HIGH COOLING AND DENUATION RATES AT KONGUR SHAN, EASTERN PAMIR (XINJIANG, CHINA) REVEALED BY $^{40}\text{Ar}/^{39}\text{Ar}$ ALKALI FELDSPAR THERMOCRONOLOGY

N.O. Arnaud$^1$, M. Brunel$^2$, J.M. Cantagrel$^1$, and P. Tapponnier$^3$

Abstract. Orthogneiss samples taken from the Kongur antiform show ages varying from 2 Ma to 1 Ma for $^{40}\text{Ar}/^{39}\text{Ar}$ ages of biotites and muscovites and fission tracks on apatites, leading to cooling rates of 150°C/m.y. Modeling of K-feldspars highlights the effect of a range of diffusion domains with contrasting diffusion characteristics, yielding closure temperatures from 400°C to 150°C. The feldspar data document the cooling history since 5 Ma and indicate a sudden change in cooling rates of the antiform at 2 Ma. At that time, cooling increases by a factor of 5, from an average of 20°C/m.y. to a minimum of 150°C/m.y. Consideration of the regional thermal history, ongoing uplift, and erosional history of the antiform during the Quaternary suggests that denudation rates have been of the order of 5-7 km/m.y. since 2 m.y. ago and could be associated with significant upward surface movement triggered by major normal faulting. The antiform is interpreted to have formed during thrusting at the Pamir front as a result of the development of thrust ramps and normal faulting at the crustal scale. Ramp stacking is an important process of mountain building, and normal faulting in this context must be regarded as a very efficient way of building high relief.

INTRODUCTION

The northwestern part of the Kunlun, at the border between China, Tadzhikistan, and Afghanistan is a wedge where the Pamir, Kunlun, and Tien Shan ranges meet. Covered by glaciers, the Kongur Shan and Muztaghata mountains (Figure 1) are the dominant structural features of this area, reaching 7719 m above plains and valleys and ranging from 2500 to 4500 m. The complexity of the present tectonic setting of that area may be better understood after a more detailed study of its present and recent dynamics. In 1990 the Sino-French Karakorum mission sampled the whole region along the Karakorum highway, and we report here the first thermochronological data and estimates of the exhumation rates of the Kongur Shan antiform, compared with investigations of neotectonics in the adjacent basins and recent erosion rates. There are many reasons for studying the cooling history of this area. Apart from the paucity of geochronological data from western Tibet, only detailed study of local cooling rates can help in reconstructing the thermotectonic and uplift history of wider structures. It is now a well-established fact that the tectonic history of the India-Asia collision raises questions about accommodation mechanisms of crustal shortening. This highly debated question may be answered through the study of cooling and uplift rates. The easiest way to build relief at the Himalayan scale is probably by thickening of the crust, and this must affect the cooling history recorded at the mineral scale. Moreover, the relations between crustal uplift and related cooling can be studied through thermochronology and may shed light upon many problems of mountain building, from the local to the whole range scale. In particular, recent recognition of the major role of normal faulting in building relief [King and Ellis, 1990] is a new challenge in which thermochronology may help to separate the different processes by which mountains grow.

The thermochronological study of the Kongur Shan antiform is of major interest, for it is one of the highest mountains in Pamir and shows a complete range of recent deformation episodes. These can be described and related both mechanically and geochronologically. Comparison of the available data suggests that cooling rates as high as 150-200°C/m.y. which could be associated with denudation rates of 5-7 km/m.y. were triggered by major normal faulting. These rates will be interpreted in the light of the recognition of coexisting thrusting and normal faulting and will be discussed in the terms of processes of mountain building in the frame of postcollisional uplift of the Tibet-Himalayan area.

GEOLOGICAL SETTING AND SAMPLES DESCRIPTION

The Kongur Shan mountain (Figure 1) and Muztaghata, its twin structure, are two topographic anomalies that necessitate a structural explanation at the crustal scale. Formed as antiform of foliation elongated along a ESE direction, they develop "en échelon" to the east of the Karakorum fault, along with small pull-apart sedimentary basin systems north and south of Tashkurgan which develop on the western termination of the Kunlun-Altn Tagh range. The Kongur massif is interpreted as a ramp antiform thrusted in a northerly direction [Brunel et al., 1992] over the Tarim crust covered with a thick (10 km) "décolé" sedimentary series of Miocene to Quaternary age. The Pamir-type thrusts with a northeastern vergence are presently active and responsible for the crustal thickening, with the total horizontal shortening probably exceeding 100 km. The Kongur massif (Figure 2) therefore forms a large antiform, 10 km high and 25 km wide. Its core is composed of augen orthogneisses and leucogranites, covered by fine gneisses and garnet-kyanite mica schists. To the north, the contact between the antiform and its Palaeozoic cover is marked by a thick (1 km) dextral ductile shear zone. Extensive nappo tectonics was described in this area [Brunel et al., 1992]. Biotites in the sole contact of the nappe give $^{40}\text{Ar}/^{39}\text{Ar}$ Jurassic ages of 146+0.7 Ma (for example, biotite K90G27, in Figure 3), but limited Quaternary displacement is also suggested. To the west and the southwest, the antiform is bounded by normal faults, which contribute to control the topography of the whole western face. The normal fault zone is marked by the development of mylonites characterized by plastic deformation and development of ductile shear bands and typical shearing structures which indicate a top to the west sense of shears. This normal faulting deformation occurs under greenschist metamorphic facies conditions, allowing plastic deformation of quartz aggregates. The core of the antiform exhibits many
fewer deformed gneisses and leucogranites, while those outcropping on the outer parts are highly deformed, therefore suggesting a close relation between the present external deformation of the antiform and the activity of surrounding faults. To the south, the Muztagh antiform is the twin structure of the Kongur, and gneisses there have yielded Jurassic ages with the U/Pb method on zircons, probably dating the protolith of the gneisses (U. Schärer, personal communication 1992). All dated samples in this study were collected on the external part of the antiform, where deformation in relation to active faulting is prominent. The mylonite sample KLB1 is a phyllonite collected from the normal fault path at 3300-m altitude, where beds of muscovite, quartz, plagioclase, and K-feldspars alternate. Small muscovites (50 μm) develop within shear bands associated with the normal fault movement. Sample K90G08 was collected 2-km to the east of KLB1 at 2900 metres altitude, whereas K90G34 is 10-km away at 2500 metres altitude. The latter is less intensely deformed compared to the phyllonite sample and contains eyes of K-feldspar 0.5- to 1-cm long, quartz, narrow layers of muscovites and rare biotite.

TECHNICAL BACKGROUND: THERMAL MODELING METHODS

The samples have been dated using fission tracks in apatites and 40Ar/39Ar on muscovites, biotites, and K-feldspars. The apatites were separated by classical means (heavy liquid, Frantz magnetic separator, and, finally, hand picking). Grain sizes between 200 μm and 80 μm were counted using the population method [Naeser 1976] after irradiation in the highly thermalized P1 site of the Orphée reactor at the Centre d'Etudes Nucléaires of Saclay, France. A 59Co pill was used as a flux monitor, as well as FC3 apatite from the Fish Canyon tuff (recommended value 28±0.5 Ma) to control the internal consistency of our results. Apatites have
Fig. 2. Geological sketch map of western Pamir in the Xinjiang region of China. Major geologic units and their tectonic relations are shown as follows: Inset shows the position of sampled areas. Numbers above the locations refer to sample numbering: 1, KLB1; 08, K90G08; 34, K90G34; 14, K90G14; 15, K90G15.

As these are the first results published from the $^{40}$Ar/$^{39}$Ar laboratory at Clermont-Ferrand, some technical information has been included detailing the techniques in the following section. Samples for $^{40}$Ar/$^{39}$Ar analyses have been separated and purified in the same way as the apatites, and high-purity 5- to 10-mg separates were irradiated at the Siloé reactor of Commissariat à l'Energie Atomique in Grenoble, France, for 24 hours in the 69 fast neutron position, third level. Reported fast neutron flux is $1.7 \times 10^{13}$ neutron cm$^{-2}$ s$^{-1}$, and the fast/thermal neutron ratio is 0.15. All samples were irradiated with CaF$_2$ and K$_2$SO$_4$ salts to account for interfering nuclear reactions, and the vessels were protected with a cadmium sheet 0.5-mm thick to limit the reactions by thermal neutrons on K. This effect appears on the correction factors we determined, as the $(^{39}$Ar/$^{40}$Ar)$_{K}$ is...
Fig. 3. (a) Age spectrum and inverse isochron diagram from a biotite from the sole contact of the allochtonous unit covering the Kongur Shan. The age inferred from the plateau is in perfect agreement with the U/Pb age on zircons (U. Schärer personal communication, 1992), and suggests that the age of metamorphism is as old as Jurassic. (b) Age spectrum and inverse isochron diagram for K90G08 biotite. Analytical dispersion is more readily explained by biotite/chlorite intergrowth, which is confirmed by the K/Ca plot. A mean age of 2.5 m.y. is inferred.

almost nils, while \( \frac{36\text{Ar}}{37\text{Ar}} \text{Ca} = (4.06 \pm 0.2) \times 10^{-4} \) and \( \frac{39\text{Ar}}{37\text{Ar}} \text{Ca} = (10.4 \pm 3) \times 10^{-4} \). These values, and their fluctuations, are similar to earlier estimates at the same facility. Several flux monitors were put in every vessel. For this we chose the LP6 biotite (128.5±0.5 Ma [Maluski, 1985]) and Caplongne hornblende (344.5±0.5 Ma [Maluski, 1985]). Analyses were carried out on a VG3600 mass spectrometer connected to an all metal extraction line divided into two sections. Step heating is achieved in a double vacuum resistance heating furnace very similar to the one described by Staudacher et al. [1978] and built by Modifications Ltd., which allows heating up to 1800°C. The temperature is controlled by a Eurotherm controller linked to a W-Rh thermocouple which lies in the bottom of the crucible, 1.5±0.5 mm from the samples. Calibration on a similar furnace [Chamberlain et al., 1991] and our own experience in melting crystals indicate that the temperature is monitored at ±10°C or better. During heating, the gas is cleaned by a nitrogen cold trap directly mounted on the furnace. Once released from the furnace section, the gas is transferred to the second section and cleaned by two SAES Zr-Al getters at 400°C and the ambient temperature, respectively, that ensure the most complete removal of water, CO\(_2\), hydrogen, and organic contaminants. Once clean, the gas is admitted into the machine and isotopically analyzed in static mode. Approximately 1 mm is allowed for equilibration, and gas remaining in the extraction system is pumped away. Each section of the line is alternately pumped after transfer of the gas from one to the other. The spectrometer source ran with a 200-μm trap current and 1-mA emission current. Two collectors were used: an axial 10^11-ohm Faraday cup and a Daly linked multiplier. Our settings and calibration give a gain multiplier/axial of 90±3 depending on the mass used for the calculation. Drift of the gain factor varied on a 3- to 4-month time interval and was regularly checked and reset by adjusting the photomultiplier voltage. Repeated analysis of known quantities of atmospheric argon gave a typical \( 40\text{Ar}/36\text{Ar} \) atmospheric ratio of 300 on the axial and 280 on the multiplier and a sensitivity of \( 10^{-18} \text{ mol/mV} \) on the multiplier. Corresponding discrimination factors of 0.996 (axial) and 1.014 (multiplier) per mass unit were found to be constant for signals ranging from 10 mV to more than 5 V for each detector. The build up blank production in the line and mass spectrometer system in static conditions is \( 5 \times 10^{-18} \) mol/min of \( 40\text{Ar} \) and negligible \( 36\text{Ar} \). The blank production of the furnace is \( 10^{-17} \) mol/min of \( 40\text{Ar} \) below 1000°C and
up to $10^{-15}$ mol/min at 1400°C with exponential evolution between 1000°C and 1400°C. Build up rates for $^{36}$Ar are always lower than $10^{-18}$ mol/min. When it was possible to calculate it (when some $^{36}$Ar was detectable), the blank isotopic composition rises with temperature to reach $40Ar/^{39}$Ar atmospheric values above 1100°C. Mass 40 and 39 were measured on the axial Faraday, while 36 and 37 were measured on the multiplier. A gain correction was then applied to compare all results on the multiplier basis. This therefore using the multiplier $40Ar/^{36}$Ar atmospheric correction factor. Line and mass spectrometer blanks were subtracted during regression of data as being part of the baseline, and furnace blanks were subtracted during age calculations as supplementary noise. With those settings we typically used 5-10 mg of sample with up to 30 heating steps. A full set of results can be obtained from the authors upon request.

Classical stepped heating has been applied to biotites and muscovites with 8 to 15 steps between 450°C and fusion at 1400°C. For K-feldspars, the multidomain theory has been assumed [Lovera et al., 1989, 1991], and we followed the heating schedule proposed by Lovera et al. [1989]. The heating is cycled to exhaust the different diffusion domains one after another as far as possible. On the Arrhenius plot, this effect is clearly demonstrated by several parallel arrays. The first one gives the reference intrinsic parameters of the smallest domain $r_0$, the activation energy $E$, and the frequency factor $D_0/r_0^2$. The largest domain is masked by the melting of the sample above 1140°C. Once $r_0$ is obtained, the following parallel arrays are normalized to that value [Richter et al., 1989] and plotted as $\log(r/r_0)$ against the percentage of $^{39}$Ar released.

The modeling of that plot was carried out numerically, using a program developed by Lovera [1992]. For each sample analysed, the relative size, volume contribution, and activation energy of each domain were fitted to the $\log(r/r_0)$ plot. We chose a plane sheet geometry to model the diffusion behavior, as demonstrated by Lovera et al. [1989, 1991], the resultant diffusion model is almost insensitive to this choice. These values were then used to model the age spectrum. The inputs include the laboratory heating schedule and the diffusion characteristics of each domain. The essential variable in the model is the cooling history. Each sample has a specific set of diffusion characteristics, and therefore a specific cooling history. Each sample cooling history is therefore unique to a given feldspar sample. The best fit gives the cooling history of the sample. Cooling histories were defined iteratively and are precise at ±5°C/m.y. and ±0.2 m.y.

Application of the multidomain theory of Harrison and coworkers [Lovera et al., 1989, 1991] is still highly debated. While some authors have defined several diffusion domains in one feldspar grain, Parsons et al. [1988, 1991], as well as others, have cast doubt upon the validity of such textures observed in transmission electron microscopy (TEM), and the effect of short time scale temperature pointing to cycling during laboratory experiments. On the other hand, TEM and scanning electron microscopy (SEM) studies can only visualize two-dimensional structures and are not sufficient to characterize coherent or permeable boundaries. More recently, a comprehensive study by Burgess et al. [1992] emphasized the role of fluid inclusions in the location of inherited trapped argon and the risk for modeling artifacts in the search for cooling histories. A study similar to the one of Parsons et al. [1988] carried out by Fitzgerald and Harrison [1993] has shown the presence of very fine structures below 1 µm which constitute subdomains that could act separately during the diffusion process. Moreover, as part of the same study, heated samples [Lovera et al., 1993] showed that no artifact or effect is produced during heating below 1000°C but that the smallest structures are suppressed, as is also proposed through the diffusion experiments. The debate continues, although in order to justify the application of the multidomain theory in the present study, some points can be made. Recent application of feldspar modeling by the multidomain theory showed a good agreement with previous results as well as the resolution of the method [Richter et al., 1991, Harrison et al. [1992] have used the method to describe fine contrasts in recent thermal histories, never producing false results or contradicting scientific evidence on diffusion.

Also, one that in the worst case, the temperature/time models are not worse than curves defined with "a priori" closing temperatures or those extracted from petrologic data obtained from experimental petrology studies that share with feldspar modeling a common questionable relation with natural processes. Criticism raised about the precision of this thermal modeling and the limits of its validity are common to all earth sciences, since a more and more quantitative approach is needed. Presently, the modeling is progressively achieved by a manual iterative technique which gives a rough idea of the precision of the model. Ongoing work (A. Provost and N. Arnaud, manuscript in preparation) suggests that an automatic inversion method of time/diffusion/temperature profiles will soon be available and will have important bearing on the precision of the approach.

RESULTS

The age of the apatites is very young. While the induced track density gives an average uranium content of 2-6 ppm (Table 1), the density of fossil tracks is very low, leading to ages averaging 1±1 m.y., regardless of differences of location in the field. The error is high because of the very low track densities and the scarcity of apatite crystals in those rocks. No age correction could be made for the same reason. The agreement between all sampling areas gives us confidence in this order of magnitude which represents cooling below 110°±20°C.

The $^{40}$Ar/$^{39}$Ar ages for all muscovites (Figure 4) are young but do not yield perfect plateaus, as variations are probably induced by atmospheric corrections. More than 80% of the spectrum of each sample constitutes a plateau, although the K90G34 sample displays a broad, U-like saddle shape, therefore theoretically giving only a maximum age. On the other hand, inverse isochron $^{36}$Ar/$^{40}$Ar versus $^{39}$Ar/$^{40}$Ar diagrams (Figure 4) give almost the same age as the plateau with a near-atmospheric composition for the trapped component, though some variation is observed. This seems to preclude an excess argon effect, and we thus interpret these dates as being close to their real age. Differences in age between samples are nevertheless greater than uncertainties and may be related to differences in altitude (500 m between KL1 and K90G34, for example), and also in slightly different times of fault movement from place to place (especially for K90G34). Differences in closure temperatures can also be considered in relation with their size [Wright et al., 1991], micas being slightly larger in K90G34 (100 µm) than in the other samples (50-80 µm). These ages range from 1.7 to 2.6 m.y. and have an average age of 2±0.3 m.y. The K90G08 biotite is more disturbed, but problems were encountered during its separation. The presence of chlorite led to the irradiation of possibly mixed grains, giving this characteristic humped age spectra complicated by $^{39}$Ar recoil.
TABLE 1. Fission Track Age Results for Apatites

<table>
<thead>
<tr>
<th>Sample</th>
<th>Altitude, m</th>
<th>Total Tracks</th>
<th>Number of Crystal Density, $10^{6}$/cm$^2$</th>
<th>Induced Tracks</th>
<th>Number of Crystal Density, $10^{6}$/cm$^2$</th>
<th>Age, m.y.*</th>
<th>Error, m.y.†</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC3</td>
<td>136</td>
<td>55</td>
<td>7.60</td>
<td>95</td>
<td>10.08</td>
<td>27.8</td>
<td>3.0</td>
</tr>
<tr>
<td>K90G14</td>
<td>2770</td>
<td>3</td>
<td>0.46</td>
<td>65</td>
<td>12.50</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>K90G15</td>
<td>2991</td>
<td>1</td>
<td>0.10</td>
<td>32</td>
<td>4.48</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>K90G34</td>
<td>3162</td>
<td>1</td>
<td>0.11</td>
<td>33</td>
<td>4.62</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

All samples are from the edges of Kongur antiform. Neutron flux was $6.19 \times 10^{14}$ n/cm$^2$ for all irradiations. Uranium content in apatites ranges from 2 to 6 ppm. FC3 standard was dated for internal consistency.

* Ages are calculated using $\lambda_p = 7.03 \times 10^{-12}$ yr$^{-1}$.
† Errors are at 1σ confidence level, calculated as the Poisson standard error [MacGee et al., 1985].

Fig. 4. Muscovite and biotite age spectra and inverse isochron diagrams from Kongur gneiss. All errors are at 1σ. Errors in the age spectra do not include the uncertainty on the irradiation factor $J$, whereas it is included in calculations of plateau and isochron ages.
Amaud et al.: High Denudation Rates at Kongur Shan

effects as suggested by Ruffet et al. [1991]. An age between 2.5-4 m.y. has been assumed for the biotite.

The K-feldspars yield spectra which are characteristic of several diffusion domains with highly varying retentivities (Table 2) resulting in two-plateau spectra. Inverse isochron diagrams (Figure 5) have been studied to distinguish possible artifacts in the spectra. It is clear that no real lineament can be resolved from these graphs. It is also impossible to distinguish reasonable lineaments for successive temperatures. As an example, two isochrons are proposed for sample K90G34. One points to an almost atmospheric trapped component, while the other suggests a trapped 40Ar/36Ar ratio much lower than 295.5, which is surprising at the very least, if not impossible. On the other hand, if points are taken independently, the scatter could reveal extraordinary variable trapped components which do not appear in the case of muscovites which are apparently the same age. It therefore seems more reasonable to interpret the scatter of the data as revealing true variation in ages. Finally, Lovera et al. [1992] have investigated the problem of argon recoil and concluded that this effect was negligible in the research of diffusion domain models. The scattering in ages is therefore interpreted as real and significant in relation to the domain structure of those crystals.

The K90G34 sample (Figure 6) exhibits an initial plateau at 1.3 m.y. rising suddenly to an average of 3.5 m.y. That second release is disturbed, probably because of the interplay of very retentive and less retentive domains. Modeling of the diffusion domain structure shows that closure temperatures range from 400øC to 150øC. The modeled age spectrum is not simple but is in agreement with the general pattern. A sharp change in the cooling history at 1.8 Ma is implied, since it is the only way to obtain a flat end to the spectrum. Though the last part of the spectrum is less well modeled, it indicates a contrast in the cooling rates from 50øC/m.y. to a minimum of 100øC/m.y. The first 5% of the gas release is masked by excess argon, and the cooling rate could be higher, especially considering the fission track ages that point toward almost the same age, suggesting that the flat plateau should be extended almost down to 0% gas. If this is so, the cooling rate may be as high as 150øC/m.y. It is interesting to note that the overall pattern is not given by the contrast in the cooling rates itself but by the variable retentivity of the domains (Table 1). The contrast in cooling acts to give the flat plateau in the first few percent of gas release.

The K90G08 sample (Figure 7) exhibits a very disturbed spectrum, which cannot be corrected using the inverse isochron diagram, suggesting very diverse trapped components that could be linked to each one of the diffusion

| TABLE 2. Characteristics of Diffusion Domains in Analyzed K-Feldspars |
|-----------------|-----------------|-----------------|
| K-Feldspar Klb1 | Size  | Volume fraction Relative to 1 | Activation Energy kJ/mol |
| smallest        | 0.04  | 0.04  | 40.00 |
|                 | 0.10  | 0.10  | 39.50 |
|                 | 0.16  | 0.16  | 40.00 |
|                 | 0.46  | 0.46  | 53.00 |
|                 | 0.12  | 0.12  | 39.00 |
|                 | 0.12  | 0.12  | 41.00 |
| biggest         | 0.08  | 0.08  | 55.00 |
|                 | 0.10  | 0.10  | 50.00 |
|                 | 0.10  | 0.10  | 50.00 |
|                 | 0.19  | 0.19  | 50.00 |
|                 | 0.05  | 0.05  | 29.00 |
|                 | 0.15  | 0.15  | 30.50 |
| K-Feldspar K90G08 | smallest | 0.33  | 55.00 |
|                 | 0.08  | 0.08  | 50.00 |
|                 | 0.10  | 0.10  | 50.00 |
|                 | 0.10  | 0.10  | 30.00 |
|                 | 0.19  | 0.19  | 50.00 |
|                 | 0.05  | 0.05  | 29.00 |
|                 | 0.15  | 0.15  | 30.50 |
| biggest         | 0.10  | 0.10  | 60.00 |

Values are deduced from modeling the log(r/to) plot.

Fig. 5. Inverse isochron diagrams for each one of the modeled K-feldspars. No distinctive alignment can be resolved, and the scattering of ages is therefore interpreted as being real.
Fig. 6. Modeling of the cooling history of K90G34 K-feldspar. The analytical procedure is detailed in the text. The Arrhenius plot obtained with a specific heating schedule (shown in inset) clearly identifies several diffusion domains whose characteristics are modeled on the log(\(\tau/\rho\)) plot and then used to fit the age spectrum with hypothetic cooling histories. Derived domain characteristics are shown in Table 2. Solid curves are experimental data, and dashed lines are the calculated models leading to the determination of the cooling curve. The large dashed line in the cooling history distinguishes between the calculated line on feldspars (solid) and its extrapolated end deduced from fission track on apatite. Note the contrast in cooling rates at 2 Ma deduced from the shape of the age spectrum. Muscovite as been plotted on the feldspar curve (see text for details) with \(\pm 75^\circ\)C as arbitrary error for closure temperature. Closure temperature of apatite is \(110\pm20^\circ\)C.

domains. It is clear, however, that an average fit through the spectrum can be drawn and that it looks a lot like the K90G34 sample, with the two plateau sat 1.4 and 3.5 m.y. The end of the spectrum cannot be modeled, because of abnormal diffusion behaviour above \(1020^\circ\)C, or unseen domains not revealed during the heating phase in laboratory. Nevertheless, modeling reveals a similar cooling history to K90G34, with a major contrast in the cooling rates at 2 Ma from \(50^\circ\)C/m.y. to \(150^\circ\)C/m.y., the whole history being displaced toward a lower temperature compared to K90G34.

The KLB1 sample (Figure 8) is also characterized by two plateaux, at 1.8 and 4.6 Ma. Here again, the same contrast accounts for the almost flat low-temperature plateau. Cooling passed from \(20^\circ\)C/m.y. to \(200^\circ\)C/m.y. (minimum) at 1.8 Ma. The same discrepancy between our model and the experimental data appears at the end of the spectra. It has no direct bearing on the time of the change in the cooling rates, however, and its effect on the magnitude of the difference is small. The cooling history recorded by this sample is displaced to lower temperatures of about \(50^\circ\)C-100°C compared to the others. This suggests either a thermal effect of the fault or a simple effect of the difference in altitude. The fact that the time of the contrast is also younger (1.5 Ma instead of 2 Ma) is in agreement with a dominating thermal disturbance.

**DISCUSSION**

**Cooling Rates**

Cooling curves deduced from K-feldspars appear to reflect a consistent story. We emphasize that the convergence in cooling histories on separate K-feldspars is not an artifact of the model, as very different diffusion characteristics have been used for each crystal. Nearby feldspars need not share common diffusion characteristics but probably reflect similar cooling histories, which is the case here.

The relative positions of the three cooling curves reflect their differences in altitude, as altitude decreases from KLB1 to K90G08 and K90G34 and therefore in increasing order of
Fig. 7. Modeling of the cooling history of K90G08 K-feldspar. The same remarks as for Figure 5 apply here. The low closure temperature of the muscovite and the discrepancy between the end of the experimental spectrum and the model are discussed in the text. A similar contrast in cooling rates is outlined by the modeling. Biotite has been excluded from the graph because uncertainty on both its age and closing temperature are too large.

The interpretation of cooling rates in the frame of regional tectonic history and the calculation of denudation rates are never straightforward (see, for example, discussions by England and Molnar, [1989] and Copeland et al. [1987]). In the following section we briefly define and discuss some important concepts and interpret our observations in the light of these concepts.

Apparent Uplift, Uplift, and Relations With Cooling Rates

Cooling of rocks generally records the return of the crust to a thermal equilibrium previously disturbed by the emplacement of hot magmatic bodies or heating associated to metamorphism. When these causes can be excluded, the most likely cause of cooling is the accommodation to new conditions brought about by vertical movement (or a movement with at least a vertical component) relative to the isotherms. In the case where it can be shown that geothermal gradient remained stable, cooling therefore traces the upward movement of the crust. This movement, and related cooling, is most simply imaged as the movement of the crust through "fixed" isotherms. Another way to look at this process is to change the reference of the movement: consider that the crust is fixed, and the isotherms move down through it. This concept, known as "apparent uplift", was first defined by Parrish [1982]. Apparent uplift describes how fast the isotherm moves down and requires an assumption about the geothermal gradient. Cooling rates and apparent uplift rates are thus different ways of looking at the...
Fig. 8. Modeling of the cooling history of KLB1 K-feldspar. The same remarks as for Figure 5 apply here. Note that the overall cooling history is displaced to lower temperatures compared to other samples, while the age of the contrast in cooling rates is a little younger. These features are discussed in the text.

Fig. 9. Summary of all thermochronologic data and modeled cooling curves. All data indicate that rapid cooling dramatically increased 1.5-2 m.y. ago in response to the onset of probable important crustal uplift. All errors on closure temperatures of micas are ±75°C.

same phenomenon, but "apparent uplift" relates more to the reason of cooling, suggesting it is related to real uplift. Making the transition from "apparent uplift" to uplift rates is always speculative. In the case where the crust is really uplifted relative to a fixed reference, apparent uplift is the only translation of this uplift. In another words, apparent uplift is the way by which uplift is recorded by the thermal structure of the crust. The relation between the two depends on how fast the crust equilibrates to the thermal changes associated with uplift. For example, very rapid uplift invariably induces an upwelling of isotherms, because the crust cools much slower than uplift would suggest. Therefore apparent uplift will be delayed in time after the onset of uplift and will tend to underestimate uplift rates at first, and then will approach the true value with time [Zeitler, 1983]. Parrish [1982] constructed thermal models showing that for minerals with medium to low closure temperature and medium to high geothermal gradient, rates measured after the onset of the rapid uplift phase represent 75-100% of the true value. Calculation of uplift from cooling rates should therefore take into account all characteristics of the thermochronometers used, the rate of cooling, the thermal conductivity of the crust, many variables that are usually not well known.
Surface Uplift

Up to now, we have defined uplift of the crust with respect to the position of a rock, which represents the slice of the crust from which it is taken and which is uplifted with respect to the isothermal structure, from hotter to cooler conditions. Implicitly, we have therefore considered that upward movement of the crust is measured relative to the coolest boundary of the system: the surface. But how does the surface move during uplift? If calculation of crustal uplift is often speculative, that of surface uplift is even worse. At this point it becomes necessary to consider the interplay of intrinsic (uplift) and extrinsic factors, namely, all surface-modeling processes (essentially erosion). Though these factors are usually poorly known, qualitative assumptions are useful (see, for example, Burbank, [1992]). For example, rapid crustal uplift in arid climate conditions will probably induce surface uplift. Note that surface uplift needs to be compared to a fixed reference, whatever it is, independent of the thermal structure of the crust. It must be stated in conclusion that until a methodology can give definite results on surface movements back in time, one will be reduced to more or less precise speculative discussions when interpreting cooling or apparent uplift rates. Keeping these definitions in mind, we will now attempt to interpret our cooling data at Kongur Shan in order to decide how cooling is related to the regional tectonic frame and crustal dynamics.

UPLIFT RATES AT KONGUR SHAN

Do our cooling rates record a return to normal thermal conditions after a regional heating? In this case the whole cooling should record only the thermal equilibration of the lithosphere after the peak of metamorphism and would have no bearing on the uplift history of the crust. The presence of feldspar ages older than those for micas seem to preclude an extensive metamorphic event younger than 5 Ma. In the absence of monazite ages on Kongur gneisses, the most likely to give the true age of metamorphism, only a qualitative approach can be made. The presence of leucogranites in the cores of Muztagh and Kongur suggests extensive melting, but they appear to be restricted to the anticline cores. Although the nappes predate antiform formation, they show no trace of regional overprinting metamorphism that would have affected the whole allochthonous pile. For example, the biotite extracted from a sample at the sole contact of the nappe shows a well-defined plateau (Figure 3) which gives an age of 146±0.7 m.y. Finally, U/Pb dating on zircons from the Muztagh leucogranitic core yielded Jurassic ages (U. Schärer, personal communication, 1992) and revealed no trace of a younger event. Note that Jurassic ages of metamorphism and denudation are the values deduced for apparent uplift (and therefore tectonic denudation, probably increasing over that period).

If cooling since 2 Ma is related to crustal uplift as we have suggested, we can then speculate about its rate. Cooling rates have been found of the order of 150°-200°C/m.y. For reasons already mentioned, we will assume a geothermal gradient of 30°C/km, yielding an apparent uplift rate of 5-7 km/m.y. This value is not a perfect description of real uplift and, as previously stated, it depends upon how fast the crustal record adjusts to the ambient thermal regime. Using the models of Parrish [1982] and Zeiller [1983] we estimate that such rapid apparent uplift rates imply true rapid uplift and constitute maximum values close to the real ones. Moreover, with such a rapid uplift, a mean geothermal gradient value of 30°C/km cannot approximate the real one, and the values deduced for apparent uplift (and therefore uplift itself) should be regarded as maximum ones. In order to be safe, we conclude that cooling rates after 2 Ma record uplift, and therefore tectonic denudation, at rates of at least 3-5 km/m.y.

How do these rates relate to surface movement 2 m.y. ago? Clearly the time interval 1-2 Ma is also associated with the onset of a largely distributed glacial period that probably affected the erosion mechanisms and could have caused rates of apparent uplift to increase [Burbank, 1992]. On the other hand, the pile of rocks now exposed shows erosion-resistant lithologies in semiarid climatic conditions such that high erosion rates may reflect or underscore those of crustal uplift [Burbank and Beck, 1992]. The cooling recorded since 2 Ma is related to the normal faulting, and the relative uplift we measure must be correlated with the formation of an important feature above the plain. Traces of recent (less than 5000 years) major landslides on the western slope of the anticline, repeated captation of river paths, as well as the inferred presence of glaciers since at least the last glaciation (J.P. Peulvast, personal communication, 1992), show that the Kongur has been a strongly expressed topographic feature through the whole Quaternary and is still being uplifted. This relation between topographic features, normal faulting, and very rapid cooling rates suggests true surface uplift, and although no exact value can be assessed, 3-5 km/m.y. are probably a maximum for the last 2 m.y.

Two types of indirect information can be used to speculate about surface uplift. First, if Pamir tectonics started 20 m.y. ago, as seems to be the case, it is likely that Kongur (7719
m) became a high topographic point early, since it belongs to the internal part of the massif. Therefore uplift with respect to the surrounding plains must be considered over this whole period. Second, Liu et al. [1992] have measured vertical movement on active normal faults around Kongur and Muztagh antinodes and concluded average values of 1-4 mm/year integrated over the age of the faults. This range is in perfect agreement with our maximum values, and we suggest that surface uplift at Gongar for the last 2 m.y. is probably somewhere in the range of 1-4 km/m.y. Aside from calculations on apparent and surface uplift, it is important to note that the result of this study demonstrates the timing of the onset of a very rapid phase of movement on the normal faults. The initial onset of normal faulting must have been at least 5 m.y. ago. The structure of the antinodes (Kongur and Muztagh) and their position are closely linked to crustal shortening dynamics in eastern Pamir. Bocquet et al. [1992] suggested that those structures are gigantic anticlinal stacks en échelon on the Karakorum fault termination. It is suggested, as is also the case in the Himalayas, that crustal thickening is responsible for the development of the normal faults at Gongar, a steady state crustal deformation comparable with the Himalayan Main Central Thrust and Everest normal fault system. Thus, what is presently seen is the oblique-upward extrusion of a crustal slice by the coeval movement of frontal thrusting and rear normal faulting. This case is therefore a demonstration of a phenomenon already suggested elsewhere [Tapponnier et al., 1990] and closely linked to mountain building by crustal stacking. Importantly in the context of ramp stacking, normal faulting becomes a very effective process which contributes to the generation of impressive surface relief.

CONCLUSION

Use of K-feldspar 40Ar/39Ar modeling with the multidomain theory and ages obtained on micas and apatites lead to the proposal of a major change in the cooling history of Kongur Shan neuesanne at 2 Ma. This contrast can be related to the onset of a major denudation event, triggered by movement along major normal faults that bounded the antiform to the southwest. Rates of uplift are of the order of 3-5 km/m.y. and surface uplift of 1-4 km/m.y. have probably been ongoing for the last 2 m.y. The structure of the Kongur-Muztagh antiforms is best explained by the coeval development of thrust systems and rear normal faults which form part of a crustal-scale complex system of ramp thrusting. It is important to note the frequent occurrence of huge normal faults with thrust systems, as is the case, for example, for the Himalayan normal fault. In each of these cases, one observes an important delay between the onset of convergence tectonics and associated thrusting, and the development of extensional deformation: almost 15 m.y. in the case of Himalaya [Copeland et al., 1987], and it might be the same in the case of the Kongur-Muztagh antiform.

To explain this fact, we suggest that a significant amount of crustal shortening and thickening is necessary before it can induce the development of extensive deformation. This amount would constitute the critical point at which ramp stacking is "mature" under the range. Kongur Shan is therefore an example where normal faulting contributes to create huge relief. This conclusion is in good agreement with a recent mechanical study [King and Ellis, 1990] which points out that normal faulting should be regarded as a very efficient tool for mountain building.

Acknowledgments. T.M. Harrison and O. Lovera are thanked for providing the feldspars modeling program as well as useful discussions. J. Capponi provided the facilities for fission track measurements. Reviews by J. Wijbrans and an anonymous reviewer considerably improved an earlier version of the manuscript. This is DBT contribution 5, 583.

REFERENCES


