K/Ar cooling ages from Zanskar Himalaya: implications for the tectonics and exhumation of Higher Himalayan metamorphic complex

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New K/Ar ages determined on biotite, muscovite and hornblende separates from the Higher Himalayan Crystalline (HHC) rocks in the Zanskar region, NW India, are presented. The implications of these Cenozoic ages on the timing of regional metamorphism, exhumation history of the HHC and extensional tectonics within the Higher Himalaya are discussed.

Of all the domains of the Himalaya (Figure 1), the Higher Himalayan Crystalline (HHC) belt with many snow-capped peaks of >6000 m height represents the greatest uplift and denudation history. The HHC rocks are separated from the Lesser Himalaya to the south by the Main Central Thrust (MCT) system1,2 and from the overlying Tethyan sedimentary rocks by a normal fault of regional dimension, called the Zanskar Shear Zone (ZSZ)3, Trans-Himadri Fault4, North Himalayan Normal Fault5 and South Tibetan Detachment System6. The HHC rocks form the main metamorphic belt of the Himalaya, exhibiting Barrovian regional metamorphism with polyphase deformation related to the India-Asia collisional tectonics7−11. These rocks were once deep-seated, but now occupy high summits. Geologists' interest in the HHC (variously called the Central Crystalline in Kumaun and the Tibetan Slab in Nepal) dates back to the 19th century, but in the recent decade, there has been a focus on quantitative analyses of the HHC towards a better understanding of the tectonic and petrologic processes that have shaped the Himalaya. Isotopic ages providing the time-temperature pathways of rocks constitute an important component of such a database.

Here we report new K/Ar ages determined on biotite, muscovite and hornblende separates from metamorphic and granitic rocks in the Zanskar region of the Higher Himalaya, northwest India (Figures 1 and 2), and discuss the geologic implications of our age data.

Tectonic setting of Zanskar Himalaya

Zanskar Himalaya offers well-exposed sections of the HHC and the Tethyan sedimentary sequence (Figure 2). The geological setting, metamorphic history and plate-tectonic evolution of the region have been presented by several researchers11−29.

The HHC belt is about 10−15 km thick, with Proterozoic to Early Paleozoic crystalline complex of gneisses, schists, amphibolites, deformed two-mica granites and migmatites. Rb/Sr isochrons determined for the Himalayan crystalline rocks in NW India have revealed three major plutonic events of 1800−2000, 1100 and 500 Ma (refs. 30, 31) like the northern parts
of the Indian shield. From the Zanskar region itself, a few age data are available which put time constraints on the emplacement of the granitic gneisses. Honegger et al. extrapolated a Rb/Sr isochron for two samples from the Suru valley as 500 Ma. Pognante et al. reported a Rb/Sr isochron (549 ± 70 Ma) for a metagranitoid and a U/Pb concordia of zircon and monazite (472.4 Ma) for an orthogneiss from southeast Zanskar-Lahaul region.

Intruding the Higher Himalaya are also two-mica (often tourmaline-bearing) Tertiary leucogranites which originated from anatectic melts of the crystalline basement. Detailed geochronologic and geologic data on the Zanskar leucogranites are lacking.

A thick sequence of the Cambrian to Early Eocene sediments of the Tethyan zone forms a syncloniorium in Zanskar and is the northwestern extension of the Lahaul-Spiti basin into Kashmir. This sedimentary sequence represents the shelf and shelf-edge facies of the northern continental margin of the Indian Plate. The lower part of this sequence is made up of low-grade metamorphosed quartzite, green-grey slates and phyllites, but for the most part the Tethyan sedimentary rocks have escaped the regional metamorphism affecting the Himalaya.

The contact between the Tethyan sediments and the HHC is defined by the northeast-dipping Zanskar Shear Zone (ZSZ) having a complex geological history of an
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Figure 2. Simplified geological map of Kashmir and surrounding regions in NW Himalaya, India, showing major tectonic units and regional metamorphic isograds. Lesser Himalayan Proterozoic Foreland (Autochthon Kashmir Window) Kashmir Group: 1, Wael Formation (granite gneiss); 2, Phyllite, schist; 3, Du Formation (quartzite, metavolcanics); 4, Carbonaceous Phyllite. Higher Himalayan Crystallines (Allochthonous): 5, Schist-gneiss, migmatised, amphibolites; 6, granitoid intrusives; 7, leucogranite. Tethyan sedimentary zone: 8, Haunanza Group; 9, Phu Volcanics; 10, Lithang Group; 11, Granite; Indus Suture Zone: 12, Deos Volcanics. 13, Main Central Thrust; 14, Zanskar Shear Zone; 15, Dras Thrust. Metamorphic isograd boundaries: 16, garnet; 17, Kyantse–sapphire; 18, Sillimanite–andalusite; 19, Sillimanite–K-feldspar. HMN, Bhoman Nala, BN, Ehot Nala; CN, Chirang Nala; DDG, Durong Glaicher, DN, Dhoolang Nala, IHNC, Higher Himalayan Crystallines, HN, Hinglu Nala, HT, Hapital Tokpo, KT, Kange Tokpo; MCT, Main Central Thrust, MT, M Buffer Tokpo; ST, Sumich Tokpo, TF, Tenusa Tokpo, ZN, Zanskar Nala, ZSZ, Zanskar Shear Zone. (Based on our own observations and those of Herren, Homegger et al, Saturava et al, Volks et al, and Stanist.)

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early overthrusting towards the southwest and a later-superposed extensional tectonics\textsuperscript{11, 29}.

Geological mapping and petrologic studies of the HHC across the Chenab, Suru and Doda valleys (Figure 2) have identified Barrovian-type metamorphism ranging from biotite grade (middle greenschist facies) through sillimanite–K-feldspar grade (upper amphibolite facies)\textsuperscript{33}. The garnet zone is observed near the MCT surrounding the Kishtwar Window, the sillimanite–K-feldspar zone exists towards the deeper structural and higher topographical levels to the northeast, and the metamorphism again lowers to garnet zone along the ZSZ in the Suru–Doda valleys. Our data on mineral paragenesis and pressure (P) and temperature (T) in the Suru valley (Figure 2) demonstrate maximum T and P of 700°C and 950–1100 MPa for the sillimanite–muscovite grade between Tangol and Parkachik, and these gradually decrease to around 450°C and 650 MPa in the basal parts of the Tethyan sedimentary sequence around Ringdom. Thermo-barometric analysis of metamorphic samples from Zanskar has also been carried out by Gilbert (1986) (cited in Le Fort\textsuperscript{35}), who estimated peak metamorphic conditions of $T = 700^\circ C$ and $P = 780$ MPa, by Pognante et al.\textsuperscript{32}, who reported $T = 650–750^\circ C$ and $P = 600–800$ MPa, and by Searle et al.\textsuperscript{33}, who obtained $T = 700–750^\circ C$ and $P = 800$ MPa. Temperature data are conformable but pressure shows large variations, probably due to uncertainties inherent in the activity models\textsuperscript{37}.

Samples for this study were collected from the HHC of the Zanskar region along the Suru River from Sankoo to Pensi La (Figure 2) during the summer of 1987. These include orthogneiss, paragneiss, mica schist, granite and amphibolite from various metamorphic zones. Figure 3 shows sample sites and lithology along with a plot of the obtained ages.

### Results and discussion

Table 1 shows the analytical data on K/Ar ages (15 biotite, 9 muscovite and 2 hornblende) obtained in this study.

In the orogenic belts that have experienced high-grade regional metamorphism, discordant radiometric ages imply the closure of various radiometric systems for mineral phases at different times and thus record the cooling of rocks subsequent to the acme of metamorphism\textsuperscript{34, 36}. The cooling age represents the time when the rock passed through a certain temperature threshold (i.e., closure temperature) below which the radiogenic stable isotope in a given mineral could be retained\textsuperscript{40}. Thus, K/Ar mineral ages obtained reveal the cooling history of the HHC rocks in the Zanskar Himalaya. We assume the following closure temperatures for K/Ar system: 300 ± 50°C for biotite; 350 ± 50°C for muscovite and 525 ± 25°C for hornblende\textsuperscript{41–44}.

Palaeomagnetic data\textsuperscript{45, 46} and palaeontological evidence\textsuperscript{47, 48} indicate that the collision of the northwestern Indian Plate with Asia occurred at 55± Ma or closer to the Cretaceous–Tertiary boundary (65 Ma). The K/Ar ages from the HHC rocks in Zanskar, being of Cenozoic age, imply that the northern edge of the Indian Plate was reactivated, metamorphosed and deformed during the Cenozoic Himalayan orogeny. K/Ar hornblende ages from two amphibolites (H14, 40.5 ± 1.3 Ma and H35, 45.5 ± 2.3 Ma) suggest that the thermal peak of the Barrovian-type regional metamorphism in the upper parts of the HHC in Zanskar was reached in the early Eocene, which is similar to the data and interpretation given for the HHC stacks in the Swat region in Pakistan Himalaya\textsuperscript{49}.

All the mica ages in Zanskar date back to early-middle Miocene (25-15 Ma). In a few cases, biotite obviously carries excess argon, as it has an apparent age larger than that of muscovite from the same rocks (e.g. sample H28 in Table 1). Such excess argon in biotite is not uncommon and has been reported from other orogenic belts\textsuperscript{50}. This is a shortcoming with the
Table 1. K/Ar age data from the Higher Himalayan crystalline rocks in Zanskar, NW India

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fraction (mesh size)</th>
<th>Sample weight for Ar (g)</th>
<th>Potassium (weight %)</th>
<th>Radiogenic $^{40}$Ar (10$^8$ ccSTP/g)</th>
<th>Nonradiogenic Ar (%)</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>Biotite</td>
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<td></td>
</tr>
<tr>
<td>H02</td>
<td>80-100</td>
<td>0.1197</td>
<td>6.91 ± 0.14</td>
<td>472.3 ± 7.7</td>
<td>34.4</td>
<td>17.5 ± 0.5</td>
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<tr>
<td>H03</td>
<td>100-150</td>
<td>0.1305</td>
<td>7.18 ± 0.14</td>
<td>450.7 ± 5.2</td>
<td>13.5</td>
<td>16.1 ± 0.4</td>
</tr>
<tr>
<td>H07</td>
<td>60-100</td>
<td>0.1165</td>
<td>7.41 ± 0.13</td>
<td>487.5 ± 5.5</td>
<td>13.1</td>
<td>16.9 ± 0.4</td>
</tr>
<tr>
<td>H11</td>
<td>32-80</td>
<td>0.1087</td>
<td>7.20 ± 0.14</td>
<td>421.1 ± 4.9</td>
<td>12.2</td>
<td>15.0 ± 0.3</td>
</tr>
<tr>
<td>H13</td>
<td>32-80</td>
<td>0.1483</td>
<td>7.52 ± 0.15</td>
<td>476.6 ± 5.2</td>
<td>9.6</td>
<td>16.3 ± 0.4</td>
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<tr>
<td>H14</td>
<td>32-80</td>
<td>0.2336</td>
<td>7.61 ± 0.15</td>
<td>417.8 ± 4.2</td>
<td>4.4</td>
<td>14.1 ± 0.3</td>
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<tr>
<td>H16</td>
<td>32-80</td>
<td>0.2200</td>
<td>7.56 ± 0.15</td>
<td>430.6 ± 4.7</td>
<td>8.2</td>
<td>15.3 ± 0.3</td>
</tr>
<tr>
<td>H19</td>
<td>60-100</td>
<td>0.1212</td>
<td>7.26 ± 0.15</td>
<td>428.5 ± 4.4</td>
<td>4.6</td>
<td>15.2 ± 0.3</td>
</tr>
<tr>
<td>H20</td>
<td>60-100</td>
<td>0.1340</td>
<td>7.88 ± 0.16</td>
<td>413.3 ± 4.4</td>
<td>7.9</td>
<td>13.3 ± 0.3</td>
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<tr>
<td>H21</td>
<td>60-100</td>
<td>0.1224</td>
<td>7.60 ± 0.15</td>
<td>402.6 ± 4.4</td>
<td>10.2</td>
<td>13.6 ± 0.3</td>
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<tr>
<td>H24</td>
<td>60-100</td>
<td>0.1042</td>
<td>7.35 ± 0.15</td>
<td>572.9 ± 6.0</td>
<td>6.8</td>
<td>19.9 ± 0.5</td>
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<tr>
<td>H25</td>
<td>80-150</td>
<td>0.1158</td>
<td>7.57 ± 0.15</td>
<td>556.5 ± 5.9</td>
<td>7.6</td>
<td>18.8 ± 0.4</td>
</tr>
<tr>
<td>H28</td>
<td>100-150</td>
<td>0.1133</td>
<td>7.57 ± 0.15</td>
<td>609.6 ± 6.5</td>
<td>7.5</td>
<td>20.6 ± 0.5</td>
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<tr>
<td>H33</td>
<td>100-150</td>
<td>0.1212</td>
<td>7.54 ± 0.15</td>
<td>663.9 ± 7.0</td>
<td>7.8</td>
<td>22.6 ± 0.5</td>
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<td>H34</td>
<td>80-150</td>
<td>0.1501</td>
<td>7.43 ± 0.15</td>
<td>654.4 ± 6.8</td>
<td>7.3</td>
<td>22.5 ± 0.5</td>
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<tr>
<td>Muscovite</td>
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<td></td>
</tr>
<tr>
<td>H01</td>
<td>100-150</td>
<td>0.1557</td>
<td>8.42 ± 0.17</td>
<td>855.1 ± 8.4</td>
<td>2.2</td>
<td>25.9 ± 0.6</td>
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<tr>
<td>H02</td>
<td>100-150</td>
<td>0.1071</td>
<td>9.00 ± 0.18</td>
<td>790.7 ± 7.9</td>
<td>2.4</td>
<td>22.5 ± 0.5</td>
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<tr>
<td>H07</td>
<td>32-60</td>
<td>0.1402</td>
<td>8.92 ± 0.18</td>
<td>623.9 ± 6.2</td>
<td>2.8</td>
<td>17.9 ± 0.4</td>
</tr>
<tr>
<td>H11</td>
<td>32-60</td>
<td>0.1049</td>
<td>6.75 ± 0.14</td>
<td>432.5 ± 4.6</td>
<td>6.8</td>
<td>16.4 ± 0.4</td>
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<tr>
<td>H13</td>
<td>60-80</td>
<td>0.1293</td>
<td>8.89 ± 0.18</td>
<td>604.4 ± 6.4</td>
<td>9.1</td>
<td>17.4 ± 0.4</td>
</tr>
<tr>
<td>H19</td>
<td>60-80</td>
<td>0.1194</td>
<td>7.63 ± 0.15</td>
<td>467.6 ± 4.9</td>
<td>6.0</td>
<td>15.7 ± 0.4</td>
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<tr>
<td>H25</td>
<td>80-100</td>
<td>0.1615</td>
<td>8.92 ± 0.18</td>
<td>631.8 ± 6.4</td>
<td>3.8</td>
<td>18.2 ± 0.4</td>
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<tr>
<td>H28</td>
<td>100-150</td>
<td>0.1060</td>
<td>9.23 ± 0.18</td>
<td>633.3 ± 6.7</td>
<td>3.9</td>
<td>17.6 ± 0.4</td>
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<tr>
<td>H33</td>
<td>100-150</td>
<td>0.1218</td>
<td>9.12 ± 0.18</td>
<td>850.3 ± 8.5</td>
<td>4.4</td>
<td>23.9 ± 0.5</td>
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<td>Hornblende</td>
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<tr>
<td>H15</td>
<td>80-150</td>
<td>0.5347</td>
<td>0.62 ± 0.02</td>
<td>98.3 ± 1.1</td>
<td>11.8</td>
<td>40.5 ± 1.3</td>
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<tr>
<td>H35</td>
<td>80-150</td>
<td>0.5553</td>
<td>0.42 ± 0.02</td>
<td>75.5 ± 0.9</td>
<td>19.6</td>
<td>45.5 ± 2.3</td>
</tr>
</tbody>
</table>

K/Ar experimental procedure: Samples were sieved and washed in ion-exchanged water to remove powder residue. Separation and purification of biotite, muscovite and hornblende were carried out by decanting, tapping and a Franz magnetic separator K/Ar dating was carried out at the Hirozuma Research Institute, Okayama University of Science. Ileya et al. 29 have given the detailed laboratory procedure. The equations for calculating the age and error follow Cox and Dalrymple 30. The constants used follow Steiger and Jager 31. Potassium content was determined by flame photometry using a 2000 ppm Cs buffer. Mineral separates (each weighing 0.05-0.08 g) were decomposed for the K-analysis by treatment with HF and HNO$_3$ in a Teflon beaker. Multiple runs (along with the unknown samples) of a working chemical standard showed the uncertainty of the K analysis to be within 2%. An average value of double runs for each sample was used in the age calculation. Samples for argon analysis were wrapped in Al foil, preheated at 150-200°C for about 24 h in vacuum. Argon was extracted in an Nb crucible at 1500-1600°C in an ultrahigh vacuum line. Clean-up of the reactive gases was done by a Ti-Zr scrubber. Argon was analysed on a 15-cm-radius sector-type mass spectrometer using isotopic dilution method and 39Ar spike. The mass discrimination was checked with the atmospheric argon once every day. The double analysis of the age standard JG-1 (91 Ma) along with the unknown samples ensured the uncertainty of the age data to be within 2%.

K/Ar age data. However, the ages reported here are useful for an approximate geologic discussion. These ages are similar to Rb/Sr biotite ages 16 and K/Ar, $^{40}$Ar/$^{36}$Ar mica ages 28 reported from Zanskar as well as those from Nepal 31 and Pakistan 30. Early-middle Miocene marks a rapid phase of uplift and exhumation in the Himalaya 32.

Assuming an average geothermal gradient of 30°C/km, the age data indicate an exhumation of ~12 km of the HHIC since ~20 Ma. The rapid exhumation of the HHIC has occurred due to two processes: (i) deep crustal ramping and imbrication causing extensional tectonics across the HHIC belt, and (ii) ensuing erosional unloading. Evidences for these
processes are (i) tectonic displacements along the ZSZ and the MCT and (ii) the Siwalik molasse deposited in front of the rising Himalaya in Miocene–Pleistocene times\textsuperscript{36,33,34}. Our samples collected across the ZSZ put time constraints on the activity of this extensional structure (Figure 3). Mica ages jump from 23 Ma (for samples H33 and H34) on the hanging wall to 18 Ma (samples H25 and H28) on the footwall of the ZSZ, demonstrating its activity in the early Miocene. Hedges et al.\textsuperscript{55} also found similar ages (19–22 Ma) for the activity of the South Tibetan Detachment System in the Everest region of Nepal. Treloar et al.\textsuperscript{56} interpreted fission track zircon ages of Zeitzler\textsuperscript{47} from the Swat region of Pakistan as timing the extensional phase of the Main Mantle Thrust at ~23 Ma. It thus seems that the extension between the HHIC and the overlying Tethyan zone took place not only synchronously with the MCT compression at depth\textsuperscript{55} but also simultaneously throughout some 2000 km of the Himalayan belt.

The HHIC in Zanskar forms a large-scale refolded domal structure with the highest-grade rocks in the core and lower-grade metamorphics towards the flanks\textsuperscript{11, 16, 22, 26, 55} along the Suru Valley, where metamorphic grade has reached up to sillimanite–muscovite around Parkachik (Figure 3). The mica ages show a trend conformable with this thermal structure. The ages become smaller towards the core of the Suru dome and are larger towards the lower-grade metamorphics on its flanks (Figure 3). It seems that the culmination parts of the Suru dome have undergone faster exhumation due to rapid uplift of the axis of the orogen. Note that highest peaks such as Kun and Nun (both >7000 m) along the Suru river from Sankoo as far as Pensi La occur in the sillimanite–muscovite zone for which youngest mica ages (13–15 Ma) have been obtained. We believe this pattern is real and testable and, although it is shown here only for the Suru Dome, it is worth the investigation in other structural domes of the Higher Himalaya.

Interestingly, the erosional and depositional record of the Higher Himalayan rocks preserved in the Siwalik molasse is consistent with the idea suggested above. Chaubhry\textsuperscript{58} has carried out heavy mineral analysis of the Siwaliks in Punjab and Kumaun. Figure 4 shows the results of his study for metamorphic minerals. Note that the influx of metamorphic assemblage not only increases from Lower to Upper Siwaliks but also higher-grade metamorphic minerals become more abundant with the passage of time.


ACKNOWLEDGEMENTS. Japan's Ministry of Education is acknowledged for awarding a Mombusho Scholarship to R. B. S. to carry out this work as part of his Ph.D. thesis submitted to Kyoto University. R. B. S. is grateful to Messrs. T. Okada, H. Takeshita and S. Fukui of Hirozen Research Institute, Okayama University of Science. Field work was made possible by the untiring help rendered by Messrs. Sandeep Singh, M. Dangwal, L. P. Singh, S. Misra and several residents in Zanzar. A. K. J. and Rm. M. acknowledge financial assistance from the Department of Science and Technology, New Delhi.

Received 10 May 1993; revised accepted 14 June 1993