T22A-0502 1330h POSTER

Owens Valley fault kinematics: Right-lateral slip transfer via north-northeast trending normal faults at the northern end of the Owens Valley fault

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The occurrence of several northeast trending normal faults along the eastern margin of the Sierra Nevada escarpment are evidence of right-lateral slip transfer across northern Owens Valley from the Owens Valley fault to the White Mountains fault zone. Interaction between the Sierran frontal normal fault and these two fault zones has created a transtensional tectonic environment, which allows for right-lateral slip transfer via a population of northwest dipping normal faults within the Late Quaternary-Holocene alluvial valley fill of northern Owens Valley. A component of normal movement within the valley floor has been documented along fifteen faults. This includes the Tungsten Hills fault, two faults near Klondike Lake, and twelve or so, some possibly linked, small NNE trending scarps southeast of the town of Bishop. One fault segment, located just past the tip of the 1872 earthquake rupture, reveals a minimum of 3.2 meters of normal throw along much of its length. This fault shows evidence for at least three large ruptures, each exhibiting at least one meter of vertical slip. In addition, a large population of normal faults with similar orientations is mapped within the immediate vicinity of this scarp segment. These faults accommodate a substantial amount of normal movement allowing for eastward right lateral slip transfer. With the exception of the Tungsten Hills fault, they are primarily concentrated along a segment of the Sierran Escarpment known as the Coyote Warp. The pre-existing normal fault geometry along this segment acts to block the northward propagation of right-lateral movement, which is consequently forced across the valley floor to the White Mountain fault zone.

T22A-0503 1330h POSTER

Unravelling the Post-glacial History of Faulting on Reykjanes Peninsula, SW Iceland

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The Reykjanes Peninsula, in southwest Iceland, is a complex tectonic system which includes the transition zone from an off-shore to an on-shore spreading segment. At the same time it exhibits many characteristics of a transform-type plate boundary. As the ridge comes onshore at the Reykjanes Peninsula it bends sharply to the east, becoming approximately 30 degrees oblique to the direction of plate motion. Because of its highly oblique geometry with respect to the NUVEL 1A spreading direction, it experiences both extension and shear which may be partitioned in both time and space. The peninsula is characterized by arrays of eruptive fissures, spaced on average approximately 5 km apart, and having an average strike of N40E. These have been described in the literature as comprising either five or four distinct volcanic systems each with their own magma supply, high temperature geothermal system, and clusters of closely spaced fractures referred to as fissure swarms. The fissure swarms are comprised of shear fractures (mainly normal faults), extension fractures (mainly gaping fissures with no shear displacement) and hybrid fractures which exhibit components of both shear (vertical offset parallel to the fracture plane) and extension (opening perpendicular to the fracture plane). Still unclear are the dynamics of this zone, how faulting and magmatism are related in time and space on the peninsula. This study presents a preliminary map of faults and open fractures for all of Reykjanes Peninsula. The map is compiled from new field data and new mapping from high-resolution, digital orthophotos. The map is contained within a GIS and overlain on both air photos and digital geologic maps. Local bedrock geology consists of Plio-Pleistocene lavas and sub-glacially erupted hyaloclastites, as well as lava flows dating from earliest post-glacial times up until 725 ybp. This study examines in particular the development of fractures in post-glacial lavas.

T22A-0504 1330h POSTER

Lost in Iceland? Fracture Zone Complications Along the Mid-Atlantic Plate Boundary

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The mid-Atlantic plate boundary breaks up into a series of segments across Iceland. Two transform zones, the South Iceland Seismic Zone (SISZ) and the Tjörnes Fracture Zone (TFZ) separate the on land rift zones from the Reykjanes Ridge (RR), and the Kolbeinsey Ridge (KR), offshore N-Iceland. Both are markedly different from fracture zones elsewhere along the plate boundary. The 80 km E-W and 10–15 km N-S SISZ is made up of more than 20 N-S aligned, right-lateral, strike-slip faults whereas the TFZ consists of a broad zone of deformation, roughly 150 km E-W and 75 km N-S. The over-all left-lateral transform motion within the SISZ is accommodated by bookshelf faulting whereas the right-lateral transform motion within the TFZ is incorporated within two WNW-trending seismic zones, spaced ~40 km apart, the Grímsey Seismic Zone (GSZ) and the Húsavík-Flatey fault (HFF). Recently collected EM300 and RESON8101 multibeam bathymetric data along with CHIRP subbottom data has unveiled some tectonic details within the TFZ. The GSZ runs along the offshore extension of the Northern Volcanic Rift Zone (NVRZ) and is made up of four left-stepping, en-echelon, NS-striking rift segments akin to those on land. Large GSZ earthquakes seem to be associated with lateral strike-slip faulting along ESE-striking fault planes. Fissure swarms transecting the offshore volcanic systems have also been subjected to right-lateral transformation along the spreading direction. As the Reykjanes Peninsula, the on land extension of the RR, the GSZ bears the characteristics of an oblique rift zone. The plate boundary segments connecting to the RR and KR are thus symmetrical with respect to the plate separation vector (105°) and orientation of individual volcanic systems. The HFF has an overall strike of N65°W and can be traced continuously along its 75–80 km length, between the Theistareykir volcanic system within the NVRZ, across the central TFZ-graben, the Skjálfandi bay, and into the largest and westernmost graben, Eyjafjardaráll (EG). Four pull-apart basins occur along the fault, the largest at the intersection with the EG, the southward magma-starved, continuation of the KR. Dikes, parallel to the HFF bear witness to it being a leaky transtensional feature. RESON8101 maps expose the tectonic fabric along the tidally swept shoreline adjacent to the main fault. The southwesternmost margin of the fault is characterised by NE-striking lavas which, along the coast, dip steeply (30–50°) westwards, towards the EG. The lavas are dissected by en echelon arrays of minor strike-slip faults intersecting the main fault at angles of N20°–30°W and N20°E. Some can be traced onto land where they exhibit complicated flower patterns. Destructive earthquakes occurred on the HFF in 1755, 1867 during an eruption offshore Tjörnes, i.e. north of the fault, and in 1872. The 1867 earthquakes where most likely associated with rift-transform interaction on the easternmost section of the fault. An intense earthquake sequence on April 17, 1872 culminated with two ~M6.5 earthquakes at 10 a.m. and 11 a.m. the next day. Based on intensity and damage reports, the ~M6.5 earthquakes originated at different segments of the HFF, near Húsavík and Flatey.

T22A-0505 1330h POSTER

Neotectonic Geomorphology of the Owen Stanley Oblique-slip Fault System, Eastern Papua New Guinea

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Previous GPS studies have shown that the Australia-Woodlark plate boundary bisects the Papuan Peninsula of Papua New Guinea and that interplate motion along the boundary varies from about 19 mm/yr of orthogonal opening in the area of the western Woodlark spreading center and D'Entrecasteaux Islands, to about 12 mm/yr of highly oblique opening in the central part of the peninsula, to about 10 mm/yr of transpressional motion on the western part of the peninsula. We have compiled a GIS database for the peninsula that includes a digital elevation model, geologic map, LANDSAT and radar imagery, and earthquake focal mechanisms. This combined data set demonstrates the regional importance of the 600-km-long Owen Stanley fault system (OSFS) in accommodating interplate motion and controlling the geomorphology and geologic exposures of the peninsula. The OSFS originated as a NE-dipping, reactivated Oligocene-Early Miocene age ophiolitic suture zone between an Australian continental margin and the Melanesian arc system. Pliocene to recent motion on the plate boundary has reactivated motion on the former NE-dipping thrust fault either as a NE-dipping normal fault in the eastern area or as a more vertical strike-slip fault in the western area. The broadly arcuate shape of the OSFS is probably an inherited feature from the original thrust fault. Faults in the eastern area (east of 148°E) exhibit characteristics expected for normal and oblique slip faults including: discontinuous fault traces bounding an upthrown highland block and a downthrown coastal plain or submarine block, transfer faults parallel to the opening direction, scarps facing to both the northeast and southwest, and spatial association with recent volcanism. Faults in the western area (west of 148°E) exibit characteristics expected for left-lateral strike-slip faults including: linear and continuous fault trace commonly confined to a deep, intermontane valley and sinistral offsets and deflections of rivers and streams by 0.5 to 1.2 km. The northern edge of the OSFS merges with the Ramu-Markham strike-slip fault near Lae. SW tilting of the footwall block (Papuan Peninsula) is responsible for the asymmetrical topographic profile of the peninsula and drowned topography along the southern coast of the peninsula.

T22B MCC: Level 1 Tuesday 1330h

Development of Fault Systems Through Time: Process and Rates IV Posters

Presiding: **L McNeill,** Southampton Oceanography Centre**; S Gupta,** Imperial College

T22B-0506 1330h POSTER

Mechanical controls on the spatial and temporal variability of faulting mechanisms in sandstone along the Moab normal fault, Utah

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Segmentation is a fundamental characteristic of faults. However, the effect of segmentation on the process of fault development, the architecture of the fault zone, and the properties of faults are poorly understood. Along the Moab fault, a basin scale normal fault with 1 km of throw in SE Utah, segmentation is associated with localized changes in the density and types of structures associated with faulting in sandstone. Changes in the types of structural elements are associated with fault development by two different mechanisms in sandstone: (1) cataclastic shear failure that produces deformation bands and (2) the repeated formation and subsequent shearing of joints that leads to the formation of a brecciated fault zone. Deformation bands are prevalent along the entire length of the fault system and band density is greatest within relays between normal fault segments that are subjected to a component of strike-parallel contraction. The joints and sheared joints only occur at intersections between normal fault segments and relays that are subjected to strike-parallel extension where they overprint deformation bands. We contend that spatial variation of the faulting mechanisms in sandstone is associated with the stress perturbation around the fault. We used the geometry and kinematics of the fault segments and an estimated burial depth of 2 km to simulate the mechanical behavior of the fault system in linear elastic boundary element models using Poly3D. We looked specifically for changes in the stress state that would cause a transition from deformation band formation to joint formation because joints are the youngest structural elements wherever they occur. Joints form normal to the least compressive principal stress when this stress exceeds the tensile strength of the rock. We also note

that cataclasis in deformation bands represent a loss of volume, whereas jointing and breccia formation are dilatant processes. Consequently the mean stress can act as an indicator to distinguish locations favored for deformation bands versus those that might favor jointing. These simulations predict less compressive mean stress and least compressive principal stress localized at extending relays and intersections where joints are observed in the field. Furthermore, the orientations of joints predicted from the mechanical models correspond to the orientation of joints measured in the field. Conversely, locally more compressive mean stress is predicted in contractional relays where the highest deformation band density is observed in the field. We therefore propose that mechanical interaction between fault segments can cause a change in faulting mechanism, and thus control the distribution of structural elements along the fault. These mechanical interactions probably change as a fault grows or is exhumed leading to temporal evolution of the fault system such as the localized transition from deformation banding to jointing. The distribution of structural elements strongly controls a fault's permeability structure. A fault's permeability structure will likely develop differently in areas where the tips of fault segments interact in contrast to portions of fault segments that are isolated from the fault tips and other segments. The overprinting of deformation band-related by joint-related structural elements indicates temporal evolution of the fault system which should be associated with changing fault properties such as permeability. We therefore suggest that fault architecture, and thus permeability, will vary systematically as fault segments grow and interact.

T22B-0507 1330h POSTER

Evolution of Fault Systems and its Associated Geomorphic Structures: Strike-Slip and Dip-Slip Fault Model Test and Field Survey

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Sandbox experiments were performed to investigate evolution of fault systems and its associated geomorphic structures caused by strike-slip and dip-slip motion on basement faults. A 600 cm long, 250 cm wide, and 60 cm high sandbox and a 200 cm long, 40 cm wide, 25 cm high sandbox were used in a strike-slip fault model test. Computerized X-ray tomography applied to the sandbox experiments made it possible to analyze the kinematic evolution, as well as the three-dimensional geometry, of the faults. The deformation of the sandpack surface was analyzed by use of a laser method 3D scanner, which is a three-dimensional noncontact surface profiling instrument. In the dip-slip fault test, a 332.5 cm long, 200 cm high, and 40 cm wide sandbox was used. The fault type, fault dip, fault displacement, thickness and density of sandpack and grain size of the sand were varied for different experiments. Field survey of active faults in Japan and California were also made to investigate the evolution of fault systems and its associated geomorphic structures. A comparison of the experimental results with natural cases of active faults reveals the following: (1) In the left-lateral strike-slip fault experiments, the deformation of the sandpack with increasing basement displacement is observed as follows. a) In three dimensions, the right-stepping shears that have a "cirque" / "shell" / "ship body" shape develop on both sides of the basement fault. The shears on one side of the basement fault join those on the other side, resulting in helicoidal shaped shear surfaces. Shears reach the surface of the sand near or above the basement fault and en echelon Riedel shears are observed at the surface of the sand. The region between two Riedels is always an up-squeezed block. b) Lower-angle shears generally branch off from the first Riedel shears. c) Pressure ridges develop within the zone defined by the right-stepping helicoidal shaped lower-angle shears. d) Grabens develop between the pressure ridges. e) Y-shears offset the pressure ridges. f) With displacement concentrated on the central throughgoing fault zone, a liner trough developed directly above the basement fault. R1 shears and P foliation are observed in the liner trough. Such evolution of the shears and its associated structures in the fault model tests agrees well with that of strike-slip fault systems and its associated geomorphic structures. (2) Low-angle and high-angle reverse faults commonly migrate basinward and rangeward with time, respectively. With increasing normal fault displacement in basement, normal fault develops within range after reverse fault has formed along range front. (3) In the fault model tests, the horizontal distance of surface rupture from the basement fault normalized by the height of sandpack (W/H) does not depend on the height of sandpack and grain size of sand. The values of W/H from the fault tests agree well with those of earthquake faults in alluvium.

T22B-0508 1330h POSTER

Flexing is Not Stretching: An Analog Study of Flexure-Induced Fault Growth

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A thin (5 mm thick) plaster layer floating on a foam rubber substrate is bent and fractured in an analog model of extensional fault growth during lithospheric flexing. The size-frequency scaling of the resulting crack populations were analyzed. Unlike lithospheric stretching models, crack populations formed during these experiments indicate that length- and spacing-frequency distributions are not well described by a power-law model. Rather, these size-frequency data are better described by a negative exponential distribution. The absence of a power-law fault distribution reflects the preferential nucleation and growth of faults in association with stress maxima along the axis of the flexing plate. In contrast, the cracks formed in response to stretching evolve, due to elastic interaction during simultaneous growth, from an initially random distribution of nucleation points to form a self-similar network of fractures. The model predicts a non-power-law fault distribution for any area of moderate or large magnitude lithospheric flexure. The outer rise of trenches is an area of undisputed flexural faulting; however, in these environments, fault distributions have not yet been analyzed. A recent model for axial highs of fast-spreading ridges suggests that lithosphere is flexed significantly as it rafts away from ridge axes. Several studies of ocean floor fault populations near axial highs report non-power-law scaling, consistent with our analog model predictions for plate flexure.

T22B-0509 1330h POSTER

Comparative study of two active faults in different stages of the earthquake cycle in central Japan -The Atera fault (with 1586 Tensho earthquake) and the Nojima fault (with 1995 Kobe earthquake)-

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National Research Institute for Earth Science and Disaster Prevention (NIED) has been conducting Fault zone drilling. Fault zone drilling is especially important in understanding the structure, composition, and physical properties of an active fault. In the Chubu district of central Japan, large active faults such as the Atotsugawa (with 1858 Hietsu earthquake) and the Atera (with 1586 Tensho earthquake) faults exist. After the occurrence of the 1995 Kobe earthquake, it has been widely recognized that direct measurements in fault zones by drilling. This time, we describe about the Atera fault and the Nojima fault. Because, these two faults are similar in geological situation (mostly composed of granitic rocks), so it is easy to do comparative study of drilling investigation. The features of the Atera fault, which have been dislocated by the 1586 Tensho earthquake, are as follows. Total length is about 70 km. That general trend is NW45 degree with a left-lateral strike slip. Slip rate is estimated as 3-5 m / 1000 years. Seismicity is very low at present and lithologies around the fault are basically granitic rocks and rhyolite. Six boreholes have been drilled from the depth of 400 m to 630 m. Four of these boreholes (Hatajiri, Fukuoka, Ueno and Kawaue) are located on a line crossing in a direction perpendicular to the Atera fault. In the Kawaue well, mostly fractured and alternating granitic rock continued from the surface to the bottom at 630 m. X-ray fluorescence analysis (XRF) is conducted to estimate the amount of major chemical elements using the glass bead method for core samples. The amounts of H20+ are about from 0.5 to 2.5 weight percent. This fractured zone is also characterized by the logging data such as low resistivity, low P-wave velocity, low density and high neutron porosity. The 1995 Kobe (Hyogo-ken Nanbu) earthquake occurred along the NE-SW-trending Rokko-Awaji fault system, and the Nojima fault appeared on the surface on Awaji Island when this rupture occurred. It is more than 10 km long with 1-2 m offset along the Nojima fault. About one year after the earthquake, NIED drilled a borehole (the Hirabayashi NIED borehole) and penetrated the Nojima fault. The Hirabayashi NIED borehole was drilled to a depth of 1838 m and recovered the drill core. The main types of rock intersected by the borehole are granodiorite and cataclastic fault rocks. Three fracture zones were recognized in cores at approximate depth of 1140 m, 1300 m and 1800 m. There is remarkable foliated blue-gray gouge at a depth of 1140 m. We investigate chemical compositions by XRF analysis in the fracture zone. The amounts of H20+ are about from 1.0 to 15.0 weight percent. We investigate mineral assemblage in both drilling cores by X-ray powder diffraction analysis. From the results, we can't recognize so difference between the two faults. But the amount of H2O+ is very different. In the Hirabayashi NIED core at a depth of 1140 m, there is about ten times as much as the average of the Kawaue core. This is probably due to the greater degree of wall-rock fracturing in the fracture zone. We suggest that this characteristic is associated with the fault activity at the time of the 1995 Kobe earthquake and the nature of fluid-rock interactions in the fracture zone.

T22B-0510 1330h POSTER

Effects of Young's Modulus on Fault-Zone Development and Displacements

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Many fault populations, particularly those formed in a single tectonic environment where the host rocks have similar mechanical properties, display a roughly linear relationship between fault rupture (trace) length (L) and the maximum vertical displacement (u). However, the linear relationships vary; not only between fault populations, but also within a population, and on individual faults as well. Thus, although roughly linear relations commonly exist for individual faults over short periods of time, over longer periods of time the correlation between rupture length and displacement has a large scatter, commonly by an order of a magnitude or more. These observations suggest that some properties of the rock determining the fault displacement may by highly variable. Field observations show that fault zones normally consist of two main structural units: a fault core and a fault damage zone. In major fault zones, the core is from several meters to tens of meters thick and contains many small faults and fractures. Its most distinctive features, however, are breccias and other cataclastic rocks. The fault damage zone, which in major fault zones may be as thick as several kilometers, consists primarily of numerous fractures and faults that commonly increase gradually in number toward the core. As the core and the damage zone change with time, so do their mechanical properties, in particular the Young's modulus (stiffness). Elastic crack models predict a linear relationship between displacement (u) and rupture length (L) during slip in a fault zone. Attempts to find universal scaling laws for L/u, however, have generally failed; partly, I suggest, because they do not take into account the changes in the mechanical properties of the fault zone as it evolves. I propose that Young's modulus affects fault displacement both spatially and temporally: spatially when the trace of a fault at a given time dissects host rocks of different stiffnesses, and temporally when the stiffness of the fault zone itself changes. During the evolution of an active fault zone, the stiffness of its damage zone and fault core normally decreases, and so does the L/u ratio of the fault. By contrast, during inactive periods sealing and healing of the damage zone and core may increase the stiffness, hence the L/u ratio in subsequent slips. This model predicts that not only will the scaling of L/u within a given fault population vary in space and time, but also that of individual faults. This model may, partly at least, explain the large temporal and spatial variation in length/displacement ratios of faults.

T22B-0511 1330h POSTER

Deciphering a Duplex: an Example From the Western Nepal Himalaya

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Because no unique answer exists for the restoration of a cross section, critical decisions must be made during the restoration process which determine the amount of shortening and overall character of the cross section. Often these decisions are straight-forward. Yet, inevitably, assumptions must be made to continue with the restoration. It is especially difficult when data density is minimal, as is true in Nepal. The far western part of Nepal as little infrastructure and acquiring ground truth data is difficult and time consuming.

Based on data from field work in the Chainpur area of the Bajhang district of far western Nepal in the Himalayan thrust belt, four models were developed for the emplacement of a duplex. Uncertainty resided in the number of faults, whether some thrust sheets were folded, and location of faults in areas that were inaccessible. Ultimately, one model was chosen based on its structural probability, fit to the ground truth data around Chainpur, and fit into the overall kinematic development of the thrust belt. A cross section was developed for the Himalayan thrust belt in far western Nepal that bisected the Chainpur area. Based on the model described above, two kinematic restorations were possible. Although the first reconstruction required more shortening, the second reconstruction utilized kinematically creative faults. I used a forward modeling approach to help understand the kinematic viability of the restorations. By starting the reconstruction at approximately 25 Ma with the emplacement of the Main Central thrust sheet and working forward in time, the reconstruction program, 2-d Move, determined that the first reconstruction was viable but the second reconstruction was kinematically impossible. This decision led to an increase in the amount of shortening in the cross section. Just as important, this example illustrates the utility of using forward modeling for the reconstruction of orogen-scale cross sections.

T22B-0512 1330h POSTER

Examination of Exhumed Faults in the Western San Bernardino Mountains, Southern California: Implications for Fault Mechanics, Earthquake Rupture, and Slip Evolution

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Detailed mapping of small-displacement, predominantly high-angle reverse faults of the late Miocene Cedar Springs Fault System was performed in the Silverwood Lake area in the western San Bernardino Mountains, California in order to compare structural and lithologic variations between faults with varying degrees of slip. The faults have been exhumed from 1-5 km depth due to the late Miocene to early Pleistocene uplift of the western portion of the range, and range in slip from several cm to 3.5 km. The host rock is the Mesozoic crystalline basement complex of granodiorite, diorite, and quartz-monzonite, with Precambrian to Paleozoic metasedimentary roof pendants. All these lithologies are cut by abundant dikes which serve as excellent offset markers. The Miocene Crowder Formation (17-9.5 Ma), consisting of arkosic sandstone and conglomerate, is also a useful marker bed. We use a rock mechanics and structural petrologic approach to study fault-related rocks. Fault zone structure and composition data were determined by using the detailed transect method to representatively sample the host rock, damage zone, and fault core. Fault kinematics were determined from exposure of an offset marker and slip indicators. Thin sections were prepared from transect samples to study the variation in microstructure across fault zones. Geochemical analysis (XRD, XRF, and ICP-MS) of samples was performed to help determine the pressure and temperature conditions of brittle deformation (indicating formation depth of the studied faults) and the nature and extent of fluid-rock interactions. The majority of the studied faults have a well-defined fault core, typically consisting of mm to tens of cm of clay gouge and/or (ultra)cataclasite, surrounded by a much thicker damage zone, on the order of m to tens of m, exhibiting a significant increase in subsidiary faults and fractures as compared to the host rock. Faults through the more competent dikes are manifested as a zone of dense fractures and faults instead of the defined fault core characteristic of the softer granitic rocks. An asymmetric slip preference to the footwall was observed in faults placing granitic rocks on top of the Crowder Formation. Damage elements, such as subsidiary faults, fractures, and veins, were inventoried in order to define the extent of the damage zone. These elements often exhibit a bimodal orientation, one sub-parallel to and the other at a high angle to the main fault. Quantitative data indicate that damage zones of larger-displacement faults contain more subsidiary faults than smaller-displacement damage zones, which are characterized more by fractures. Calculated slip from the high-angle reverse faults spans five orders of magnitude, from the cm scale to the hundreds of m scale. Fault core thickness initially increases with slip amount, but core thickening slows substantially between 10-100 m of slip. This suggests that the fault core develops early and large amounts of displacement can be accommodated on relatively narrow, discrete slip surfaces.

T22B-0513 1330h POSTER

Variations in Frictional Behavior of Fault Gouge Along a low Angle Normal Fault System.

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The Panamint Valley fault system contributes up to 2.0 mm/yr of slip to the Eastern California Shear Zone, and has been interpreted to have developed as a low-angle detachment system. More recent studies of young scarps suggest that the fault currently accommodates oblique normal slip. Recognizing the complications in explaining low angle normal faulting using classic fault mechanics we investigate frictional properties of natural fault gouge from selected locations along low-angle normal faults in the southern portion of Panamint Valley. Gouge samples were collected along an 8.5 kilometer North-South transect stretching from Jail Canyon to a small canyon approximately 1 kilometer North of Big Horn Canyon. We investigate potential variations in the frictional behavior of gouges from these fault zones. Gouge samples were recovered by removing weathered surface debris and carving out roughly 8"x 8" blocks of fault gouge. All samples were crushed, milled and sieved to produce a uniform particle size distribution ranging from 30 to 350 microns. In the experiments we sheared 7mm thick layers of fault gouge in a servo-controlled biaxial deformation machine, using a double-direct-shear configuration at room temperature and humidity. The experiments consisted of an identical series of velocity steps and slide-hold-slide load cycles over a range of normal stresses to define the Coulomb-Mohr failure criteria and the friction constitutive properties as a function of slip velocity and state. Stress-strain curves show that shear strength exhibits a peak followed by shear at a steady-state friction level or slight strain weakening during load cycles run at normal stresses <20 MPa. At normal stresses from 30-50 MPa, the fault gouges exhibit a transition to strain hardening. For normal stresses <50 MPa, shear strength increases predictably in a stepwise manner as normal stress is increased. For higher normal stress (> 100 MPa in most samples, depending on clay content), this stepwise increase decays and shear strength becomes nearly independent of normal stress. The steady-state coefficient of friction ranged from 0.2 to 0.6. Initial results indicate velocity strengthening frictional behavior, steady-state frictional strength increases with increasing slip velocity, for normal stresses from 5-150 MPa. A few of the gouges exhibit velocity strengthening at 5 MPa and a transition to velocity weakening at normal stresses from 10-20 MPa, with a transition back to velocity strengthening above 30 MPa. We studied the magnitude of friction velocity dependence as a function of normal stress. We produced thin sections of the sheared layers for detailed microstructural analysis. The Coulomb failure parameters and the friction behavior are related to microstructures preserved in the deformed gouge layers. We also relate deformation behavior to mineralogical differences between samples, which were determined using X-ray diffraction (XRD).

T22B-0514 1330h POSTER

Constant Long-Term Slip Rates Along the Mojave Section, San Andreas Fault Determined From Cosmogenic ^{10}Be and ^{26}Al Analysis in Boulders on Displaced Alluvial Fans

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Remnants of 6 alluvial fans are displaced 0.6-16.5 km southeastward from their original location at the mouth of Little Rock Creek (LRC) along the Mojave section of the San Andreas fault (SAF). The surfaces of the two closest fans, displaced 0.6 and 1.75 km, are rough with numerous exposed boulders, whereas the most distant fan (16.5km) has a smooth surface with essentially no exposed boulders. To determine the ages of fan surfaces from boulders at the surface, it is necessary to estimate the boulder erosion rate and the cosmogenic nuclide inheritance from prior exposure in the LRC drainage system. Inherited values, measured in sediments at the mouth of the river, range between 8500 and 71500 ^{10}Be atoms g^{-1}quartz. Boulder erosion rate was determined from measurements of in-situ ^{10}Be in bedrock pinnacles. The amount of offset is determined by measuring the distance along the fault from the northwestern most point of each fan and the piercing point within the LRC. The determination of the piercing point is somewhat uncertain and depends on the understanding of the historical development of the LRC outlet. Preliminary results of in-situ cosmogenic ^{10}Be and ^{26}Al analyses from boulders located on the two closest displaced fan surfaces suggests that their minimum ages range between 22.5$\pm$2.4 and 44.0$\pm$4.7 ka using a boulder erosion rate of 10 m My^{-1}and inheritance value of 8500 ^{10}Be atoms g^{-1}quartz. These ages imply an average slip rate of 3.8$\pm$ 0.5 cm yr^{-1}. If an inheritance value of 71500 ^{10}Be atoms g^{-1} quartz is used, calculated ages range between 14.3$\pm$1.1 and 32.5$\pm$3.4 ka and the average slip rate is 6.7$\pm$0.6 cm yr^{-1}. Considering plate tectonic kinematics in this region, we think that the higher slip rate is unreasonable. Significant erosion of boulders and erosion of the fan surfaces of the more distant fan remnants, displaced 6.5-16.5 km from the mouth of the LRC, prevent direct calculation of fan ages based on cosmogenic measurements of boulders at the surface. Ages of these fans were determined by modeling the ^{26}Al/^{10}Be ratio for burial age dating. Preliminary results of in-situ cosmogenic ^{10}Be and ^{26}Al analysis from buried samples indicate burial ages that range between 291$\pm$30 and 466$\pm$49 ka. These ages imply an average slip rate of 3.4$\pm$0.2 cm yr^{-1}. Several estimates of the Holocene and late Pleistocene slip rate between the Carrizo Plain and Cajon Pass have been previously calculated using ^{14}C dating of offset morphologic features. Most of these estimates range between 2 to 3.5 cm yr^{-1}. Our results suggest that slip rate has been relatively constant for at least the past 450 ky and lies within the range of previous late Pleistocene and Holocene estimates.

T22B-0515 1330h POSTER

Structure of Fault Zones at the Brittle-Plastic Transition Zone of the Continental Earth Crust: A Case Study at the Hatagawa Fault Zone

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Occurrence of fault rocks was analyzed along an exhumed brittle-plastic fault zone in the earth crust, the Hatagawa Fault Zone of NE Japan. A conspicuous cataclasite zone with a maximum width of 100 m extends continuously for at least 40 km along the HFZ, corresponding to an inland earthquake as large as M7. The cataclasite zone was formed at the temperatures above 220 degree in Celsius and the activity had terminated by 98 $\pm$ 2.5 Ma with an activity without plastic deformation. Although mylonite zones with a sinistral sense of shear are distributed for the entire length of 45 km along the HFZ, the microstructural and deformation temperature analyses revealed a presence of the zone where deformation temperature was lower than 310 degree in Celsius and that it's length along the HFZ is approximately 6 km. In this zone, the microstructure of fault rocks indicates that the deformation condition was at the brittle-plastic transition. It can be considered that the depth of the brittle-plastic transition at lower deformation temperature zone was shallower than other part the fault zone. Such change in the depth of the brittle-plastic transition can result in a significant stress concentration and the nucleation of large earthquakes. There is a possibility that the cataclasite zone along the HFZ was formed by the propagation of the earthquake which was nucleated at the lower deformation temperature zone and this zone was the nuclei of inland earthquakes along the HFZ.

T22B-0516 1330h POSTER

Slip rate estimation by low temperature thermochronology for major extensional detachments in Cycladic islands.

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Rates of tectonic processes are of fundamental importance for understanding deformation of the lithosphere. Rates of extensional faulting in the magmatic arc of the Miocene Hellenic subduction zone in the Aegean, is one of the world's best examples of a retreating subduction zone. As subduction retreated with time to the south, accreted high-pressure rocks shifted from a fore-arc position via an intra-arc into a back-arc position. The Cycladic islands in the central Aegean became part of the magmatic arc in the Late Miocene and are now in a back-arc position. The Cyclades are famous for their blueschists and spectacular extensional detachments. The blueschists formed in the Early Tertiary at depths of 50-60 km, and it is widely assumed that subsequent exhumation of the blueschist unit was chiefly accomplished by detachment faulting. However, most of this detachment faulting operated in arc as indicated by intrusion of arc-related granites into the footwalls of detachments at a time when the blueschist were largely exhumed. Detachment faulting in fact accomplished less than 10 km of blueschist exhumation. Using apatite and zircon fission-track and apatite (U-Th)/He ages from a horizontal profile parallel to the tectonic transport direction of major extensional detachments on the Cycladic islands of Tinos, Mykonos and Naxos, we estimate slip rates for these detachments. For Tinos, zircon and apatite fission-track (FT) ages range respectively from 12.2 $\pm$ 0.6 to 14.4 $\pm$ 0.8 Ma and 11.9 $\pm$ 1.3 to 12.8 $\pm$ 1.2 Ma whereas (U-Th)/He apatite ages range from 10.0 $\pm$ 1.0 to 11.9 $\pm$ 1 Ma. For Mykonos, zircon FT ages range from 10.7 $\pm$ 0.6 to 13.0 $\pm$ 0.6 Ma and apatite FT ages from 10.5 $\pm$ 0.9 to 12.5 $\pm$ 1.2 Ma; (U-Th)/He apatite ages are from 8.9 $\pm$ 0.7 to 11.1 $\pm$ 0.9 Ma. Using the same methods on Naxos, we obtain 9.7 $\pm$ 0.5 to 11.8 $\pm$ 0.6 Ma (zircon FT method), 8.2 $\pm$ 0.6 to 11.2 $\pm$ 0.9 Ma (apatite FT) and 8.9 $\pm$ 0.9 to 10.7 $\pm$ 0.9 Ma (apatite (U-Th)/He). These three methods yielded consistent results and indicate that the ages decrease in the hanging-wall slip direction. The results permit to calculate slip rates for the detachment faults of $\sim$ 3 km Myr $^{-1}$ for Tinos, $\sim$ 6.5 km Myr $^{-1}$ for Mykonos and $\sim$ 5.5 km Myr $^{-1}$ for Naxos. Our slip rate for Naxos is in agreement with the only previously known estimate of $\sim$ 5.8 km Myr $^{-1}$ (John and Howard 1995) as deduced from K-Ar and Ar/Ar ages on biotite, white mica and hornblende. Furthermore, these ages suggest that all three detachments operated synchronously. They indicate rapid cooling of the footwalls as confirmed by long mean confined track lengths ($>$ 14 μm) for fission tracks in apatite. We propose that the development of the detachments in the thermally softened magmatic arc aided fast displacement. The higher slip rates on Naxos and Mykonos as compared to the slip rate on Tinos may be due to the fact that the Tinos granite intruded pretectonically to the Tinos detachments whereas the granites on Naxos and Mykonos intruded synkinematically to both detachments.

T22B-0517 1330h POSTER

Fault Development In The Imbricate Thrust Pile Under Variable Basal Friction And Slope Geometry From The Sand Box Analog Modeling

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We performed a series of sand box experiments to model mechanical constraints, especially variable geometries and friction of the decollement, on the fault development at the leading edge of imbricate thrust piles in natural accretionary wedges. The models with different basal friction (low and high) and slope geometry (0 and 5 degrees) are conducted by using Toyoura sand with grain size less than 0.18 mm and model dimension of 12.5 cm in length by 10 cm in width by 0.6 cm in thichness. All the models are shortened under constant slow rate from the rear wall side and the other side is fixed. The results from the selected four models show that the growth of sand wedge depends on the basal slope geometry. When the basal slope is horizontal, the wedge grows up continuously, and in contrast to this, the wedge grows up episodically when the basal slope is dipped five degrees to hinterland. Total of six faults developed after 48 percent bulk shortening in low basal friction models whereas after 57 percent in high basal friction models. Four faults formed in linear space before 20 percent bulk shortening in all models. After 20 percent bulk shortening, fault spacing become twice of before. Otherwise, after 20 percent of bulk shortening the wedge grew up more or less equilibrium and fault development was controlled by the basal shear stress and friction in order to attain critical wedge growth. Key words: Analog modeling, sand box, fault development, basal friction, slope geometry, accretionary wedge, decollement

T22B-0518 1330h POSTER

3-D Numerical Simulations of Relay Growth and Breaching Along Normal Faults Using the Distinct Element Method

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Three-dimensional numerical models of neutral relay zones on normal faults that cut massive sandstone host rocks have been constructed using the distinct element method code, Particle Flow Code in 3-D (PFC3D). The models successfully reproduce the geometries, displacement profiles and strains observed in natural relay zones. In contrast to boundary element method simulations, the modelled relay ramps dip towards the hanging wall, consistent with observations of most natural relays. The modelling shows that relay zones with aspect ratios of 1, 2 and 3 - values that are typical of many naturally occurring relays - are stable structures that grow' by progressive rotation of an approximately planar relay ramp without significant propagation of the relay-bounding faults prior to breaching. Stable growth is terminated when a breaching fault propagates across the top or bottom of the relay ramp. Breaching fault propagation is not instantaneous and the ramp continues to rotate, and therefore transfer displacement between the relay-bounding faults, until the relay zone is hard linked. Following hard linkage, displacement is accommodated by slip on the through-going fault surface. The modelling results confirm previous conceptual models of relay growth and breaching based on geometric and kinematic analysis of natural relay zones.

T22B-0519 1330h POSTER

The San Andreas Fault-Zone at Tejon Pass: Internal Structure and Grain-Size Distribution

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The exhumed fault-zone of the San Andreas near Tejon Pass, the Big Bend region of California, displays exceptional exposures of the gouge material. The main segments of the San Andreas Fault in this region bound a few hundred meter wide zone in which the most conspicuous gouge lithology is the pulverized Tejon Lookout granite of Cretaceous age. This body forms a 60-120 m wide zone that extends for more than 2 km along the San Andreas. We have studied the large scale structure of this fault-zone (Dewers et al., 2002, AGU Fall meeting), and we discuss here the small-scale maps (1:5-1:10) of portions of the pulverized granite within the fault-zone and the particle-size-distribution (PDS) of the gouge. The small-scale maps reveal a multitude of shear surfaces with 10's of cm of slip and sub-meter spacing. The dominant transport direction along these surfaces is normal to the trend of the San Andreas, displaying either normal or reverse dip-slip motion. There is a striking lack of shear surfaces and slip striations parallel to the San Andreas Fault. We used a laser particle size analyzer (range 0.04-2000 micron) to measure the PSD of tens of samples of the granitic gouge collected along a 70 meter long traverse across the fault-zone and at the sites of the small-scale mapping. The PSD measurements were conducted by running the laser particle size analyzer for extended periods up to 3 days (Dewers et al., 2003, AGU Fall meeting). The gouge systematically disaggregates during the long PSD runs and its intrinsic mean grain size is smaller than one micron. Further, granitic gouge zone displays relatively uniform PSD from 0.1 m scale to its entire sampled width (70 m). These macro- and micro-properties of the San Andreas gouge at Tejon Pass indicate that (1) the gouge did not form by shear parallel to the San Andreas, (2) the pervasive pulverization could account for a large portion of the earthquake energy balance.

T22B-0520 1330h POSTER

A Numerical Investigation of Drainage Network Evolution During Fault Interaction and Linkage

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We have coupled together a numerical fault growth model and a surface process model (CASCADE; Braun and Sambridge, Basin Research, 9, 27-52, 1997) to study the way in which drainage basin geometry and river long profiles respond to the progressive formation and linkage of an underlying fault network. The numerical fault growth model simulates nucleation, propagation and displacement accumulation on a population of steeply dipping extensional faults. Elastic interaction between faults is included, resulting in significant displacement rate variations in space (along neighbouring fault segments) and through time. The most significant temporal variations in slip rate are those associated with fault linkage events in which the linking fault segments experience increased rates of slip while adjacent faults in foot-wall and hanging-wall areas become inactive. The size, elevation and lateral continuity of topographic uplifts (footwall highs) and depocentres (hanging-wall lows) vary through time as the faults grow and link. The faults appear as sub-vertical scarps that can grow in height and length through time. Fluvial erosion, diffusive hill-slope processes, landsliding, lake formation and sediment deposition are all included in the surface process model. Orographic effects are not considered. The tectonic model outputs maps of elevation change. These maps are input sequentially into the surface process model to drive tectonic elevation changes while erosion and deposition are ongoing. The spatial and temporal scales of the coupled model have been chosen to correspond with an area of active extensional faulting in Lazio-Abruzzo, Italy. Normal fault development in this area during the last 3 Myrs has resulted in interaction and incipient linkage between several fault segments that vary in length from 20 to 40 km, within a 150 km long fault array. For this area we have river long profiles derived from a high-resolution DEM, and field measurements of river channels crossing faults that have experienced a temporal variation in throw rate. These data will be compared directly with outputs from the coupled numerical model.

T22B-0521 1330h POSTER

Characteristics of logging data for fracture zones in Hirabayashi NIED borehole drilling through Nojima fault

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The Hyogo-ken Nanbu earthquake (1995.1, MJMA=7.2) activated the Nojima fault in the northern part of Awaji Island, southwest Japan and a surface rupture appeared more than 10km long. After the earthquake, the Hirabayashi NIED borehole was drilled penetrating through the fault zone to a depth of 1838m from a point about 302m SE from the surface trace of the Nojima fault. In the borehole, physical well logging was done from 251m depth down to the bottom. At the same time, cores were collected from 1000m depth with an almost 100% recovery rate and remarkable fractured zones containing cataclastic rocks were confirmed at three depths, around 1140m, 1300m and 1800m. Gamma ray logging survey indicates that the intensity of natural gamma ray changes abruptly within the interval of intrusive rocks. Matching values of depths at the boundaries between intrusive rocks and host rocks, the calibration equation was obtained between "core depth" and "logging depth"; "core depth" is measured by adding up lengths of drilling pipes and "logging depth" is measured by the total length of the cable taken down a logging tool. Results of well logging show that, in the depth interval of host rocks , normal resistivity is from several hundreds to several thousands ohm m, micro resistivity is several tens ohm m, P wave velocity is 5 - 6km/sec, density is about 2.6g/cm3 and neutron porosity is several %. On the other hand, in the depth interval of the fracture zone, those properties decrease down to several tens ohm m, several ohm m, 2 - 4km/sec, 1.5 - 2.0g/cm3 and increase up to several tens %, respectively. Investigating correlations between physical properties measured by well logging in the Hirabayashi NIED borehole, three fracture zones are characterized. In fracture zones, neutron porosity is beyond 10%, P wave velocity is less than 5 km/sec. The decreasing rate of density is higher and the logarithm of normal resistivity increases more gently with the increase of neutron porosity than in the depth interval of host rocks. The correlation between neutron porosity and P wave velocity is not clear and normal resistivity does not obey the Archie's relation in the fracture zones. The fracture zone at a depth of 1800m indicates some different characters from other two fracture zones; P wave velocity, density and neutron porosity appear to change gently contrasting to a remarkable decrease of normal resistivity.

T22C MCC: 3005 Tuesday 1340h

Role of Large Strike-Slip Faults in Tectonics of the Tibetan Plateau II

(joint with G)

Presiding: **B Ritts,** Utah State University**; S A Graham,** Stanford University

T22C-01 1340h INVITED

400My of Deformation Along Tibet Active Strike Slip Faults

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While it is widely accepted that strike slip faults in Tibet accommodate a significant part of the tertiary convergence between India and Asia, the true Cenozoic magnitude of the offset is still largely debated. Direct dating of Cenozoic piercing points is the most powerful tool to assess the total offset, but their use is not always possible. Therefore one gets to use older markers although this leads to significant results ONLY at the supreme condition that pre-Cenozoic movement of those markers be accurately known. The Kunlun and Altyn Tagh faults for example form a prominent example of Tibetan presently active fault, but they also constitute geological frontiers between blocks of different geological histories accreted at various times since early Paleozoic. One may thus question how much of the visible offset is indeed Cenozoic. Although deformation facies agree with recent kinematics, multi-geochronological approach indicates a series of events from 280-230 Ma to 120±10 Ma. The former may be linked either with suturing of the Qiantang and Kunlun blocks farther to the south, or collision further to the north or east in the Qilian Shan and Bei Shan ranges, while the latter range appears to be growing in importance with ongoing work but is still largely unexplained. Oblique subductions of collision to the north of the Qilian Shan are adequate candidates. Argon loss suggests that deformation was associated to a 250-300°C thermal pulse that lasted 5 to 20 Ma after the onset of movement (Arnaud et al., 2003). Unroofing on all faults occurred much later, around 25 Ma ago when sudden cooling suggests a component of normal faulting (Mock et al., 1999). Strong inheritage was also found along the Ghoza active fault, in central western Tibet. Of course the fact that some of the deformation is much older than the Cretaceous and shares compatible deformation criteria with the present-day deformation leads to false appreciation of the pure Cenozoic offset, potentially concluding to an over or underestimation of the true Tertiary deformation. However these earlier deformation zones can also be used as transcrustal markers to evaluate Cenozoic offset, suggesting for example for the Altyn Tagh fault a minimum offset of 400 km, in agreement with other estimations of post-Jurassic offset (Meyer et al., 1998, Sobel et al., 2001, Ritts et al., 2000). The key to a clear assessment of tertiary movements along the strike slip faults and their true importance in building of the Plateau is thus the very detailed dating of recent, usually cold and/or badly equilibrated, deformation facies. This is complicated by the very nature of the deformed rocks, usually far from the geochronologist standards ! High resolution in situ dating from high to low temperatures with very careful study of the deformation is thus a prerequisite, as well as a complete study of the regional geological history. This is the case for ongoing studies along the Karakorum fault where a continuous deformation from 20 Ma to the present can be characterized with details through time. Arnaud, N., Tapponnier, P., Roger, F., Brunel, M., Schärer, U., Wen, C., and Xu, Z., 2003, J Geophys Res-Solid Earth, v. 108. Meyer, B., Tapponnier, P., Bourjot, L., Métivier, F., Gaudemer, Y., Peltzer, G., Guo Shunmin, and Zhitai, C., 1998, Geophys. J. Int., v. 135, p. 1-47. Mock, C., Arnaud, N.O., and Cantagrel, J., Marie, 1999, Earth and Planetary Science Letters, v. 171, p. pp.107-122. Ritts, B.D., and Biffi, U., 2000, Geological Society of America Bulletin, v. 112, p. pp.61-74. Sobel, E.R., Arnaud, N., Jolivet, M., Ritts, B.D., and Brunel, M., 2001, GSA special publication v. 194, p. 247-267.

T22C-02 1355h INVITED

A reality check on the timing of initiation, geological offsets, slip rates and geodetic rates on the Karakoram strike-slip fault.

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Total geological offset of 1000 km along the dextral Karakoram fault (Peltzer & Tapponnier 1989) were based on incorrect correlation of granite belts from the Pamir to S. Tibet and active slip rates of 30mm/yr-1 were based on an assumption of the age of offset post-glacial features (10 ± 2 ka; Liu et al. 1992). Detailed mapping and U-Pb and 40Ar/39Ar geochronology has confirmed that total dextral offsets are less than 120 km, the timing of initiation of the fault must have been younger than 15 Ma and that exhumation of sheared leucogranites and migmatites occurred between 15-11 Ma (Searle et al., 1997; Dunlap et al., 1998). We stress that: 1. All Tibetan fault slip rates published prior to 1996 are invalid as no precise timing constraints on the post-glacial Quaternary features were used. The common assumption was that all glacial features were formed 10 ± 2 ka, without any absolute dating. The glacial and fluvial features used to constrain offsets could have been awry by a factor of 3 or 4 (from 3.5 Ma - 20,000 ka). 2. Recent slip rates derived from cosmogenic isotope dating of offset Quaternary features should be treated with immense caution because during the continual recycling process of glacial moraine or alluvial fan burial, exposure and re-deposition, it cannot be known precisely which phase of exhumation is being dated. 3. Long-term geological slip rates on offset granites, precisely constrained by U-Pb geochronology remain the best estimates of timing of initiation, total finite offset and slip rates on Tibetan strike-slip faults. 4. The Karakoram fault is unlikely to be a lithospheric scale fault, because (a) temperatures beneath the southern part of the Tibetan plateau and beneath the faults are high enough to induce melting (>700°C at only 20 km depth), and (b) the lower crust beneath these faults must be underplated cold, old granulite facies crust of the Indian shield. 5. There appears to be a distinct lack of seismicity located along the Karakoram fault today. GPS data suggest that right-lateral slip parallel to the Karakoram fault occurred at 3.4 ± 5 mm/yr (Gaur 2002). If this figure is meaningful, then the slip today must be taken up mainly by aseismic creep, which suggests high temperatures occur at shallow depths along the fault, consistent with continuous but sporadic, and very young high-temperature metamorphism and anatexis in the southern Karakoram (Fraser et al. 2001). References cited: Dunlap, W.J., Weinberg, R.F. & Searle, M.P. 1998. J. Geol. Soc. London, 155, 903-12. Fraser, J.E., Searle, M.P., Parrish, R.R. & Noble, S.R. 2001. Bull. Geol. Soc. America, 113, 1443-55. Gaur, V. 2002. Abstract, 17th Himalaya-Karakoram-Tibet Workshop, Sikkim. Peltzer, G., Tapponnier, P. 1988. J. Geophysical Research, 93, 15058-117. Searle, M.P., Weinberg, R.F. & Dunlap, W.J. 1998. In: Continental Transpressional and Transtensional Tectonics. Geol. Soc. London Spec. Pub. 135, 307-26.

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Detrital zircon provenance analysis of Oligocene sandstone in the eastern Xorkol basin and its implications for the magnitude of displacement along the eastern Altyn Tagh fault

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Oligocene strata in the eastern Xorkol basin north of the Altyn Tagh fault (ATF) consist of interbedded pebble to cobble conglomerate and red mudstone deposited in a braided fluvial environment. Ubiquitous imbrication in the conglomerate beds yields paleocurrent measurements indicative of north to northwest-directed paleoflow, suggesting sediment derivation from the southern side of the ATF. Clast types include slate, phyllite, limestone, dolomite, metavolcanic rocks and metasandstone, indicating a low-grade metamorphic source terrane with few granitic intrusions. In order to better characterize the source of Oligocene detritus, a sandstone sample was collected in the uppermost Oligocene strata for SHRIMP detrital zircon age dating. Most of the zircon grains are zoned in structure and pink in color with few fractures. Thirty spot analyses yield a characteristic age distribution for the sandstone. Except for 5 analyses which give discordant ages between 650 Ma and 830 Ma, 19 analyses are clustered around 917 Ma with a standard deviation of 42 Ma, and the other 6 analyses lie between 1100 Ma and 1700 Ma. The zircon grains have a mean Th/U ratio of 0.42 with standard deviation of 0.19, typical for zircons of magmatic origin. The resulting zircon age distribution puts important constraints on the source of the Oligocene detritus in the eastern Xorkol basin. The lack of Paleozoic zircon ages eliminates the main part of the central Qilian Shan, the southern Qilian Shan and Qaidam basin as possible sources because they contain widespead Paleozoic plutons. It also eliminates the Ordovician and Silurian volcaniclastic rocks of the northern Qilian Shan as a possible source inasmuch as their detrital zircons, shed from a synchronous magmatic arc in the central Qilian Shan, are predominantly early Paleozoic in age. Therefore, the only possible sources are Cambrian and Neoproterozoic strata in the southern part of the northern Qilian Shan and the northernmost part of the central Qilian Shan, where the Neoproterozoic strata contain zircon grains whose U/Pb ages are concordant at 930 Ma and zircon grains whose ages range between 1000 and 1600 Ma. An Oligocene piercing point is thus deduced by realigning this possible source and the Xorkol basin, consistent with 350-400 km of left-lateral offset along the eastern segment of the ATF. Determination of the magnitude of displacement along the eastern ATF is critical for understanding the nature of this fault and its role in the formation of the Tibet Plateau. Because the areally small northern part of the northern Qilian Shan beyond our piercing point is unlikely to accommodate a significant portion of the 350-400 km of left-lateral offset along the ATF, northeastward extrusion must have existed to assist in accommodating this offset, indicating that the ATF was an extrusion boundary, at least in the early Neogene. On the other hand, the 350-400 km of left-lateral offset is smaller than the offset along the western segment of the ATF. This decrease in offset indicates that the ATF is also a boundary across which slip was transferred into crustal shortening of the Qilian Shan and the Qaidam basin.

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Gaoligong and Chong Shan Shear Zones, Yunnan, and Accommodation of the Northward Movement of India Relative to Indochina During the Mid-Cenozoic

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