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.

G24A-05 1630h

The effects of the definition of a stable Eurasian reference frame on geodetic velocity estimates along its boundaries

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The geodetic definition of a stable Eurasian reference frame has long suffered from having a disproportionate number of stations in its European portion and from the fact that the available stations east of the Ural mountains are all in, or close to, the central Asian deformation zone. This has affected, for example, the ITRF2000-Eurasia definition of Altamimi et al. (2002). Only recently this situation has changed with the availability of sufficiently long time-series of IGS stations in central and northern Siberia. These data has effectively been used by Calais et al. (2003) and Steblov et al. (2003). It has become evident that there is a systematic difference between the definition of a Eurasian reference frame from studies that include or exclude stations east of the Ural. The pole of rotation that explains the difference is located in Eastern Europe. The rate difference results in up to 4 mm/yr in Southeast Asia. All geodetic studies from the Mediterranean to Southeast Asia appear to use different definitions of stable Eurasia. We explore here the effects of adopting different definitions of Eurasia on the geodetic velocity estimates along Eurasia's southern margin, including Nubia, Arabia, India, and East- and Southeast Asia. We show that, compared to Nubia's motion relative to European stations, its motion relative to Eurasia is 12° more clockwise (CW) in the eastern Mediterranean and 20° more counter-clockwise (CCW) west of Gibraltar. Both solutions are significantly different form geologic estimates, but velocities in a Eurasian reference frame are noticeably closer to the geologic estimates than the velocities in a European definition. Bahrein (Arabia) moves 3° CW and 1 mm/yr faster relative to Eurasia than to a European defined Eurasia. The motion of Bangalore (southern India) could be 3 mm/yr slower and 2° CCW relative to a Eurasian fixed reference when only stations in Europe are used. At Shanghai and Singapore using only European stations would give a velocity 30° CW from a solution that includes Siberian stations. Other examples will be discussed as well. Finally, it is important to point out that any comparison with geologic plate motion models should be based on a geodetic definition of the Eurasian plate that includes Siberia stations, because the Artic Ridge (which is used in geologic plate motion estimates) extends to 120°E. Also, no-net-rotation (NNR) estimates of Eurasia based on geologic models should be avoided, because its definition is significantly different from geodetic estimates, largely as a result of the inclusion of the Asian deformation zones in the geologic NNR definition.

G24A-06 1645h

The Signatures of Tectonics and Glacial Isostatic Adjustment revealed by the Strain Rate in Europe

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Tectonics and Glacial Isostatic Adjustment (GIA) are simultaneously taken into account in order to quantitatively define their role on crustal deformation in Europe. A spherical finite element model, based on the thin viscous shell approach and suitable to predict tectonic deformation, and a spherical stratified viscoelastic Earth model, based on the normal mode approach to quantify the effects of GIA, are used to predict the intraplate deformation in Europe. Model predictions are compared with the geodetic strain rate obtained from ITRF2000 velocity solutions. Our results confirm that both geophysical processes influence intraplate deformation in Europe, with tectonics playing the leading role south of Potsdam, while GIA is the only mechanism north of Onsala. Both geophysical processes affect the deformation at intermediate latitudes,where the contributions to the deformation coming from tectonics and GIA are of the same magnitude and the combined tectonic plus GIA model succeeds to reproduce the eigendirections of the local predominantly SSW-NNE directed compression. The stiffening in the eastern European platform is crucial to shield the north-eastern regions from the compressional effects of Africa-Eurasia convergence and to allow SE-NW directed extension in Fennoscandia driven by GIA.

G33A CC: 516 B Wednesday 1330h

Observations of Glacial Isostatic Adjustment and Contemporary Ice-Ocean-Mantle Mass Redistribution I *(joint with H, OS, S, T, C, GC, PP, SEDI)*

Presiding: **H Scherneck,** Chalmers University of Technology**; J A Henton,** Natural Resources Canada**; A Capra,** University of Bologna

G33A-01 1330h INVITED

Global Inverse Approach to ice Mass Variations Using Data Combination

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Ice mass balance, sea level rise, and post-glacial rebound (PGR) are all manifestations either directly or indirectly of mass and thermal variations in the volatile cryosphere and hydrosphere of the Earth with multiple spatiotemporal scales. The southern hemisphere is especially important because of its huge ice mass reservoir. The coupling of multi-processes with various parameters makes their separate determination extremely difficult. On the other hand, surface mass variations leave many significant geodetic and geological signatures that are now being accurately measured and documented. A global simultaneous inversion of data combination offers exciting opportunities to unravel the complex processes collectively and objectively with statistical rigor. Gravity data from satellite laser ranging (SLR) and CHAMP/GRACE missions, satellite altimetry, and GPS deformation measurements will aid in providing a description of the short period variations having elastic Earth response with unprecedented global coverage, accuracy and resolution. Remarkable agreements have been found for annual n=1 and low degree zonal surface mass variations between SLR and inverse GPS results. For secular present-day variation and PGR, our analyses indicate that the combination of GRACE and ice altimetry may allow for separation of their signatures. For example, assuming that GRACE and Icesat perform to full expectation, and that the "compaction error" is smooth, the mean Antarctic present-day ice mass balance can be determined to about 4 mm/yr, corresponding to an error of 0.1 mm/yr in its contribution to sea-level change. A further combination with relative sea-level (RSL) history can significantly improve parameter separation and enhance temporal resolving power. Global and targeted regional GPS data are also complimentary for long-wavelength improvement and spatial coverage.

G33A-02 1345h

Separating GIA and Water Mass Redistribution Combining satellite and in situ Measurements:Preliminary Results From GRACE.

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Recent satellite missions provide new and valuable information to better understand the complex ice-ocean-Earth system. We present a method to combine satellite measurements with other in situ measurements and independent information. The final goal of this methodology will be to use all possible available observations to separate the contributions of time-variable accumulation, glacial isostatic adjustment and ice mass change. We will examine how to optimally combine time variable gravity from GRACE, altimeter measurements from ICEsat/GLAS, GPS measurements of vertical velocity, ice core measurements of compaction through time, radar-derived estimates of snow density, and InSAR estimates of height change. We will discuss the strengths and limitations of combining these different data sets, including complexities in estimating compaction trend using ice cores collected before the final epoch of satellite measurement, and how estimates of precipitation fields from Global Circulation Models may improve estimates of ice mass trend and GIA.

G33A-03 1400h INVITED

Direct constraints on GIA motion in North America using GPS

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We use continuous and episodic Global Positioning System (GPS) data to measure the movement caused by glacial isostatic adjustment (GIA) due to glacial unloading in eastern North America. At present it is challenging to quantify GIA motion in North American due to the limited number of continuous GPS sites (CGPS) in and around Hudson Bay, the area of maximum glacial loading. Episodic GPS (EGPS) sites provide a low cost and higher density alternative, but often have large errors, especially in the vertical. However, the large vertical signal due to GIA (>10mm/yr) in the area of maximum uplift permits this motion to be resolved, even with EGPS data. We present data from 130 CGPS sites throughout North America and almost 100 EGPS sites of the Canadian Base Network (CBN). The CBN sites are located across central and southern Canada and have been episodically occupied between 1994 and 2002. We detect a coherent pattern of vertical motions around the area of maximum glacial loading, Hudson Bay. The observed velocities are initially large and upward, and decrease southward from Hudson Bay to zero, delineating the hinge line near the Great Lakes. The position of the hinge line is in agreement with some numerical GIA predictions. The horizontal residual velocities after removing the motion of the rigid North American plate also show a consistent, but more complex pattern than the vertical velocities. In particular we observe larger than expected motions on the east side of the Canadian Rocky Mountains, possibly reflecting larger ice loads and/or changes in mantle viscosity. We believe that this velocity field provides the first comprehensive direct description of GIA motion and can be used to constrain GIA model predictions.

G33A-04 1415h

New GPS and Raised Shoreline Measurements of Rapid Uplift in Southern Alaska.

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Five years of campaign-style GPS observations at 74 sites indicate uplift rates of 10 - 32 mm/yr over a large area of southern Alaska. Studies of raised shorelines at 27 sites throughout the region show rapid sea level changes, consistent with the distribution and magnitude of the GPS determined uplift rates. Dendrochronology of 14 of these shorelines gives the onset of uplift at 1850 to 1880 AD. Two of the shoreline study sites show 5.5 m of sea level change since then, in Dundas Bay and Upper Lynn Canal, and the remaining 25 shoreline sites describe a pattern of smoothly decreasing uplift with increasing distance away from Glacier Bay. Both the raised shorelines and the GPS data indicate greatest uplift surrounding areas of post-Little Ice Age (LIA) deglaciation. Using a combination of independent studies, geomorphic indicators and historical observations of the ice extent in Glacier Bay, we have built a model of LIA expansion and retreat of the Glacier Bay Icefield. Total ice volume lost in Glacier Bay since 1750 AD is on the order of 2500 km^3, with ice thickness changes up to 1.5 km. We will present viscoelastic rebound models using this ice load model, and combined with ice models based on airborne laser altimetry of present day ice loss. Earth models that invoke a 50 km thick elastic crust over a 100 km thick asthenospheric layer with viscosity of 1 x 10^{19} Pa s can

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