and that considerable crustal mass is exported from the region fluvially. Thus, it is likely that the Three Rivers serve as significant spatially extensive sinks of mass at the Earth's surface. This inference has not been taken into consideration in godynamic models to date. Under these conditions, eastward motion of the thickened crust of Tibet to the side of the indentor does not have to propagate indefinitely to the east; it could well be offset by surface mass removal in the Three Rivers region. A simple mass-balance calculation suggests that a modest erosion rate of only 0.2 mm/yr could account for a significant component of the eastward mass flux ~10%, and 2 mm/yr would allow all the easterly crustal advection out of Tibet to be consumed by erosion.

T41E-04 0930h

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The Nanga Parbat-Haramosh Massif (NPMH) is located in the northwest Himalaya of Pakistan and is a map-view extrusion of Indian crust surrounded on three sides by the island arc rocks of the Ladahk and Kohistan terranes. Located in the northwest Himalayan syntaxis, the NPHM has experienced a complex tectonic and metamorphic history involving an earlier Himalayan metamorphic event associated with crustal thickening, and a later metamorphic overprint associated with rapid uplift and exhumation. Here we show that the highest grade metamorphism and fluid flow are coincident with the highest topography which suggests a cause-effect relationship.

Metamorphic mineral assemblages reveal steep concentric metamorphic gradients away from the granulite grade cordierite-sillimanite bearing massif core into upper-greenschist and amphibolite facies rocks toward the flanks. Thermobarometric data also show distinct variations within the massif with rocks in the rapidly denuding core recording low-pressure metamorphism (4-6 kbars), and rocks toward the eastern margin recording high pressure metamorphism (10-14 kbars) similar to adjoining Ladahk terrane rocks. Partial melts of leucogranite stocks and migmatite are also exposed in the highest-grade core of the massif and are noticeably absent or rare along the flanks of the massif. Isotopic studies of these granites suggest that these granites formed as a result of in-situ melting under fluid present conditions. In addition, fluid inclusion and stable isotopic analysis shows that rocks within the core of the massif have been infiltrated by meteoric fluids down to depths near the brittle-ductile transition, and these fluids exit the flanks of the massif along steep, bordering faults.

T41E-05 0945h

Structure and Chronology of Nanga Parbat Haramosh Massif

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The western Himalayan syntaxis, in northern Pakistan, culminates in the ENE-trending Nanga Parbat-Haramosh Massif (NPHM). Our structural and isotopic age results show that the NPHM is a young (~10 to 0Ma) and active crustal-scale antiformal/thrust pop-up structure. Thrust displacement at NPHM is on two principal marginal shear zones, E-vergent on the eastern side, and WNW-vergent (the dominant zone) on the western side; in the southern NPHM both zones are intimately linked with granitic plutonism. Ion microprobe U(Th)Pb results from granites of 2 to 8 Ma show that the present exposure level in the southwestern (Diamir) portion of the western shear zone was active under ductile conditions during this interval; brittle fault structures pervasive across this 5km-wide shear zone are younger than most granite intrusion. A 6.5Ma granite cross-cutting NPHM western margin mylonites in the Indus gorge, 60km north of Diamir, implies older entry to brittle faulting in the northern NPHM at the present exposure level. This is consistent with our cooling age results (N to S younging) and inferred lesser total exhumation in the north compared with the NP summit region. The southeastern NPHM margin, defined by the easterly-vergent Rupal-Chhichi Shear Zone (RCSZ), also involves mostly granitic rocks with pervasive ductile S/C fabrics, suggesting syn-kinematic plutonism. The overall lens shape of the shear zone suggests to us that the granite emplacement has been accommodated by a pull-apart regime on the dextral/oblique thrust shear zone. Crystallization ages from undeformed granite near, but outside the outer margin of the shear zone are about 20Ma; a small crosscutting dike within the outer part of the shear zone gives ages ranging from ~20 to 9Ma, and biotite cooling ages in this area suggest transition to temperatures below the brittle-ductile transition by about 10Ma. In contrast, granite dikes outside but near the northwest margin of the RCSZ give crystallization ages in the range 1 to 2.5Ma. We propose that there has been an inward migration of plutonism and (largely ductile) strain on the RCSZ. Rapid gradients in biotite cooling ages from a few Ma (inside NPHM) to 10Ma and up (outside), clearly delineate the location of both the western and eastern marginal shear zones of southern NPHM. We infer that the present western marginal fault zone of NPHM descends eastwards into an active ductile shear zone, a successor to the older ductile shear zone exposed at the surface. Extensive mapping across southern NPHM has found no major structures that require young orogen-scale structural unroofing, and we infer that sustained high erosion rates are required for the rapid young exhumation. The WNW-directed shortening at NPHM may accommodate differential arc-parallel motion along the Himalaya at the syntaxial bend.

T41E-06 1020h

Snap, Crackle, Pop! Seismicity and Crustal Structure at Nanga Parbat, Pakistan, Himalaya

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A dense seismic array deployed in the Himalaya of Pakistan provides new insight into active processes associated with crustal reworking during orogenesis. Nanga Parbat, an 8 km high peak etched from Indian crust, is the characterized by extremely rapid exhumation (5-10mm/yr), the presence of hot springs, young intrusive rocks (<1 Ma), and young metamorphism (<1 Ma). As part of a multidisciplinary study we deployed a 60 station, three component, mixed broadband-short period array in an approximately 50 x 60 km area at the massif to characterize active seismicity (fault geometry and kinematics) and determine crustal structure beneath the mountain.

In a four month time window (May-September 1996) we recorded over 1500 associated events. Joint inversion for velocity and hypocentral location yields Vp=5.6-5.8 km/s and Vs=3.3 to 3.5 km/s within the main massif. This yields relatively low Vp/Vs ratios and low Poisson's ratio consistent with high SiO2 content, high temperatures, and the presence of fluids/vapor phases in the shallow crust. Prominent but complicated S wave arrivals at stations throughout the array rule out the possibility of a substantial magma body beneath Nanga Parbat. This observation is consistent with magnetotelluric data indicating a resistive crust beneath the massif. Local seismicity is distributed along strike beneath the massif with the highest concentration of events associated with the region of highest topography. A cessation in seismicity to the west corresponds to the trace of the Raikot fault a young active structure juxtaposing Indian Pre-Cambrian gneisses against mafic rocks of the Kohistan Island arc. A sharp cut off in seismicity to the east is bound by the main ridge crest of the massif. The adjacent Kohistan terrane is virtually aseismic. Hypocenters projected to a NW-SE cross section are restricted to very shallow depths. The abrupt cutoff of seismicity with depth is shallowest beneath the summit (5 km bsl) and deepens to 8 km bsl to the NW and SE outlining a prominent antiformal shape defining a thermal boundary associated the transition from brittle to ductile deformation. This observation is consistent with petrologic and thermochronologic data indicating very high geothermal gradients (60-100/km) at Nanga Parbat. While we see many clean impulsive arrivals, others appear more harmonic, not unlike seismic signatures observed in geothermal systems suggestive of fluid circulation under pressure at shallow depths. These events are intriguing given the evidence for recent igneous activity focused at the core of the massif and evidence from fluid inclusions indicating a dry steam phase associated with a hydrothermal system below 3 km depth. While we recorded both thrust and right-lateral strike- slip focal mechanisms, many of the focal mechanisms are extensional and can be attributed to extension in the near-surface above a growing antiform as well as brittle failure facilitated by fluids under pressure. Of particular interest is a cluster of events associated with the Tato hot springs defining a well-constrained fault plane, a possible pathway for fluid migration.

T41E-07 1035h

Distribution of Partial Melt Beneath Nanga Parbat, Northern Pakistan

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A broadband magnetotelluric survey has been conducted around Nanga Parbat (elevation 8125 m) in order to constrain the distribution and type of partial melt beneath the mountain. This peak has experienced 9-18 km of exhumation in the past 3 My, resulting in an average rate of 3-6 mm/y. Granitoids and migmatites with ages of less than 1 Ma attest to the active reworking of continental crust, as does the abundant hydrothermal activity (hot springs, alteration products along faults). Because of the difficult access (half of the sites were accessible only by foot with porters), only 21 stations were collected. However, careful placement of the sites permitted delineation of the major structures. The N-S profile across the peak shows clear evidence of resistive crust to depths of at least 40 km, with an average resistivity over 1000 ohm-m. While there may be isolated pockets of fluid-rich rock or fluid-saturated magma, the overall region is devoid of interconnected fluids. Such an interpretation is consistent with evidence from fluid inclusions from above the brittle-ductile transition showing a steam-dominated geothermal system and from seismic data showing passage of S waves through this section of crust. Below this transition, any fluids generated escape because of the rapid advection of mass through the transition. The E-W profile located less than 10 km south of the peak shows clearly a conductive structure associated with the Rupal- Chichi shear zone. This conductor is relatively shallow and does not extend beneath the peak, although the shear zone may do so. Interpretation of both profiles required 3-D models in order to identify which modes could be approximated with 2-D structures. Additionally, tipper data provided key constraints on the distribution of crustal conductors.

T41E-08 1050h

Feedback between uplift, denudation, and tectonics at Nanga Parbat, western Himalayas

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A very active regime of northwest-directed shortening in the Nanga Parbat area is manifested by the northwest-verging and rapidly uplifting Nanga Parbat antiform (NPA) and the southeast-dipping Lichar thrust fault which outcrops along the northwestern overturned limb of the NPA. These coupled structures are part of a 200km long belt of northwest shortening from the western Syntaxis to the Main Karakorum Thrust. Generally, brittle and Quaternary structures in the Indus and Gilgit valleys suggest west- to northwest-directed shortening in the Kohistan terrane west of the massif. This shortening is coupled with two prominent Quaternary faults, one left-lateral and striking west-northwest along the Gilgit River valley, the other right-lateral and striking west-southwest along the Indus River valley. They are interpreted as transfer faults between broad belts of northwest shortening south of the Indus and north of the Gilgit rivers from a much narrower portion of the belt corresponding to the highest relief and the Lichar thrust. Along this portion of the belt, shortening seems to be confined to the massif, within and east of the Indus Gorge. Accordingly, earthquakes are concentrated east of the river within the hangingwall block of the Lichar thrust and are prominently lacking west of the river in the footwall block of this thrust. This pattern of regional shortening may stem from the effect of the Indus gorge on the tectonic regime where this gorge is normal to the shortening. A very large stress is derived from the combined effect of the weight of the mountain and the lack of weight along the gorge. The tectonic regime responds to this superposed topographic stress by increasing the rate of slip on the Lichar thrust in an attempt to fill the gorge from below. This attempt is futile, given the effectiveness of the river to remove material and to maintain its grade. Thus, the gorge casts a stress shadow to the northwest and shunts the shortening which is taken up completely east of the gorge and may account for exceptionally rapid uplift at Nanga Parbat. Once established, the drainage pattern in active mountain building orogens may have a major effect on tectonics. A river capture in the evolution of the Indus drainage may account for the onset of rapid uplift at Nanga Parbat.

T41E-09 1105h

High Magnitude Differential Denudation in Nanga Parbat Himalaya, Pakistan.

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The Nanga Parbat massif near the west end of the Himalaya in Pakistan is characterized by some of the strongest relief on Earth, with its summit at 8125 m, and its base at 1100 m on the Indus River. Topographic analysis using a high-resolution digital elevation model indicates high mass removal. Measurement of modern process rates, coupled with radiometric, cosmogenic and IRSL dating of exposed rock and surficial sediments from mass movement, glaciers, rivers, and catastrophic floods show differential erosional unroofing of the massif. Mass movements dominate in small alpine basins where denudation ranges $0.03 - 0.5$ cm yr^{-1}. Large rockslides may be locally removed from river

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T41D-06 0830h POSTER

Complexities in the Seafloor Spreading History of the Lau Basin

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We present a ~200m resolution compilation of Lau Basin marine geophysical data (14-23S). A refined 3D magnetization inversion derived from the merged bathymetry and magnetics data reveals average Brunhes opening rates of ~60 mm/yr on the NW Lau Spreading Center, as much as ~100 mm/yr near Mangatolu triple junction (MTJ), and 60-100 mm/yr (increasing northwards) on the Eastern and Central Lau Spreading Centers and the Lau Extensional Transform Zone (ELSC, CLSC and LETZ respectively). Studies of the magnetization inversion in conjunction with interpreted neovolcanic zones from the sidescan data show that the MTJ has rotated and overprinted crustal fabric during Brunhes Chron time. An overlapping spreading center links the southern limb of the MTJ with the Funalei Rift. An ~015 trend in the crustal fabric along the CLSC and the ELSC also implies a clockwise rotation for these spreading segments since anomaly 2 time. A series of magnetic lineations in the western basin are identified; however, the origin of these lineations remains enigmatic. The crustal fabric accompanying these lineations mimics that formed by seafloor spreading on the currently active CLSC and LETZ.

T41D-07 0830h POSTER

Asymmetric sea-floor spreading in the central Mariana Trough

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We present detail sea-floor spreading history of two ridge segments in the central Mariana Trough (MT) at 18N and provide the evidence of relative movement of the spreading axes toward the trench, using the bathymetry, the magnetic and the gravity data. Multi-narrow beam bathymetry and shipboard three-component magnetometer data were collected by two surveys (KH921 and Y9612) in this area. We also used marine gravity anomaly from satellite altimetry (Sandwell and Smith, 1997) and predict bathymetry from dense altimetry and sparse shipboard bathymetry (Smith and Sandwell, 1997). Sea-floor spreading of the MT is very similar to that at the slow-spreading Mid-Atlantic Ridge in two main points; 1) the morphology shows existence of median valley neovolcanic zone and spreading axis segmentation, and 2) the mantle Bouguer anomaly shows existence of "Bull's eyes" along the axes. Main differences are deeper sea-floor and asymmetric sea-floor spreading in the MT. The asymmetric features are 1) the center of the "Bull's eyes" in the northern segment locates west of the spreading axis and 2) relative movements of the spreading axes toward the east (trench side). The axis movements are ascertained by the crustal age. The downward component of the geomagnetic anomaly field allows us to identify the geomagnetic isochrons until 6 Ma (magnetic isochron 3A) in the western side, while in the east we could follow only 2 Ma (magnetic isochron 2). The age identification from the northern segment shows an eastward ridge axis jump by 5 km at the age of 3 Ma when the half-spreading rate is slowing down from 22 to 15 mm/year. The result from the southern segment suggests that the axis moved eastward by 30 km between 3 Ma and 1 Ma. Furthermore, the present axis of the southern segment determined from bathymetry, locates much closer to eastern Brunhes-Matuyama boundary. The axis movements toward the trench is probably the reason of the unclear magnetic anomaly in the east side and this movement probably leads that the positions of the spreading axes keep certain distance from the trench. The asymmetry is a key point to understand mechanism of back-arc spreading.

T41D-08 0830h POSTER

Crustal Structure across the Xisha Trough of South China Sea

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In fall 1996, a wide-angle seismic experiment with Ocean-Bottom-Hydrophones (OBH) was carried out across the Xisha Trough in the northwestern part of the South China Sea. 10 OBHs were deployed and retrieved along the 230 km NNW-SSE oriented profile coincident with MCS line SO49-23 acquired in 1985 by the BGR, Hannover. Favourable weather conditions and the powerful 4x10L airgun array rendered a very good quality of data with seismic signals observed in distances of up to 110 km. Earlier interpretations of the BGR reflection data show a complex structure of syn- and post-rift sediment, characterized by half-grabens and rotated fault blocks. The 2D ray-tracing forward modeling of the wide-angle data does not only confirm the shallow structure but also reveal the deep crustal structure down to the uppermost mantle. P-wave velocity first increases rapidly from 5.5 km/s at the top basement to 6.0 km/s within a few kilometers depth and then gradually to 6.8 km/s above the Moho. On both sides, the total crustal thickness decreases rapidly towards the center of the Xisha trough from more than 22 km to 12 km within 60 km distance. Considering only the pre-rift crust, the thinning is more dramatic from 20 km to only 8 km. No significant interface was found inside the crust, but taking the 6.4 km/s isoline as the boundary of the upper-lower crust, the thinning takes place mainly in the upper crust. The velocity in the uppermost mantle has a normal value of 8.0 km/s. The sharp Moho and lack of high velocity layer in the lower crust imply no magmatic underplating during the rifting. The similarity of crustal structure on both sides of the Xisha Trough suggests that the South China continental margin and the Xisha micro-continental block have the same pre-rift origin. The crustal structure across the Xisha trough differs significantly from those found across the eastern part of the South China continental margin, thus strongly suggesting a difference in the related rifting process.

T41D-09 0830h POSTER

The Late Paleozoic Evolution of the Parana Basin: An Example of Subduction-Induced Subsidence

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The Parana Basin formed within the interior of present-day South America through a sequence of major depositional events from the Ordovician to the Cretaceous. In this study, we focus on the Permo-Carboniferous phase of sedimentation and consider a mantle flow mechanism to explain part of the development of the basin. The stratigraphic record indicates that during this time period the region experienced an episode of long-wavelength subsidence with a component of tilt down to the south-west. The tectonic regime during deposition was controlled by convergence along the nearby Panthalassan margin of Gondwana and there is evidence for subduction beneath the continent associated with the consumption of the Paleo-Pacific oceanic plate. We propose that part of the subsidence of the Parana Basin was due to the dynamic response of the lithosphere to mantle flow viscously coupled to this contemporaneous subduction event. We present numerical simulations of mantle convection driven by descending viscous slabs and compute the associated dynamic topography. The predictions of subsidence are able to reconcile both the thickness of the sediment deposition and the maximum horizontal wavelength of the basin tilt.

T41E MC: 122 Thursday 0830h
Fire and Ice - The Geomorphology of Metamorphism: Mesoscale Linking Between Surficial and Crustal Processes I *(joint with H, V)*

Presiding: **P Zeitler**, Lehigh University; **C P Chamberlain**, Dartmouth College

T41E-01 0835h INVITED

Big Mountains, Big Rivers and Hot Rocks; Beyond Isostasy

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Pre-existing topography generally influences deformation in convergent zones by deflecting flow away from topographic loads and toward lower elevations. The topographic contribution to normal and shear components of stress cause pre-existing mountains caught in continental collision to be unlikely locations for deep exhumation. However, several large isolated massifs do exhibit deep exhumation levels, including modern granulites and crustal melts, within their high elevation core. This deflection of deep crustal material into the topographic highs rather than around the load into surrounding lower elevations provides insight into the dynamic interaction among erosion, metamorphism and deformation.

Using three-dimensional numerical models we show that one set of conditions that leads to massif development is through concentration of strain initially along efficient rivers that incise transverse to the orientation of the mountain chain. Incision causes advection of hot, weak material toward the river channel which in turn further concentrates strain. Advection and decompression of deep crustal material produces partial melting thereby further reducing the relative strength of the massif and further concentrating strain. Coupling between deformation and melting causes progressive rheological weakening that overtakes erosion as the primary influence on strain concentration. From this point on, material is partitioned into the growing weak massif as the inhibiting effect of topographic load is reduced in relative importance.

Erosional/rheological coupling may cause large embayment in the shape of an orogen, as in the Himalayan western syntaxis and cause the formation of very high elevations at orogen velocity corners, as in the Himalayan eastern syntaxis. Large rivers with sufficient power to maintain near steady state profiles during orogenic uplift provide the trigger for this strain concentration. Consequently, the spacing of high grade granulite domes and igneous bodies in older convergent belts may reflect the spacing of large transverse rivers. In addition, any process, such as glaciation, that widens the aperture of channel incision can aid initiation of the melt episode.

T41E-02 0855h INVITED

Rapid Rise of High Mountains Caused by Melt in the Lower Crust

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Rapid pulses of uplift and exhumation occur in the presence of melt. Detailed work on the relation of melt to structural and metamorphic features in several orogenic belts shows that metamorphic rocks, along with partial melt, can be rapidly transported with minimal loss of heat from lower crustal depths to middle crustal depths. The weakening due to the intrusion of melt or to the formation of melt by anatexis may initiate the rapid rise of the metamorphic rock; the presence of the melt helps maintain high temperatures during exhumation.

The evidence for the rise of the metamorphic rock includes the superposition of lower pressure metamorphic assemblages on syn-compressional higher pressure metamorphic assemblages. The deformation fabrics affecting the higher pressure assemblages were made during thrusting of higher temperature rocks on lower temperature rocks. The resultant P-T-time path is the clockwise path from 8 - 10 kbar to 3 - 4 kbar described for several orogenic belts. Rapid cooling, which follows development of the lower pressure metamorphic assemblages, is well documented in several belts by thermochronometry. The metamorphic rocks have been over 300oC at surprisingly shallow levels (1 -2 kbar) during the rapid cooling, as documented by fluid inclusion studies. The growth of the lower pressure assemblages and the rapid cooling are best attributed to the rapid exhumation of rock before it could cool to a steady state conductive thermal gradient.

The rapid exhumation is likely associated with a rise of topography accompanying crustal thickening during thrusting. The most dramatic examples of rapid exhumation following crustal thickening are in the Himalayas, which may have experienced repeated pulses of uplift and exhumation beginning in the late Miocene and continuing to the Present. The time interval for each pulse appears to be less than 5 Ma.

T41E-03 0915h

Dual Interest in the Three Rivers of Eastern Tibet: As Markers of Strain, and as Exporters of Crustal Mass from the Region

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Extensive lithospheric deformation on the eastern margin of the Indian/Eurasian collision has brought three major rivers in exceptionally close proximity. For several hundred kilometers, the Salween, Mekong and Yangtze Rivers are only tens of kilometers apart, about ten times closer than other rivers aligned with the orientation the maximum shear strain and anomalous topological relationships, are consistent with on the order of 1000 km of northward motion of India relative to southern China concentrated largely in a zone roughly 200 km wide. We suggest that deeply incised river valleys can be conservative markers of regional strains in that they move with the underlying continental crust over time scales that can exceed 10 Myr. In the Three Rivers region, the rugged landscape transversed by large rivers inset into deeply incised gorges strongly suggests that the area is undergoing significant erosion,

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