IMPLICATIONS OF DETRITAL ZIRCON FISSION-TRACK DATING FROM THE LINKOU TABLELAND, NORTHERN TAIWAN

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Abstract

In order to estimate the paleorate of the denudation of the northern Hsuehshan Range and southeastern China, a total of ten core samples were collected from the Linkou Tableland for detrital zircon fission-track dating (FTD). The detrital zircon grain FT ages of the Linkou Gravel Formation range widely from 0.9 Ma to over ~190 Ma. Each sample shows 2-3 populations in the grain-age distribution, implying the sediments of the Linkou Tableland were derived from three distinct source terranes. The zircon grains that have FT ages between 4.1 ± 0.9 Ma and 90.8 ± 18.4 Ma (1σ) Ma are inferred to be derived from the northern Hsuehshan Range. The grains that have ages of < ~6 Ma are regarded as totally reset due to the Penglai Orogeny. With the assumption of a thermal gradient 30°C/km and a closure temperature of 240°C for zircon FT system, cooling and exhumation rates during the period of 6 ~ 1 Ma are calculated as 81.0 ~ 46.2°C/Myr and 2.7 ~ 1.5 mm/yr, respectively. Moreover, the oldest component of the zircon FT ages ranges from 91.5 ± 1.1 to 245.6 ± 201.7 (1σ) Ma with three best-fit peak ages between 110 and 160 Ma, obviously implying that unreset zircon grains of the Western Foothills in Taiwan were most likely derived from the Jurassic - Cretaceous rocks in Southeast China. It suggested that the cooling and exhumation rate during the period of ~160 to ~7 Ma are estimated at 2.8 ~ 2.2°C/Myr and 0.10 ~ 0.07 mm/yr, respectively.
COLLISION AND STRIKE-SLIP TECTONICS IN THE KOPEH DAGH AND EAST ALBORZ-BINALUD RANGES, N.E. IRAN: A MULTIDISCIPLINARY STUDY TO CONSTRAIN THE CENOZOIC TO PRESENT-DAY TECTONIC HISTORY

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The East Alborz-Binalud and Kopeh Dagh mountain ranges are located in NE Iran and represent the northern limit of deformation in this part of the Alpine-Himalayan collision zone. The tectonic history of this region spans from the Cimmerian Orogeny (Late Triassic - Jurassic) to the more recent fold and thrust and transpressional tectonics associated with the Alpine Orogeny, which is ongoing today. Previous research has concentrated on the distribution and slip-style of active faults that accommodate regional shortening (due to Arabia-Eurasia collision) at the present day. The onset of the present-day kinematics has been estimated at ~10 Ma, by extrapolating total strike-slip offsets at present-day fault slip-rates (estimated from GPS velocities). However, a synthesis of the tectonics of this region over the whole Cenozoic remains poorly constrained.

Stratigraphic relationships indicate the East Alborz-Binalud mountains were uplifted earlier than the Kopeh Dagh. However, very little is known about the timing of uplift of these ranges, due to the absence of fossils or dateable material in the continental Red Beds deposited along the range flanks during this time (various estimates for uplift range between 5-30 Ma).

This paper presents a new thermochronological study of the East Alborz-Binalud and East Kopeh Dagh mountains to better constrain the timings of uplift and exhumation, based on apatite fission track analysis of 15 samples. These were located across the eastern end of the Kopeh Dagh Range, on the road from Mashad to Sarakhs, with two further transects spanning the southern and northern flanks of the Binalud mountains (part of the East Alborz), near Neyshabur and Mashad. We combine our data with published constraints on the active deformation of the region (from GPS, Quaternary dating and tectonic geomorphology studies) to extend our understanding of how the tectonics of NE have evolved over longer geological timescales.
IS FOCUSED EROSION ENHANCING DENUDEMENT OF DOMES IN THE PAMIR MOUNTAINS?

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The relationship between deeply exhumed gneiss domes of high-grade meta-sediment and meta-granite and focused glacial and fluvial erosion in the Chinese Pamir Mountains provides important new information regarding the geological and geomorphological processes modifying tectonism during the Indo-European collision.

At the western end of the Tibetan Plateau, two major gneiss domes, Kongur Shan and Muztagh Ata, lie in the footwall of the west-dipping Kongur detachment system. Rapid exhumation of the domes began at 6-8 Ma, immediately after peak metamorphism at ~27 km depth (Robinson et al., 2004). At the foot of the Kongur Shan Dome, both ⁴⁰Ar/³⁹Ar mica and apatite fission track thermochronometers yield Plio-Pleistocene cooling ages (Arnaud et al., 1993; Brunel et al., 1994; Robinson et al., 2004; 2007) which are significantly younger than ages obtained along strike of the Kongur Detachment (Robinson et al., 2004; 2007) and from the hanging wall. This suggests that the major portion of the exhumation of these domes has been accommodated along the Kongur detachment fault. Furthermore these data suggest a locally more extensive exhumation in the vicinity of the two domes.

The highest topography in the footwall of the detachment is correlated with the domes, with the peaks Kongur Shan (7719 m) and Muztagh Ata (7546 m) towering >3000 m above the surrounding plateau. The highest topography and the greatest relief are found in the vicinity of the domes. This region is also host to the largest glaciers with the greatest valley spacing, the greatest debris cover, and the lowest ELA, which results in the excavation of large parts of the core region of the domes. The degree of glaciation and of glacial erosion varies dramatically along the length of the detachment. Glaciers are smaller and cleaner in the north and glaciation is virtually absent in the south. Fluvial incision along the Gez River, immediately north of the Kongur dome, contributes to erosion of the footwall of the Kongur detachment as well. Today precipitation is delivered both by Westerlies, with a minor contribution from the Indian summer monsoon, and is localized by the topographic anomalies formed by the domes (Seong et al., in review).

We suggest that focused glacial erosion in the region of the Kongur Shan and Muztagh Ata domes may have enhanced exhumation in this region of the Kongur detachment, driving a positive feedback with a thermally and mechanically weakened crust, resulting in a “tectonic aneurysm.” Alternatively the enhanced glacial erosion might be a passive result of tectonic exhumation, in which tectonically formed high peaks lead to greater orographic precipitation, resulting in the development of larger glaciers. The goal of this ongoing study is to use new and existing thermochronologic data to quantify the temporal and spatial variation in exhumation. A key question is whether observed cooling ages can be correlated with the erosional capacity of the system. Is there a pattern to the cooling histories which can be related to regional spatial and temporal climatic changes, or is exhumation of the domes driven by tectonics alone?

Approach and Methods

We collected samples for apatite fission-track and ⁴⁰Ar/³⁹Ar thermochronologic analysis from a series of vertical profiles in the footwall and spot samples in from the hanging wall along the length of the detachment. Here we present our preliminary results, combined with published data (Fig. 1). Twenty new apatite fission track (AFT) and about 10 new muscovite and biotite ⁴⁰Ar/³⁹Ar data combined with previously published ⁴⁰Ar/³⁹Ar data (Robinson et al., 2004; 2007; Arnaud et al., 1993; Brunel et al., 1994) provide an improved view of the exhumational pattern in space and time.

Preliminary Conclusions

Cooling rates for the last 2-5 Ma are rapid in the vicinity of the domes, as shown by young AFT and argon mica ages and high apparent exhumation rates shown on the age-elevation plots. Along the footwall of the Muji segment in the NW (Fig. 1; 1), the cooling rate appears to have slightly increased at a poorly resolved time around 3-8 Ma. Topography in this region reflects intense river incision as well as glacial erosion in the upper reaches of the drainage basins. In the middle section, around and between the Kongur Shan and Muztagh Ata domes (Fig. 1; 2, 3, 5), cooling rates have increased in the last 1-3 Ma. Glaciation in this region is quite extensive. The exceptional size of the glaciers, the steepness of headwalls, and the degree of debris cover all point to the erosive power of these glaciers. Incision along the Gez River where it crosses the range north of Kongur Shan may also contribute to exhumation. In contrast, south of the Muztag Ata dome, the cooling rate observed in the upper Yarkand river (Fig. 1; 4) has not significantly changed in the last ~8 Ma. There is little evidence for glacial erosion in this region, which is instead dominated by incision along the Yarkand River and minor tributaries. The height of the topography, the relief and the degree of glaciation drop off rapidly south of Muztagh Ata towards this region.

<table>
<thead>
<tr>
<th>Temp</th>
<th>Mineral</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>120 ± 15 °C</td>
<td>Apatite fission track</td>
<td>Reiners and Brandon, 2006</td>
</tr>
<tr>
<td>270 ± 30°C</td>
<td>Ar Kspar MDD model result</td>
<td>Robinson et al., 2004</td>
</tr>
<tr>
<td>340 ± 30 °C</td>
<td>Ar biotite, slow cooling</td>
<td>Reiners and Brandon, 2006</td>
</tr>
<tr>
<td>370 ± 30 °C</td>
<td>Ar biotite, fast cooling</td>
<td>Reiners and Brandon, 2006</td>
</tr>
<tr>
<td>360 ± 30 °C</td>
<td>Ar muscovite, slow cooling</td>
<td>Reiners and Brandon, 2006</td>
</tr>
<tr>
<td>410 ± 30 °C</td>
<td>Ar muscovite, fast cooling</td>
<td>Reiners and Brandon, 2006</td>
</tr>
<tr>
<td>500 ± 50 °C</td>
<td>Th-Pb Monazite plus thermobarometry</td>
<td>Robinson et al., 2004</td>
</tr>
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Table 1: Closure temperatures used for Age - Temperature plots (Fig. 1).

There appears to be a correlation between the magnitude of change in Pliocene cooling rate and the extent of glaciation. The Pliocene timing of the inflection point suggests a link with the regional onset or intensification of glaciation concurrent with the onset of Northern Hemisphere glaciation. However, more samples must be analyzed before the correlation between enhanced glacial erosion and more rapid exhumation can be convincingly demonstrated.

Acknowledgment
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A fundamental question in the study of climate and tectonics of mountain belts is whether late Cenozoic climate change has led to enhanced erosion, increased supply of coarse sediments, and perhaps accelerated tectonic rates. In the case of mountainous areas such as the Kyrgyz Tien Shan, enhanced glacial erosion due to a colder, wetter climate as well as enhanced fluvial erosion due to increased precipitation and/or a more variable climate have been proposed as mechanisms to explain increased erosion rates in the Plio-Pleistocene (e.g., Zhang et al., 2001).

Although this hypothesis is appealing, it has been difficult to test, as one must disentangle the tectonic and climatic signals. In order to show that late Cenozoic climate change has exerted the dominant control on late-stage exhumation in an orogen, one must first understand the earlier deformation pattern that can be attributed to tectonism. For instance, if the earlier pattern was spatially and temporally varying exhumation, one might conclude that this was driven by the propagation of deformation due to tectonism. If the late Cenozoic deformation pattern shifted to spatially and temporally synchronous exhumation, one might conclude that climatically enhanced erosion provided a more plausible explanation than a pure tectonic mechanism. The high, glaciated Kyrgyz Tien Shan offer a natural laboratory to test this question because the Cenozoic exhumation history can be well-constrained using thermochronology.

The Kyrgyz Range, at the northern margin of the Tien Shan, has grown higher as it lengthened along strike (Sobel et al., 2006). Prior to exhumation, the study area consisted of a low-relief sedimentary basin; these deposits were deposited above a regional erosion surface which cruzets basement units. A late pulse of rapid exhumation is associated with enhanced erosion due to orographically increased precipitation and glaciation. However, it is unclear if this second pulse is linked to the range reaching a critical elevation threshold or to regional climatic change. In the former case, the second exhumation pulse should propagate along the range in the same sense that the range has developed; in the latter case, the onset would be synchronous. In the Kyrgyz range, it was not possible to test this idea with thermochronology because most of the rocks outcropping in the range contain poor quality apatite that is unsuitable for (U-Th-Sm)/He analysis due to unfavorable lithologies. However, the granitic Terskey Range, a structurally similar range located to the southeast, offer an ideal location to examine this question.

Preliminary Data
Four ~1000m vertical profiles were collected in the hanging wall of the main, north-vergent thrust, spaced ~25 km apart along strike. An additional suite of samples was collected deeper in the range behind the westemmost- transect. To date, AFT analysis has been conducted from the westemmost-transect; this and two other profiles have been analyzed using (U-Th-Sm)/He analysis on apatite. AFT analyses were conducted at Universitaet Potsdam; (U-Th-Sm)/He analyses were conducted at the University of Melbourne. The results are shown in Figure 1.

Helium analysis was typically conducted on aliquots of 3 similar-sized grains. Three aliquots were analyzed from most of the samples. Typically, a range of ages was obtained from each sample. Most samples yielded replicatable young ages as well as older ages. In addition, these youngest ages form linear trends on age-elevation plots, suggesting that they represent geologically significant episodes of cooling. Where both AFT and (U-Th-Sm)/He data are available, the young He ages are younger than the AFT ages. Therefore, we disregard the anomalously old ages.

AFT and (U-Th-Sm)/He data from the Barskoon gorge profile, the westemmost sampling region, define parallel trends on the age-elevation plot; these have apparent exhumation rates of ~0.08 km/Myr. The uppermost AFT sample appears to represent a sample which resided for a long period within the partial annealing zone (PAZ); hence, the onset of rapid exhumation defined by the base of the exhumed PAZ appears to be ~31±5 Ma. This age is earlier than expected given the known regional geology. An alternative interpretation would be that the sample at 3300m has been partially reset, such that the onset of exhumation is later and the initial exhumation is more rapid. Additional track-length data will be required to discriminate between these two possibilities.

The (U-Th-Sm)/He data from the Kichikyzulsu and Turgenaksu profiles both define linear trends on age-elevation plots; these have apparent exhumation rates of ~0.1-0.25 km/Myr and ~0.2 km/Myr, respectively. Significantly older ages obtained at high elevations along the Kichikyzulsu profile suggest that the base of the Helium partial retention zone (PRZ) has been sampled; the onset of exhumation is roughly constrained to be between 10 and 20 Ma. The onset of rapid exhumation at the Turgenaksu profile can only be constrained as pre-dating the oldest, ~11 Ma sample. AFT analysis should better constrain the earlier portion of both of these exhumation histories. The presence of the regional erosion surface on the south flank of the range implies that the total amount of exhumation is relatively limited and hence the onset of exhumation likely occurred during the middle Miocene.
Preliminary Interpretations

Combining the apparent exhumation rate with the age of the youngest samples from each transect provides an estimate of the amount of exhumation that has occurred since that sample cooled through the Helium PRZ. For the Barskoon gorge, Kichikyzulsu, and Turgenaksu profiles, this implies 1 to 1.2 km, 0.7 to 1.8 km, and 1.5 km of exhumation, respectively, assuming that the exhumation rate remained constant. Assuming an average surface temperature of 10°C and a closure temperature of 65°C, ~55°C of cooling has occurred during this exhumation. In turn, this implies that the apparent geothermal gradient in the region of the three profiles was 55-46°C/km, 79-31°C/km, and 37°C/km, respectively.

The Barskoon gorge AFT samples have Dpar values which, together with the slow cooling rate, suggest a total annealing temperature of 100-110°C (Ketcham et al., 1999). Since the AFT and (U-Th-Sm)/He trends on the age-elevation plot are separated by about 850 m, this implies an apparent geothermal gradient of 53-65°C/km. This calculation uses the ~31±5 Ma onset of exhumation; a younger onset would imply that the exhumation rate has changed over the time sampled and therefore this simplistic calculation is precluded.

The small magnitude and slow rate of exhumation that has occurred suggests that there has been only limited advection and hence limited perturbation of isotherms. However, the calculated apparent geothermal gradients are surprisingly high. One possibility is that the isotherms are not horizontal and evenly spaced due to structural rotation or topographic perturbation. An alternate interpretation, at least for the Kichikyzulsu and Turgenaksu profiles, is that exhumation rates have increased since the samples cooled through the PRZ due to either climatically enhanced erosion or increased tectonism accompanied by enhanced erosion. The latter explanation suggests that the basal samples could have been exhumed from more typical depths of 2-3 km since passing through the helium PRZ.

The apparent exhumation rates reported herein are lower than those from the structurally similar Kyrgyz Range. The highest rates from that range, 0.3 to 1.5 km/Myr, are associated with the removal of ~1.5 km of sediment that formerly overlaid the range (Bullen et al., 2003; Sobel et al., 2006). Possible reasons for the discrepancy include a slower shortening rate, a thinner sedimentary cover, or less efficient erosion. Additional thermochronologic studies combined with an improved stratigraphic record will help to refine these interpretations concerning exhumation mechanisms and rates.

Acknowledgment

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References


PERTURBATION OF ISOHERMS BELOW TOPOGRAPHY: CONSTRAINTS FROM TUNNEL TRANSECTS THROUGH THE ALPS

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Thermochronology is often applied for deriving exhumation rates in orogenic systems, either by using age-elevation-relations (AER) or by combining cooling ages of different radiogenic systems with different closure temperatures (mineral pair method). These approaches rely on the assumption of flat-lying isotherms. Topography, however, influences the heat flow in the shallow crust, so that shallow isotherms follow the shape of topography in a dampened fashion, with compressed isotherms below valleys and widened isotherms below ridges (e.g. Stüwe et al., 1994, Mancktelow and Grasemann, 1997). This perturbation leads to potential overestimations of exhumation rates derived from thermochronology. The extent of isotherm perturbation largely depends on geologic and geomorphic parameters such as denudation rate, relief amplitude, topographic wavelength, geothermal gradient, and age of relief formation.

For this study, we collected samples along four tunnels and corresponding surface sections through the Western and Central Alps. These tunnel transects provide a unique opportunity for testing the influence of isotherm perturbation on thermochronology-derived exhumation rates under a given framework of denudation rate, topographic wavelength, relief amplitude and geothermal gradient (see also Focken et al., 2007). In addition, comparing the age patterns along the different transects yields important information about the late-stage evolution of the Alpine orogenic system. The studied transects are the Mont Blanc tunnel in the Western Alps, and the Simplon, Lötschberg and Gotthard tunnels in the Central Alps. All transects are situated in areas with typical geomorphic characteristics of active orogens, with a pronounced relief and high present-day uplift rates. If isotherms were perturbed during closure of the radiogenic system, then this should be reflected by the age patterns along the tunnel, with older ages beneath valleys and younger ages beneath ridges.

Geological Setting

The Mont Blanc, Lötschberg and Gotthard transects are situated within the External Crystalline Massifs (ECM), which form a discontinuous belt along the external periphery of the Central and Western Alps. They belong to the Helvetic realm of the Alps and are part of the pre-Alpine European crust. The Simplon transect, by contrast, belongs to the Penninic realm, which was thrust over the Helvetic realm along the Pennine frontal thrust (Fig. 1).

![Figure 1: Positions of the studied transects in the Western and Central Alps](image-url)
Results of AFT and AHe thermochronology

AFT data – tunnel: AFT ages along the Gotthard and Mont Blanc tunnels are uniform and cluster between 6 and 7 Ma and around 4 Ma, respectively. AFT ages along the Lötschberg and Simplon tunnels are more variable and range between ~3 and 7 Ma. The Lötschberg tunnel shows a trend to decreasing ages towards the south, whereas along the Simplon transect, AFT ages decrease slightly from the central to the northern part of the tunnel. For none of the four tunnels, AFT patterns are correlated with topography.

AFT data – surface: All sections show a rough correlation between age and elevation. For the same elevation level (2000 to 3000 masl), the Simplon transect yielded the oldest AFT ages, followed by the Gotthard and Lötschberg transects. The Mont Blanc transect yielded the youngest AFT ages (Table 1).

AHe data – tunnel: AHe ages along the Simplon transect are older (Table 1). Ages along the Mont Blanc and central and southern part of the Simplon tunnel uniformly cluster around 2 Ma.

AHe data – surface: Surface AHe ages of the same elevation level (2000 – 3000 masl) are similar for the Lötschberg and Mont Blanc profile, clustering around 5 Ma. AHe ages from the Simplon are also similar, but with a higher spread of ages (2 to 8 Ma). Oldest AHe ages are again observed for the Gotthard profile, ranging from 8 to 10 Ma for an elevation of 2000 – 3000 masl (Table 1).

Regional implication for the late-stage evolution of the Alps

The regional evolution of the four tunnel transects is described in more detail by Pignalosa et al. (this volume), Reinecker et al. (this volume), and Glotzbach et al. (2008a, b, and this volume). Here, we mainly compare the four different sections.

Compared to the other ECM, the Mont Blanc massif experienced the strongest exhumation. This is also reflected by the present-day high elevation and pronounced relief. No fault activity with significant vertical offset is detectable along the Mont Blanc, Lötschberg, and Gotthard transects. The whole Gotthard and the northern part of the Lötschberg transect seems to be largely unaffected by tectonic activity since ~10 Ma, and were constantly exhumed with a rate of ~0.5 km/Ma since ~10 Ma. We therefore suggest that the absence of tectonic activity led to a long-term exhumational steady-state, which in turn argues against a climatically-triggered increase in exhumation rates at ~5 Ma, as proposed by previous studies (e.g., Willett et al., 2006, Cederbom et al., 2004).

The southern part of the Lötschberg transect, by contrast, is influenced by normal faulting along the RSFZ, resulting in accelerated exhumation of that part of the transect since ~3.5 Ma. A slight increase in exhumation rates towards the Rhone valley is also observed along the northern part of the Simplon tunnel. Thus, the post-3.5 Ma exhumation pattern of that area is similar to the present-day uplift pattern, showing a pronounced maximum along the Rhone valley. The Simplon and Lötschberg transects show a similar AFT age range, whereas at elevation of 2000 to 3000 m, AFT ages along the Simplon transect are older (Table 1). This implies that between ~14 and 7 Ma, there was still differential vertical movement between the Lötschberg and the Simplon areas, which ceased at ~7 Ma. The slightly younger AHe ages of the Simplon tunnel may be explained by its higher present-day tunnel temperatures partly within the range of the He partial retention zone. The clustering of AHe ages around 2 Ma, particularly for the Mont Blanc and Simplon tunnels, may reflect the strong regional effect of Alpine glaciation on exhumation patterns (see also Glotzbach et al., Pignalosa et al., Reinecker et al., (this volume) for a more detailed discussion).

Effect of topography on shallow crustal isotherms

None of the tunnel transects revealed a simple correlation between age patterns and overlying topography, neither for the AFT system nor for the AHe system. The uniform AHe ages, particularly for the Mont Blanc and the central-southern part of the Simplon tunnel suggest that the pronounced present-day reliefs of these areas are young features which mainly formed after 2 Ma, presumably as a result of Alpine glaciation. Particularly for the Lötschberg and the Simplon transects, tectonic activity had a much stronger effect on age patterns and paleo-heat distribution than the shape of topography. Furthermore, as demonstrated for the Gotthard tunnel by Glotzbach et al. (2008a), positions of isotherms are also strongly controlled by advective and convective heat flow and internal heat production. Accordingly, no systematic overestimation of exhumation rates derived from surface profiles was detected. We tentatively conclude that for orogens with similar geomorphic and geologic characteristics as the Alps, AER can be used for deriving exhumation rates without the need for a “topography correction”. Our study also showed that the palaeo-positions of closure isotherms carry a wealth of information on the structural and geomorphic evolution in orogenic systems. We therefore suggest to use sampling approaches which involve vertical elevation profiles as well as horizontal iso-elevation profiles.

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The rugged St. Elias orogen in southern Alaska is one of the western hemisphere's few examples of active terrane accretion and is an ideal setting to investigate the interaction of climate and tectonics and the effect of glacial erosion on orogenesis (Jaeger et al., 1998; Meigs and Sauber, 2000) (Figure 1). The orogen has been constructed by oblique collision and partial accretion of the Yakutat microplate at the syntectonic bend in the Pacific-North America plate boundary since the Middle Miocene (Pflafrker et al., 1994; Bruhn et al., 2004). Deformation is currently focused on the windward flank of the orogen within a thin-skinned fold and thrust belt that accommodates ~3 cm/yr of shortening. This thrust belt may be approximated as a critical Coulomb wedge, as it lies above a subducting slab and is composed of poorly-indurated, offscaped Cenozoic stratigraphy with a tapered mean topographic profile. The orogen has been glaciated for the past 5.5 Ma (Lagoe et al., 1993), but the extent of glaciation increased following the Mid-Pliocene Warm Interval (after ~3-2.5 Ma) and again after ~0.7-1.0 Ma (Lagoe and Zellers, 1996; Lisiecki and Raymo, 2005). Presently about half the orogen is covered by temperate, wet-based glaciers, although ice coverage extended to the edge of the continental shelf during the Pleistocene glacial maximum (Péwé, 1975). The orogen has rugged coastal topography that receives heavy orographic precipitation of ~3-6 m/yr, which decreases to ~0.6 m/yr on the leeward flank of the range. Glacier equilibrium line altitude thus rises (and the extent of glaciation decreases) with increasing distance inland from the coast (Berger and Spotila, 2008). Sediment yield into the Gulf of Alaska has increased throughout the Neogene (Rea and Snoeckx, 1995), and has been very high throughout the Holocene and particularly in the past 100 years (Hallet et al., 1996; Jaeger et al., 1998). Widespread bedrock and detrital thermochronometry from the orogen indicate that exhumation has been rapid but spatially and temporally heterogeneous (O'Sullivan and Currie, 1996; Spotila et al., 2004; Johnston, 2005; Berger and Spotila, 2008; Berger et al., 2008; McAleer et al., in rev.; Berger et al., in rev.; Enkelmann et al., this volume). Here we highlight recent progress in understanding this orogen using bedrock thermochronometry.

Figure 1: Major structures of St. Elias orogen in southeast Alaska, plotted on a shaded relief map (from Berger et al., 2008). Note that area shown as Figure 2 does not correspond to Figure 2 here.
Figure 2: Apatite (U-Th)/He ages in the St. Elias orogen (from Berger and Spotila, 2008). The youngest AHe ages are contoured and occur near glacier ELA on the windward flank. Contours of 0.5, 0.75, and 1.0 Ma should approximate exhumation rates of 4.0, 2.7, and 2.0 mm/yr. Modern ELAs for southward-flowing glaciers are shown as thick blue lines. ELA during the last glacial maximum (LGM) is assumed to be ~300 m lower (Péwé, 1975) and approximated as the dark blue line. The “ELA front” is the zone between modern and glacial maxima ELA on the windward flank.

Figure 3: Cross section through the central St. Elias orogen (Figure 2), summarizing the orogen as a doubly-vergent, thin-skinned, windward-facing orogenic wedge that is heavily influenced by glacial erosion (from Berger et al., 2008). Inactive terrane boundaries are shown as irregular dashed lines. Active and inactive thrust faults are shown as heavy solid and dashed lines respectively. The proposed Bagley fault is shown as a southward-dipping thrust. The inactive CSEF is shown as offset by the Bagley fault at depth. Numbers by AHe sample locations are exhumation rates (mm/yr).

Figure 4: Relationship between topography, ELA, precipitation, and AHe age along a north-south profile (AA’, Figure 2) (from Berger and Spotila, 2008). The green box shows the “ELA front”, where mean Quaternary ELA (i.e. zone between modern and LGM ELA) intersects mean topography of the windward flank. The two curves of mean annual precipitation are from (A) a model that integrates regional data with an orographic function and (B) synthesis of regional data. AHe ages (red triangles) for samples within 50 km of AA’ were projected orthogonally. The dashed pink line approximates the trend of AHe ages, and the red box highlights the youngest ages.
The pattern of apatite (U-Th)/He ages across the orogen also reveals a potential association between long-term denudation and glacial erosion (Berger and Spotila, 2008). Cooling ages less than 1 Ma (and as young as 0.4 Ma, corresponding to exhumation 4–5 mm/yr, based on calculated closure temperatures and an elevated geothermal gradient that takes into account heat advection using a 1-dimensional thermokinematic model) are concentrated in a narrow, coast-parallel band near the glacier equilibrium line altitude (ELA) front, where mean Quaternary ELA intersects the windward flank of the orogen (Péwé, 1975) and thus where time-averaged, unit ice discharge within individual glaciers should be a maximum (Figure 2). This band of denudation is not correlated with individual faults, structural trends, or known concentrations of precipitation (Figure 4), and Berger and Spotila (2008) propose that it is produced by focused glacier sliding at or near the "ELA front". This hypothesis is consistent with a simplistic view based on theoretical predictions, 1-d numerical simulations, and short-term observations, that erosion along individual glaciers should scale with the flux of ice over rock (Andrews, 1972; Hallet, 1979). It is problematic, however, given that exhumation is rapid all along the ELA front, regardless of the variation in glacier size along-strike. If glacial erosion scales with ice flux, the most rapid denudation should occur beneath the largest glaciers (e.g. the Bering glacier). Yet long-term denudation and glacier drainage area (a proxy for relative differences in modern ice discharge) do not correlate along the ELA front. Berger and Spotila (2008) reconcile this by proposing a more complex conceptual model of orogen-scale glacial erosion, in which the most rapid long-term denudation occurs where the zone of high ice flux intersects the orogen's structural-topographic front. The lack of correlation between denudation and glacier drainage area within this zone suggests that the erosional power of all glaciers along the ELA front is sufficient to keep pace with tectonic rock uplift, that erosion by small glaciers and mass wasting are coupled to incision by large glaciers, or that large glaciers may have reached threshold of maximum erosion rate (e.g. over-deepening). This implies that glaciers may act as denudational "buzz saws" or excavators (Brozovic et al., 1997), that focus denudation near the narrow ELA front and can control the removal of crust from orogens. This interpretation supports theoretical models of orogenic wedges, in which glaciers focus denudation and partition deformation (Tomkin and Roe, 2007), and illustrates an important climatic control on orogenic behavior.

The bedrock cooling history through multiple closure temperatures also suggests that climate has played a significant role in the denudation and deformation of the St. Elias orogen (Berger et al., in rev.). Apatite fission-track and zircon (U-Th)/He and fission-track ages show that the pattern of exhumation inferred from apatite (U-Th)/He ages could not have been in place prior to the Quaternary. Cooling rates across the windward flank increased dramatically at ~1 Ma, but have remained slow and steady on the leeward flank. This acceleration in bedrock cooling corresponds to an increase in denudation rate from ~0.3 mm/yr to ~3 mm/yr in the core of the orogen. The timing of this change was roughly coeval with the intensification of glaciation at ~1–0.7 Ma (Lageo and Zellers, 1996; Lisiecki and Raymo, 2005). It also coincided with a ten-fold increase in sedimentation rate in the Gulf of Alaska (Rea and Snoeckx, 1995) and a shift in deformation away from the toe of the fold and thrust belt. Offshore seismic reflection images suggest that deformation within the Pamplona Zone terminated at about the time that glaciers advanced onto the continental shelf during the mid-Pliocene (Berger et al., in rev.). This suggests that a cessation in shortening within the offshore portion of the wedge was coeval with increased onshore denudation and lowering of the submarine critical taper by subsequent sedimentary burial. If correct, this implies that Quaternary climate change focused glacial denudation and reorganized deformation within the orogenic wedge, including out-of-sequence thrusting and acceleration of backthrusting in order to maintain critical taper. This is consistent with model results that indicate that active wedges should contract in response to increases in erosion (Whipple and Meade, 2004; Tomkin and Roe, 2007).

References

APATITE FISSION TRACK THERMOCRONOLOGY, EXTERNAL HUMBER ZONE, WESTERN NEWFOUNDLAND APPALACHIANS: APPLICATION OF COUPLED MULTI-COMPOSITIONAL INVERSION MODELING AND IMPLICATIONS FOR PETROLEUM PROSPECTIVITY

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The external Humber Zone of the Appalachian Orogen of western Newfoundland is characterized by a Cambro-Ordovician carbonate-dominated platformal succession that was structurally overridden and deformed in Middle Ordovician through Devonian times (Taconian, Salinian, and Acadian orogenies) and locally disrupted during the Carboniferous (e.g., Waldron et al., 1998). Contractional structures are largely thin-skinned in style (low-angle, large-displacement thrust faults), and are crosscut locally by late thick-skinned (basement-involved) thrusts. The Early to Middle Ordovician Taconian Orogeny involved initial obduction of ophiolitic complexes as well as structural slices of deformed Cambrian shelf rocks, some high in organic content. Post-Taconian deformation, which included significant displacement on low-angle thrusts, resulted in structural juxtaposition and folding (potential petroleum traps) of platform carbonates (potential petroleum reservoirs) above organic-rich rocks (potential petroleum sources). The largest traps involved the late-stage inversion of thick-skinned normal faults, which were initiated in the Taconian foreland prior to arrival of the thin-skinned Humber Arm Allochthon and the development of a structural triangle zone (tectonic wedge) along the leading edge of the orogen in Devonian time (e.g., Stockmal et al., 1998, 2004; Cooper et al., 2001).

The timing of thermal maturation of the potential source rocks relative to the timing of formation of the major structural traps has obvious and critical implications for the petroleum prospectivity of this area. Hydrocarbon seeps, first recognized nearly 200 years ago, have spurred sporadic exploration for over a century. The most recent round of serious exploration occurred in the 1990s, with much reduced activity continuing to the present. The first modern well, Port au Port #1, was drilled on Port au Port Peninsula in 1994-1995 and discovered the Garden Hill South field, which produced light sweet crude oil (51 °API). Follow-up wells, including one in the near offshore in the Gulf of St. Lawrence, have been disappointments. The principal challenge is development of a reliable and predictive reservoir model. The leading model involves karstification associated with a flexural bulge unconformity, coupled with a reservoir model. The leading model involves karstification associated with a flexural bulge unconformity, coupled with a reservoir model.

For apatite fission track (AFT) analyses were gathered mainly from outcrop but also from two of the recent exploration wells on the Port au Port Peninsula. These samples span the entire stratigraphic section from the crystalline Grenville-age (ca. 1 Ga) basement, through the Cambrian-dominated Lower Cambrian platformal and slope successions, to the Middle Ordovician to Lower Devonian clastic foreland succession, and finally to the remnants of a regional Carboniferous to Permian successor basin (the Maritimes Basin). Structurally, samples are from the far-transported Humber Arm Allochthon, the parautochthonous basin and platformal succession, the essentially autochthonous foreland succession (structurally uplifted above the leading-edge triangle zone), and the post-orogenic overlap succession. All samples show significant annealing with mean track lengths ranging from 11.5 to 12.9 microns. Of the 20 samples we have modeled in detail, ten have a full suite of probe analyses and three have partial analyses (F, Cl, OH, O). All but two of the 20 pass the χ2 test for uniformity, and all have been examined for possible multiple age populations using the binomial peak-fitting program, Binomfit (Brandon, 2002). The two samples that fail the χ2 test are cuttings samples from the Port au Port #1 well, and Binomfit clearly indicates discordant grains (three grains out of a total of 34 in one sample, and one grain of 36 in the other) that are likely caved from higher up the borehole. Removal of the contaminant grains results in solid χ2 passes. Those samples for which we have full probe analyses have been examined for possible multiple compositional populations, using measured ages and track lengths, and the calculated t0% parameter of Carlson et al. (1999). The majority of grains are fluorapatites, with some modest substitution of Ca by Na, Mn, and Fe. Calculated t0% values across the suite of samples range from 0.5088 to 0.8621, with mean values of interpreted populations ranging from 0.6513 to 0.8488.

The low-temperature thermochronology of this structurally complicated region is assessed using an updated version of the inversion routine described by Issler et al. (2005) that allows for simultaneous inversion of samples with multiple compositional populations. The multi-kinetic inversion program (AFTINV) yields an objective set of thermal histories that fit observed AFT ages and track length distributions. AFTINV allows for incorporation of various geological constraints (e.g., depositional age, overlying stratigraphy, unconformities, limits to erosion and deposition rates, etc.), as well as thermal maturation indicators, if available (e.g., %R0, CAI, Tmax, etc.). The ability of AFTINV to handle multi-kinetic populations in a single sample is essential to interpreting some of the western Newfoundland AFT samples. AFTINV generates a set of forward-modeled time-temperature histories (nominally 300) that satisfy all input constraints. For some samples run as single populations, AFTINV will not produce more than a few (if any) acceptable time-temperature histories even after tens of millions of forward models. However, these same samples, run simultaneously as separate populations (as many as four), will result in a full set of 300 solutions in a few million forward models or less.

Assessment of this suite of 20 samples indicates that following post-depositional burial and post-orogenic erosion, all AFT samples were refitted into the AFT partial annealing window (~60-120 °C; ~oil window) in post-Visean times, due to burial beneath the Carboniferous to Permian Maritimes Basins. The magnitude and timing of peak temperatures, however, are dependent in part upon structural position with respect to the inverted thick-skinned thrusts. On the Port au Port Peninsula, the principal thrust-inverted thick-skinned fault is the Round Head Thrust (RHT), a few million forward models of which lies the Garden Hill South field referred to...
above. At the deepest stratigraphic levels within the Cambro-Ordovician platform, in the immediate hanging wall of the RHT, peak temperature occurred prior to fault inversion (during Devonian Acadian orogenesis). At equivalent stratigraphic levels in the RHT footwall, and at shallower levels in both footwall and hanging wall, peak temperatures were not achieved until post-Viséan burial beneath the Maritimes Basin.

Peak thermal maturity therefore post-dated the late Acadian development of large, thick-skinned structural traps. Thus, these structures have high potential prospectivity, as evidenced by the initial discovery well. Modeled AFT samples from western Newfoundland, Anticosti Island, and the Gulf of St. Lawrence all indicate that the Maritimes Basin was substantially thicker and of greater extent than commonly believed, with concomitant implications for petroleum exploration throughout the region.

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SYN-OROGENIC EXTENSION: LATE MIocene EXHUMATION OF THE SHAXDARA GNEISS DOME, SOUTHERN PAMIRS

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Great advances in the understanding of collisional orogens have resulted from research in the Tibet–Himalaya system, but its westward continuation, the Pamir Mountains remains little studied. The Shaxdara gneiss complex of the southwestern Pamirs is a large (~100×300km) outcrop of high-grade metamorphic rocks, previously regarded as Archean-Proterozoic basement accreted to Asia during Paleozoic or Mesozoic (Vlasov et al., 1991). New zircon and monazite U(Th)/Pb ages and field mapping suggest a Paleozoic-Mesozoic origin of the paragneisses metamorphosed and intruded with in a Cretaceous active continental margin and overprinted by late Oligocene–Miocene crustal thickening.

Structural observations and apatite fission-track and (U-Th)/He thermochronology reveal rapid Miocene exhumation to upper crustal depth under N-S extension, contemporaneous with the ongoing India–Asia convergence. Syn-orogenic extension to such extent entailing gneiss-dome formation is unparalleled in the Himalaya–Tibet orogen. This exposure of deep crustal levels in the Pamirs provides insights into mid-lower crustal processes largely concealed in Tibet and offers new possibilities for the understanding of collisional orogenies.

Pre-Himalayan history

The Shaxdara gneiss dome encompasses most of southern Tajikistan and extends westward into Afghanistan. The central part of the dome (southwest Tajikistan) consists of high-grade migmatitic gneisses and (garnet)-biotite-schists, locally kyanite- and sillimanite-bearing, and subordinate calc-silicates and marbles; lithologies are similar in the (western) Afghan part (Vlasov et al., 1991). Along the Afghan–Tajik border the dome is deeply incised by the N-S running Pjansch valley, creating up to 2500m topographic relief.

Less topographic relief exists in the eastern part of the dome, which is partly covered by Quaternary sediments. To the south and northeast gneisses pass into the late-Paleozoic Wakhan slates (e.g. Buchroithner, 1980) and Permian to Jurassic marine (meta-)sediments and reef carbonates, which also outcrop widely in the southeastern Pamirs (Leven, 1995). Locally, Paleozoic (meta-)sediments have been mapped overlying the gneisses both in the central and eastern part of the dome. We interpret the Shaxdara paragneisses as high-grade equivalents of the Paleozoic-Mesozoic elastic-carbonaceous sequence.

Cretaceous plutonic rocks are prevalent in the Southern Pamirs (Vlasov et al., 1991) and belong to a continuous magmatic belt of ~200 km width. It is attributed to flat-slab northward subduction of young oceanic lithosphere of the Shyok back-arc basin and collision of the Kohistan-Ladakh island arc with Asia ~80 Ma (Rolland et al., 2000); the active continental margin can be traced to the Lhasa block of southern Tibet (Gangdeze arc; Schwab et al., 2004).

After accretion of the Kohistan-Ladakh arc continuous crustal thickening and shortening caused protracted sillimanite-grade metamorphism and magmatic activity in the Shyok suture area, with a major magmatic pulse ~24 Ma (Fraser et al., 2001). Latest Oligocene–late Miocene zircon and monazite U(Th)/Pb ages from pegmatites, granites, and migmatitic gneisses from the Shaxdara dome (unpublished data) and early to late Miocene hornblende and mica \(^4\)Ar/\(^39\)Ar cooling ages (Hubbard et al., 1999; own unpublished data) suggest that in the Southern Pamirs upper amphibolite grade conditions likewise persisted through the Oligocene-Miocene.

Miocene exhumation

The overall structure of the Shaxdara gneiss is subhorizontal layering of migmatitic paragneisses. Migmatization produced melts that formed granitoids of variable size. Migmatization and intrusion of large intrusive bodies occurred syn-kinematic to N-S extension. Deformation is overwhelmingly top-to-south flow evolving form high-grade to low-grade conditions (syn-migmatitic shear zones, biotite–sillimanite–andalusite–amphibole, polyphase shear zones, brittle-ductile shear zones), suggesting a continuous process of top-to-N-S extension under N-S to NW-SE extension from high-temperature migmatization and granitoid emplacement to upper crustal brittle conditions.

A major normal fault is observed at the southern dome margin crosscutting shallow south-dipping mylonitic gneisses and juxtaposing them against Late Triassic metapelites. We interpret a major normal fault zone (South Pamir Fault) following the Pjansch valley along the southern dome margin, which accommodates exhumation of the Shaxdara gneiss dome, as evidenced by our structural data and the pronounced change in metamorphic grade across the Pjansch valley.

Apatite fission-track ages from 23 samples from the Shaxdara dome document late Miocene cooling. Two age–elevation profiles in the west-central dome indicate rapid late Miocene (4-9 Ma) exhumation at a rate of ~1–2 mm/yr. Ages increase systematically with distance from the South Pamir Fault from 3.6 Ma directly at the southern Pjansch river to ~9 Ma at the northern dome margin. This age variation and our structural analysis point to structurally controlled exhumation of the Shaxdara gneiss starting along the northern dome margin at least at 10 Ma and progressively exhuming the footwall of a major south-dipping shear zone; its southern margin is outlined by the southern Pjansch River. A rolling-hinge model (Wernicke and Axen, 1988) of exhumation along a detachment fault, the South Pamir Fault, is envisaged to account for late Miocene cooling.

The eastward continuation of the South Pamir Fault beyond ~72°30’E is enigmatic. We tentatively propose that it passes into a low-angle detachment fault dipping eastward beneath low-grade sedimentary rocks of the southeastern Pamirs; this shear zone has previously been interpreted as low-angle thrust beneath a nappe rooting in the Rushan-Pshart suture zone to the north (Burtman and Molnar, 1993; Schwab et al., 2004).

Two granite samples from structurally high levels from the northeastern dome margin yield consistent ages of 15.7 and 15.9 Ma, about 9 Ma older than expected based on their elevation and distance from the South Pamir Fault. In contrast, one sample from a lower elevation is in agreement with the general trends. We suggest that the two older
samples are located structurally above the detachment and represent fault bound blocks that have been dragged northwards during continuing exhumation along the South Pamir fault.

Tectonic denudation ceased in the early Pliocene. Preliminary apatite (U-Th)/He ages may indicate a renewed episode of rapid cooling starting in the late Pliocene or Pleistocene, which is likely related to river incision in the central dome and may account for the high topographic relief there. The pronounced difference in topographic relief between the eastern and west-central dome argues against a purely climatic cause for Pleistocene river incision.

What drives Miocene extension?

Miocene N-S extension in the Pamirs is coeval with ongoing N-S directed convergence between India and Asia at a rate of 4.8 cm/yr (Le Pichon et al., 1992). The en echelon arrangement of several gneiss domes in the western Pamirs suggests a common origin as antiforms resulting from crustal thickening and sinistral transpression along the western margin of the Pamirs. Transpression resulted from indentation of the western syntax of India into Asia and an overall anticlockwise rotation of India during its northward path (e.g., Le Pichon et al., 1992). Transpression is also evident from the Darvaz and Herat strike-slip faults and trend of fold-thrust belts in the Tajik foreland basin.

We attribute doming and extension to overall transpressional thickening of the entire crust by frontal intracontinental subduction and long-wavelength-low-amplitude buckling within the western Pamirs and concurrent to upper crustal extension compensating for excess thickening. Upper crustal extension may have been facilitated by thermal weakening due to Tertiary intrusions that are mostly confined to the domes. A relation between onset of extension from 4.8 to 4.5 cm/yr at 7 Ma and concomitant clockwise rotation of the convergence direction (Le Pichon et al., 1992) likely put an end to extensional doming in the western Pamirs.

Synorogenic extension has been documented earlier in the Himalaya (South Tibetan Detachment fault; e.g., Burchfiel et al., 1992) and proposed to account for the Kongur Shan normal fault in the eastern Pamirs (Brunel et al., 1994). Identification of an extensional gneiss dome of comparable size to the Shaxdara dome is however unparalleled in the Himalaya-Tibet system.

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KINEMATIC AND THERMAL HISTORY OF THE CHUKUNGKENG ANTICLINE, CENTRAL TAIWAN

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Taiwan Orogeny has resulted from oblique collision between the Luzon arc and the passive continental margin of the Eurasia plate since 6.5 Ma. The Western Foothills contains upper Oligocene to Neogene shallow marine to shelf sedimentary rocks and synorogenic upper Pliocene and Pleistocene strata. A classic fold- and thrust belt has developed during collision and imbrication has repeated these strata in the orogenic wedge. In contrast to many fault-bend folds developed around the western foothill, the Chukuangkeng Anticline is a tight fold with detachment folding mechanism and it is also a major hydrocarbon occurrence in Taiwan. Here we use the apatite fission track dating to reveal the thermal history and kinematic history of the Chukuangkeng Anticline. We collected samples from exposed outcrop and from a 2600 m deep well, located on fold axis of the anticline. We found that below the mid-Miocene strata, all strata are totally reset and the reset ages are from 1.5–2 Ma. Considering the total shortening of the Chukuangkeng Anticline is 15 km and we calculate average shortening rate is 7.5–10 mm/yr since 2 Ma. Assuming the average geothermal gradient is 25°, the uplift rate is 2.2–2.9 mm/yr.
GEO- AND THERMOCHRONOMETRIC CONSTRAINTS ON TERTIARY NORMAL FAULTING AND BASALTIC VOLCANISM ALONG THE CENTRAL ARABIAN FLANK OF THE RED SEA RIFT SYSTEM

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The Red Sea rift system is one of the best-exposed examples of continental rifting and has significantly contributed to our understanding of rupturing modes and mechanisms of continental lithosphere. Critical geologic data used to determine the tectonic evolution of the Red Sea rift system come mainly from two Gulf of Suez and the Egyptian and Yemeni margins of the Red Sea; the rift flanks in Sudan and Saudi Arabia have remained largely unstudied. To improve our understanding of this system, this study investigates the timing of development of extensional structures and rift-related Tertiary basaltic volcanism along the central Saudi Arabian flank of the rift system, usingapatite and zircon (U-Th)/He thermochronometry on the exhumed rift flank and magnetite (U-Th)/He and whole-rock ⁴⁰Ar/³⁹Ar dating of Harrat basalts that interact with rift-related extensional faulting.

Geo- and thermochronometric techniques, coupled with structural and stratigraphic analysis, are used to elucidate the structural evolution of the main rift border fault system and structurally-controlled extensional basins parallel to the trend of the main Red Sea rift within the Arabian Shield. Constraints on the dynamics of rift flank deformation are achieved through the collection of long-base line thermochronometric transects that traverse the entire Arabian shield from the coastal escarpment to the inland sedimentary cover sequences and short-base line elevation transects in the footwall of major normal faults along the main rift border and with inland extensional basins (Fig. 1). Long-base line transects aim to resolve the timing of rift flank uplift and exhumation and are coupled with new geophysical models predicting the pattern of lithospheric modification during the rupturing of continental lithosphere. Detailed vertical transects, on the other hand, are used to constrain the timing of normal faulting to better understand the spatial and temporal evolution of rift-related normal faulting both along strike and across the entire rift margin. This combined approach allows for the reconstruction of the evolution of early rift architecture (incl. the importance of pre-existing structural fabrics), strain distribution during progressive rifting, and subsequent wholesale modifications of the rift flank due to thermal and isostatic factors.

The fieldwork has focused on two areas along the central portion of the Saudi Red Sea margin in the Yanbu and Medinah areas. The main rift-margin escarpment in the Yanbu region is characterized by complex border-fault system, juxtaposing exhumed Precambrian rocks in fault-bound footwall block against Oligo-Miocene syn-rift strata. The area is also characterized by post-faulting uplift of wave-cut platforms and middle Miocene carbonate platforms. Several structurally-controlled extensional basins inboard from the main coastal escarpment and border fault system parallel the trend of the main Red Sea rift and outline a much broader rift well beyond the modern rift margin. The most prominent of these extensional basins is the NW-trending Hamd-Jizil basin located north of Medinah (~130 km inland), measuring ~200 km along strike and up to 20 km in width (Fig. 2). The Hamd-Jizil basin is structurally characterized by an en-echelon set of two diffusely-linked half-grabens (Hamd and Jizil) that are bound along their NE margins by NW-SE-trending high-angle normal faults that appear to be controlled by the pre-existing structural grain produced by the Late Proterozoic Najd Fault System. The incised half-graben fill exhibits a thick stack of syn-rift sandstones and conglomerates and is overlain by syn- to post-extensional Tertiary basalt flows of adjacent harrat volcanic fields. Offset basalt flows cap syn-rift siliciclastic sequences and Neoproterozoic rocks on either side of a major basin-bounding fault in the Hamd half-graben. Near the southern terminus of the Hamd-Jizil Basin, several generations of basalt flows have been cut by basin-internal faults that show differential displacement along the basin-bounding fault in Wadi al Qattar. In addition to bedrock thermochronometry, this study also employed magnetite (U-Th)/He and whole-rock ⁴⁰Ar/³⁹Ar dating of syn- and post-kinematic basin flows, to determine eruption ages of Harrat volcanism, constrain the timing of rift-related normal faults, and shed light on the post-rift geomorphic evolution of the originally internally-drained Hamd-Jizil basin.

Preliminary (U-Th)/Heapatite and zircon analysis of samples from both short- and long-base line transects reveal a temporally spatially distinct cooling history for the central rift flank (Fig. 2). At the north end of the field area, Jabal Samar, an exhumed footwall suspected to be related to Red Sea rift development, shows a mid-Miocene apatite cooling age of 14.7 ± 0.9 Ma. Similarly, a silicified felsic volcanic rock from the uppermost syn-rift sequence in the central Hamd half-graben yields a zircon (U-Th)/He age of 13.6 ± 1.1 Ma. In stark contrast, apatite (U-Th)/He ages from a vertical transect (VT - 2) in the handing wall SW of the Jizil half-graben and apatite and zircon (U-Th)/He ages from Jabal al Bayda show Permo-Triassic apparent cooling ages (210 – 240 Ma), reflecting background cooling ages found throughout the Arabian Shield.

In conclusion, early Red Sea rifting affected a wide area well inboard from the prominent modern Red Sea escarpment and the main border-fault system. Geo- and thermochronometric constraints coupled with structural and stratigraphic observations illustrate that during early to middle Miocene times extensional faulting occurred in the Hamd-Jizil half graben system contemporaneously with faulting along the main border fault complex in the central portion of the Saudi Red Sea margin. Faulting appears to have stopped in the Hamd-Jizil basin region and the main border complex and migrated basin-ward in the middle Miocene, contemporaneously with rift reorganization and the establishment of the Dead Sea-Gulf of Aqaba transform. Newapatite and zircon (U-Th)/He ages from the unextended Arabian Shield appear to be related to wide-spread denudation of the Arabian-Nubian Shield during Neo-Tethyan rifting.

Figure 1: Regional map of Red Sea showing full extent of sample locations for geo- and thermochronologic analysis and area of fieldwork concentration (Figure 2).

Figure 2: Simplified structural map of Hamd-Jizil Basin including both completed and pending (U/Th)/He age results.
THERMOCRONOLOGY OF FAULT ZONES: CONCEPTS AND EXAMPLES

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Quantitative assessment of heat generation and transfer along faults and associated with fault movement is of primary importance in understanding the dynamics and structural history of faulting [e.g., Scholz, 1996], as well as in constraining the heat budget and tectonocly evolution of mobile belts [e.g., Fukahata and Matsu’ura, 2001]. Among a range of methodologies available to investigate thermal regimes around faults, thermal history analysis using radiometric dating methods is extremely useful because it reveals temporal changes of temperature in the fault zone rocks. This approach also allows us to place important constraints upon the ages of fault motions.

Zircon fission-track thermochronology

FT investigations of rocks from fault zones require consideration of two factors that are worth special attention. First, fault rocks may have been subjected to hydrothermally-pressurized conditions at some stage during fault development. To evaluate this factor, laboratory heating experiments of zircon were carried out using a hydrothermal synthetic apparatus [Brötz et al., 2002; Yamada et al., 2003]. The observed FT annealing characteristics are indistinguishable between the heating carried out at atmospheric and hydrothermally-pressurized conditions. This probably validates the application of annealing kinetics based on the experiments at atmospheric conditions to rocks subjected to hydrothermal conditions in nature, such as those in fault zone and plate subduction settings.

Second, frictional heating along a fault is a short-term phenomenon with heating durations on the order of seconds, significantly shorter than the conventional laboratory heating having durations of ~0.1 to 10000 hours. Thus, high-temperature and short-term annealing experiments were newly designed and conducted using a graphite furnace coupled with infrared radiation thermometry [Murakami et al., 2006]. Their results show that the observed track length reduction by 3.6 - 10 sec heating at 599° - 912°C is slightly more advanced than that predicted by the FT annealing kinetics based on the conventional laboratory heating for 4.5 min – 10000 hr at 350° – 750°C [Yamada et al., 1995b; Tagami et al., 1998]. The short-term annealing data were used to revise the kinetics [Yamada et al., 2007].

In addition, as a more general problem, the radiation damage accumulated through time may alter the annealing characteristics and, accordingly, kinetics function. Our recent results of 1 hr laboratory heating experiments indicate that annealing temperatures are indistinguishable for zircons of ~0.6 to 70 Ma (spontaneous track density of ~0.05 to ~7 x10³ cm⁻²) [Matsu’ura et al., in prep.]. The results, coupled with previous data, imply that an identical annealing model works well for many of the Cenozoic and late Mesozoic zircons.

Application to the Nojima fault

Zircon fission-track (FT) analysis has extensively been conducted by our group on the Nojima fault, which was activated during the 1995 Kobe earthquake (Hyogoken-Nambu earthquake; M7.2) [Tagami et al., 2001; Murakami et al., 2002; Murakami and Tagami, 2004; Tagami and Murakami, 2000, 2007]. Rock samples were collected from the University Group 500 m (UG-500) borehole, Geological Survey of Japan 750 m (GSJ-750) borehole, the fault trench at Hirabayashi, and nearby outcrops. In the two boreholes that penetrate the fault at depth, zircon FTs were partially annealed in the samples nearby the fault. The age of onset of cooling from the zircon partial annealing zone (ZPAZ) was estimated by the inverse modeling of FT data using the Monte Trax program; i.e., ca. 4 Ma within ca. 3 m (in the hanging wall only) from the fault plane in the UG-500, and ca. 31-38 Ma within ca. 25 m from the fault in the GSJ-750. On the basis of one-dimensional heat conduction modeling as well as the general positive correlation between the FT annealing and deformation/alteration of borehole rocks, those cooling ages in both boreholes probably represent ancient thermal overprints by heat dispersion or transfer via fluids in the fault zone. Calculation of in-situ heat dispersion indicates the resulted temperature increase of ca. 1 degree C, if the frictional heat is homogeneously and instantaneously dispersed via fluids to a 3 m-wide zone. Because such a small temperature increase does not advance significantly the zircon FT annealing [Yamada et al., 1995b, 2007; Tagami et al., 1998], it is likely that the thermal overprints were caused by migration of hot fluids along the fault zone from deep crustal interior.

For the fault trench samples, zircon FTs of the 2 - 10 mm thick pseudotachylite layer were totally annealed and subsequently cooled through ZPAZ at ca. 56 Ma, which is interpreted as the time of (final stage) of pseudotachylite formation. It is suggested, therefore, that the present Nojima fault was formed in the Middle Quaternary by reactivating an ancient fault initiated at ca. 56 Ma at mid-crustal depth.

Also conducted were (1) zircon (U-Th)/He analysis of the Nojima pseudotachylite layer and surrounding rocks [Reiners et al., 2006] and (2) K-Ar and Ar/Ar analysis of gouge samples of Nojima fault mainly collected on outcrops [Zwingmann et al., in prep.]. These additional results will also be incorporated to give a better picture of the tectonocly history of the Nojima fault.

Other examples

I will also present results from other areas: (1) zircon FT analysis of a boundary fault between the Okitsu mélange and overriding coherent unit of the Shimanto accretionary complex, which is assigned to ancient seismogenic zone in the plate subduction zone (Sato et al., in prep.) and (2) zircon FT and U-Pb analysis of a pseudotachylite of the Asuke shear zone (Murakami et al., 2006). These data will help us to further extend the methodological remarks on the thermochronology of the fault zones.

References


THERMOCHRONOLOGY THROUGH FISSION TRACKS IN ZIRCON: METHODOLOGICAL STUDY AND APPLICATION

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Abstract
Analyses of zircon surface through Optical Microscopy, micro-Raman spectroscopy and Scanning Electron Microscopy (SEM) showed that theetching varies from grain to grain. This also happens in different areas of the same zircon grain surface doing with that just in a small area of the grain the tracks density is uniform. Through the analyses done in this study we can see that these grains (that depending on the sample is most in the mineral separation) can be used to determine its age. This methodology was used to determine the ages of samples collected in Bauru Group basin located in north of Paraná basin at southeast São Paulo state of Brazil. The fission tracks ages results are compatible geologically.

Introduction
Zircon can be used as natural detector of $^{239}$U fission fragments determined through the Fission Track Method. These fragments leave tracks in the zircon lattice with few angstroms of diameter. The fission track analyses through optical microscopy can be accomplished after a convenient chemical etching of the zircon samples with NaOH:KOH (1:1), to (225 ± 2) ºC, for periods among 4-72 hr (Tagami et al., 1990, Garver, 2005). The zircon samples in this work were etched for 18 hr.

It was observed that the etching varied of grain for grain and in some cases in the surface of the same grain. This phenomenon is known as etching anisotropy. This anisotropy affects uniform revelation of fission tracks in the grain surface. With the objective to study this phenomenon, micro-Raman spectroscopy and Scanning Electronic Microscopy (SEM) analyses had been carried out. Both the characterization techniques had been used to determine which grains areas were indeed zircon. The micro-Raman spectroscopy evaluated the crystalline lattice in the areas with and without fission tracks and the SEM technique evaluated chemical composition.

Through this methodology and the Fission Track Method (FTM) material was characterized from the Bauru Group basin located in the north part of the Paraná basin at southeast São Paulo state of Brazil.

Methods
The micro-Raman spectra (showed in the figures below), in the x-axis has the wavenumber/em$^{-1}$ of each characteristic element of zircon and in the y-axis has the relative intensity. Measurements were made with the laser 514.5 nm, with potency of 100% perpendicular to the c-axes of the zircon. In all cases the spectra are similar to the standard zircon of Mud Tank, Australia, with almost perfect crystallization (Palenik et al 2003; Menneken et al., 2007). The SEM images were obtained with an Oxford Instruments model LEO 430 with a resolution of 108 eV, accelerating voltage 20 kV, working distance of 19 mm, beam current 3 x 10$^{-8}$ A and vacuum of 1 x 10$^{-4}$ torr. SEM images were obtained with nominal increase of 1030x, while optical images with nominal increase of 100x, 200x and 1000x.

To evaluate crystalline-damage in the zircon as a function of the etch time, samples were etched for six hours sequential etches between 0 and 18 hours. While that to study the etching anisotropy the samples had been submitted for 18 hours etch only.

Results
As the grains reacted to etching, micro-Raman spectroscopy studies had been carried out to evaluate two factors: i) the crystalline-damage in function of the etching; and ii) etching anisotropy. In i) we used a sample from João Pessoa, Paraíba State, Brazil (courtesy of Millennium Inorganic Chemicals Company), called JP here. This zircon was submitted to micro-Raman spectroscopy without etching, with 6, 12 and 18 hours of etching, respectively. We can observe the existence of three different types of zircon grains, here called homogeneous, anomalous and inhomogeneous, respectively. The homogeneous grains have distributed superficial uniform tracks while that the anomalous lose all its crystalline structure after the first six hours etching. The inhomogeneous grains have small areas that preserve the crystalline structure and in these areas there is a uniform track distribution. Figure 1 shows homogeneous (A), anomalous (B) and inhomogeneous (C) zircon grains.

The results indicate that the zircon crystalline-damage increases in function of etching time in the homogeneous grains (figure 1-A) but there is not a total lost of crystalline structure in heavily etching, so these zircon grains are the ideal for dating. On the other hand in the anomalous zircon grains (figure 1-B) the structure crystalline is totally lost in the first etch process (6 h). In the inhomogeneous zircon grains (figure 1-C) there are two areas where the track density is uniform and its structure crystalline is not lost after the final etch process (18 h). After a SEM analyzed of these zircon grains we can see that in the areas where the track density is uniform its chemical composition is similar to the standard zircon (68% ZrO$_2$ and 32% SiO$_2$, Palenik et al 2003; Menneken et al., 2007). On the other side the areas where there are no tracks and the crystalline structure is lost they have a chemical composition very different of the standard zircon (73.82% ZrO$_2$, 0.72% SiO$_2$, 19% CO$_2$, 1% Na$_2$O and 0,65% K$_2$O). This result suggests that the inhomogeneous zircon grains also can be used to determine fission track ages.

In figure 2 there are two areas in the zircon grain that have a uniform tracks density and another area where there that lacks tracks, yet both areas maintain the crystalline structure after the standard etch. This phenomenon is known as etching anisotropy. To evaluate this, initially, micro-Raman spectroscopy was used to observe if there is some alteration in the zircon lattice crystalline that justified this anisotropy.


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Zircon samples from Bauru Group basin, Brazil, had been used in this analysis, these kind of grains are different those analyzed above. The figure 2a and 2b shows a zircon grain that shows this anisotropy. It is important to emphasize that this characteristic coexists in many zircon grains of the sample after mineral separation. These kinds of grains have a uniform uranium distribution indicate by external detector method. In figure 2a we can see that the two areas (figure 2b, area A and area B) with and without tracks present similar micro-Raman spectra after the etching but the main band width (Full Width Half band-Maximum, FWHM) of B area is larger than A area. This variation must simply to the presence of tracks in area B, but it does not indicate any alteration of lattice crystalline of view point the micro-Raman spectroscopy. That is, this analyze not explain the anisotropy phenomenon then SEM measurements were accomplished in the same zircon grain.

<table>
<thead>
<tr>
<th>Sample</th>
<th>ZCOB31</th>
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<tbody>
<tr>
<td>Area</td>
<td>ZCOB31</td>
</tr>
<tr>
<td>A</td>
<td>ZCOB31</td>
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<tr>
<td>B</td>
<td>ZCOB31</td>
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<tr>
<th></th>
<th>ZCOB31</th>
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<tbody>
<tr>
<td>ZrO₂ (%)</td>
<td>68,41 ± 0,41</td>
</tr>
<tr>
<td>SiO₂ (%)</td>
<td>30,73 ± 0,61</td>
</tr>
<tr>
<td>HfO₂ (%)</td>
<td>1,14 ± 0,13</td>
</tr>
</tbody>
</table>

*Table 1: Chemical composition obtained through SEM*
The Scanning Electronic Microscopy, SEM, was used to analyze if there are some chemical element that could explain the etching anisotropy. The results are presented in Figure 3 and Table 1. The yellow points indicate where the chemical composition was analyzed.

In Table 1 we can see that the mean values (15 points in area A and 12 in area B) of ZrO$_2$, SiO$_2$ and HfO$_2$ in the areas A and B of the zircon grains are statistically compatible. Therefore there is no variation of the zircon main chemical elements (see for example, Murakami et al, 1991, Zhang et al, 2000 and Utsunomiya et al., 2004) in the areas with and without tracks. Of these analyses we can concluded that maybe other chemical element, that escape of the SEM resolution, can be influencing the occurrence of this phenomenon. This phenomenon of anisotropy also was observed in a zircon natural monocrystal. The age of these kinds of grains (inhomogeneous and anisotropic) also can be accomplished, in the areas where the tracks density is uniform, trough fission track External Method.

This methodology was used to determine the fission track ages of samples collected in Bauru Group basin located in north of Paraná basin at southeast São Paulo state of Brazil. The fission track ages results are compatible geologically (Rocha Campos et al., 1988; Almeida e Carneiro 1998).

### Conclusion

The results indicate that the homogenous zircon grains are the most appropriate for determine the fission track age but in general the amount of these grains is sparse in the mineral separation. On the other hand the inhomogeneous zircon grains (and those with anisotropy effects) that are more frequent in the mineral separation also can be used through External Detector Method of fission track dating. Another important application is in samples from hydrocarbon exploration wells where the amount of zircon grains is very small.

### Acknowledgement

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DENUDATION OF THE HIMALAYAN OROGEN

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Introduction

The Himalaya, extending ~2500 km from the western syntaxes, Nanga Parbat, to the eastern syntaxes Namche Barwa is forming the southern termination of the Tibetan Plateau. This large convergent orogen is marked by spatial variations in deformation and climate, both of which would suggest non uniform exhumation histories of rocks forming the mountain front. For example, the chronology of deformation across the Himalayan front is marked by a southward progression of faulting [Gunner, 1964; Hodges, 2000; Lofft, 1975; Yin, 2006], after the extrusion of partial molten mid-crustal layer during the early Miocene [Beaumont et al., 2001; Grujic et al., 1996; Nelson et al., 1996]. It has been suggested, however, that erosional exhumation may be highest in the syntaxes of the orogen compared to the Himalayan front [Burg et al., 1998; Zeitler, 1985; Zeitler et al., 1993]. Finally, growth of the orogens and plateaus are significant events, that have modified global and regional climate. For example, plateau development is linked to both development of the Asian Monsoon and plausible to a worldwide decrease of atmospheric CO2 concentration [Raymo and Ruddiman, 1992]. To test these models a better understanding of the exhumational history of the Himalaya is needed and was the key motivation for this work.

This Study

For this study we chose to use the three most successfully applied and extensively distributed thermochronometer. We compiled together ~850 Apatite (AFT), Zircon Fission Track (ZFT) and 40Ar/39Ar-white mica (40Ar/39Ar) mineral cooling ages exclusively obtained from bedrock sampling derived from ~40 previously published studies – complete reference list is provided on request: rasmus@erdw.ethz.ch) – see Figure 1. As the majority (~40%) of the thermochronology samples are sourced in the High Himalaya (HH), in contrast to partially sporadic coverage in the LH and TH, we decided to focus on the HH to compare along-strike variations. We conduct a systematic survey by applying a 1D therm-kinematic and erosional model to reconstruct and quantify the spatiotemporal evolution of denudation along the arc since ~23 Ma. At ~23 Ma, after achieving a thickened crust and peak metamorphism, rock-uplift started with the onset of decompression from ~8kbar/600-750°C [e.g., Dezes et al., 1999; Guillet et al., 1999; Searle et al., 1999] with the extrusion of high metamorphic weak mid-crust [Grujic et al., 1996; Nelson et al., 1996]. Our motivation to carry out this study was to address the following questions: (1a) To what extent have Himalayan denudation processes varied in space and time over the last 23 Myr? (2) Are exhumation rates obtained along Himalayan front comparable to rates from the Himalayan syntaxes? (3) Also, are spatial and temporal variations in exhumation derived from transects perpendicular consistent with their corresponding provenance studies?

Using thermochronologic constrains and 1D thermal modeling we quantify the following range of denudation rates along southern Himalayan margin. Within the HH AFT, ZFT, and 40Ar/39Ar yield ages ranging from 0.5-3, 2-12, 6-19 Ma, respectively, whereas in the LH and TH AFT ages range from 3-10 Ma and 2-40 Ma, ZFT ages range from 10-14 and 10-40 Ma, and Ar/Ar from 10 and 19-40 Ma, respectively. For our analyses we divided the Himalaya into five main regions A, B, C, D, and E (see Fig. 1) with no less than 20 samples per region. Perpendicular to strike we subdivided each region using the extent of tectono-morphic units such as HHC versus LHC as natural boundaries. We used 1D-thermkinematic model to convert cooling ages into denudation rates through the following steps: (a) We determined a mean AFT, ZFT, and 40Ar/39Ar cooling age of the data within each region and used the one standard deviation in the ages to define the upper and lower limit of the age-groups. (b) We determined average denudation rates between the time when the rocks passed the closure temperature and arrived at the surface, where age-group-limits defines the upper and lower limits. The program gives a full prediction of how the cooling age for the specific thermochronometer will change as a function of denudation rate (Fig. 2). (c) We calculated the transient denudation rates between closure of each thermochronometer system by using a relationship introduced by Ehlers et al. [2003].

The multiple thermochronometer data sets made available by many publications allow the quantification of the exhumation rates over different temporal and spatial scales. Major spatial changes in denudation in the HH are observed approximately ~17±2 Ma, and ~2±1 Ma and approximately contemporaneously (~2 Myr) along strike of the orogen. Second for example, in Central Nepal (CN in Fig. 2B) the thermochronology data indicate rapid denudation (~2 mm/yr) between ~23 and ~16 Ma, decreased exhumation ~0.8 (~1.0-0.4) mm/yr from ~16 ~ 2 Ma, and ~2.5(±2.5-0.7) mm/yr between ~2Ma and present day. Strike perpendicular transect suggest strong changes in denudation across the southern Himalayan margin. Both rocks of LH and TH compartments are characterized by rates below 1mm/yr, whereas HHC and LHC are often significantly higher (~1.5 mm/yr), see Fig. 2C. Furthermore we were able to extract individual exhumation pathways for both the HHC and LHC. Whereas the HHC reveal the classic the three-phase denudation history as introduced earlier, the thermochronologic data obtained within the LHC suggest consistent high denudation with rates ranging between 1.5-2.5 (~2.1) mm/yr over the last 11 Myr.
Within the core region of the Himalayan Syntaxes (regions A & E, Fig. 1a) a have previously been characterized as having some of the worldwide highest denudation rates (~5-10 mm/yr over the last 3-5 Ma) [e.g., Burg et al., 1998; Zeitler et al., 1993]. Our thermo-kinematic model results however, suggest a slower rate (~5 mm/yr) between 5 and 2 Ma and ~2.5~2 mm/yr after 2 Ma, lower than high temperature chronometer suggest. This discrepancy could be due to the lack of sensitivity of low temperature thermochronometer data to variations in denudation rates during rapid exhumation >1~2 mm/yr (e.g. see figure 1b). Thus, we consider our estimated denudation rates as a minimum. This suggests that the compartment effected by vigorous erosion has propagates southward between ~17-2 Ma. From ~3~2 Ma to present, however rapid denudation is affecting the entire High Himalaya (both HHC and LHC) again. Interestingly, the two strike perpendicular transects (Fig. 3) reveal that the extent of rapid denudation in Central Nepal effects also the southern TH, compared to NW-Himalaya rapid exhumation is limited to HHC and LHC.

The denudation history of a mountain belt can also be recorded by the sediments deposited into the foreland basin and provide an independent constraint on orogen evolution. The results of recent studies of the Himalayan foreland basin [e.g., Bernet et al., 2006; Burbank et al., 1996; DeCelles et al., 1998; Najman et al., 2002; Szulc et al., 2006; van der Beek et al., 2006] are in general agreement with spatiotemporal variation we have detected. Surprisingly consistent with our results the provenance studies suggest: (a) decreased erosion of the HHC during middle Miocene (b) increasing exhumation of LH units since about ~12-10 Ma, (c) two coexisting population in the detrital ZFT (one characterised constant lag time ~4 Ma, the other the ages range consistently between 16 and 12 Ma) record of Central Nepal suggest the coexistence of slow and more rapid denuding crystalline units between ~17 and 3 Ma [Bernet et al., 2006].

Conclusions

In summary, exhumation is focused to a narrow and continuous, ~40~80 km wide belt. Our results suggest that (1) all major changes in exhumation along southern Himalayan margin are contemporaneously (~2 Myr) along strike and approximately similar to half as high as compared to exhumation rates obtained in the Syntaxes. (2) Despite vigorous erosion affecting the southern Himalayan margin since ~23 Ma, the mountain front has tectonically reorganized itself and shifted location of focused denudation through time. While during the middle Miocene the focus of exhumation has propagated southward to the LHC, which has been exhumed continuously with rates of 1.5 to 2.5 (+1.5/-0.5) since then, the HHC to the north has been characterised by significant changes with rapid denudation (2-3 +2/-1 mm/yr) before ~17 and after ~3 Ma and decreased rates (0.7 +0.2/0.1 mm/yr) in-between. (3) In general our results are in

good agreement to provenance studies derived from uplift foreland basin sediment.

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EROSIONAL VARIABILITY ALONG THE NORTHWEST HIMALAYA SENSITIVITY IN LOW TEMPERATURE CHRONOLOGY TO CHANGES TO SPATIAL VARIATIONS IN EROSION

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Introduction
Erosional exhumation and topography in mountain belts are temporally and spatially variable over million-year time scales due to changes in both the location of deformation and climate. We investigate spatiotemporal variations in exhumation across a 150x250 km compartment of the NW Himalaya, India. 24 new and 241 previously published apatite (AFT) and zircon fission-track, and white-mica 40Ar/39Ar ages are integrated with a 1D-numerical model to quantify rates and timing of exhumation along strike of several major structures in the Lesser, High and Tethyan Himalaya.

In this study we quantify the spatial and temporal distribution of exhumation over times scales of 10^2-10^3 yr along the southern Himalayan margin in NW India. The spatial distribution of a large database of thermochronometer cooling ages is used as a proxy for the trends in long-term distribution of exhumation. Subsequently, we evaluate if the long-term trends in exhumation are correlated with modern observations of topography, structure, and climate using present-day rainfall, relief and specific stream-power data. As previous studies are limited in their regional extent (20x20 km) [e.g., Lal et al., 1999; Schlup, 2003; Sorkhabi et al., 1996], we present 24 new apatite fission-track ages (AFT) linked to 241 previously published Apatite Fission Track (AFT, n=122) and zircon fission-track (ZFT) ages (n=58), as well as 40Ar/39Ar-white mica (40Ar/39Ar-wM) ages (n=61) (see Fig. 1c for AFT, ZFT, and 40Ar/39Ar sample locations) [Jain et al., 2000; Lal et al., 1999; Schlup, 2003; Schlup et al., 2003; Searle et al., 1999; Sorkhabi et al., 1996; Thiede et al., 2004; Thiede et al., 2005; Thiede et al., 2006; Vannay et al., 2004]. Our study integrates previous and new work by evaluating spatial and temporal variations in exhumation within a 150 x 250 km segment in the NW-Himalaya. A one-dimensional (1D) advective thermal model is used to calculate exhumation rates for each thermochronometer system and compare the predicted exhumation rates to morphometric variations across the range front.

Conclusions
Our results indicate that crustal exhumation documented along the southern slopes of the Higher (or Greater) Himalaya occurred in a belt of rapid exhumation, possibly similar to what has been observed in the western and eastern synteses of the orogen, as well as in central Nepal. More proximal and internal regions of the orogen (the LH and TH) experienced an order of magnitude lower exhumation during the same time. Temporal variations in exhumation in the High Himalaya are spatially consistent in a 40-80 km wide region along 200 km of strike of the area studied, and are insensitive to structural variations.

Our main findings indicate:
1. Major temporal variations in exhumation occur in the early-middle Miocene and at the Pliocene/Pleistocene transition, respectively. Most notably, minimum estimated exhumation rates for the internal and northern compartments of the High Himalaya, forming the hanging wall of the MCT, were highest (~3 mm/yr) between ~23-19 Ma and (~2 mm/yr) between 4-0 Ma, with a deceleration in rates (0.4-0.8 mm/yr) noted between ~19-4 Ma.
2. Contemporaneously, in the footwall of the MCT to the south, we obtained consistent high exhumation rates of 2-3 mm/yr between 11 and 4 Ma and possibly longer, for Lesser Himalayan Crystalline rocks.
3. Although rainfall, relief, and specific stream power (proxies for modern erosion) in the Himalaya are among the highest globally, spatial correlations between calculated long-term exhumation rates and these proxies are poor. We interpret this poor correlation to be the consequence of either (a) spatiotemporal variation in erosion of timescales shorter than the thermochronometers are able to detect (b) a lack of sensitivity in cooling changes to spatial variations in erosion in rapidly exhuming regions (>1 mm/yr), and/or (c) that the thermochronometer samples in this region cooled under topographic conditions that only weakly resemble the present-day conditions. Consequently a strong correlation between long-term exhumation and relief or stream power could still exist in our study area, but is not resolvable with the thermochronometric data available in this study.
4. Our new AFT-data improve constraints on the tectonic evolution of the Lesser Himalaya. They suggest that crystalline nappe emplacement and post-tectonic regional thermal re-equilibration prior to 12-10 Ma was followed by river incision and erosion-driven exhumation with average rates of ~1 mm/yr since at least ~6 Ma until present.

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THERMOCHRONOLOGIC EVIDENCE FOR A POLEWARD TRANSITION FROM DESTRUCTIVE TO CONSTRUCTIVE GLACIAL CONTROL ON MOUNTAIN BUILDING: AN EXAMPLE FROM THE PATAGONIAN ANDES

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The erosive power of alpine wet-based glaciers has been hypothesized to be sufficient to control the ultimate height of actively developing mountains regardless of the rate at which uplift occurs - a process informally referred to as the ‘glacial buzzsaw’. This idea is corroborated by the observation of remarkable correlation between glacial equilibrium line altitude (ELA) and mean elevations in several major mid-latitude active orogens including the Patagonian Andes [1] independent of highly variable late Cenozoic exhumation rates. However are such observations consistent with current understanding of the physics of glaciation and glacial erosion? Does long-term glacial erosion act at the scale of an orogen? To answer such questions requires appreciation of the non-linear feedbacks between orogenic wedge mechanics, surface processes, and climate change. Simple conceptual analysis indicates that the erosional response of an orogen will differ dependent on whether ELA lowering and glacial erosion efficiency during late Cenozoic climate change is slow and weak (leading to little change in overall erosion rate), or rapid and strong (leading to strongly enhanced erosion rates). The magnitude of change in erosion rate is also dependent on whether the orogen responds by passive isostatic rebound (lower rates) or active uplift driven by accretion (higher rates). This analysis is supported by new results from a coupled geodynamic and surface process computer model that incorporates realistic crustal rheology and a physics-based glacial erosion model [2]. Alternatively, if after onset of climatic cooling, glacial erosion is inefficient, owing to, say, the inception of cold-based glaciers and/or slow-moving ice sheets, then no increase in erosion rates is predicted.

To investigate and test the magnitude, rates, timing and hence efficiency of glacial erosion, we have undertaken a large thermochronologic study (fission-track and (U-Th)/He dating) incorporating numerous samples from various latitudes along the Andes of Chilean Patagonia: a high latitude active orogen with a well-documented late Cenozoic tectonic, climatic, and glacial history. Our database includes (as of June 2008) 219 apatite fission track (AFT) and 147 uraninite (U-Th)/He (AHe) sample ages collected south of ca. 38°S. New data from regional east-west transects at 38-40°S, 43-44°S, 47-49°S (Figure 1a-c) reveal that the highest rates and magnitudes of late Cenozoic erosion are restricted to the main divide and its windward higher precipitation eastern flank where Alpine glaciation has been most prevalent. Here several age-elevation relationships (Figure 2) demonstrate a marked and consistent acceleration in erosion at ~8 to 6 Ma to rates of ~0.4 to 0.6 mm/yr, coeval at all latitudes with the timing of onset of major glaciation in the region between ca. 5 and 7 Ma [3], but well after initial surface uplift of the Patagonian Andes at around 17-14 Ma [4]. Erosion rates estimated from the thermochronologic data at these latitudes north of about 48°S are consistent with the conceptual predictions for either (1) moderately efficient glacial erosion acting on an active orogen, or (2) very efficient glacial erosion (i.e. a strong glacial buzzsaw) acting on an inactive orogen responding by passive isostatic rebound. Evidence of active tectonic uplift at some of these latitudes related to transpressional faulting [1] favors the former prediction. In contrast, all available (non-volcanic) low temperature thermochronometric data so far collected from further south (49-52°S) show no evidence of enhanced late Cenozoic bedrock erosion (Figure 1d) along the main divide - with old >10 Ma apatite (U-Th)/He (AHe) and fission track (AFT) ages, as well as preserved early Pliocene lava flows - despite the presence of widespread modern Alpine valley glaciers and fiord development. The transition to older AHe and AFT ages along, or close to the main divide further south can be seen in the latitudinal transects in Figure 3. These data therefore imply that long-term glacial erosion has been considerably less efficient further south over the last ca 5 to 7 Ma. This is further corroborated by the anomalously high non-volcanic summit elevations of the main Cordillera within the South Patagonian ice field between 46°S and 51°S situated well above the modern and last glacial maximum ELA.

Implications and Conclusion

Miocene marine sedimentary rocks (ca. 9 Ma) now at 1950m elevation on the leeward side of the Patagonian Andes at about 48°S [5] clearly imply ongoing active uplift of the divide at these latitudes. We therefore postulate that south of about 45°S the long-term climate averaged over the many glacial cycles of the late Cenozoic at the orogen scale has favored a regime of cold-based low erosional efficiency glaciation and/or slow moving ice sheets, whereas to the north the long-term glacial regime has been dominated by erosive warm-based Alpine glaciation leading to suppression or destruction of topography through the ‘glacial buzzsaw’ effect. To the south higher summit and mean elevations imply that here cold-based glaciation has acted to shield the surface from significant erosion during the late Cenozoic and hence acted as a constructive control on active mountain building at the orogen scale. This has allowed the orogen to increase in height so that significant portions of the mountain range are preserved above the ELA.

Such a long-term latitudinal transition in glacial regimes is further corroborated by poleward changes in seismically imaged sedimentary facies in the fiords of southern Chile [8] from a temperate glacio-climatic regime in the northern and central Chilean fiords (north of 48°S) to a sub-polar climatic regime in southernmost Chile (55°S). The presence of cold-based ‘protective’ glaciation (or even non-glaciated frozen ground) through much of the late Cenozoic in active orogens could have other implications such as explaining the presence of isolated high plateaus. Also, if 45°S to 50°S in the Patagonian Andes represents a global long-term average change in glacio-climatic regime, this may have implications for long-term southern hemisphere paleoclimatic and paleoceanographic models.
Figure 1: Four east-west transects across the Patagonian Andes at different latitudes showing the trend in both AFT age (blue) and AHe age (green). The top three profiles (a-c) show a distinct "u-shaped" age minima for both thermochronometers (< ca. 5 Ma) on the windward (enhanced precipitation) side of the range, close to the main divide, whereas the profile furthest south (d) shows no such relationship, despite the presence of widespread fiords and ongoing glaciation. Yellow dots show all samples collected and dated by both AHe and AFT. Grey line marks N-S swath used in Figure 3.
Figure 2: Age-elevation relationships from two high relief transects from the Patagonian Andes: (a) Apatite fission track AER from the Conguillo Area (39°S) showing possible acceleration of enhanced cooling at ca. 10 to 12 Ma and 7-8 Ma. (b) Apatite (U-Th)/He AER from same samples showing onset of enhanced erosion at ca. 5 Ma at rates of ca. 0.4 mm/yr approximately co-incident with the onset of major glaciation in southern South America; (c) Apatite fission-track AER from the Futuleufu Area (44°S) showing a similar ‘break-in-slope’ at ca. 6-7 Ma indicative of acceleration of erosion rates to ca. 0.5 mm/yr; (d) Apatite (U-Th)/He ages from same samples show a similar AER, although with more scatter probably due to the areal extent of samples from more than one high relief transect.
Figure 3: Latitudinal profiles of apatite AHe and AFT ages along the main Patagonian Andes divide compared to maximum elevation (from 4° swath) and mean elevation (from 2° swath), as well as the modern and mean glacial ELA [6, 7]. Note that with the exception of some ages from independently dated Pliocene (5 Ma) rhyolites at ca. 50°S, the minimum AHe and AFT ages show a gradual increase south of about 45°S.

References:
APPLICATION OF DETRITAL ZIRCON ANALYSIS TO IDENTIFY PROTOLITH AGE, BASIN EVOLUTION, POTENTIAL CORRELATIVES, AND PROVENANCE OF PENETRATIVELY DEFORMED BLUESCHIST-FACIES METASEDIMENTARY ROCKS, NORTHERN ALASKA

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U-Pb ages of detrital zircons from rocks in a regionally extensive, penetratively deformed metamorphic terrane illustrate the power of the method for characterizing subunits within the protolith package, limiting the age of those subunits, and correlating subunits with unmetamorphosed sequences, in addition to the traditional application of identifying provenance. Detrital zircon isotopic data were collected using both LA-ICP-MS and SHRIMP-RG instruments.

The Nome Group is a Mesozoic blueschist-greenschist facies terrane that covers an area of roughly 200 by 200 km on the Seward Peninsula, northwestern Alaska. The Nome Group consists of several thick mappable lithologic packages, scattered carbonate rocks with an uncertain relationship to those lithologic packages, and small bodies of orthogneiss. Mesozoic ductile and penetrative deformation largely obliterated primary sedimentary and igneous textures. Sparse conodont and megafossil collections and zircon ages from orthogneisses provide limited age control, and were interpreted to indicate Neoproterozoic and Paleozoic protolith ages for the unit overall (Till et al., 1986). On the basis of these limited data, reconstructions of the protolith package in the context of an evolving Neoproterozoic and Paleozoic continental margin was not possible.

Lithologic components of the Nome Group are mixed at centimeter, meter, and decameter scales. However, the consistent association of a few lithologic components, likely derived from a compositionally limited source area, allows definition of distinct mappable packages (Figure 1). Ages assigned to packages on Figure 1 reflect detrital zircon age brackets, conodont data, and geologic reasoning. Two lithologic packages produced consistent detrital zircon populations, indicating a strong link between lithology and provenance (Figure 2, see units Ocs and Dcs).

All four of the samples from package Ocs are characterized by peaks in the 570-700 Ma range and a few grains older than 1 Ga (Figure 2, #1-4); three other samples from this unit produced a similar age distribution (Amato et al., 2003). The depositional age of this unit must be latest Proterozoic or younger. Two of ours, and two previously published age distributions from this package, contain 1-2 grains of Cambrian or Ordovician age, possibly suggesting that the depositional age is younger than Neoproterozoic. One 278 Ma grain is not considered significant (Figure 2).

Figure 1: Simplified geologic map of southwest Seward Peninsula, Alaska, showing distribution of detrital zircon samples. Lithologic packages are listed in order from structurally highest to lowest in the explanation (Oim to Ds).

Four of the seven samples from package Dcs produced very similar age distributions (Figure 2, #6-9). These samples have a prominent peak at 420-440 Ma, with lesser peaks from 500-700 Ma, and a few older grains. The youngest grain populations in these geographically distributed samples are Early and Middle Devonian, suggesting a Devonian or younger depositional age for the unit. Of the three remaining samples, two are from drill core collected immediately above and below a mineralized zone that is lithologically different from the rest of Dcs (Figure 2, #10-11). One of these has no age overlap with the more typical age distributions for unit Dcs, and contains zircons that are predominantly 1000-1500 Ma, with a few older grains (Figure 2, #11). These Mesoproterozoic ages are also seen in one of the few samples we have from another lithologic package in the Nome Group (DOx, Figure 2, #12), and are remarkably similar to age distributions from samples in central Alaska from penetratively deformed metamorphic rocks of the Ruby terrane and Minook complex (Bradley et al., 2007). The second sample from the core contains a broad set of Paleozoic and Proterozoic peaks that overlap peaks in Dcs, Ocs, and DOx (Figure 2, #10). The youngest grain populations in this section of core are Late Devonian, allowing a Devonian or younger protolith age. The final sample from Dcs (Figure 2, #5) has populations that overlap with some typical Dcs ages, but has a significant population similar to those in package Ocs. This may reflect an overlap of source areas for the two units, or a mapping problem.

Figure 2: Detrital zircon age-probability distributions, Nome Group, Seward Peninsula, Alaska. Numbers to the right of the curves correspond to sample locations shown in Figure 1. Circled peaks represent single grain ages of questionable significance.
Ds is a pelitic schist originally thought to be the oldest lithologic package (Precambrian?) in the Nome Group (Till et al., 1986). The single sample from Ds that yielded zircons contained a small population of Middle Devonian grains (Figure 2, #13). This is significant for potential correlations of the Nome Group protolith. The combined lithologic and detrital zircon characteristics of packages Dcs and Ds indicate that the younger parts of the Nome Group protolith were more siliciclastic in character than the older parts, which contain significant carbonate and mafic material. This transition to siliciclastic sedimentation in the latter part of the Devonian hints at a possible parallel with the evolution of the continental margin preserved in the Brooks Range (Till et al., 2008), and deserves careful scrutiny.

The general consistency of detrital age distributions within lithologic packages Ocs and Dcs (with the exception of the few lithologically atypical samples) reflects consistency in source terranes during deposition of each package, and an evolution of source terranes feeding the continental margin during the early Paleozoic. The unusual detrital zircon age distributions from the mineralized section in Dcs may reflect development of a sub-basin during the mineralization event.

Detrital zircons from the Nome Group may have been derived, in part, from local sources. The consistent, broad peak between 570 and 700 Ma for Ocs may in part reflect derivation from local basement, represented by small 670-680 Ma orthogneiss bodies in the Nome Group (Patrick and McClelland, 1995; Amato et al., 2004; Aleinikoff, unpub. data) and a large ~565 Ma orthogneiss in nearby high-grade metamorphic rocks (Aleinikoff, 2006). Most of the Devonian detrital zircon ages in Dcs and Ds correspond to felsic igneous events known in northern Alaska. However, neither the 420-440 Ma (Silurian) zircons common in Dcs nor the 1000-1500 Ma populations in Dcs and DOx can be tied to a source in northern Alaska.

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Patrick, B.E., and McClelland, W.C., 1995, Late Proterozoic granitic magmatism on Seward Peninsula and a Barentian origin for Arctic Alaska-Chukotka: Geology, v. 23, n. 1, p. 81-84.
Introduction
Unraveling the kinematics and exhumation history of the Himalaya, the largest mountain belt on Earth and the largest provider of sediments to the world’s oceans, has important implications for our understanding of mountain building processes, the interaction between tectonics, climate and erosion, as well as seismic risk assessment. Here, we explore the capacity of thermochronological data to quantitatively constrain the kinematics of the central Himalaya at two different time scales: we use a transect of newly acquired in-situ apatite fission-track (AFT) ages across the central Nepal Himalaya to place constraints on the kinematics of the mountain belt over the last few million years, and we extract the kinematic and exhumation history of the belt since ~20 Ma from a dataset of detrital zircon fission-track (ZFT) and mica Ar-Ar (MAR) thermochronology collected within the orogenic Siwalik deposits of central and western Nepal. To do so, we employ a newly developed 3-D thermal-kinematic model, based on the Pecube code, which allows the prediction of thermal histories and thermochronological ages for rocks exhumed along crustal-scale faults of any geometry. The model tracks the distribution of thermochronological ages at the surface throughout the model run, thus allowing comparison with both the in-situ and the detrital thermochronological record.

In-situ thermochronology and recent kinematics of the central Himalaya
The central Himalaya is characterized by several crustal-scale thrust faults; the Main Central Thrust (MCT), which separates the highly metamorphic Greater Himalaya from the lower-grade Lesser Himalaya, the Main Boundary Thrust (MBT), which puts Lesser Himalayan rocks over Mio-Pliocene synorogenic Siwalik sediments, and the currently active Main Frontal Thrust (MFT), along which the Siwaliks overthrust the Ganges foreland basin (Gansser, 1964; Le Fort, 1975).

Geophysical and structural data suggest that these thrusts branch at depth on a single major shear zone and mid-crustal detachment known as the Main Himalayan Thrust (MHT), characterized by a major mid-crustal ramp underlining the MCT zone (Fig. 1; Avouac, 2003; Schulte-Pelkum, 2005). Current shortening rates across the central Himalaya are ~21 mm/yr and are mainly accommodated by the MFT on Holocene timescales (Avouac, 2003; Lavé and Avouac, 2001).

In recent years, controversy has arisen about the recent kinematics of the central Himalaya, with some authors (Hodges et al., 2004; Wobus et al., 2003; 2005) arguing for Plio-Pleistocene reactivation of the MCT, possibly driven by climatically enhanced exhumation of the Himalayan topographic front. The main arguments for this model are a sharp increase in thermochronological ages from the Greater to the Lesser Himalaya across the MCT zone, as well as a sharp morphological transition. In contrast, Avouac (2003)

and Bollinger et al. (2006) suggest that these observations are equally well explained by steady-state sliding of the Himalayan orogen over the MHT combined with tectonic underplating at the mid-crustal ramp.

In order to assess these opposing models, we collected new apatite fission-track (AFT) data along a transect from the Greater Himalaya to the MFT across central Nepal and combine our new data with published AFT and high-temperature mica Ar-Ar (MAR) ages (Fig. 1). AFT ages increase linearly from ≤ 1 Ma in the MCT zone to 5-10 Ma in the outermost part of the Lesser Himalaya, without a sharp transition. We use a modified version of the Pecube 3D thermal evolution code (Braun, 2003) that incorporates lateral motion along faults in order to quantitatively extract constraints on the kinematics of the mountain belt from these data. The model partitions the 21 mm/yr convergence into under- and overthrusting on the MHT; the latter can be partitioned into motion on the MFT and MCT. Fitting the observed AFT-age pattern, using our thermal-kinematic model with exhumation occurring simultaneously along several thrust faults, requires only minimal, if any, reactivation of the MCT (Fig. 2).

Detrital thermochronology and long-term kinematic evolution of the central Himalaya
Recent detrital thermochronology data collected from Siwalik sediments in western Nepal (Bernet et al., 2006; Szulc et al., 2006) suggest a major phase of exhumation occurred between ~15-20 Ma, as a significant proportion of both detrital ZFT and MAR single-grain ages fall within this age range, independent of the depositional age of the samples (Fig. 3). This is also the time of a major tectonic transition in the central Himalaya, from an Early Miocene phase characterized by localized exhumation in the Higher Himalayan crystalline belt along the MCT to a steady-state forward-propagating system in the Late Miocene-Pliocene (DeCelles et al., 2001; Robinson et al., 2006).

We are using the same model as that developed for constraining the recent kinematics of the Himalaya to study the past kinematic evolution as recorded by detrital thermochronology. We use the observed probability-density distribution of detrital ZFT and MAR ages as a constraint on the model, comparing it with predicted age probabilities at the surface of the model through time. Our modeling of the detrital data aims at understanding the phase of rapid exhumation and the associated (climatic, tectonic?) controls on the change in kinematics.

Conclusion and perspectives
Three-dimensional thermal-kinematic modeling of the type developed here enables to extract quantitative information on orogen kinematics from thermochronology data. Our preliminary model results show that young AFT ages in the Greater Himalaya do not necessarily require reactivation of the MCT, in contrast to earlier qualitative interpretations. Thermochronological age patterns are most strongly controlled by the mid-crustal ramp in the MHT, which determines exhumation pathways.

The topography of the Alpine belts of Europe is the consequence of recent tectonic activity and climatically-modulated erosional processes. Climate and tectonics are coupled in mountain belts through the ability to redistribute mass and the physical need to respond to such redistribution respectively. Known climatic changes in the last 10 Myr have impacted the erosional processes across Europe and, arguably, have contributed to major tectonic changes. Our scientific understanding of the nature of the coupling between climate and tectonics is in its infancy, but potentially it represents the fundamental driver for mountain topography. This project aims to test alternative mechanisms for the potential coupling of climate and tectonics at various scales across Europe; this will be achieved through improved documentation of the rates and distribution of erosion during the Neogene and through modeling the tectonic response to this signal of erosion.

Climate has changed strongly over the last 10 Myr in Europe, with the onset of Northern Hemisphere glaciation the most dramatic example of such change. Northern Hemisphere ice sheets started to build up between ~10 and ~6 Ma, as indicated by the presence of ice-rafted debris in high-latitude oceanic sediment cores, but their rapid expansion only took place between ~3.2 and 2.5 Ma (Maslin et al., 1998; Mudelsee and Raymo, 2005). A key period for climatic change in Europe appears to be the time between 3 and ~6 Ma, i.e. the Late Miocene – Pliocene transition, when closure of the Panama Isthmus marked the onset of modern Northern Hemisphere circulation dominated by the Gulfstream, between 4.6 and 3.2 Ma (Haug and Tiedeman, 1998); more regionally, the Messinian Salinity Crisis lead to desiccation and subsequent reflooding of the Mediterranean between 5.6 and 5.3 Ma (Krijgsman et al., 1999). Possible causal relationships between these events have been extensively discussed but remain controversial, as does the cause of onset of widespread Northern Hemisphere glaciation (Driscoll and Haug, 1998; Maslin et al., 1998).

Regional climate records, mostly based on pollen data, indicate Early Pliocene climatic conditions in southern Europe to have been significantly warmer (+1-4°C) and wetter (+ 400-700 mm/yr) than both the present and Miocene climates (e.g., Fauquette et al., 1999).

COUPLED CLIMATIC/TECANTONIC FORCING OF EUROPEAN TOPOGRAPHY REVEALED THROUGH THERMOCHRONOMETRY – THE “THERMO-EUROPE” PROJECT


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All of the above signals have the potential to significantly alter erosion rates through the growth of mountain glaciers, increased precipitation, regional base-level lowering or intensified climatic oscillations. Initial, high profile studies have hinted at changing erosion rates through this time. Global increases in erosion rates and sediment flux since ~4 Ma have been documented by Zhang et al. (2001). On a European scale, Kuhlemann et al. (2002) have shown that sediment yield from the Alps has increased by a factor 3 since ~5 Ma; this finding has recently been corroborated by Vernon et al. (2008), who showed from a compilation of thermochronological data within the Alps that exhumation rates have increased similarly since this time. Champagnac et al. (2007) have shown that the increase in sediment flux from the Alps can be explained by relief increase through valley carving, implicitly suggesting a major role for Quaternary glaciations in changing erosion rates and the topographic evolution of the Alps. Cederbom et al. (2004) documented the switch from sediment deposition to erosion in the Alpine foreland basin ~5 Ma, inferring isostatic rebound in response to increased erosion in the Alps at this time. Willett et al. (2006) also inferred increased erosion rates in the Alps linked to dessication and subsequent reflooding of the Mediterranean during Messinian times. Muttoni et al. (2007) have demonstrated changing sediment yield at 0.87 Ma from the Southern Alps linked to changing vegetation.

Within a single mountain belt, temporal variations in denudation rates are, however, not necessarily climatically induced but can be caused by natural variability in the intensity and locus of deformation (Hoth et al., 2007; Naylor and Sinclair, 2007). A key to distinguishing between tectonic and climatic forcing of variations in denudation rates is thus to look for apparent synchronicity in erosion signal between different mountain ranges and to correlate these with well-dated global or regional climatic events.

Aims and objectives of the project

From the above review, a number of key questions emerge, the answers to which will guide our understanding of the coupling between climate, erosion and tectonics: (1) Can we document and quantify variations in erosion rates in, and/or sediment flux from, mountain belts through time and
can we link these two measurements? What resolution can we achieve in the establishment of a record of erosion rates through time? (2) Can we establish the timing of these variations with sufficient temporal and spatial resolution to enable correlation between different study areas? (3) Can we use this information to discriminate climatic and tectonic forcing on the topographic evolution of the region? (4) Can we reveal changes in topography due to changing rates and processes of erosion (e.g., increased relief due to valley carving)? (5) Can we document and model the tectonic response to changing erosion rates and topography, and can we establish couplings in the system?

We address these questions by combining (a) acquisition of new thermochronologic data on denudation rates and seismic data on sediment-flux from selected key areas; (b) development of new methods to increase the resolution of the thermochronologic record; (c) development of quantitative interpretational techniques that permit us to extract information on relief development and transient denudation rates and (d) investigation of the potentially coupled effect of climate-induced and tectonic variability in denudation rates.

Within the European context, most of the discussion of potential coupling between climate and tectonics has centered on the Alps, because of the relative abundance of data in this mountain belt as well as the paradoxical simultaneous evidence for limited tectonic activity but increased denudation rates since ~5 Ma, together with relatively rapid present-day rock uplift rates (cf. review in Champagnac et al., 2007). However, accelerated Pliocene denudation rates have been documented for all tectonically active mountain belts in Europe, e.g., the Betic Cordillera (Johnson, 1997; Reinhardt et al., 2007), the Alpines (Balestrieri et al., 2003), the southern Carpathians (Leever et al., 2006; Sanders et al., 1999) and the Caucasus (Morton et al., 2003). In the Pyrenees, where orogenic activity ceased after Oligocene times, there are indications for renewed denudation since ~10 Ma (Fitzgerald et al., 1999), the timing and amount of which is not well constrained and remains controversial (Gibson et al., 2007). Possible renewed denudation of the Pyrenees has also been linked to Pliocene climate change and relief development (Babault et al., 2005).

The project concentrates on various mountain belts throughout Europe, which will mostly address questions (1) and (2) above, with projects concentrating on the acquisition of new high-resolution data from key sites within and around the Alps, as well as on the development of quantitative interpretational techniques, which will primarily address questions (3) and (4).

Strategy

Key to discriminating between climatic and tectonic forcing of erosion is the temporal correlation of phases of denudation with distinct climatic or tectonic events, and the correlation between denudational phases in distinct mountain belts. Recent advances in low-temperature thermochronometry have revolutionized our ability to resolve erosion rates through time, but no large-scale, systematic study has been conducted to apply techniques at a continental scale in order to resolve potential climatic signals. Recent advances that develop and test in this project are: Numerical modeling of thermochronologic age-elevation profiles (Braun, 2002; Gallagher et al., 2005), allowing constraints on temporal variations in cooling rate and, in the optimum case, relief development; Forward and inverse modeling of the 3D temperature field from dense thermochronologic datasets, enabling discrimination of temporal variations in regional denudation rates from focused denudation and relief development (Braun, 2002; Ehlers et al., 2006); Multiple thermochronometric analysis (e.g., apatite fission-track, zircon and apatite (U-Th)/He) within a strategic sampling scheme, to significantly increase the resolution with which temporal variations in denudation rates can be resolved; Newly developed apatite He/He thermochronometry, which has the potential to push the resolvable temperature range further toward the surface and to provide unprecedented ability to resolve most recent denudation and relief development (Shuster et al., 2005); Detrital thermochronology on well-dated Mid- to Pliocene sediments will track variations in denudation rates of the source areas during this critical time interval. In order to increase the efficacy and resolution of the detrital approach, double dating by fission-track and (U-Th)/He techniques, ideally on the same individual grains, is being developed as well as quantitative modelling-based interpretations (e.g., Rahl et al., 2007). Combining detrital thermochronology with quantifications of sediment flux through high-quality seismic and well data provide a unique combination of tools aimed to resolve denudation and relief history; Numerical and analog models to aid in understanding and conceptualising the different couplings and feedbacks in the tectonic-erosion-climate system, and to provide testable predictions to be compared to new and existing datasets.

An additional goal is to develop these techniques further as a community. Optimal combined sampling and modeling strategies need to be developed, as modeling tools are continuously being refined. Precise and reproducible (U-Th)/He and FT dating of young, low-U apatite poses a technical challenge, which is exacerbated in the case of detrital samples or He/He thermochronometry. Investments in European infrastructure are required to face these challenges.

References


Introduction

The northwest Himalaya shows strongly contrasting relief, opposing deeply incised mountain ranges characterized by extremely rapid exhumation (Burbank et al., 1996; Schneider et al., 2001; Zeitler et al., 2001) and some of the highest peaks in the world (i.e., the Karakorum Range and Nanga Parbat Massif) to high-altitude, low-relief areas such as the Deosai plateau in northern Pakistan (Fig. 1). The origin and evolution of such plateau regions in the NW syntaxis of the most active continental collision in the world remain elusive. Here, we report the first low-temperature thermochronology (apatite fission-track, apatite and zircon (U-Th)/He) data from the Deosai Plateau and use thermal history modeling to show that the plateau has undergone continuous slow (≤200 m/My) denudation and has thus been stable since at least 35 Ma. We compare these exhumation histories with published thermochronology data from other high-elevation, low-relief regions in the northwest Himalaya (Kohistan, Ladakh batholith, Tso Morari). We show that plateau remnants share common morphologic characteristics and denudation histories, which are comparable to those of the western Tibetan plateau. These results imply that such plateau regions may be remnants of an Eocene south-western Tibetan plateau that was more widespread than today and that was subsequently dissected by rivers following major faults.

Geologic setting

High-elevation, low-relief regions in the northwest Himalaya are mainly found within the Kohistan-Ladakh arc complex, which forms the backbone of the NW Himalayan belt and separates the Indian and Asian plates (Fig. 1). The Karakorum range to the north constitutes the former Eurasian margin and was thrust over the Kohistan-Ladakh arc along the Main Karakorum Thrust in the Shyok suture zone since ~75 Ma (Paterson and Windley, 1985). The Kohistan-Ladakh arc was in its turn thrust over Himalayan rocks of the Indian plate along the Main Mantle Thrust in the Indus Suture Zone since the onset of Himalayan collision at ~55 Ma (de Sigoyer et al., 2000; Guillot et al., 2003). Major crustal thickening, high-grade metamorphism and building of topography occurred between ~55 and 40 Ma (Treloar et al., 1989), followed by rapid exhumation of the Nanga Parbat dome since Late Miocene times (Schneider et al., 2001).

Denudation history of the Deosai Plateau

We have applied apatite fission-track (AFT) and apatite and zircon (U-Th)/He (AHe, ZHe) thermochronology to elucidate the denudation history of the Deosai Plateau (Fig. 2). Samples were collected at elevations between 2500 and 4000 m on the plateau surface itself, as well as on its northeast rim and in the high Astore valley, which drains the plateau to the west. AFT ages vary between 14.6±1.1 and 27.0±3.5 Ma, with youngest ages encountered in the Astore valley and oldest on the northeast plateau rim. For the higher closure-temperature ZHe system, weighted mean ages from replicate determinations vary between 22.1±1.0 Ma for a sample collected at 2960 m elevation on the northeast flank of the plateau and 39.4±7.4 Ma for the central plateau (3961 m elevation). The lower-temperature AHe ages are consistent with the other data and vary between 10.9±1.0 Ma in the Astore valley and 15.1±0.3 Ma on the eastern rim. Overall, these ages imply slow cooling and exhumation rates that are at least an order of magnitude lower than those encountered in the adjoining Nanga Parbat and Karakorum massifs (Foster et al., 1994; Schneider et al., 2001; Zeitler et al., 2001).

We have modeled the cooling history of three samples for which we dispose of thermochronology data for multiple systems, using the HeFTy code (Ketcham, 2005). All cooling histories obtained using this approach consistently show remarkably constant slow cooling at rates of ~5°C/Myr since at least 35-40 Ma (Fig. 2), translating into constant long-term denudation rates of ≤200 m/My since this time for reasonable values (25-30 °C/km) of the geothermal gradient. The inferred history of constant slow denudation of the plateau has several major implications: firstly, it contradicts the hypothesis that widespread low-relief surfaces in the northwest Himalaya result from efficient glacial erosion during Quaternary times (Brozović et al., 1997); such erosion would have been recorded as a phase of rapid recent denudation that is not observed in the data. Secondly, they suggest a continuous history of slow denudation since Eocene times, i.e. only 15-20 My after the onset of India-Asia collision. This implies that the Deosai plateau surface developed early in the Himalayan history and limits the phase of orogenic relief growth in the Ladakh-Kohistan arc to earliest Tertiary times. Although thermochronology data do not directly record surface uplift, the simplest explanation for the inferred constant denudation rates is that the plateau had reached its present-day elevation already during Eocene times, as a later phase of surface uplift would have triggered an erosional response that would have been recorded by the thermochronology data.

Regional implications

When comparing our inferred cooling history for the Deosai plateau with scattered thermochronology data from other high-elevation, low-relief regions in the northwest Himalaya, a remarkably consistent picture appears. AFT ages from elevations >3000 m in western Kohistan are 15-19 Ma (Zeitler, 1985), whereas zircon fission-track (ZFT) ages determined on the same samples are 34-38 Ma. In the Ladakh batholith, samples from elevations >4000 m are characterized by AFT ages between 15 and 25 Ma (Kirstein et al., 2006; Kumar et al., 2007), with age-elevation relationships indicating apparent exhumation rates of ~100 m/Myr between ~30 and ~10 Ma. Two ZFT ages from the Ladakh batholith are 41-43 Ma (Kumar et al., 2007). Samples from the high-elevation (4500-5000 m) Tso Morari massif (Schlup et al., 2003) yield AFT ages between 15 and 30 Ma and ZFT ages of 35-45 Ma; these data were interpreted as recording rapid exhumation between 50 and 40 Ma, followed by steady and slow denudation rates since that time (de Sigoyer et al., 2000; Schlup et al., 2003).
Figure 1: Morphological and tectonic framework of the northwest Himalaya. Black dots: summits >7000 m (larger dots: >8000 m). Main tectonic boundaries: MKT, Main Karakorum Thrust; MMT, Main Mantle Thrust; MCT, Main Central Thrust; MBT, Main Boundary Thrust; MFT, Main Frontal Thrust. Star: epicenter of the 2005 Balakot earthquake. Main morpho-tectonic units and river systems are also indicated. Inset shows location within Himalayan-Tibet system. Modified from Pécher et al., Stress field evolution in the Northwest Himalayan syntaxis, Northern Pakistan (submitted to Tectonics).

Figure 2: AHe (orange), AFT (green) and ZHe (blue) ages for samples from the Deosai Plateau, overlain on shaded relief map of the plateau. Major tectonic boundaries, rivers and peaks are indicated.

Figure 3: Time-temperature paths for 3 samples from the plateau surface, obtained using the HeFTy thermal-history inversion code.

It thus appears that all high-elevation, low-relief areas in the northwest Himalaya show a similar history of slow, continuous cooling since Middle Eocene times, implying that they may all have been at high elevations since. No published thermochronology data are available from western Tibet to compare these histories with, but we have analyzed a sample from our collection that yielded an AHe age of 17.2±0.6 Ma and a ZHe age of 24.7±0.5 Ma, implying a very similar cooling history. The simplest explanation for the common cooling histories and morphological characteristics of the western Tibetan plateau and the high-elevation low-relief surfaces in the northwest Himalaya is that they have the same origin. We therefore suggest that these isolated plateau remnants can be considered as pieces of an early, highly elevated Tibet plateau, which was dismembered since Early Miocene times by inception of longitudinal Indus river drainage (Sinclair and Jaffey, 2001) and movement along the Karakorum fault (Valli et al., 2007).

References


RADIALPLOTTER: A JAVA APPLICATION FOR FISSION TRACK, LUMINESCENCE AND OTHER RADIAL PLOTS

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Single-grain dating has become common practice in fission track, ⁴⁰Ar/³⁹Ar, U-Pb and luminescence dating. Because single-grain signals are smaller, the measurement uncertainties of single-grain ages are typically larger and more variable than those of multi-grain aliquots of the same sample. Invented by Rex Galbraith in 1988, the radial plot is a graphical method for comparing several estimates that have different precisions.

RadialPlotter is a user-friendly application for generating radial plots. It has the following advantages over existing programs such as Trackkey or MacTrack. (1) The program was developed solely for radial plots and does not perform any other functions for data reduction or interpretation. Therefore, radial plot functions are not buried deep inside the menu structure and the interface is very straightforward. (2) RadialPlotter was written in Java (version 5) and is, therefore, perfectly platform independent. (3) In addition to fission track radial plots, RadialPlotter also offers the possibility to generate radial plots for luminescence dating, or any other kind of data such as (U-Th)/He or U-Pb ages. Hopefully, this will give the radial plot the wider user base which it deserves. RadialPlotter can be downloaded free of charge from http://pvermees.andropov.org/radialplotter

**Figure 2:** The input screen defaults to fission tracks when the program starts. \( N_s \) is the number of spontaneous tracks, \( N_i \) is the number of induced tracks counted over the same area in an external mica detector. There currently is no direct implementation for ICP-MS based fission track data, but radial plots can still be produced using the 'Other' option with the single-grain ages and their uncertainties as input (see Figure 5).

**Figure 3:** Generating a radial plot is as simple as creating or opening an input file and clicking the 'Plot' button. An optional third column of data (e.g., Cl-concentration, \( D_{par} \), ...) will be used for a color scale. If this column is left blank, there will be no color scale.

Figure 4: Input data are saved in a .csv comma-separated format. The radial plot can be saved in either a .png image format (at screen resolution), or in a .pdf vector format, which can be opened and edited in graphics software such as Adobe Illustrator or CorelDraw.

Figure 5: Basic editing tools are available for generating an input file. Data can be copied and pasted to and from Microsoft Excel.

Figure 6: Three kinds of input are currently implemented: fission tracks, luminescence and 'other'. Each corresponds to a slightly different looking input form. For 'Other', this contains just the sample name and three (2+1) columns of data.

Figure 7: RadialPlotter offers three scaling transformations for fission tracks. The 'Arcsin' option is not available for luminescence dating and other data.
Figure 8: RadialPlotter creates an optimal radial scale by default, but this can be adjusted so that radial plots for different samples of the same study can share the same scale, thus facilitating their comparison.

Figure 9: Colors are linearly scaled between the minimum and maximum value of a sample set, and can be easily customised in the color chooser.