G23A CC: 516 A Tuesday 1330h

The Mechanics of Shallow Subduction Zones II *(joint with S, T, SEDI)*

Presiding: **J Sauber,** NASA Goddard Space Flight Center**; S Mazzotti,** Geological Survey of Canada**; R Dmowska,** Harvard University

G23A-01 1330h INVITED

Geodetic And Seismic Signatures of Episodic Tremor And Slip Beneath Vancouver Island, British Columbia.

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Slip events with an average duration of about 10 days and effective total slip displacements of several centimetres have been detected on the deeper (25 to 45 km) part of the northern Cascadia subduction zone plate interface by a network of continuously recording Global Positioning System (GPS) sites. The slip events occur down-dip from the currently locked, seismogenic portion of the plate interface, and, for the geographic region around Victoria, British Columbia, repeat at 13 to 16 month intervals. These episodes of slip are accompanied by distinct, low frequency, non-earthquake tremors, similar to those reported in the forearc region of southern Japan, prompting the naming of this phenomenon as Episodic Tremor and Slip (ETS). The tremor-like seismic signals have now been identified beneath most of Vancouver Island. For northern Vancouver Island, where plate convergence is at a much slower rate, return periods of about 14 months were also observed for significant (duration exceeding 7 days) tremor sequences, but about 6 months out of phase with southern Vancouver Island. Slip associated with northern island tremors has not been resolved clearly enough to allow modeling because of sparse GPS coverage, but 3 to 4 mm surface displacements coincident with the most recent tremors were observed at two newer GPS stations located on the northwest coast of Vancouver Island. The total amount of tremor activity, and by inference slip activity, appears to be the same in northern and southern Vancouver Island and therefore independent of plate convergence rate. ETS activity is observed to migrate along the strike of the subduction zone at speeds of 5 to 15 km/day and this migration does not appear to be impeded by the Nootka Fault Zone that marks the change in subduction rates. It is strongly suspected that the youth of the subducting plate and the release of fluids from slab dehydration are key factors contributing to the episodic, semi-brittle behaviour of the ETS zone. It is likely that the ETS zone constrains the landward extent of megathrust rupture, and, because slip events on the deeper plate interface increase stress on the locked plate interface located up-dip, it is possible for an ETS event to trigger a great thrust earthquake.

G23A-02 1345h INVITED

Silent Earthquakes, Structure, and Seismotectonics of the Mexican Subduction Zone

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Based on tide gauge, levelling and GPS data, we find evidence for a sequence of silent earthquakes in 1972, 1979, 1996, 1998, 2002, and 2003 in the central part of the Mexican subduction zone (Guerrero and Oaxaca states). Characteristic duration of these events was 4-6 months and the maximum equivalent magnitude exceeded Mw7.5. In all cases, with the exception of the event of 1996, the slow aseismic slips initiated in the Guerrero seismic gap and propagated laterally along the strike of the subduction zone. However, the propagation velocity of 2 km/day could be estimated reliably only for the most recent 2002 event. The observations indicate that the total area affected by the 1972 and 2002 slow events may have been greater than 300x700 km2. The shallow, subhorizontal configuration of the plate interface in Guerrero and partly in Oaxaca appears to be a controlling factor for the physical conditions favorable for such extensive slow slip. The entire partially coupled interplate zone in Guerrero is of 160 km width (starting 55 km inland from the trench) while the seismogenic, shallowest part of it is only 40 km wide. The elastic half space dislocation models (EHSDM) applied to invert the observed slow aseismic slip displacements (2002 event) can not distinguish between the two main scenarios: (a) slow slip of 10 cm occurring on the entire coupled interface, and (b) slip of 15-20 cm taking place only on the transition part of the plate interface from 90 to 180 km. In the first case the anticipated large thrust earthquake in the Guerrero seismic gap should be somewhat delayed, while on the second case the seismic rupture may be advanced. Thermo-mechanical modeling of the Mexican subduction zone shows that the coupling cutoff of 450°C on the plate interface at 180-205 km from the trench is achievable only for the subhorizontal configuration of the subduction zone. In this case the predominant metamorphic facies on the surface of subducted crust should be blueschists. There are, however, several observations which can not be explained in the frame of the EHSDM, e.g., a considerable tilt observed in the coastal area and a relatively large displacement on the Popocatepetl volcano (400 km from the trench) during the 2002 silent earthquake.

URL: http://tlacaelel.igeofcu.unam.mx/~vladimir/guerrero_level/deform0.html

G23A-03 1400h

Modeling of Subduction Zone Slow/Slient Slip Events in Deeper Parts of the Seismogenic Zone

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Recent high resolution GPS measurements have detected slow and silent (or aseismic) slip events near the downdip end of the seismogenic zone at Japan, Cascadia and Mexico subduction zones [Hirose et al., 1999; Ozawa et al., 2001; Dragert et al., 2001; Lowry et al., 2001; Ozawa et al., 2002]. To investigate possible physical mechanisms, we apply a Dieterich-Ruina rate and state friction law to a three dimensional shallow subduction fault, which is loaded by imposed slip at rate V_{pl} ($\sim 10^{-9}$ m/s) far downdip along the thrust interface. Friction properties are temperature, and hence depth, dependent, so that sliding is stable ($a-b>0$) at depths below about 30 km. The system is perturbed into a nonuniform slip mode by introducing small (0 to 5%) along-strike variations in the constitutive parameters a and $(a-b)$. Simulation results show large events with multiple magnitudes at various along-strike locations on the fault, with different recurrence intervals, like natural interplate earthquakes. More interesting, we observe that the large heterogeneous slip at seismogenic depths (i.e., where $a-b<0$) is sometimes accompanied by events that have clearly aseismic slip rates (10 to 10^2 V_{pl}), which are comparable to the 10^{-9} to 10^{-8} m/s slip rates inferred in Japan and Cascadia Subduction zones [Hirose et al., 1999; Ozawa et al., 2001; Dragert et al., 2001]. These aseismic slip events usually nucleate below the less well locked "gap" regions (slipping at order of 0.1 to 1 times plate convergence rate V_{pl}) between more firmly locked regions (slipping at 10^{-4} to 10^{-2} V_{pl}). Some have aseismic slip rate fronts that migrate more than 100 km in the strike direction with a maximum speed $\sim$ 20 km/year, at depths near or below the downdip end of the seismogenic zone. This migration speed is of the same order as the along-strike slip propagation in 1997 Bungo Channel event, southwestern Japan [Ozawa et al., 2001] and 2001 Tokai region event, central Japan [Ozawa et al., 2002], but much lower than the estimated $\sim$ 6 km/day of the 1999 Cascadia subduction zone event [Dragert et al., 2001]. Some just rupture limited areas below the gap regions. They tend to weaken the locking intensity (i.e., increase the slip rates) around the gap regions, which may become potential nucleation sites for future large events. Furthermore, nucleation, rupture propagation and re-locking behaviors, much like during a large earthquake, are also observed in some of these aseismic events, although they take place only near or below the downdip end of seismogenic zone. The transitional behavior of the friction law around the downdip end of the seismogenic zone may be a cause of the observed aseismic slip events. We are investigating the influence of constitutive parameters a and $a-b$ (magnitude and distribution) on the aseismic slip patterns, and also of the length scale D_c which must be chosen larger than realistic to make simulations possible.

G23A-04 1415h

A Thermomechanical Model of Low-angle Subduction in Central Andes Combining Geological and Recent (GPS) Deformations

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Thermomechanical interaction of the low-angle subducting oceanic plate with the overriding continental plate may result in intensive tectonic shortening of the upper plate (subduction orogeny). Factors controlling such behaviour remain poorly understood. Here we present a fully coupled thermo-mechanical model of the extreme case of the subduction orogeny, a development of the more than 4 km high Altiplano-Puna plateau in the Central Andes in Cenozoic time. The same model attempts to explain present-day (GPS)deformation. Our 2-D finite element thermomechanical model explores the interaction of the subducting Nazca plate with the overriding South America (SA) plate in the 1200 km long and 400 km high model box. The model employs realistic stress- and temperature-dependent visco-elasto-plastic rheology, shear heating and gabbro-eclogite transformation. The velocities, at which overriding plate enters the model box and the subducting plate leaves the box, are prescribed by boundary conditions constrained by geological observations. The interface between the slab and the upper plate is modelled as a few kilometer thick subduction channel with the two optional rheologies: (i) the Mohr-Coulomb elasto-plastic rheology with the very low friction coefficient (less than 0.05), and (ii) temperature dependent viscous rheology similar to the reported rheology for the wet quartzite. At each modelling time step both rheologies are tested and the energetically more efficient rheology is used. The modelling results replicate well geological evolution of the Central Andes during the last 10 Myr if the overriding velocity of the stable SA is set to be high (25-30 mm/yr) and increasing with time, and friction coefficient in the subduction channel is set to 0.03-0.05. The same model replicates well also the GPS observations if small (10 percent of the value) temporal changes of the friction coefficient in the subduction channel are allowed, which generate a seismic cycle. Locking depth in such a model increases with decreasing friction coefficient in the subduction channel.

G23A-05 1430h

Crustal Deformation and the Seismic Cycle across the Kodiak Islands, Alaska

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The Kodiak Islands are located approximately 130 to 250 km from the Alaska-Aleutian Trench where the Pacific plate is underthrusting the North American plate at a rate of about 57 mm/yr. The southern extent of the 1964 Prince William Sound (M_w = 9.2) earthquake rupture occurred offshore and beneath the eastern portion of the Kodiak Islands. Here we report GPS results (1993-2001) from northern Kodiak Island that span the transition between the 1964 uplift region along the eastern coast and the region of coseismic subsidence further inland. The horizontal velocity vectors range from 22.9 ± 2.2 mm/yr at N26.3°W ± 2.5°, about 150 km from the trench, to 5.9 ± 1.3 mm/yr at N65.9°W ± 6.6°, about 190 km from the

trench. Near the northeastern coast of Kodiak the velocity vector above the shallow, locked main thrust zone is between the orientation of PCFC-NOAM plate motion (N22°W) and the trench-normal (N30°W). Further west, our geodetic results suggest the accumulation of shear strain that will be released eventually as left-lateral motion on upper plate faults such as the Kodiak Island fault. These results are consistent with the hypothesis that the difference between the Pacific-North American plate motion and the orientation of the down going slab would lead to 4-8 mm/yr of left-lateral slip. Short-term geodetic uplift rates range from 2 - 14 mm/yr, with the maximum uplift located near the axis of maximum subsidence during the 1964 earthquake. We evaluated alternate interseismic models for Kodiak to test the importance of various mechanisms responsible for crustal deformation rates. These models are based on the plate interface slip history inferred from earlier modeling of coseismic and post-seismic geodetic results. The horizontal (trench perpendicular) and vertical deformation rates across Kodiak are consistent with a model that includes the viscoelastic response to : (1) a downgoing Pacific plate interface that is locked at shallow depths,(2) coseismic slip in the 1964 and (3) interseismic creep below the seismogenic zone. The change in orientation of the horizontal velocity vector occurs down-dip from the locked main thrust zone. In southern Kodiak, the coseismic slip in the 1964 earthquake was smaller than in the northern Kodiak region; yet, the horizontal, interseismic velocities as a function of distance from the trench are comparable to those in northern Kodiak. Based on the earthquake history prior to, and following the 1964 earthquake, we hypothesize that the plate interface in southern Kodiak slips in more frequent large earthquakes than in northern Kodiak.

G23A-06 1445h

17 August 1906: Resolving the twin eights by the PDFM method

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On 17 August 1906, two major earthquakes (M > 8 according to Gutenberg) occurred within 30 minutes of each other in the Aleutian Islands and Central Chile, respectively. Their simultaneity has led to confusion in their interpretation. We use the remarkable collection of seismograms gathered by Rudolph and Tams [1907] to conduct a new seismological study of the events, based on the PDFM method introduced by Reymond and Okal [2000]. The Aleutian event is well located at the Eastern end of the 1965 rupture zone, next to the intersection of the Bowers Ridge with the Aleutian arc. It has generally larger spectral amplitudes than the Chilean event, but the Pacific-wide tsunami was generated by the latter, based on the reinterpretation of maregrams originally published by Honda [1908]. This supports Okal's [1992] remark based on Love-to-Rayleigh spectral ratios that the Aleutian quake cannot be an interplate thrust event. Our preferred PDFM solution calls for an oblique mechanism (strike 186 deg.; dip 67 deg.; slip 116.) with a moment of 3.5E28 dyn-cm at a depth of 60 km. This geometry is reminiscent of the 1994 Kuriles earthquake. The Chilean event cannot be relocated instrumentally, but abundant felt reports put its epicenter near Valparaiso. A robust, depth-independent thrust mechanism (strike 1 deg.; dip 15 deg.; slip 114 deg.) is obtained with a moment of 2.8E28 dyn-cm, in excellent agreement with estimates based on isoseismals [Kanamori, 1977]. The latter can also account for the moderate tsunami recorded both locally and in the far field.

G24A CC: 516 A Tuesday 1530h

New Advances in Global Plate Kinematics and Dynamics From Space Geodesy II *(joint with S, T, SEDI)*

Presiding: **T Dixon,** University of Miami**; C Kreemer,** Collge de France**; W Holt,** State University of New York at Stony Brook

G24A-01 1530h INVITED

Reference Frame Improvements

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Use of a stable reference frame can greatly simplify the interpretation, comparison, and combination of geodetic position estimates. Many improvements over the past decade led to the construction of ITRF2000 which provides stability at the level of about 1 mm/yr horizontally and 2 mm/yr vertically. Many techniques contributed to the construction of ITRF2000 with the origin provided by SLR, the scale provided by SLR and VLBI, and densification provided by GPS. Access to the frame is typically achieved through a set of positions and velocities which are used for alignment or constraint. A number of issues are being considered for future improvement including strategies to provide better regional access to the frame, methods to handle non-linear effects such as seasonal loading and seismic deformation, incorporation of origin and scale information from GPS, and integration of estimates from Galileo.

G24A-02 1545h INVITED

Plate Motions From Space Geodesy

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We integrate results from satellite laser ranging (SLR), very long baseline interferometry (VLBI), and global positioning system (GPS) geodesy to determine GEODVEL, a set of the relative angular velocities of most of the earth's major plates. Using two decades of SLR data and two decades of VLBI data, we determine angular velocities and linear velocities more accurately than others have from just one decade of GPS data. We assign sites to plates on the basis of geologic 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. The GEODVEL angular velocities differ insignificantly from a second set of plate angular velocities that we determine from site velocities in the International Terrestrial Reference Frame 2000 [Altamimi et al. 2002]. That the two sets of angular velocities are nearly equal suggests that both sets are accurate. The GEODVEL angular velocities differ significantly in places from prior estimates. In particular, several GEODVEL relative angular velocities differ significantly from the corresponding relative angular velocities of NUVEL-1A, which is based on 3.2-Myr-average spreading rates from marine magnetic anomalies, azimuths from bathymetric data along transform faults, and from earthquake slip vectors. Differences between GEODVEL and NUVEL-1A are large for angular velocities involving the Nazca plate and for North America-Pacific, Eurasia-Pacific, India-Eurasia, and Arabia-Eurasia. Some of these differences are presumably due to changes in plate velocities since 3.2 Ma, but some may be due to biases in NUVEL-1A. For example, we explore whether differences for the latter four angular velocities might be accounted for by incorporating motion across the east African rift, which is neglected in plate motion model NUVEL-1A. As another example, the GEODVEL and NUVEL-1A India-Australia relative velocities differ significantly, but the former agrees with a new set of angular velocities from plate reconstructions that recognize the existence of a separate, previously unrecognized Capricorn plate between the Indian and Australian plates [Royer and Gordon 1997].

G24A-03 1600h INVITED

Comparison of space geodetic and geologic plate models. Are the differences real and what what do they tell us?

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GPS geodesy can improve understanding of plate motions, diffuse and poorly-located plate boundaries, and striking intraplate deformation. Although much has been learned using by geologic GPS geodesy can improve understanding of plate motions, diffuse and poorly-located plate boundaries, and striking intraplate deformation. Although much has been learned using by geologic plate motion models based on magnetic anomalies, transform azimuths, and earthquake slip vectors, comparison of their results with GPS offers valuable insight. GPS sites in plate interiors directly resolve motion between plate pairs, such as Nubia-Somalia and India-Eurasia, where we do not have marine magnetic data. GPS data can be compared to data spanning longer time intervals to identify both limitations of models and real temporal changes in plate motion, which are suggested by initial data and seem likely in areas where boundary geometry has been evolving. Finally, GPS data can directly measure deformation within plates. Once space geodetic results become robust (long enough time series of data at a suitable number of sites), discrepancies between them and geologic models spanning millions of years can indicate either limitations in the million-year models, or changes in plate motions over time. Analyses of different plate pairs around the world have found both effects. For example, present Nazca-Pacific spreading and Nazca-South America convergence are significantly slower than the 3 Ma average rate predicted by NUVEL-1A. The convergence deceleration is consistent with a trend extending back to at least 20 Ma implied by paleomagnetic data, implying a possible negative feedback between Andean uplift and plate convergence. Conversely, GPS data resolve recognized problems with the Caribbean plate motion in NUVEL-1A, giving a better and geologically plausible result. Another interesting case is in the Indian Ocean region. Nubia-South America motion has been slowing and may be part of a regional set of coupled plate motion changes. It seems likely that India-Eurasia and/or Arabia-Eurasia (Persian Gulf) convergence slowed in the past few Ma, perhaps due to feedback with mountain building, and that Nubia-Arabia (Red Sea) spreading is also slowing.

G24A-04 1615h INVITED

Plate Kinematics in Northeast Asia Constrained by GPS

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GPS observations in Siberia combined with global observations, collected in 1995-2003, allow us to improve constraints on the geometry and relative motion of the Eurasian (EUR), North American (NAM), and Pacific (PAC) plates [1]. In contrast to our earlier work and to other published studies, we estimate simultaneously both the relative plate rotation vectors (RV) and the translation rate of the reference frame (RF) which is treated as a free parameter. With this approach, we get identical values of RV regardless of which RF is used. Our estimate of RV for the EUR-NAM pair and the estimate based on the ITRF2000 catalog differ significantly because of the non-uniform sampling of EUR in ITRF2000, with most stations clustered in Europe. There are small (<1 mm/yr) but systematic plate-residual velocities within stable EUR, westward in Siberia and eastward in Europe, which, if real, indicate a small relative motion of these formerly independent plates. By comparing velocities relative to EUR and to NAM, we conclude that east Siberia to the east of the Cherskiy Range belongs to the North American plate. This fact was assumed in the literature for three decades but not proven because of uncertainties with the plate boundary arising from the ambiguous seismicity. Smaller plates in east Asia, such as Amurian and Okhotsk, are not required by the GPS velocities in our analysis. [1] Steblov, G.M., M.G. Kogan, R.W. King, C.H. Scholz, R. Bürgmann, and D.I. Frolov, Imprint of the North American Plate in Siberia revealed by GPS, Geophys. Res. Lett., 30(18), 1924, doi:10.1029/2003GL017805, 2003.