Timing and mechanisms of Central Himalayan exhumation: discriminating between tectonic and erosion processes

Ana-Voica Bojar,1 Harald Fritz,1 Stefan Nicolescu,2 Martin Bregar1 and Ravi P. Gupta3
1Institute of Earth Science, Karl-Franzens University, Heinrichstrasse 26, A-8010 Graz, Austria; 2Department of Geology and Geophysics, Yale University, PO Box 208109, New Haven, CT 06520–8109, USA; 3Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee 247667, India

ABSTRACT

The ability to deduce exhumation mechanisms from thermal-chronological data is hampered by the fact that assumptions on the thermal state of the lithosphere have to be made. Additional argumentation is generally required to discriminate between erosion-controlled and tectonically induced exhumation. This problem can be overcome by studying the spatial distribution of zircon and apatite (U-Th)/He and fission track data. In this work the variation of four different low-temperature isotopic systems generating age trends along a sampling line is used to infer mechanisms of Quaternary exhumation in the Central High Himalayan Metamorphic Belt. Observed zircon age trends with southwards increasing cooling ages (from 0.5 to 1.7 Ma) are attributed to tectonically induced exhumation. The uniform apatite cooling ages clustered c. 0.5 Ma are attributed to erosion.

Terra Nova, 17, 427–433, 2005

Introduction

For many years the Himalayan orogen has served as natural laboratory for studying the relationship between tectonics, erosion and topographic evolution of mountain ranges. Literature data suggest early Miocene exhumation for the Neohimalayan phases (e.g. Hodges, 2000) followed by accelerated denudation during the past few million years. The accelerated denudation may have been triggered by either enhanced erosion, possibly related to global climate change (Zhang et al., 2001), or by recent tectonic activity, as suggested from seismic movements within the Himalayan Metamorphic Belt (Kayal, 2001).

Here we present (U-Th)/He and fission track (FT) ages of zircon and apatite, supplemented by tectonic interpretation along a section crossing major structures within the Central Himalayan Crystalline Wedge. Interpreting the spatial age variations allows for distinguishing between tectonic- and erosional driven denudation processes.

Geology

Studies from the past decade have shown that the Himalayan metamorphic crustal fragments have undergone episodic exhumation. The oldest structures of the Neohimalayan phase formed in the Early Miocene, when both, the Main Central Thrust Zone (MCT) and the South Tibet Detachment Zone (STDZ) were active during southward extrusion tectonics (Hodges et al., 1992). Subsequently, the Main Boundary and Main Frontal Thrust Zones developed south of the main axial zone (Hodges, 2000). Whereas the external thrusts have remained active until present times, the Central Himalayan Metamorphic Belt has been considered relatively immobile.

Based on: (i) provenance studies of sediments eroded from the Himalayas (Fagel et al., 1994; Derry and France-Lanord, 1997; White et al., 2000); (ii) studies on cosmogenic isotopes and U-series dating of alluvial deposits, as well as fission track data (Zeitler et al., 1982; Sorkhabi et al., 1996; Leland et al., 1998; Jain et al., 2000; Vance et al., 2003; Thiede et al., 2004; Vannay et al., 2004); and (iii) geophysical data suggesting active tectonics within the Himalayas (Kayal, 2001), several authors (Hurtado et al., 2001; Burbank et al., 2003; Hodges et al., 2004) support a regional phase of Pliocene to Quaternary deformation and denudation in the Higher Himalayan Unit.

In the Goriganga Valley, between Munsyari (30°07’N, 80°15’E, 2100 m a.s.l.) and Martoli (30°21’N, 80°12’E, 3300 m a.s.l.) (Figs 1 and 2), several units separated by major tectonic boundaries are exposed (Valdiya, 1980; Sinha, 1989; Paul, 1998). From north to south these are: (i) the Tethys Himalaya (TH), composed of low-grade Proterozoic to Mesozoic sediments juxtaposed along the STDZ on (ii) high-grade gneisses of the Higher Himalayan Sequence (HH). The HH has been thrust along the Vaikrita Thrust (VT), an equivalent of the MCT over (iii) micaschists and Proterozoic orthogneisses of the Lesser Himalayan Metamorphic Sequence (LHM). The Munsyari Thrust (MT), in footwall position with respect to the LHM, represents an imbrication zone incorporating rocks from the LHM and sediments from (iv) the Lesser Himalaya (LHS).

Three distinct zones, with low temperature dynamic fabrics overprinting Miocene mylonites, occur in the Goriganga section. Along the STDZ, brittle, northward dipping extensional shear zones developed. Cataclastic, southward-directed thrust zones are located next to the VT and MT. Pronounced changes in topography and abrupt change in channel gradient, often related to fault activity or change in erosivity (Whipple, 2001), coincide with the position of the tectonic boundaries (Figs 1c and 2b). This can be interpreted as a hint to the fact that young tectonic activity may have controlled the evolution of mountain morphology. To decipher timing and the mechanism of the late exhumation history, systematic FT and (U-Th)/He data were collected along the Goriganga Valley (Fig. 2a).
Methods and results

Fission track and (U-Th)/He analyses were carried out in the Graz University FT laboratory, and the Yale University thermochronology laboratory, respectively. The analytical methods employed are described by Bojar et al. (1998) and Mitchell and Reiners (2003). The (U-Th)/He system has a closure temperature of approximately 180 °C in zircon (Reiners et al., 2004) and of approximately 70 °C in apatite (Farley, 2000; Reiners et al., 2004). For the FT system, the uppermost limit of the partial annealing zone of 250 °C (zircon) and 120 °C (apatite) were considered (Gleadow and Duddy, 1981; Zaun and Wagner, 1985). In this paper we define a ‘high temperature system’ as one that includes both zircon (U-Th)/He and FT, with blocking temperatures between 180 and 250 °C and a ‘low temperature system’ as one that includes apatite (U-Th)/He and FT, with blocking temperatures between 70 and 120 °C. We consider that this simplification prevents overinterpretation.

The thermochronological data (Tables 1 and 2; Fig. 2c) show variations in the cooling ages of the different crustal blocks, as well as systematic cooling age variations within individual units. A pronounced age-break is present between TH and HH with (U-Th)/He zircon ages of 2.5 Ma north of the STDZ and 0.5 Ma immediately south of it. Within the HH, both (U-Th)/He and FT zircon ages increase steadily from 0.5 Ma in the north to 1.2 Ma in the south, whereas apatite ages are clustered between 0.4 and 0.6 Ma. In the LHM, zircon ages range from 1.0 to 1.7 Ma; apatite ages are between 0.7 and 0.8 Ma. Finally, south of the MT, apatite and zircon ages are both c. 1.5 Ma. Although only one (U-Th)/He age is available from the TH, we consider the break in ages along the STDZ significant. We interpret this, together with the observed structures (Fig. 1c), as supporting northward normal faulting after 2.5 Ma. Taking the error bars, minor offset is observed along VT and MT. Age variations within a single tectonic unit show significant differences between low and high temperature systems (Fig. 2c). These variations are used to qualitatively constrain the exhumation mechanisms.

Exhumation mechanisms

Two techniques are commonly used to estimate cooling and exhumation rates from thermochronological data. The ‘mineral pair’ technique uses cooling ages from isotopic systems with
different closing temperatures. Using this approach assumptions on the geothermal gradient and changes in the geothermal gradient have to be made. We deliberately abstain from calculating exhumation rates from mineral pairs because of uncertainties of thermal gradients that may be perturbated by the exhumation process itself (e.g. Mancktelow and Grasemann, 1997; Safran, 2003). However, data show that final cooling was not simultaneous across the investigated profile; the HH passed the high temperature isograde c. 1 Ma later than the LHS (Fig. 3). The second method uses the vertical variation of ages derived from a single isotopic system. This technique is not applicable to our study because no correlation between ages and elevation has been found. Instead we noticed a strong correlation between ages and position within individual tectonic units (Fig. 2c). Consequently, we used a technique that considers lateral age variation along a sampling line.

The lateral variation of the cooling ages is controlled by the shape of two surfaces (topography and palaeo-isotherm surface) and the exhumation rate of rock particles moving towards surface. The shape of topography is a combined effect of tectonics and erosion. The shape and level of the palaeo-isotherm that defines the closure temperature level is controlled by the overall initial geothermal gradient and the temperature perturbation induced by tectonics and erosion. The velocity and displacement path of a specific particle defines the time elapsed since a rock sampled at the surface left the closure temperature level. The effect of various particle paths, shapes of the palaeo-isotherm as well as topography on age variation is first considered theoretically.

Same ages along a sampling line

Provided a velocity field where rock particles follow the same path with equal velocity, parallel oriented surfaces and palaeo-isotherms will always give the same ages along the sampling line. Ages are simply the ratio between the isotherm-to-surface distance $D$ and velocity $v$ of a particle $(\text{Age}_D = D/v)$. In the case of a particle path inclined at an angle $\phi$ with respect to the surface and the isotherm (Fig. 4a),
The above equation enables to calculate the distance a rock particle travels between the isotherm and surface. This translates into age variations along the sampling line, which correspond to the slope in a plot of age vs. distance between sampling points (Fig. 4d). Taking the length $X$ between the sampling points equal to 1, the slope of a normalized age distribution within an exhuming block may be calculated as:

$$\text{Slope} = \frac{\Delta D}{\Delta X}$$

where $\Delta D$ is the change in corrected age and $\Delta X$ is the change in distance between sampling points.

### Table 1 Apatite and zircon fission track ages

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tectonic unit</th>
<th>Elevation (m)</th>
<th>No. of crystals</th>
<th>Spontaneous track density $N_s$ ($10^6$ tracks cm$^{-2}$)</th>
<th>Induced track density $N_i$ ($10^5$ cm$^{-2}$)</th>
<th>Dosimeter $N_d$ ($10^8$ cm$^{-2}$)</th>
<th>Age (Ma)</th>
<th>Probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P27</td>
<td>HH</td>
<td>2960</td>
<td>20</td>
<td>0.098 (13)</td>
<td>13.061 (1869)</td>
<td>3.319 (3319)</td>
<td>0.4 ± 0.2</td>
<td>92</td>
</tr>
<tr>
<td>P36</td>
<td>HH</td>
<td>2550</td>
<td>25</td>
<td>0.075 (18)</td>
<td>12.107 (2896)</td>
<td>3.319 (3319)</td>
<td>0.4 ± 0.2</td>
<td>95</td>
</tr>
<tr>
<td>P58</td>
<td>HH</td>
<td>2300</td>
<td>15</td>
<td>0.053 (4)</td>
<td>8.234 (620)</td>
<td>3.319 (3319)</td>
<td>0.4 ± 0.4</td>
<td>91</td>
</tr>
<tr>
<td>P61</td>
<td>HH</td>
<td>2230</td>
<td>22</td>
<td>0.052 (9)</td>
<td>9.095 (1567)</td>
<td>3.319 (3319)</td>
<td>0.4 ± 0.2</td>
<td>60</td>
</tr>
<tr>
<td>P62</td>
<td>HH</td>
<td>2200</td>
<td>30</td>
<td>0.063 (17)</td>
<td>8.577 (2302)</td>
<td>3.319 (3319)</td>
<td>0.5 ± 0.2</td>
<td>91</td>
</tr>
<tr>
<td>P80</td>
<td>HH</td>
<td>1400</td>
<td>30</td>
<td>0.024 (6)</td>
<td>4.631 (1135)</td>
<td>3.319 (3319)</td>
<td>0.3 ± 0.2</td>
<td>94</td>
</tr>
<tr>
<td>P82</td>
<td>LHM</td>
<td>1650</td>
<td>25</td>
<td>0.088 (16)</td>
<td>7.930 (1440)</td>
<td>3.319 (3319)</td>
<td>0.7 ± 0.4</td>
<td>34</td>
</tr>
<tr>
<td>P100</td>
<td>LHM</td>
<td>1700</td>
<td>25</td>
<td>0.068 (14)</td>
<td>5.348 (1106)</td>
<td>3.319 (3319)</td>
<td>0.8 ± 0.4</td>
<td>58</td>
</tr>
<tr>
<td>P104</td>
<td>LHM</td>
<td>1790</td>
<td>20</td>
<td>0.092 (17)</td>
<td>7.004 (1300)</td>
<td>3.319 (3319)</td>
<td>0.8 ± 0.4</td>
<td>86</td>
</tr>
<tr>
<td>P121</td>
<td>LHS</td>
<td>1800</td>
<td>15</td>
<td>0.024 (9)</td>
<td>5.228 (379)</td>
<td>3.319 (3319)</td>
<td>1.4 ± 1.0</td>
<td>36</td>
</tr>
<tr>
<td>Zircon</td>
<td>ZP54</td>
<td>2350</td>
<td>16</td>
<td>1.350 (54)</td>
<td>39.250 (1570)</td>
<td>4.506 (4506)</td>
<td>0.9 ± 0.4</td>
<td>79</td>
</tr>
<tr>
<td>ZP58</td>
<td>HH</td>
<td>2300</td>
<td>10</td>
<td>1.560 (29)</td>
<td>38.000 (950)</td>
<td>4.506 (4506)</td>
<td>1.0 ± 0.4</td>
<td>17</td>
</tr>
<tr>
<td>ZP100</td>
<td>LHM</td>
<td>1700</td>
<td>10</td>
<td>2.191 (50)</td>
<td>59.230 (3152)</td>
<td>4.506 (4506)</td>
<td>1.0 ± 0.4</td>
<td>32</td>
</tr>
<tr>
<td>ZP117</td>
<td>LHS</td>
<td>1790</td>
<td>9</td>
<td>2.273 (45)</td>
<td>45.707 (905)</td>
<td>4.506 (4506)</td>
<td>1.3 ± 0.4</td>
<td>99</td>
</tr>
</tbody>
</table>

*Mass weighted average radius.
†Fraction of total alpha particles retained (Farley et al., 1996).
‡Average analyses.
Substituting for $D\phi$ from above gives:

\[
\text{Slope } = \frac{x^2 \sin \alpha - x^1 \sin \alpha}{x^2 - x^1}
\]

which can be written as:

\[
\text{Slope } = \frac{\sin \alpha}{\sin(\phi - \alpha)}
\]

When the palaeo-isotherm is parallel to the surface, no age variation (zero slope) is obtained. An age variation within an exhuming block exists only for variable particle velocities or when the sampling line is at an angle to the isotherm. The transfer of the ‘normalized’ slope to real dimension is straightforward, as an age is simply the ratio between the distance a rock particle has travelled ($D\phi$) and the velocity $v$:

\[
\text{Age } = \frac{D\phi}{v}
\]

Thus the slope of the age variation ($\Delta \text{age}/\Delta x$) becomes:

\[
\frac{\Delta \text{age}}{\Delta x} = \frac{\sin \alpha}{\sin(\phi - \alpha)} \frac{1}{v}
\]

In the case of constant exhumation velocities throughout an exhuming block, a ‘normalized slope’ relates to the real age variation along a sampling line by a proportionality constant equal to the particle velocity. The unknown variables for this equation are the particle velocity $v$, the angle between surface and the isotherm $\alpha$, and the particle path with respect to surface $\phi$. This last parameter is easily obtained from structural field analyses. Age variations along the sampling line are discussed for two end member cases: (i) for constant velocity and an angle between the sampling line and the closure temperature isotherm, and (ii), for variable velocities and isotherm parallel to surface. We use these geometric relationships to qualitatively infer the exhumation mechanisms of the study area.

Discussion and conclusions

In the geological framework of the Goriganga Valley, several exhumation scenarios are possible.

1 Southward extrusion without topographic evolution: when tectonic exhumation at constant rates within extruding HH and LHM blocks is entirely balanced by erosion, no topography evolves. As no lateral cooling is present and thermal perturbation by faulting is neglected, the isotherms are parallel to the surface and the slope defined by age vs. distance is zero for the isotopic systems (Fig. 5a).

2 If tectonic exhumation is not balanced by erosion and topography evolves, it allows for lateral cooling and perturbation of isogrades (Braun, 2002). This effect is pronounced parallel to the sampling line (N-S) where the wavelength of topography is large (tens of km) compared with small wavelength (approximately 10 km) in W-E. Thus, the palaeo-isotherms are not parallel to each other and to
surface. As the lateral cooling effect decreases with depth, the amplitude of isotherm perturbation diminishes at depth, too. This implies negative slope (ages decreasing southward) for the high temperature cooling ages and approximately zero slope for low temperature ages (Fig. 5b), a scenario not supported by our data.

3 Positive age slopes are obtained only when tectonic exhumation velocities decrease southward within distinct units (Fig. 5c). For the study area southward extrusion or clockwise rotation of HH induced by normal faulting along the STDZ are plausible tectonic settings. The latter scenario may induce perturbation of isotherms next to the STDZ (Mancktelow and Grasemann, 1997), causing no-linear age pattern with rapidly decreasing ages towards the STDZ. However, this would imply positive slopes for both, the high temperature and low temperature isotopic systems, which is not seen in our data.

4 The data presented here suggest a mechanism conducive to a positive slope for the high temperature, and a zero slope for the low temperature cooling ages. The zero slope is best explained by parallelism between the closure isotherm and surface. A plausible scenario is erosion with rates proportional to topography (Schaller et al., 2001; Vance et al., 2003) (Fig. 5d). Erosion is prominent in the uppermost portions of the rock pile and may have affected only the low temperature cooling ages sensitive to thermal disturbances within the upper 3–5 km of the crust. The high temperature cooling ages displaying thermal disturbances down to 7–8 km point to a different exhumation mechanism. Thus, we consider two different mechanisms to explain the observed age distributions. First, we suggest a phase of tectonic exhumation with decreasing rate towards the south. Tectonic exhumation rates exceed erosion rates, leading to the positive slopes in the (U-Th)/He and FT zircon ages. Second and subsequent, erosion rates balances tectonic exhumation rates (Burbank et al., 2003), causing a zero slope of low temperature cooling ages, as indicated by FT and (U-Th)/He in apatite. This is in concordance with interpretations by Vance et al. (2003) who report tectonically induced accelerated exhumation with onset at c. 4 Ma and present exhumation predominantly accommodated by erosion (Vance et al., 2003; Thiede et al., 2004).

Acknowledgements
We thank P. Reiners for constructive discussions. M. Bickle, K. Hodges, K. Stüwe and two anonymous reviewer are thanked for comments on a previous version of the paper. M. Treffer and S. Cudrigh helped with field work and sample preparation. M. Bichler is thanked for sample irradiation. The Austrian Research Foundation is acknowledged for grants P12837 and P16258.

References


Received 18 November 2004; revised version accepted 19 March 2005

© 2005 Blackwell Publishing Ltd

433