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Understanding the interaction between sea-level changes and tectonic activity during the Holocene is essential in determining long-term tectonic deformation rates and in identifying prehistorical earthquake events along active margins. The Guerrero coast extends along the active Pacific margin of southwest Mexico and parallels the trench where the Cocos Plate subducts beneath the North American Plate. The last major earthquakes occurred in Guerrero in 1899, 1907, 1909, 1911, and 1957, but none have occurred since the major 1911 (Ms=7.6) earthquake in the northwest segment of the Guerrero seismic gap. The Guerrero gap is currently considered to be matured for a severe earthquake of estimated Mw= 8.1 to 8.4. We present preliminary results of geomorphic field surveying, sediment coring, and geochemical and microfaunal analyses of cored sediments on the Guerrero coast. The Coyuca lagoon strip of the Guerrero coast consists of long barrier beaches, behind which extends a lagoon, beach ridges, extensive swamps, mangrove swamps, salt pans, floodplains, alluvial plains, fluvial terraces, and abandoned meanders. Abandoned meanders and fluvial terraces indicate that the Coyuca River has migrated to the southeast. This migration, and changes in hill elevations near the coast, suggest a southeast tilting of this coastal segment. The morphology of the Guerrero coast has no evidence of long-term coastal uplift. This is consistent with short- term tide gauge measurements (1953-1999) and GPS data (1992-2000) indicative of subsidence rates of 3 mm/yr (Kostoglodov et al., 2001) in this area. Five cores up to 5.5 m depth were taken nearby the Mitla, Coyuca, Tres Palos and Tecomate lagoons. Core stratigraphies show clear sequences of interbedded peats and clays, interspersed with sand units. The peat-clay sequences are similar to those observed along active margins elsewhere, and indicate fluctuations between marine and brackish/freshwater conditions. Two cores included sediments with archeological remains (pottery). The stratigraphic data, coupled with geomorphic evidence, indicate changes in relative sea-level associated with long-term tectonic deformation. On-going radiocarbon dating of shells and charcoal, and detailed geochemical and micro-faunal (i.e. pollen, ostracod and foraminiferal) analyses are being used to constrain the timing and confirm the nature of these sea-level change events.

URL: http://seis.natsci.csulb.edu/tramirez/tramirez.html

G22D-07 1510h

Characteristic and Uncharacteristic Earthquakes as Possible Artifacts: Applied to the New Madrid and Wabash Seismic Zones

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Generally, the largest events, characteristic earthquakes (CE), appear more often than expected from the Gutenberg-Richter relation. Whether this effect is real or apparent is an interesting question since apparent differences can arise from several possible situations. If the known history is shorter than or comparable to the recurrence time of largest events, apparent CEs can occur because sampling bias allows anomalous short recurrence to be observed more frequently (fractions of earthquakes cannot be observed). Alternatively, apparent CEs can occur if paleoseismic data overstimate magnitudes or underestimate recurrence. In the New Madrid Zone (NMSZ), simulations suggest that because the 2000 year paleoseismic record is 4× the accepted recurrence for CEs, there is a small probability of observing apparent CEs. A more significant effect is that paleoliquifaction data regionally appear to overestimate magnitudes. It is commonly assumed that the distribution of liquifaction, used for paleomagnitudes, near the NMSZ is smaller that seen globally. Liquefaction features extending 250 km from an earthquake in the NMSZ are interpreted as evidence for an M 8.3 event, rather than an M 7.6 as would be inferred from the global curve. This practice arose because the curve was calibrated assuming an M 8.3 for the 1811-12 events whereas more recent analysis finds M∼7.4. Hence either the largest earthquakes are CEs or the paleoevents were smaller than those in 1811-12. The opposite effect occurs in the Wabash Valley Seismic zone, where the paleoearthquakes appear "uncharacteristic", less frequent than would be inferred from instrumental seismicity. The paleoseismic record is long enough that the discrepancy is unlikely to be a sampling artifact. Hence either the uncharacteristic behavior is real, or the paleoseismic record captures only a small fraction of the large preinstrumental earthquakes.

G22D-08 1525h

The Evolution of the Seismic-Aseismic Transition During the Earthquake Cycle: Constraints from the Time-Dependent Depth Distribution of Aftershocks

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We have demonstrated that in the aftermath of large earthquakes, the depth extent of aftershocks shows an immediate deepening from pre-earthquake levels, followed by a time-dependent postseismic shallowing. We use these seismic data to constrain the variation of the depth of the seismic-aseismic transition with time throughout the earthquake cycle. Most studies of the seismic-aseismic transition have focussed on the effect of temperature and/or lithology on the transition either from brittle faulting to viscous flow or from unstable to stable sliding. They have shown that the maximum depth of seismic activity is well correlated with the spatial variations of these two parameters. However, little has been done to examine how the maximum depth of seismogenic faulting varies locally, at the scale of a fault segment, during the course of the earthquake cycle. Geologic and laboratory observations indicate that the depth of the seismic-aseismic transition should vary with strain rate and thus change with time throughout the earthquake cycle. We quantify the time-dependent variations in the depth of seismicity on various strike-slip faults in California before and after large earthquakes. We specifically investigate (1) the deepening of the aftershocks relative to the background seismicity, (2) the time constant of the postseismic shallowing of the deepest earthquakes, and (3) the correlation of the time-dependent pattern with the coseismic slip distribution and the expected stress increase. Together with geodetic measurements, these seismological observations form the basis for developing more sophisticated models for the mechanical evolution of strike-slip shear zones during the earthquake cycle. We develop non-linear viscoelastic models, for which the brittle-ductile transition is not fixed, but varies with assumed temperature and calculated stress gradients. We use them to place constraints on strain rate at depth, on time-dependent rheology, and on the partitioning of deformation between brittle faulting and distributed viscous flow associated with the earthquake cycle.

G22E MCC: 2010 Tuesday 1600h

Insights Into the Earthquake Cycle III *(joint with OS, S, T)*

Presiding: **S L Hamilton,** University of Durham**; W Thatcher,** U.S. Geological Survey

G22E-01 1600h INVITED

Incubation of Chile's 1960 Earthquake

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Infrequent occurrence of giant events may help explain how the 1960 Chile earthquake attained M 9.5. Although old documents imply that this earthquake followed great earthquakes of 1575, 1737 and 1837, only three earthquakes of the past 1000 years produced geologic records like those for 1960. These earlier earthquakes include the 1575 event but not 1737 or 1837. Because the 1960 earthquake had nearly twice the seismic slip expected from plate convergence since 1837, much of the strain released in 1960 may have been accumulating since 1575. Geologic evidence for such incubation comes from new paleoseismic findings at the Río Maullin estuary, which indents the Pacific coast at 41.5° S midway along the 1960 rupture. The 1960 earthquake lowered the area by 1.5 m, and the ensuing tsunami spread sand across lowland soils. The subsidence killed forests and changed pastures into sandy tidal flats. Guided by these 1960 analogs, we inferred tsunami and earthquake history from sand sheets, tree rings, and old maps. At Chuyaquen, 10 km upriver from the sea, we studied sand sheets in 31 backhoe pits on a geologic transect 1 km long. Each sheet overlies the buried soil of a former marsh or meadow. The sand sheet from 1960 extends the entire length of the transect. Three earlier sheets can be correlated at least half that far. The oldest one, probably a tsunami deposit, surrounds herbaceous plants that date to AD 990-1160. Next comes a sandy tidal-flat deposit dated by stratigraphic position to about 1000-1500. The penultimate sheet is a tsunami deposit younger than twigs from 1410-1630. It probably represents the 1575 earthquake, whose accounts of shaking, tsunami, and landslides rival those of 1960. In that case, the record excludes the 1737 and 1837 events. The 1737 and 1837 events also appear missing in tree-ring evidence from islands of Misquihue, 30 km upriver from the sea. Here the subsidence in 1960 admitted brackish tidal water that defoliated tens of thousands of trees. We sampled 45 such trees, some of them completely dead and the rest surviving only from shoots near the ground. One-third of these trees lived through the 1837 earthquake; they contain over 180 annual rings. Five of the trees also contain rings earlier than 1737. From this evidence, we tentatively infer that the islands underwent more subsidence in 1960 than they did in 1737 or 1837. Comparisons with old Chilean documents for the estuary further suggest that subsidence in 1837 did not approach that of 1960. In their depiction and description of the Misquihue islands in 1874, surveyor Francisco Vidal and botanist Carlos Juliet show nothing like the ghost forests seen today. Twice in the first 37 years after the 1837 earthquake, surveyors mapped as emergent several islands that the 1960 earthquake would lower into tidal water. Today, 43 years after they subsided in 1960, these islands remain submerged as barren intertidal flats. Research supported by Fondecyt 1020224.

G22E-02 1615h INVITED

Elastic and Viscoelastic models of Crustal Deformation in Great Earthquake Cycles

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Ideally, a model of subduction zone earthquake cycles should include tectonic loading, fault friction, and viscoelastic stress relaxation. Such a model is not yet available. The loading mechanism is rarely addressed. A model does not address tectonic loading if some part of the fault is assigned a slip rate. Models based on rate and state dependent friction laws are useful in demonstrating how seismic fault slips may occur and stop as a result of the interplay between fault frictional behavior and system rigidity. For comparison with geodetic observations, however, the most widely used models treat the fault motion in a purely kinematic fashion, that is, the fault slip (or state of locking) is estimated from surface observations regardless of the loading mechanism and friction properties. These include the forward and inverse elastic dislocation and viscoelastic models. Without addressing the loading mechanism, extra care should be taken to ensure that the assigned or estimated fault motion is physically valid. It is often difficult to distinguish between contributions to surface deformation from fault motion and from stress relaxation of the rock material. The same deformation observations can be explained by different models, and any published model merely portrays one particular understanding of the processes being studied. It is usually assumed that aseismic slip of the fault, such as "afterslip" and interseismic silent slip, is of the time scale of days to years, but viscoelastic stress relaxation of the system has a time scale of decades to hundreds of years. On the basis of the time scale argument, we modeled earthquake cycles at the Cascadia and Chile subduction zones using a 3-D spherical finite element viscoelastic model with a mantle viscosity of about 10^{19} Pa s. Contemporary crustal deformation of the Cascadia forearc, 300 years after a great earthquake, can be explained by the viscoelastic model. The observation that GPS sites 300-400 km landward of the rupture region of the 1960 great Chile earthquake are presently moving seaward, opposite to the motion of the coastal sites, can be explained by stress relaxation. Elastic models can also fit most of the observations by assuming that all deformation is due to fault motion. The fault motion thus determined effectively includes contribution from stress relaxation.

G22E-03 1630h

Long-term Postseismic Deformation Following the 1964 Alaska Earthquake

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Geodetic data provide a rich data set describing the postseismic deformation that followed the 1964 Alaska earthquake (Mw 9.2). This is particularly true for vertical deformation, since tide gauges and leveling surveys provide extensive spatial coverage. Leveling was carried out over all of the major roads of Alaska in 1964-65, and over the last several years we have resurveyed an extensive data set using GPS. Along Turnagain Arm of Cook Inlet, south of Anchorage, a trench-normal profile was surveyed repeatedly over the first decade after the earthquake, and many of these sites have been surveyed with GPS. After using a geoid model to correct for the difference between geometric and orthometric heights, the leveling+GPS surveys reveal up to 1.25 meters of uplift since 1964. The largest uplifts are concentrated in the northern part of the Kenai Peninsula, SW of Turnagain Arm. In some places, steep gradients in the cumulative uplift measurements point to a very shallow source for the deformation. The average 1964-late 1990s uplift rates were substantially higher than the present-day uplift rates, which rarely exceed 10 mm/yr. Both leveling and tide gauge data document a decay in uplift rate over time as the postseismic signal decreases. However, even today the postseismic deformation represents a substantial portion of the total observe deformation signal, illustrating that very long-lived postseismic deformation is an important element of the subduction zone earthquake cycle for the very largest earthquakes. This is in contrast to much smaller events, such as M 8 earthquakes, for which postseismic deformation in many cases decays within a few years. This suggests that the very largest earthquakes may excite different processes than smaller events.

G22E-04 1645h INVITED

Relative land/sea-level movements and great Holocene earthquakes, Alaska

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The “earthquake deformation cycle” (EDC) model describes relative sea-level (RSL) movements associated with large plate boundary earthquakes. On March 27, 1964, an earthquake of magnitude 9.2 occurred along the south coast of Alaska, USA. By applying quantitative transfer functions to microfossil data collected from contemporary tidal flats, marshes and wetlands together with observational data from 1964 we can calibrate models of Holocene environmental change represented by fossil assemblages in sediment sequences. We use the transfer function models to quantify relative sea-level changes through multiple Holocene EDCs in Alaska and separate co-seismic from non-seismic events. Geological evidence from four sites around the Cook Inlet - Girdwood, Ocean View (Anchorage), Kenai and Kasilof, support a four phase EDC model that in the zone of co-seismic submergence comprises: (1) Relatively rapid land uplift and sedimentation immediately after an earthquake, i.e. the post-seismic period; (2) Centuries-long inter-seismic period of slower relative land uplift caused by strain accumulation along the locked portion of the Alaska-Aleutian subduction zone; (3) A pre-seismic period of relative sea-level rise (relative land subsidence) lasting approximately a decade; (4) Rapid co-seismic land subsidence during a great (Mw > 8) earthquake. The four sites record evidence of Holocene co-seismic submergence in the form of multiple peat-mud couplets. Not all events are recorded at each site, the interval between events is variable and the magnitude of submergence varies from less than 0.5 m to greater than 2.0 m. A unique finding is the identification and quantification of pre-seismic RSL rise prior to each co-seismic event. Biostratigraphic changes that reveal a pre-seismic RSL rise typically occur over 1 to 5 cm of sediment, are dated at Kenai and Girdwood (for the 1964 earthquake) to start approximately 10 years before the event and indicate pre-seismic RSL rise up to 0.2 m. This is strong evidence to suggest that pre-seismic movements may represent a precursor to a great earthquake. Independent work based on twentieth century observations and limited to only parts of an EDC describe possible mechanisms for this phenomenon. This has potential implications for other subduction zone locations including Chile, Japan and the Pacific Northwest of the USA and Canada.

G22F MCC: 2010 Tuesday 1710h

Bowie Lecture

Presiding: **V Dehant,** Royal Observatory of Belgium**; J T Freymueller,** University of Alaska, Fairbanks

G22F-01 1715h INVITED

Episodic Tremor and Slip in the Cascadia Subduction Zone: A Story of Discovery

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For more than two decades, seismologists at the Pacific Geoscience Centre puzzled over the episodic appearance of simultaneous ”noise” on seismographs from stations located over the Cascadia subduction zone in southwestern British Columbia. With the 1992 initiation of continuous GPS monitoring in Victoria, B.C., another puzzle presented itself in an inexplicable 5-mm westward displacement of the then solitary regional continuous GPS monument over a period of about a week in October 1994. These observations remained unexplained (and unrelated) until recently. Beginning in 1996, as a result of improvements in GPS orbits and regional densification of continuous GPS networks, transient aseismic crustal motions lasting from periods of a few days to over a year were starting to be recognized. For the Pacific Northwest, detailed analyses of continuous GPS data successfully resolved a spatially coherent, transient signal that occurred in August 1999. Unrelated to after-slip that can follow great thrust earthquakes or to shallow slow-slip ”tsunami” earthquakes, this signal, detected at 7 contiguous GPS sites, was characterized by a change in site positions ranging from 2 to 5 mm over a period of 6 to 15 days in a direction opposite to long-term deformation motions. This brief reversal was modeled by $\sim$2 cm of slip on the plate interface, providing the first evidence for discrete ”silent” slip events occurring on the deeper Cascadia subduction zone. In early 2002, researchers at Central Washington University established the surprising regularity of Cascadia slip events on the plate interface underlying southern Vancouver Is. and northwestern Washington State. Eight slip events were identified between 1992 and 2002, with a recurrence interval of 14.5 ±2 months. Next, Japanese scientists discovered the episodic occurrence of unique, non-volcanic tremors at average depths of about 30 km along the Nankai Subduction Zone. The similarity of the average depth of slip and the migration velocity of slip for the GPS-determined Cascadia slip events, to the depth and migration velocity of the Japanese tremors triggered the search for seismic signatures for the Cascadia slip events. An examination of seismic records from 1996 to 2002 for sites on Vancouver Is. revealed that what had previously been deemed surface noise was signal from seismic tremors that accompanied slip events. The Cascadia tremors were found to be similar in character to the Japanese deep tremors. In addition, their source region was found to coincide with, or directly overlie, the region of the subducting slab interface where transient slip occurs. The close correlation of tremors with slip coined the naming of the phenomenon as Episodic Tremor and Slip (ETS). The physical processes which give rise to this dynamic behavior on the deeper plate interface are not yet well understood. To date, only the Nankai and Cascadia subduction zones have been observed to share aspects of this behavior, suggesting that this phenomenon may be restricted to young subduction zones. The release of fluids, contact with a hydrated mantle wedge, and episodic changes in shear strength or mechanical coupling may all play a part in governing this behavior. Possible connections of ETS with the development of ”E-zone” reflector bands, basal erosion, and pulsating metamorphism await further research. In the context of seismic hazard, the ETS zone may mark the down-dip limit of coseismic rupture of the next megathrust earthquake. Also, since it is conceivable for a slip event to trigger a large subduction thrust earthquake, the onset of ETS activity could identify times of higher probability for the occurrence of megathrust earthquakes.

G31A MCC: 2010 Wednesday 0800h

Satellite Measurements of Temporal Gravity Variations I

Presiding: **M M Watkins,** Jet Propulsion Laboratory, California Institute of Technology**; R S Nerem,** University of Colorado

G31A-01 0800h

GRACE Gravity Field Analysis Results from JPL

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The Jet Propulsion Laboratory serves as the GRACE gravity field analysis verification center, generating independent gravity solutions for assessing the error characteristics of the fields through comparison with the other centers (UTCSR and GFZ), and performing studies to develop optimal parameterizations which may improve the field quality. In addition, we provide a quick gravity solution turnaround capability to assess the utility of alternate Level-1 algorithm implementations. In this presentation, we will present the most recent gravity field results from GRACE, with special attention to summarizing our best understanding of the Level-1 data quality and influence on the field characteristics, and the effects on the fields of varying parameterizations (orbital arc lengths, nuisance parameterization and sub-arc lengths, etc) in the Level-2 analysis.

G31A-02 0815h INVITED

Low-degree temporal gravity field variations using CHAMP data

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The ability to recover with CHAMP the Earth’s gravity field homogeneously and precisely from only a few weeks’ worth of GPS satellite-to-satellite tracking data stimulates the investigation of temporal gravity field variations as seen by CHAMP. From a multi-annual exploitation of CHAMP data, time series of low degree spherical harmonic gravitational coefficients are derived and evaluated in the spatial and spectral domain by comparison with geophysical data and models covering atmospheric, oceanic and hydrologic mass redistributions. The space/time resolution and stability obtainable with a mission like CHAMP in recovering short-term environmentally induced gravity field variations were estimated. From experience gained up to now with the CHAMP data processing, the investigations are restricted to spherical harmonics up to degree/order 4, i.e. spatial wavelengths not shorter than 10000 km. The coefficients’ time series are simultaneously derived in a comprehensive global gravity field solution with the higher-degree terms kept time-invariant. Results from both CHAMP-only and CHAMP combined with selected Laser satellite solutions are studied.

G31A-03 0830h

GRACE Gravity Field Product Description and Mission Profile

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