S41F MCC: 3011 Thursday 1020h

Subduction and Lithospheric Deformation in South America III

(joint with G, T)

Presiding: **J N Kellogg,** University of South Carolina**; M Anderson,** University of Arizona

S41F-01 1020h

First-order Crustal Compositional Changes along the Active South American Margin Dominate the Segmented Nature of the Andean Orogen (15°-47°S)

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The Andean Cordillera is a continuous feature along the western margin of South America that has been constructed by a simple common process of ocean-continent collision. However, the Andes show a remarkable continental-scale along-strike segmentation of both the current geotectonic regimen and long-term geological evolution. Here we investigate the hypothesis that differences between the Central (15°-33.5°S) and Southern (33.5°-47°S) Andes are caused by inherited compositional and hence rheological variations along the South American plate. A quantitative interpretation of elastic thickness (Te) estimates in the framework of a brittle-elasto-ductile rheology demonstrates that Te < 10 km, which characterizes the axis of the Central Andes, is only possible if the bulk crustal composition is felsic, while Te > 35 km along the Patagonian Cordillera segment (39°-47°S) of the Southern Andes implies a mafic-intermediate composition. This result is consistent with the available geological, geochemical and geophysical information, and indicates that the weak rheology of the quartz-dominated Palaeozoic basement characteristic of the Central Andean crust has been modified and *rigidized* toward the Southern Andes by the development of a stationary Meso-Cenozoic magmatic arc along the Patagonian Cordillera. This compositionally-caused rheological difference along the Andean margin should be consider a key factor in the understanding of the Late Cenozoic geodynamic evolution of the orogenic process.

S41F-02 1035h INVITED

Brittle to Viscous Transition, Modeling the Evolution of the Andean Plateau

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Although numerical and analytical models of plateau development stress the importance of viscous deformation as a requirement for plateau growth, we present a series of numerical 2-D experiments that illustrate the formation of brittle plateaus as emphasized by geologic studies. The role of brittle deformation in plateau formation is particularly apparent for the Andean Plateau in Bolivia where balanced cross-sections through the Andean fold-thrust belt indicate upper crustal shortening of 300-330 km through predominantly eastward propagating brittle fault systems. Although associated mantle deformation is not fully understood, only half of the original 880 km length of mantle lithosphere is preserved in the orogen. Much of the preserved mantle lithosphere is interpreted to be Brazilian shield. The models of plateau growth that we present show both the development of a plateau through brittle deformation processes and the importance of intracontinental subduction of mantle lithosphere for the eastward propagation of deformation. The rheological structure of the model is controlled by the initial temperature distribution and the temperature boundary conditions. The brittle parts of the lithosphere are modeled as a frictional and cohesional material. The ductile lithosphere is modeled as a non-Newtonian Maxwell visco-elastic material. The initial conditions for the model include a strong cold lithosphere adjacent to a younger, warmer lithosphere that corresponds to the 400-200 Ma passive margin/ extensional basin on the western edge of the South American continent. Subduction of the Nazca oceanic plate is included as the driving mechanism applied as compressional velocity boundary conditions on the model. Initial deformation in the model is focused in the center of the passive margin basin, on a pre-existing weakness in both the crust and lithosphere. Westward dipping intracontinental subduction of mantle lithosphere pulls down the overlying crust and facilitates the eastward propagation of brittle deformation. With time heat associated with a radiogenic, thickened crust decreases the viscosity of the lower crust and facilitates plateau growth through viscous processes. The force history curve of the experiments shows a continuous decrease in the force required to drive the deformation that is due to the negative buoyancy generated by the subducting lithosphere. This process is mainly responsible for the generation of space that allow the eastward propagation of plateau. The curve flattens when the plateau reaches the edge of the cold lithosphere, the subducting slab stalls, and plateau growth is continued through viscous-dominated deformation.

S41F-03 1050h

Cenozoic History of the Interaction of the Nazca and South America Plates: a Numerical Study for the Central Andes

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Large-scale tectonic shortening in the Central Andes and Neogene uplift of the Altiplano-Puna plateau was preceeded by Eocene uplift of the Chilean Precordillera and subsequent rapid eastward expansion of compressional deformation between 40-30 Ma, by the marked decline of the magmatic arc activity at 33-23 Ma and by a strong increase of the convergence rate between the Nazca and South America (SA) plates at 25-20 Ma. We use 2-D numerical thermo-mechanical modelling of the interaction of the subducting Nazca plate and the overriding SA plate during the last 40 Myr to explore the possible relation between these events. The model employs realistic visco-elasto-plastic rheology, shear heating and phase transformations. The interface between the slab and the upper plate is modelled as a few km thick subduction channel with low-friction Mohr-Coulomb rheology, the friction coefficient being the major modelling parameter. We show that variation of this parameter in the plausible range of 0.02-0.07 may dramatically change stress and strain fields in the upper plate. Preliminary modelling results show that at friction coefficient of 0.05-0.07 the stress field in the overriding plate must have changed from minor extension to strong compression in response to the increase of the convergence rate. This could cause extensive tectonic shortening of the overriding plate if it had been rheologicaly weakened beforehand. We quantitatively explore possible mechanisms of such weakening, and currently favour the following scenario yielding the best fit. At ca. 40 Ma an oceanic plateau entered the trench; its motion below the SA plate caused eastward expansion of compressional deformation at 40-30 Ma followed by flattening of the slab and cessation of volcanism. After the plateau was subducted at 25-20 Ma, the slab retreated which intensified the asthenospheric corner flow. This event coincided temporally with the acceleration of the convergence rate inducing increased compression in the upper plate where the subduction-channel friction coefficient was relatively high. After some 10 Myr, required for the corner flow to heat and hence weaken the lithosphere of the upper plate, the latter failed and tectonic shortening accelerated despite slowdown of convergence rate.

S41F-04 1105h INVITED

Sedimentary and Geomorphic Record of Crustal Shortening, Thickening, and Surface Uplift in the Eastern Cordillera of Bolivia

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A variety of sedimentary basins and preserved geomorphic surfaces chronicle the Cenozoic history of subduction-related deformation in the central Andes. In Bolivia (the region of maximum horizontal shortening, crustal thickening, and surface uplift in the Andes), most recent studies indicate that the crust has thickened principally by east-west shortening. Assuming Airy isostatic balance, which applies to most of the modern Altiplano and Eastern Cordillera, the geologic record of shortening should serve as a proxy for surface elevation through time. The structural histories of Cenozoic sedimentary basins distributed across the Eastern Cordillera of Bolivia between 17° and 20° S clearly indicate shortening from roughly 40 Ma to 20 Ma, with limited shortening thereafter, suggesting most surface uplift in the Eastern Cordillera prior to 20 Ma. This conclusion, however, is in direct conflict with paleobotanical estimates of Miocene paleoelevation. The problem may be addressed, in part, through stratigraphic, sedimentologic, and structural analyses of three distinctive categories of sedimentary basins across the Eastern Cordillera: Eocene-Oligocene foreland basins; early Miocene intermontane basins; and late Miocene-Pliocene basin fill capped by subhorizontal geomorphic surfaces. Whereas foreland basin deposits represent syn-contractional sedimentation at low elevation, the other stratigraphic packages represent largely post-contractional accumulation at higher elevations. Considerations of the stratigraphic ages, depositional systems, and structural settings within the context of regional kinematic reconstructions provide a template for evaluating the temporal variations in surface elevation. Most significant are sedimentologic and structural similarities between early Miocene and late Miocene-Pliocene basin-fill packages, suggesting limited surface uplift in the Eastern Cordillera during this time frame, consistent with paleoelevation predictions based on the shortening record.

S41F-05 1120h

Crustal structure of central Chile and Argentina

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Utilizing data collected during the recent Chile-Argentina Geophysics Experiment (CHARGE) we study the crustal structure of central Chile and Argentina. The CHARGE PASSCAL array consisted of 22 broadband seismometers that were configured in two transects at 30°S and 36°S. Records from teleseismic P and PP arrivals were used to calculate receiver functions to image crustal and upper mantle structure. We study geographic variations in structure by stacking receiver functions into common conversion point bins. A strong Moho signal on the northern transect can be clearly seen at a depth near 40 km below the eastern Sierras Pampeanas. However, to the west of a major suture zone at 67°W, between the eastern and western Sierras Pampeanas, we no longer detect a simple Moho signal as receiver function arrivals are much more elusive. Instead, we find low-amplitude broad arrivals around 50-60 km depth under the western Sierras Pampeanas, Precordillera, and Andes. These arrivals indicate that the crust thickens to the west and correlate well with crustal thickness variations based on Pn arrivals. Mid-crustal arrivals are also present in this region of thicker crust. By comparing arrival times of multiple phases on receiver functions we determine that the crustal Vp/Vs ratio varies with lower values near 1.75 to the east of 67°W, indicative of felsic crust, and higher values over 1.8 to the west, that can result from a more mafic crust. On the eastern portion of the southern transect we detect a strong Moho signal near 40 km depth that appears to be deepening to the west. When investigating how receiver function characteristics vary azimuthally, we find a positive Moho signal for the western portion of the northern transect when stacking only data sampling the Moho from the southwest backazimuth. When the area is sampled by data from northwestern backazimuths a negative arrival is present at the same depth. The azimuthal dependence we observe for the Moho signal can explain why stacking data from multiple azimuths results in low amplitude signal from the Moho. We do not detect any significant azimuthal dependence on Moho characteristics in the southern transect, or the eastern portion of the northern transect. Results of receiver function forward modeling indicates that an anisotropic layer at the base of the crust between depths of 30 and 50 km with a fast axis oriented towards the northwest and an axis of symmetry plunging near 50 degrees can produce arrivals similar to those observed on the western portion of the northern transect. Although investigating the properties of anisotropic structures in this manner suffers from non-uniqueness, these models provide a possible explanation to the observed azimuthally dependent signal. If anisotropy in this depth range results from crustal flow, our observations could be produced by flow in the northwest-southeast direction that may be associated with crustal thickening.

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S41F-06 1135h

The Role of Flat Subduction in Andean Evolution

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Transient changes in subduction geometry – from normal to flat to normal – and the attendant magmatic and tectonic effects of slab dewatering, continental lithospheric hydration and asthenospheric flow during closing and opening of the subduction zone mantle wedge, have strongly influenced the tectonomagmatic development of the Andes. In the central Andes, the processes of normal-to-flat-to-normal subduction developed in several stages starting with normal subduction. The transition from normal to flat subduction coincides with cessation of main arc magmatism and extensive crustal deformation in the eastern altiplano and eastern cordillera. During flat subduction, water from the slab infiltrates and hydrates the overlying continental lithosphere, resulting in advective cooling manifest by low surface heat flow. Lithospheric hydration is concentrated not only in the usual forearc region but also within the inner arc, particularly in the zone of resubduction where amphibole breaks down and the slab dips steeply into the mantle. The transition from flat to normal subduction brings an influx of asthenospheric material from depth into the growing mantle wedge above the slab. Hot asthenospheric mantle in contact with hydrated lithosphere of the inner arc produces widespread melting of both mantle and crust beneath the eastern ranges coupled with ductile deformation, which in the central Andes was associated with oroclinal formation. The magmatic activity and orogenic uplift accompanying the transition from flat to normal subduction began near the zone of resubduction (the inner arc) and broadened westward as hot asthenospheric material flowed into the mantle wedge above the sinking slab. The cycle is complete when westward broadening of volcanic activity culminates in a resumption of calc-alkaline volcanism along the main volcanic arc. The crust beneath the main arc may be thickened and uplifted by the intrusion or underplating of mantle-derived magmas. Eruptive activity in the inner (eastern) arc, much of it anatectic and correlated with periods of crustal deformation, gradually died out, while the thermally thinned and weakened lithosphere of the eastern cordillera and subandean belt formed a ductilized zone in which compressive stresses were concentrated in Neogene time. The tectonic collapse of the inner arc is correlated with the Neogene formation of the Bolivian orocline. By contrast, the western cordillera and the western altiplano, underlain by the Arequipa-Antofalla cratonic block, underwent relatively minor deformation.

S41F-07 1150h

Regional Tomographic Inversion of P-wave Travel Times in Central Chile and Argentina, between 30° and 36° south.

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We use regional P-wave travel times to model upper mantle structure beneath Chile and Argentina between 30° and 36° S. This area is of particular interest, because north of 33°S, the subducted Nazca plate descends normally to a depth of 100 km, but then flattens out, continuing along a subhorizontal path for some 400 km before resuming a normal subduction angle and descending into the mantle. South of 33°, the Nazca plate subducts with a constant dip. This difference in subduction style from the north to the south is correlated with changes in volcanism, seismicity, and orogenic structure. Data for this study comes from the CHARGE project, a 22 station broadband portable seismic deployment, and first arrival P-picks from the ISC catalog recorded at an additional 30 stations operated by INPRES and the Seismological Service of the Universidad de Chile. We use the tomographic inversion method of Zhao et al. [1994] to invert over 3100 P-wave picks from over 170 events recorded at 54 stations. This tomography method allows for the introduction of discrete discontinuities, such as the Moho and the top of the subducting slab, which allows for clearer vertical resolution because smearing across these boundaries is reduced. Preliminary results show evidence of low velocity zones possibly associated with the dehydration of the subducting oceanic plate. To the south where the Nazca plate descends at a dip of 30°, the low velocity zone appears to be confined to a narrow area above where the subducted plate reaches 100 - 125 km depth and corresponds to the region beneath the active volcanic arc. To the north, the low velocity zone persists, extending east beneath the Sierras Pampeanas. This correlates well with the flat slab area, indicating that the Nazca plate may dewater continuously as it subducts east until it resumes a normal descent angle into the mantle. However, arc volcanism north of 33° S has been dormant for 8 Ma, suggesting that it is the cold thermal regime of the flat slab, rather than a lack of water, that is primarily responsible for shutting down the arc volcanism. Zhao, D., A. Hasegawa, and H. Kanamori, Deep structure of Japan subduction zone as derived from local, regional, and teleseismic events, *Journal of Geophysical Research, 99*, 22313-22329, 1994.

S41F-08 1205h

Mantle Structure Beneath Central South America

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Making use of 60 digital broadband seismic stations that have operated across central South America in recent years, we have undertaken an inversion for the upper- and uppermost lower-mantle P- and S-wave velocity structures beneath the region. We have combined data from four portable PASSCAL-type experiments as well as the 3 GTSN permanent stations (LPAZ, BDFB and CPUP) and 1 Geoscope station (SPB) located in the region. The portable data were deployed at various times between 1992 and 1999 and include: 28 sites from the Brazilian Lithosphere Seismic Project (BLSP: Carnegie Institution of Washington and Universidade de Sao Paulo), 16 sites from the Broadband ANdean JOint experiment (BANJO: Carnegie Institution of Washington and University of Arizona), 8 sites from the Seismic Exploration of the Deep Altiplano project (SEDA: Lawrence Livermore National Laboratory) and 4 sites from the University of Brasilia. The P- and S-wave relative delay times are independently obtained via a multi-channel cross correlation of band-passed waveforms for each teleseismic event. These data are then inverted using an iterative, robust, non-linear scheme which parameterizes the 3-D velocity variations as splines under tension constrained at over 120,000 nodes across South America between latitudes of 15 and 30 degrees South. Amongst other features, we robustly image the high-velocity subducting Nazca plate penetrating into the lower mantle and the high-velocity root of the 3.2 Gyr old Sao Francisco Craton extending to depths of 200-300 km. We will discuss the consistency between our tomographic models and predictions of dynamic mantle models based on plate tectonic reconstructions of subduction.

S41G MCC: 3009 Thursday 1020h

The Energy Budget of the Earthquake Machine II *(joint with G, T, NG)*

Presiding: **R E Abercrombie,** Boston University**; A McGarr,** U.S. Geological Survey

S41G-01 1025h INVITED

Earthquake Fracture Energies and Weakening of Faults by Thermal Pressurization of Pore Fluid

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Seismic inferences of fracture energy G constrain how fault strength degrades during slip and allow testing of candidate physical mechanisms. Recently G has been estimated by interpreting parameters from seismic slip inversions within a self-healing rupture model (Rice, Sammis and Parsons, 2003), and by studying the scaling of radiated energy and stress drop with earthquake size (Abercrombie and Rice, 2003). Those and earlier studies suggest that for larger events (slip > 0.1 m), G ranges from 0.1 to 10 MJ/m^2 with average of 2-4 MJ/m^2. There is a clear trend for G to increase with slip over the broad range from mm to m slip. Sibson-Lachenbruch thermal pressurization of pore water is examined as a possible general fault weakening mechanism for large crustal events. For adiabatic and undrained conditions, with strength given by the effective stress law with a constant friction coefficient f, the thermal properties of water in this context (Lachenbruch, 1980; Mase and Smith, 1988) lead to $G = 1.7(\sigma_n - p_o)(1 + r)h$. Here h is shearing zone thickness, σ_n is normal stress, assumed constant during slip, p_o is ambient pore pressure, and r is the ratio fractional volume change of pore space per unit pore pressure increase divided by the compressibility of the pore fluid. Dilatancy is neglected; if confined to only the early phases of slip, it decreases p_o from ambient and so increases G, but the effect may be modest. The model predicts exponential decay of strength with slip, with e-folding slip distance $1.7(1 + r)h/f$. The total temperature rise in K is $\approx 0.6(1+r)(\sigma_n - p_o)$ where the latter factor is in MPa. Estimating r = 1-2 and evaluating $\sigma_n - p_o$ as overburden minus hydrostatic pore pressure at 7 km as a representative centroidal depth for large crustal events, we obtain $G \approx$ 1-6 MJ/m^2 for h = 2 to 10 mm. Shear zone thicknesses towards the lower end of such a range are suggested by recent field studies (Chester and Chester, 1998), which identify a narrow principal failure zone within a 10s of mm thick ultracataclastic core. Temperature rises are 150-230 K and preclude melting, although rises at 14 km may be twice larger and temperature there could reach the onset of melting. That predicted G compares favorably with the above seismically inferred range. For $f = 0.6$, the slip needed to fully experience the weakening (as twice the e-foldng slip) is of order 0.02-0.17 m, so many smaller slip events will not experience full weakening. G values estimated seismically for them should be smaller, as seems to be the case (Abercrombie and Rice, 2003). Those smaller G values may be influenced by more modest weakening mechanisms like studied in rate and state friction, which are likely to dominate at sub-mm slip. Corrections to the thermal pressurization estimate of G for large events arise because the shearing zone may not retain its water during failure, so that strength is not fully reduced, and from the feature that fast-moving ruptures fronts generate enough stress off the main fault plane to cause secondary failure within the bordering damage zone (Poliakov et al., 2002; Rice et al., 2003). The latter effect becomes particularly strong as rupture speed approaches its subsonic limit (Rayleigh speed for mode II); it consumes energy and increases G, but also leaves freshly failed material immediately adjacent to the shearing zone. That will promote drainage, for which an elementary model will be described. Complete strength loss then cannot be achieved by the pore fluid mechanism and temperature continues to rise so that ultimately melting occurs if slip becomes large enough.

S41G-02 1045h INVITED

Slip localization on narrow surfaces within exhumed fault zones: implications for earthquake rupture processes and seismic energy budgets

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Observations of exhumed faults, with net offset ranging from cm to km, indicate that fault slip is often accommodated on slip surfaces only mm's to cm's thick embedded in a damage zone 10's to 100's m thick. The same deformation textures observed in the smallest faults are seen along faults of greater length and offset. We use rock mechanics and earthquake energy and moment relationships to show that slip zone thickness t is a function of seismological parameters (seismic efficiency η, defined as the proportion of the total driving stress that contributes to seismic radiation, τ_a), fault gouge properties (grain surface area per unit mass of fault gouge S, density ρ), co-seismic slip, D and the fracture energy (crushing energy per unit area of rupture G), according to the relationship t = τ_a D /η S ρ G. By using reasonable values of these parameters this relationship predicts that the thickness should be of the order of millimeters, close to our field observations. Given that G scales with rupture size and that the other parameters vary over a narrow range, this equation shows that co-seismic slip should remain restricted to narrow zones across a large range of slip magnitudes (rupture areas). During a rupture, stored strain energy is partitioned into radiated seismic energy, E$_a$, work done against frictional resistance to slip,