M 6.7 earthquakes off Hyuganada.

The second event occurred just west (down dip) of the Tokai seismic gap. We utilize the Network Inversion Filter, recently modified by McGuire and Segall [2002] to invert the GPS observations. The improved method enables us to implement non-negativity constraints and automatic estimation of hyperparameters, including spatial and temporal smoothing.

The results of the Bungo event show that the slip initiated just south of southwesternmost Shikoku Island and propagated west to the Bungo Channel. The result clearly demonstrates that the slow event has no connection with the Hyuganada earthquakes, though it may have been triggered by those preceding events. The total aseismic moment release corresponds to Mw 7.2. The Tokai event initiated following major volcanic activity in the Izu Islands (since the end of June, 2000). The slip initially accelerated during the first 8 months. The slow slip event is not yet over; the present slip-rate is the same as in 2001. Currently the cumulative moment release corresponds to Mw 6.8. We note that both events occurred at sites where the plate interface shows significant lateral bending. Such a geometry, as well as heterogeneity of fault constitutive parameters, may be important in generating slow events.

G61A-0968 0830h POSTER

Post-seismic and Inter-seismic Deformation Associated With Long-rupture (~900 km) Great Subduction Earthquakes

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Some great subduction earthquakes rupture very long segments of plate boundaries. The 1960 Chile ($M_w=9.5$) and 1964 Alaska ($M_w=9.2$) earthquakes both ruptured fault segments about 900 km long. The 1700 Cascadia ($M_w=9$) earthquake was inferred to have involved most of the ~1000 km long margin. These earthquakes are expected to induce prolonged post-seismic deformation. In both Chile and Alaska, GPS measurements indicate that although coastal sites are moving landward as expected near a locked subduction fault, inland sites are moving in the opposite direction. The seaward motion of the inland sites is interpreted to be a delayed response to the previous great earthquake. Rupture during the earthquake instantaneously stretches the forearc seaward and induces a static elastic shear stress in the deeper part of the fault and the upper mantle. Subsequent stress relaxation allows the inland areas to move seaward to "catch up" with the coseismic motion while the coastal sites are already moving landward due to the locking of the fault. The observed deformation pattern yields information on the viscosity of subduction zone upper mantle. Using a mantle viscosity of 3×10^{19} Pa s in a 3-D viscoelastic finite element model, we can explain the GPS-observed Chile postseismic deformation. A similar model is developed for Alaska. Using a similar viscosity for the Cascadia margin, crustal deformation observed at present, 300 years after the previous great earthquake, can be well explained. In the present model, the velocity-strengthening behavior of the aseismic part of the fault is approximated using a thin viscoelastic layer, but the long-term post-seismic and inter-seismic deformation is not sensitive to details of the short-term (a few years) behavior of the fault.

G61A-0969 0830h POSTER

Toward an Aseismic Slip Budget in Guerrero, Southern México

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Recent studies indicate that aseismic slip events release a significant fraction of total strain accumulation in subduction zones. GPS data from Cascadia and

Guerrero, Mexico, further suggest that events at those locations repeat on time scales of one to a few years. These events call into question a fundamental assumption used to interpret campaign-style GPS measurements in subduction zones: Namely, that (absent large earthquakes) the displacements measured at intervals of several years represent a velocity associated with steady-state slip on the megathrust. Transient aseismic displacements typically occur over timescales of a few weeks to a few years, so are aliased by campaign-style measurements. Nevertheless Guerrero GPS data show evidence for at least three transient slip events: A large (equivalent $M_w=7.3$) event observed at seven continuous sites in 2001-02; a smaller ($M_w=6.5-6.8$) event in 1998 recorded at one continuous site and several campaign sites, and afterslip following the 1995 $M_w=7.3$ Copala earthquake, observed at only four campaign sites. Estimating the spatial distribution of anomalous slip requires that we separate transient displacement from the steady-state velocity, but this separation is poorly constrained if the number of measurement epochs is not much larger than the number of transient events. Hence, if steady-state velocity is permitted to be a free parameter, only the 2001-02 event is well-constrained. The solution space for the earlier two events is better constrained if steady-state velocities are required to fit a backslip model of steady-state slip on the subduction interface. We find that slip in 2001-02 activated approximately the same region as slip during the combined 1995-96 and 1998 transient events. The total anomalous slip during the latest event averaged 19 cm. For this slip deficit to be stored during the ~3.5 years between the 1998 and 2001-02 events would require nearly 100% coupling, but the best-fit model of steady-state slip predicts significantly less coupling on that portion of the megathrust. This suggests that part of the strain released during this year's event was stored prior to the earlier events.

G61A-0970 0830h POSTER

Aseismic Slip on the Northern Cascadia Subduction Zone: A Regular but Unique Process?

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Our closer re-examination of 1994 to 2002 data from continuous GPS sites in southwestern British Columbia and northern Washington State has confirmed the occurrence of seven aseismic slip events on the deeper subduction interface underlying the inner margin of the northern Cascadia Subduction Zone (CSZ). At any given site in the region of detection, the transient surface displacements observed for each event are strikingly similar in amplitude, direction, and duration, indicating a repetitive process within a confined location. The areal patterns of total surface displacements that accompany each slip suggest that this location is centered beneath southern Vancouver Is. and the eastern Olympic Plateau. The augmented rates of strain accumulation between slip events also appear uniform from one inter-slip period to the next, again suggesting a recurring process that is spatially confined. To date, this pronounced "sawtooth" displacement pattern caused by elevated stress accumulation for a period of about 60 to 70 weeks followed by a two-week period of aseismic stress reduction has not been observed in other subduction zones or even in the southern CSZ. It is possible that the arch in the subducting Juan de Fuca plate and the contact with hydrated mantle material on the deeper (25 to 45 km) subduction interface are two factors contributing to this (possibly) unique behaviour. At these depths, temperatures exceed 550°C and it is conceivable that the release of fluids from metamorphic reactions involving hydrated minerals corrodes inter-granular shear strength, ultimately resulting in aseismic slip, followed by an escape of fluids, a resulting rapid cooling, and a subsequent recovery of shear strength.

G61A-0971 0830h INVITED POSTER

New Large Aseismic Slow Slip Event in Guerrero, Mexico

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Thrust type aseismic slip events (transient slips or "aseisms") have recently been reported in various subduction zones. The observed aseisms have equivalent Mw of 6-7 and their duration varies from several days to a few years. An important feature of these slow events is that they usually occur near or just down-dip of the seismogenic portion of the megathrust. The aseisms may be an important part of the seismic cycle of large thrust subduction zone earthquakes. In Guerrero, Mexico, we detected several such events of different magnitude in 1972, 1979, 1995, 1998, and 1999-2000 using tide gauge, leveling, and GPS data. In 2001-2002 the network of 7 continuous GPS stations recorded a new large aseismic slow event (equivalent Mw 7.3) in Guerrero, which apparently started in the beginning of October 2001 and its peak slip phase lasted from the end of December 2001 until the end of April 2002. The surface deformation associated with this slip was observed on an area of more than $\sim 350 \times 200$ km². The maximum velocity of the recorded crustal motion, $V_h = 14.6$ cm/yr, $A_z = 213.3^\circ$, $V_z = 6.5$ cm/yr, is on the CAYA GPS station, located on the coast in the central part of the Guerrero seismic gap. The steady inter-seismic rate at this station was $V_h = 2.3$ cm/yr, $A_z = 45.5^\circ$, $V_z = -1.2$ cm/yr before the aseism. There are at least two models that can fit the observed deformations during the new Guerrero aseismic event. The first model predicts an average thrust slip of ~ 13 cm and a temporary regional extension of the continental block. The aseismic slip occurred on nearly the entire plate interface, approximately within 30 to 220 km from the trench. The slip zone includes the shallow seismogenic interface and the deeper subhorizontal interface, which is usually considered as aseismic. Elastic half space dislocation models of the deformation observed several years before (interseismic locking) and during the last aseism reveal three distinct segments on the plate interface, which are distinguished by a coherent change of coupling and aseismic slip values. The second possible model concentrates the larger aseismic slip on the shorter interface, from 90 to 180 km from the trench, and leaves the upper shallow seismogenic interface totally or partially locked. This would imply that while the new aseism could release a significant amount of the entire elastic strain energy previously accumulated in the subduction zone below Guerrero, the seismic hazard on the Guerrero gap has not been reduced by this event.

G61A-0972 0830h INVITED POSTER

The 1998-2002 Deep Megathrust Slip Event, Alaska

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Aseismic slip events are proving to be extremely frequent at subduction zones worldwide, and they come in a wide variety of sizes and durations. One of the largest not immediately following an earthquake affected southern Alaska from 1998 through 2002. In the summer of 1998, sites across a broad region of southern Alaska began to move in a southerly direction, relative to their pre-event motions. North of Anchorage, sites that had been moving to the NNW, in the direction of relative plate motion, instead began moving to the SSW. The observed change in velocity was as much as 25 mm/yr. The southward motion decreased with time,

until in 2002 the sites began to move northward again. As of this writing, the event has not totally decayed to zero, but it has very nearly done so. The total horizontal surface displacements caused by this event are up to 100 mm.

We have investigated this event using a variety of 3D modeling techniques. The event affected a part of the plate interface that lies well down-dip of the 1964 coseismic rupture, with the updip end of the creep event being 70-100 km down-dip of the down-dip end of the coseismic rupture. Because the dip angle of the megathrust is exceptionally shallow here, the updip end of the creep event lies at only 35-40 km. From GPS data recorded prior to the event, we infer that this region of the plate interface was creeping at approximately the average rate of plate motion (and produced no surface deformation); during the first two years of the event this rate doubled to approximately twice the rate of plate motion.

Over 1998-2001, the temporal behavior of the slip event is consistent with a simple afterslip model, in which the displacement is proportional to $\log(t-t^*)$, with t^* being the time of the event. Such a response could result from a fault obeying rate and state dependent friction undergoing a sudden increase in shear stress. The puzzle raised by this sort of model is that the slip event did not follow any seismic event - it appears to have begun and ended aseismically. A new model of subduction zone dynamics is required that can explain the occurrence of events like this.

G61A-0973 0830h POSTER

Preseismic, Postseismic and Slow Faulting in Subduction Zones

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The last several years have witnessed a broad reappraisal of our understanding of the energy budgets of subduction zones. Due primarily to the deployment of continuous geodetic instrumentation along convergent margins worldwide, we now recognize that fault rupture commonly occurs over rates ranging from kilometers per second to millimeters per day. Along with transient postseismic slip, both isolated and episodic slow slip events have now been recorded along convergent margins offshore Japan, Alaska, Mexico, Cascadia and Peru, and thus would appear to constitute a fundamental mode of strain release only observable through geodetic methods. In many instances, postseismic creep along the deeper plate interface is triggered by seismogenic rupture up-dip. Continuous GPS measurements from three earthquakes in Mexico (Mw=8.0, 1995), Peru (Mw=8.4, 2001) and Japan (Mw=7.7, 1994) show that deep postseismic creep was triggered by local Coulomb stress increases of the order of one half bar produced by their mainshock ruptures. For these three events, afterslip along their primary coseismic asperities is significantly less important than triggered deep creep. Deeper slow faulting does not have to be triggered by adjacent seismogenic rupture. In Cascadia, eight episodic slow slip events since 1991 have been recognized to have an astonishingly regular 14.5-month onset period, the most recent of which began in February of 2002. For these events, time dependent inversion of GPS data map the propagation of creep fronts and show they released moment with magnitudes in excess of Mw=6.5. If they occur throughout the Cascadia interseismic period, then cumulatively they rival the moment release of the infrequent Mw=9.0 megathrust events. Most recently, an 18-hour precursor to an Mw=7.6 aftershock of the 2001 Mw=8.4 Peru earthquake was detected at Arequipa, Peru. This precursor appears as a 3 cm departure from a continuous time series broken only by the coseismic displacements of the mainshock and its large aftershocks. Inspection of three years of data prior to the precursor shows this signal to be unprecedented. Together, these examples paint a picture of a complex feedback mechanism between weakly and tightly coupled fault regions: transient creep loads nearby locked regions that upon failure reload nearby creeping sections. This type of recursive interaction leads ultimately to deterministically chaotic earthquake clustering through time.

G61A-0974 0830h POSTER

Aseismic Slip and the Nisqually Earthquake

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Continuous Global Positioning System (GPS) stations in the Pacific Northwest move northeast with respect to the North American plate as a result of coupling along the subducting Juan de Fuca plate. In early 2001 GPS stations from southern Puget Sound to northern Oregon reversed this northeast direction of motion for several weeks. The reversed motion shares some of the spatial and temporal signatures of aseismic creep events (or silent earthquakes) previously reported farther north along the Cascadia plate interface [1,2], although the periodic recurrence observed farther north has not been established here. The strongest aseismic motion was detected southwest of Seattle at the GPS stations SATS and RPT1. On February 28, 2001, during this period of aseismic slip, the Mw 6.8 Nisqually earthquake ruptured a normal fault within the Juan de Fuca plate. The rupture occurred at some 50 km depth; its epicenter lies between these two stations. The aseismic motion preceding the earthquake is consistent with slip on the plate boundary. The displacements from the Nisqually earthquake itself are in good agreement with calculations using fault parameters from the inversion of seismic data.

1) Herb Dragert, Kelin Wang, and Thomas S. James, Science, 292, 1525-1528, 2001

2) M. Meghan Miller, Tim Melbourne, Daniel J. Johnson, and William Q. Sumner, Science, 295, 2423, 2002

G61A-0975 0830h POSTER

Segregation of Source Areas of Slow Slip Events and Asperities of Major Seismic Events on the Subduction Interface Around the Japanese Islands

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Following the 1989 Sanriku (Mw7.4) and the 1992 Sanriku (Mw6.9) earthquakes on the subducting interface of the Pacific plate, anomalous tsunamis were excited (Hatori, 1993). The source areas of the anomalous tsunamis do not overlap with coseismic asperities of nearby large earthquakes, as inferred by Yamanaka and Kikuchi (2002). These observations show that, after major seismic faulting of the 1989 Sanriku and the 1992 Sanriku earthquakes, adjoining area slipped at rates that were one-order slower than coseismic rates and caused significant tsunamis. Following the tsunamis, afterslips with time constants of around 10 days and 1 day, respectively, were recognized by geodetic data. Also, static moments from the geodetic data were a few times larger than values calculated from seismic data (Kawasaki et al., 1995). Due to insufficient resolution of source parameters of the afterslips, it is unknown if these source areas overlap with the source areas of the anomalous tsunamis.

We have documented several silent earthquakes that occurred in Japan over the last several years, including the 1989 Tokyo Bay (equivalent magnitude of Mw5.9, around 1 day), the 1996 Off-Boso (Mw6, around 5 days), the 1997 Bungo Channel (Mw6.8, around 1 year), the 1999 Off-Choshi (Mw5.6, a few days), the 2000 Off-Choshi (Mw5.6, a few days) and the 2001-2002 Tokai (Mw6.8, 1-2 years, ongoing) events.

The silent earthquakes around the south Kanto district occurred along the transition zone at depths of 30-40 km between the coupled and uncoupled regions along the subduction interface of the Philippine Sea plate. Their source areas do not appear to overlap with the major asperity of the 1923 great Kanto earthquake (Wald and Somerville, 1996) nor with the source area of the 1703 historical Kanto earthquake (estimated from inversion of tsunami data, Murakami and Tsuji, 2002), which were the dominant events in the past several centuries in the Kanto district.

Summarizing these observations, (1) slow slip events of diverse time constants from hours, days, months to years have occurred, (2) the total amount of interplate moments released by the slow slip events is too small to fill gaps in the moment budget, and (3) faulting areas of the silent slip events do not overlap with the asperities of the coseismic slip of large earthquakes, suggesting that the controlling factor of the slip modes is a frictional property.

G61A-0976 0830h POSTER

Modeling Silent Slip Events along the Unstable-stable Transition in Subduction Zones

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Recent high-resolution GPS observations of crustal movements revealed that silent slip events occurred in and below the deeper part of the seismogenic zone. For example, Ozawa et al. (2001) detected a silent thrust slip event in the deeper part of the Tokai subduction zone, which is a well-known seismic gap along the Suruga-Nankai trough. This event started from the beginning of 2001 and is migrating at the speed of about 20 km/year. Slip velocity of silent events is roughly estimated to be 10^{-8} - 10^{-9} m/s that is little larger than the velocity of relative plate motion.

To investigate the mechanism of silent slip events, we simulate the earthquake generation processes of a thrust fault in 3-D elastic half-space. First, we use the ordinal Dieterich/Ruina rate- and state-dependent friction law with cut-off velocity to the rate-dependence. We give depth distribution of constitutive law parameters based on experimental studies. Below the depth of the unstable-stable transition, critical weakening displacement begins to increase due to an increase of plastic deformation between micro-asperities. Around the transition zone, slow slip events are expected to occur due to large critical weakening displacement and small stress drop. The results of numerical simulations show that stationary slips proceed at the deeper part of the fault region, and then, they proceed gradually upward due to the stress concentration along the unstable-stable transition zone. In some cases, eventual silent slips occur at the deeper part of the seismogenic fault 10-50 years before instability. The slip velocity of this event is 10^{-9} m/s that is close to the observed value of slip velocity. A few years before instability, slip acceleration occurs along the transition zone. In some cases, silent slip events migrate horizontally along unstable-stable transition zone at the speed of about 10 km/year. Finally slip is localized into a narrow area at the deeper part of the seismogenic fault. Silent slip events can be interpreted as events caused by the stress concentration along the unstable-stable transition zone and the transitional behavior of the friction law.

Around the unstable-stable transition zone, actual frictional behavior is thought to be very complex. Shimamoto (1986) performed experiments using Halite to investigate frictional behavior around the unstable-stable transition. The results show the complex behavior where strength depends on strain rate: at a very low strain rate, strain rate strengthening occurs, at an intermediate strain rate, strain rate weakening occurs, and, at a high strain rate, strain rate strengthening occurs. These results suggest that at a very low strain rate, flow law is at work, at an intermediate strain rate, frictional instability can occur, and, at a high strain rate, strong viscous dissipation is at work. Using a spring and slider block system, we can reproduce slow slip events with this kind of friction law.

G61A-0977 0830h POSTER

Characterization of slow faulting with subdaily GPS positioning

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Over the last several years, data from continuously operating GPS stations have been used to detect transient deformation associated with large subduction zone earthquakes. Most recently, the Mw=8.4 June 23, 2001 Peru earthquake ruptured the Nazca-South American plate interface to become the largest event in the last 30 years. The mainshock was followed by a vigorous aftershock sequence, including three events with moment magnitudes of Mw=6.7, 6.5, and on July 7, an Mw=7.6 event. Two-hour position estimates from a continuous GPS station located at Arequipa, Peru, document transient deformation at time scales from hours to days. These signals are obscured by daily position estimates highlighting the need for utilizing sub-daily positioning to increase our ability to detect transient aseismic faulting. Station positions are estimated as stochastic processes with white noise resets every 2 hours using 24-hour data arcs. By applying stochastic resets to the coordinates only, the geometric strength of the 24-hour data arc for estimating carrier phase biases and atmospheric delays is retained. Station position estimates are thus obtained at a higher rate without significant systematic artifacts associated with higher frequency error sources. While modeling station positions as a white noise process may produce a time series that is noisier than a random walk model, it is a more conservative approach to identifying transient deformation. With this estimation scheme, subsequent position estimates remain uncorrelated in time, which is not the case with random walks. Moreover, the white-noise approach side steps the need to establish an a priori rate of random walk process noise which neither suppresses a true signal nor introduces erroneous deformation artifacts.

G61A-0978 0830h POSTER

Interplate coupling changes in the Tokai region, Japan, estimated from the vertical movements by leveling and tide gauge during 1960-2002

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The large earthquakes of more than magnitude 7.8 have repeatedly occurred along the Nankai-Suruga trough with an interval of 100-150 years. Since the last events of the 1944 Tonankai and 1946 Nankai earthquakes, it has passed more than 50 years. Recent findings of the 2001 slow slip event in the Tokai region by GPS dense continuous network led us to re-examine the possibility of slow slip events from the 1960s to the present in the Tokai region. We discuss the spatial changes of interplate coupling to make clear. Tide gauge measurements have continuously recorded at four sites since the 1960s and the precise leveling has repeated every year or every two year since the 1970s in the Tokai region by GSI. We estimated the changes of interplate coupling from these vertical movements. Characteristics of the interplate coupling are; 1) interplate coupling area apparently reached just beneath the Mikawa bay, which is located 30km depth of plate boundary, and 2) main area of the interplate coupling does not limited to the shallow plate boundary of coast area, but it extends to the in-land area. Sagiya (1999) already discusses the interplate coupling model from GPS measurements, respectively. However there are some differences between the observation and model calculation. Especially Sagiya's model could not explain exactly the subsidence at Omaezaki and the uplift at Oodaka, which is 100km west of Omaezaki. Moreover the convergence rate of the Philippine Sea plate is estimated to be about 2 cm/yr from the GPS measurements at the Suruga trough whereas those are 4 to 5 cm/yr at the Nankai trough (Heki and Miyazaki, 2001). The interplate coupling in the 1960s shows the subsidence rate at Omaezaki was less than 5mm/yr and it was about a half in 197s-1990s. It is suggested that interplate coupling is not full beneath Omaezaki in 1960s. Moreover the uplift is not detected at the inland area (Ise Bay) in 1960s. It could also suggest that the interplate coupling might have been weak in the eastern part of the Tokai region, suggesting the effects of afterslip due to the 1944 Tonankai earthquake. We also conclude that the intraplate coupling along the Suruga-Nankai Trough has changed episodically.

G61A-0979 0830h POSTER

Interplate coupling model and slow slip events in the Tokai region, Japan

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During 2001 in the Tokai region, Japan, GPS network by GSI detects the abnormal horizontal movements with the steady convergence movements due to interplate coupling and these abnormal movements are apparently kept going at present. By using the time dependent analysis with the GPS data, slow slip events are clearly illustrated and showed that the source area are limited to rather narrow region around Hamana Lake, which is located 60km west of Omaezaki (Ozawa, et al., 2001). The analysis is based on the residual of the ground deformations subtracted from the general trend and seasonal variations estimated from the data for a few years before March, 2000. Yamamoto et al (2001) pointed out that there might exist the changes of the annual changes in the coordinates observed by GPS measurements, and concluded that the estimated slow slip events might affected by such annual changes. We re-examined the ground deformation by fixing the Gujo-Hachiman GPS site, which is located about 200km NW of Omaezaki and used by interplate coupling model by GPS measurements (Sagiya, 1999). We estimated the trend and annual displacements in each year from 1996. Characteristics of the obtained ground deformation are: 1) Convergent displacements at the Tokai region in the four years, are episodic since April 1996 to March 2000 and show the decrease of rate and their variations of up to 80 % in the period of April 1999 to March 2000. 2) Convergent displacements disappeared in the western Tokai region, from Mikawa bay to Hamana Lake since January 2001, and the southeastward displacements are observed in the western area of Omaezaki. Convergent rates do not decrease in the

northern area and west coast of Suruga Bay. These suggest source region of the slow slip would not limited to rather narrow region around Hamana Lake, but it might extend to the further northern area, at least 60 km NE of Hamana Lake. Vertical movements by precise leveling (GSI, 2002) indicate the migration of the uplift area toward the east from the Hamana Lake, suggesting the source region of the slow slip event could also migrate to the east- or northeast-ward in significant amount. We may conclude that the source region of the slow slip movements could migrate towards the deeper part of the strongly coupled plate boundary of the anticipated Tokai earthquake (the invasion of the asperity ?).

G61B MCC: Hall C Saturday 0830h

Geophysical Modeling Using Spaceborne InSAR Measurements I Posters (joint with S, T)

Presiding: H Zebker, Stanford University; B Minster, Scripps Institution of Oceanography

G61B-0980 0830h POSTER

InSAR and GPS Analysis of Ground Subsidence in Mexico City

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We describe the recent subsidence of Mexico City due to ground water withdrawal using a combination of Interferometric Synthetic Aperture Radar (InSAR) for high spatial resolution and Global Positioning System (GPS) data for calibration and improved temporal information. Groundwater extraction in the basin of Mexico exceeds recharge, lowering the water table by 0.1-1.5 m/yr, reducing pore fluid pressure in the aquifer and overlying aquitard, and leading to compaction of lacustrine shales and surface subsidence.

We used ERS-2 data for Interferometric SAR analysis. Results indicate land subsidence in Mexico City between February 1996 and January 2000 at rates as high as 378 mm/yr in the eastern metropolitan area. The downtown region shows rates up to 115 mm/yr. GPS data suggests that these rates have been steady at least since 1995 and are due to steady declines in the water table. Available well data indicate consistent water level drops over the last decade, concurrent to the near-constant subsidence rate measured by both GPS and InSAR. Static groundwater level define an approximate linear relation between water level drop and surface subsidence: Correlation of the InSAR fringe pattern with mapped stratigraphic units indicates that maximum subsidence is primarily controlled by unconsolidated Quaternary lacustrine clays and silts in the shallow sub-surface, marking ancient Lake Texcoco, now obscured by urban construction on the old lake bed.

G61B-0981 0830h POSTER

Prospecting for Horizontal Surface Displacements Accompanying Land Subsidence in Antelope Valley, CA Using InSAR

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Comparing InSAR-displacement maps derived from acquisitions on ascending and descending satellite passes over Antelope Valley, California we investigate the importance of horizontal surface displacements in a 3-year subsidence pattern with a maximum subsidence of ~6 cm. Horizontal displacements have generally been assumed to be negligible in studies of land subsidence over extended areas. This assumption has been justified with the large horizontal extent of the compacting subsurface units relative to their thickness and