of magnitude larger shaking. Both waveforms and cataloged events indicate no triggering occurred following the Honshu, Tottori and Kuril Islands mainshocks. We do not interpret the one indefinite local event recorded by TKO as evidence for mid range dynamic triggering, implying that the 2.5 cm/s shaking at TKO did not exceed the local triggering threshold. Additionally, the lack of triggering following Honshu, Tottori, and Kuril Islands suggests that the 1, 2.5 and 2.6 cm/s shaking at distances of 182, 238, and 267 km, respectively, creates lower bounds for the dynamic triggering thresholds at the respective locations. This assumes the bound is frequency independent. In none of the cases were thresholds exceeded over a large enough region or by large enough amplitude to produce a statistically significant increase in the cataloged rate of seismicity during the period from 1997 to 2002. All previously documented examples of triggering have occurred following shallow earthquakes with $M_w > 7$. With the exception of Volcano Islands, all of the events of this study have $M_w < 7$, and have no triggering associated with them. This suggests two possibilities: either events with $M_w > 7$ are required to produce sufficient shaking to trigger seismicity, or Japan is less susceptible to triggering than the western US or Greece. We assume that the depth of the Volcano Islands earthquake prohibits any substantial surface shaking. We conclude that more data is required associated with shallow, crustal events with $M_w > 7$ in order to determine whether or not Japan is susceptible to regional triggering.

S32F-07 1730h

Expected Spatio-temporal Aftershock Patterns for Different Tectonic Regimes

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Co-seismic damage created through shear rupture provides a high permeability fracture zone through which high pressure fluid pulses can propagate. In regions where fluids are trapped at high pressure by a geologic seal, the co-seismic rupturing of that seal allows the instant communication of high (lithostatic) and low (hydrostatic) pressure regions. The amplitude of the pressure difference depends on the depth but can be very large (for example, the difference is 170MPa for a trapped source at 10 km). The propagation of such a large pressure pulse will open fractures in the damage zone, travel at very high velocity, and trigger aftershocks by significantly reducing the effective normal stress in the regions through which it propagates. If aftershocks are driven by this mechanism, then aftershock distributions in space and through time should show a spatial distribution that depends on the type of faulting. Expected aftershock distributions are shown from modeling results for strike-slip, normal, and thrust fault events. The pressure pulse is modeled as a non-linear diffusion process where permeability is a strongly non-linear function of the effective normal stress acting on fractures. Results are compared with measured aftershock sequences.

S32F-08 1745h

Stress transfer and aftershocks

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The earthquakes that are most readily associated with stress transfer are aftershocks. There are three important "laws" associated with aftershocks: (1) They satisfy Gutenberg-Richter frequency-magnitude scaling, (2) they decay in time according to Omori's law, and (3) they satisfy Bath's law. Bath's law states that the difference in magnitude between main shocks and their largest aftershocks is approximately constant, independent of the main shock magnitude. We propose a modified form of Bath's law by extrapolating the frequency-magnitude statistics of measured aftershocks of a given main shock to infer the largest aftershock. We consider eight earthquakes that occurred in southern and Baja California between 1987 and 2002 with magnitudes equal to or greater than 5.5. The difference in magnitude between main shock and largest aftershocks were 1.23+0.046 (Bath's law) and the difference in magnitude between main shock and inferred largest aftershocks were 1.21+0.27 (our modified Bath's law). We show that the applicability of the modified Bath's law implies that the fractional stress transfer responsible for aftershocks is a constant independent of main shock magnitude and that this scaling varies by about 25%. We find that about 95% of the energy dissipation due to an earthquake is associated with the main shock and 5% with the aftershocks.

S41A MCC: 3011 Thursday 0800h

Subduction and Lithospheric Deformation in South America I *(joint with G, T)*

Presiding: **L Wagner,** University of Arizona**; A Tassara,** Institut für Geologische Wissenschaften, Freie Universitat Berlin

S41A-01 0800h

Measuring Active Faulting in Bolivia: the 1998 Aiquile Earthquake

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The Aiquile region of central Bolivia is situated in the core of the actively deforming Bolivian Orocline. Palaeomagnetic data show that differential rotations consistent with oblique convergence have continued over the past 10 Myr. Structural mapping of the sub-Andean fold-and-thrust belt to the east shows that the majority of this convergence has occurred there as shortening; however there exists a significant transverse component of motion which must be accommodated as strike-slip faulting elsewhere. Many topographic lineations assumed to be related to strike-slip faulting have been identified in the area around Aiquile, however none has been associated with large earthquakes or demonstrated to be active over the past million years. On 22nd May 1998, a $M_w = 6.5$ earthquake struck the region, the largest shallow earthquake to occur in Bolivia for 50 years, resulting in over 105 fatalities and rendering thousands homeless in the towns of Aiquile and Totora and their surrounding villages. Seismic observations of the event are inconclusive; the correct orientation and style of the faulting – either right-lateral strike-slip on a N–S fault, or left-lateral on an E–W fault – cannot be determined as large uncertainties in earthquake location mean we do not know *a priori* which of the two nodal planes in the focal mechanism is the fault plane, or upon which structure the earthquake occurred. We present here the first study of a Bolivian earthquake using InSAR. Despite the rugged nature of the terrain in the Aiquile region, with its sharp changes of relief ($\sim$ 3000 m over 20 km) – a consequence of its location between the high Altiplano to the west and the foreland basin to the east – we demonstrate that by using freely-available SRTM digital elevation data we can correct for topographic artifacts and generate a clear deformation signal. Our preferred model is for slip on a N–S-striking fault, with a location which validates Modified Mercalli Intensity maps constructed from field observations and local damage reports.

S41A-02 0815h

Comparison of co-seismic and post-seismic slip of large earthquakes in southern Peru and northern Chile

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We use InSAR, GPS, and seismic data to constrain the location of co-seismic and post-seismic slip on the subduction interface in southern Peru and northern Chile. We focus on the July 30, 1995, M_w 8.1 and the January 30, 1998, M_w 7.1 northern Chile earthquakes as well as the November 12, 1996, M_w 7.7 and June 23, 2001, M_w 8.4 southern Peru earthquakes. For all four earthquakes, we invert body-wave seismic waveforms and geodetic data (InSAR for all earthquakes and GPS where available) both jointly and separately for co-seismic slip. In northern Chile, we constrain the temporal and spatial evolution of post-seismic afterslip using about 30 interferograms spanning 1995-2000 and GPS data from the German SAGA array (spanning 1995-1997, including vertical displacements). In southern Peru, we use InSAR data, and GPS data from the Arequipa station to constrain post-seismic after-slip. Comparison of these events provides insight into the rupture process of large subduction zone earthquakes and the mechanisms of post-seismic after-slip. The plate tectonic setting for all the earthquakes is similar (convergence rate, plate age, etc.), but the amount of post-seismic after-slip is different. There is significant slip after the 2001 earthquake (equivalent to approximately 20% of the co-seismic moment), but compared to other recent subduction zone earthquakes, there is little slip following the other three events. The different amounts of post-seismic slip are not obviously related to differences in the dynamic ruptures of each event, but might be related to along-strike variations in material properties (like sediment thickness).

S41A-03 0830h

CASA GPS Results: Lithospheric Deformation and the Earthquake Cycle in the Ecuador-Colombia Subduction Zone

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The Ecuador-Colombia subduction zone is a potentially important laboratory for observing the effects of variations in lithospheric buoyancy on seismic coupling. Subduction of the aseismic Carnegie Ridge is associated with pronounced margin-parallel variations in crustal thickness and buoyancy of the downgoing lithosphere. The subduction zone has been ruptured repeatedly in 1906 (Mw = 8.8), 1942 (Mw = 7.9), 1958 (Mw = 7.8), and 1979 (Mw = 8.2). The 1958 and 1979 ruptures have been linked to asperities on the interplate surface. Simple elastic boundary element and viscoelastic models were used to simulate CASA (Central And South America) GPS-observed surface deformation. The results suggest that interseismic elastic strain accumulation is occurring evenly (50% apparent elastic locking) throughout the Ecuador-southern Colombia forearc. However, on-going postseismic relaxation of a viscous upper mantle (10E19 Pa S) following the 1979 earthquake masks the true total strain rate in southern Colombia. In southern Ecuador south of the ridge-trench intersection, despite apparent uniform interseismic elastic locking, no large historic earthquakes (Mw>7) have been recorded. The relationship between subducting lithospheric buoyancy and seismic coupling cannot be resolved yet because of the paradox of apparently uniform elastic locking but non-uniform historic seismicity restricted to asperities north of the ridge. The CASA observations of lithospheric deformation associated with the earthquake cycle in the Ecuador-Colombia subduction zone are tantalizing but tentative at this point, because of limited spatial resolution (>100 km average spacing) and limited temporal resolution (only one continuous GPS station in the Ecuador-southern Colombia forearc).

URL: http://estrella.geol.sc.edu/~agl/Projects.htm

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S41A-04 0845h

The Seismogenic Coupling Zone in Central Chile - Amphibious Experiments SPOC (Subduction Processes Off Chile)

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Nearly all interplate megathrust earthquakes occur in the seismogenic coupling zone between converging plates. In the area of the 1960 Chile earthquake (Mw = 9.5), we aim at a quantitative understanding of the seismicity and its relation to processes operating at depth and at the surface. As a first step, the offshore experiment SPOC with RV SONNE was combined with an

onshore-offshore, active-passive seismic experiment between 36° and 39°S, crossing the rupture area of the 1960 Chile earthquake. The campaign comprised: (1) a 2-D wide-angle component recording chemical shots and airgun pulses along three consecutive E-W onshore profiles; (2) a seismic reflection experiment in the onshore-offshore transition; and (3) a 3-D component which recorded both active and passive sources. Offshore, the upper plate is split into many segments with pronounced forearc basins and a narrow accretionary wedge. A thick subduction channel seems to cause a non-frontally accreting subduction mode. Along the westernmost part of the southernmost E-W refraction seismic line, the profile spread of the active reflection seismic survey at 38°15' S was 54 km long, and also recorded the airgun shots of the marine profile with the first 18 km of its spread. Different mainly eastward dipping reflection bands are observed. Between 5-25 km depth the internal structure of the Palaeozoic accretionary wedge is described. Reflections between 16-42 km correlate with Wadati-Benioff seismicity and are interpreted as imaging the top of the downgoing plate. In the central part of the profile a break in reflectivity located below the axis of the coastal cordillera more or less coincides with the intersection between the oceanic plate and the continental Moho. This break in reflectivity also approximately correlates with the downdip end of the seismogenic plate interface as defined by geodetic modelling. These new seismic data provide the geometry of the subduction zone in the area, and hence we suggest the relocation of the 1960 Chile earthquake at 73°05' W.

S41A-05 0900h

SEISMOTECTONIC CHARACTERISTICS AROUND THE ARICA BEND, CENTRAL ANDES (16°S-20°S): PRELIMINARY RESULTS

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The Arica bend region corresponds to the main along strike geometrical change observed in the western South America subduction zone. As a first step, one could think that the geometry of the underlying subduction plate could be symmetric respect with an axis oriented along the direction of convergence between the Nazca and South American plates and passing through the Arica bend. However, the situation is different. The topography of the Altiplano and the characteristics of the subduction do not exhibit the same symmetry north and south of the Arica bend, suggesting that the tectonic of the Central Andes depends strongly on the dynamics of subduction. The Arica bend acted in the past as a geometrical barrier that stopped the ruptures of the large earthquakes of the southern Peru and northern Chile regions. The historical sequence of large earthquakes occurring along the interplate contact of southern Peru and northern Chile compromised different segments of the area associated with the largest earthquakes reported. The 2001 earthquake is not equivalent with the large previous one that occurred in 1868, the analysis of macroseismic parameters suggests that the 2001 earthquake is similar to the 1784 one. The southern segment of the 1868 seismic gap, the Ilo-Tacna (South Peru) segment, remains still intact, joint with the northern Chile seismic gap. In order to better understand the seismotectonic characteristics of the subduction process in the Ilo-Tacna segment and compare them with that observed in northern Chile, we deployed 27 short period three component stations from the U. of Chile-IRD-France around the Arica bend, between November 2002 and March 2003, from the coastline to the Altiplano. 19 stations of the temporary network were installed in southern Peru and 8 of them in northern Chile, that complemented the coverage area of the 13 stations of the permanent seismic network that is in operation there since 1994, through a joint project with the IPG-Strasbourg, IRD-France, the University of Tarapacá and the University of Chile. The about 3000 microearthquakes recorded by the seismic networks permitted a detailed definition of the Wadati-Benioff zone in southern Peru and northern Chile region, around the Arica bend. The average dip angle of the subducting slab observed in northern Chile is similar with that obtained in southern Peru, however, the interplate contact seems less active in the Arica bend with respect to that observed north and south of it. The intracontinental seismicity beneath the Chilean and the Peruvian forearc, joint with shallow seismicity beneath the magmatic arc can be also observed in southern Peru, as well as in northern Chile; those earthquakes are located between the surface up to 60 km depth, suggesting a lineament almost perpendicular to the dip of the subducting slab. This intracontinental seismicity is in agreement with previous results of the lithospheric characteristics of the Central Andes related with the reological, thermal behaviour and the depth of the Moho, and could be interpreted as a result of local tilting deformation, accommodating the elevation of the Altiplano.

S41A-06 0915h

Anisotropy in the Chile-Argentina Flat Slab Subduction Zone, South America

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The South American subduction zone exhibits a dramatic change in dip of the subducting Nazca plate from latitudes 30° S to 36° S beneath Chile and Argentina. At 30° S the slab flattens at a depth of approximately 100 km under Argentina and extends at that depth almost 300 km eastward before continuing its descent into the mantle. South of 33° S, the slab has a uniform dip of approximately 30°. We are analyzing teleseismic and local earthquakes for seismic anisotropy to better understand the deformation and mantle flow associated with this change in subduction geometry. Earthquakes were recorded by 22 portable broadband seismic stations as a part of the CHile ARgentina Geophysical Experiment (CHARGE). In this study, we analyzed teleseismic SKS and SKKS arrivals from earthquakes with epicentral distances 85°-140° from the network as well as S arrivals from local earthquakes in the subducting slab. Preliminary shear wave splitting analyses of local S waves exhibit splitting times of 0.1-0.4 s with a heterogeneous azimuthal distribution of fast axes at some stations in the north, directly above the flat slab. The highest quality results for shear wave splitting from teleseismic events give similar results in this region. We observe larger splitting times (∼0.8 s) with fast directions oriented E-W at stations in the northern part of our network, eastward of the flat slab region. In the southern part of our network, we observe generally N-S fast directions and a broad range (0.2-0.6 s) of splitting times. Preliminary results for the southern portion of our study region are consistent with a model in which N-S mantle flow resulting from retrograde motion of the subducting Nazca plate controls the direction and magnitude of the mantle anisotropy as suggested by Russo and Silver (1994). In the flat slab zone, however, the fast polarization axis is perpendicular (i.e. E-W) to that predicted by the retrograde slab model. We therefore suggest that the local bending geometry of the subducting slab could produce mantle flow in an E-W direction.

S41A-07 0930h

Top-to-Northwest Shear of Nazca Subducted Slab Beneath Andean Region

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The peculiar morphology of Wadati-Benioff Zone (WBZ) beneath Andean region and the focal mechanism of deep (h>500 km) South American earthquakes, present controversial seismotectonic characteristics of the subducting process of Nazca plate beneath South American plate. WBZ beneath Andean region presents almost flat behaviour under Central-Northern Peru region, and beneath Central Chile/NW Argentina region, intercalated with steeply portions of the slab in Southern Peru and Northern Chile. The almost completely aseismic portion between 300 and 500 km of depth is also an irregular characteristic of Nazca slab. Besides the polemic morphology of that WBZ, focal mechanism of deep South American earthquakes is another controversial subject. There are several hypotheses trying to explain a suitable origin for deep earthquakes - deeper than 500 km - which occur in depths with high temperature and pressure conditions, being improbable brittle failure occurs. We propose in this work - based mainly in the spatial distribution of a new set of hypocentral data, and in the joint interpretation with recent published results related to seismotectonic aspects of Andean region - a top-to-northwest shear of the portion of Nazca subducting plate between 24^oS and 01^oS, in such amount its deepest corresponding extremes, around 600 km of depth, seem to be, at present, under latitudes of 29^oS and 06^oS, respectively. The northwestern displacement of South American plate may be provoking that shear process of Nazca slab, which is larger at shallower depths of the slab, and limited to those latitudes in Central Andean region. The NW displacement of Nazca slab could explain the flat subduction beneath Central-Northern Peru region as a consequence of a probable northwards migration of the buoyant Nazca ridge after subduction under South American plate in around 15^oS. This hypothesis permits to infer an almost horizontal focal mechanism for the very deep South American earthquakes, similar to the mechanism on a sub-horizontal nodal plane determined for the M_W 8.3 deep Bolivian event of June 1994

S41A-08 0945h

High-resolution Imaging of Subduction Zone Seismicity: Evidence for a Fluid-controlled Double-seismic Zone in the Nazca Plate

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We present high-precision relocations of large numbers of earthquakes associated with the subducting Nazca Plate below the Central Andes. The new locations are computed by applying waveform cross correlation and double-difference relative location to locally and globally recorded phase pick and/or waveform data, reducing both measurement and velocity model errors, respectively. Relative location uncertainties are typically smaller than the scale-length of the tectonic units in which the events occur, ranging from a few 100 m to a few km (depending on the distribution and quality of available data). Relocations of intermediate-depth earthquakes (80-130 km), using local seismic data and a 3-D model to predict travel-time differences, reveal a fine-scale double-layered Wadati-Benioff zone (WBZ). Correlation with steep-angle reflection data locates the upper and lower band of seismicity at the top of the 8-9 km thick oceanic crust and in the uppermost oceanic mantle, respectively. Analysis of focal mechanisms and waveform similarities suggest that earthquakes in the oceanic crust occur on pre-existing normal faults which slip due to hydraulic embrittlement caused by increasing pore pressure from metamorphic dehydration. Accumulation of small earthquakes at the top of the oceanic crust may demonstrate repeated rupturing of a low permeability seal that acts as a barrier against the upwelling fluids. In both layers extensional faulting predominates, suggesting a weak mechanical coupling between the oceanic crust and mantle. Relocations at around 200 km depth, using globally recorded phase pick and waveform data, reveal a sharp, approximately 15 km thick WBZ, right below what seems to be an (aseismic) bend in the subducting plate. The thickness of the WBZ at these depths is similar to what is observed at shallower depths, and about 50% narrower than what is seen in existing earthquake catalogs. There is some indication of fine-scale layering of seismicity within the plate, but a more detailed analysis of all available data, in particular smaller events, is needed to confirm this observation. Earthquakes at around 530 km depth show strong spatial and temporal clustering that persists over the 25 year observational period. The two clusters investigated occur in a narrow depth range, and form linear structures that parallel the general strike of the subducting plate.