Onset timing of significant unroofing around Qaidam basin, northern Tibet, China: constraints from $^{40}\text{Ar}/^{39}\text{Ar}$ and FT thermochronology on granitoids

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Abstract

$^{40}\text{Ar}/^{39}\text{Ar}$ and fission track thermochronological results from two granitoid suites in the mountain ranges along the northern and southern edges of Qaidam basin constrain the timing of a Tertiary denudation event and their tectonic association in northern Tibet. The cooling histories based upon $^{40}\text{Ar}/^{39}\text{Ar}$ and fission track ages suggest a rapid cooling event (7.5–10.7 °C/Ma) during Oligocene–early Miocene time. This cooling event is thought to reflect an increasing denudation rate associated with the rapid uplift and denudation of the North Qaidam and Kunlun Shan mountain ranges. With consideration to the field evidence, sedimentation rate of the Qaidam basin, and the propagation rate along the Altyn Tagh fault, the rapid uplifting and denudation are probably due to crustal thickening associated with Cenozoic propagation of the Altyn Tagh fault in accommodating the collision of India with Asia.

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1. Introduction

Although Murphy et al. (1997) suggested that a significant portion of southern Tibet was elevated to 3–4 km during the Early Cretaceous, most features of the Himalayan belt and the Tibetan plateau are the result of India–Asia collision during the Cenozoic. Cenozoic activities in the Tibetan plateau and adjacent areas have long been the focus of a number of geological studies on lithospheric accommodation mechanisms, particularly the partitioning of thickened homogeneous crust with horizontal compression, and lateral extrusion along major strike-slip faults under continental collision (Tapponnier et al., 1986; Dewey et al., 1988; Avouac, 1991). Tapponnier et al. (1990) suggested that local crustal thickening would also occur under lateral extrusion due to

(1) progressively filled sedimentary basins, and (2) formation of large anticlines by major thrusts ‘branching’ from strike-slip faults.

One of the major strike-slip faults associated with the Cenozoic tectonics of this range is the Altyn Tagh fault zone. The Altyn Tagh fault zone separates the Tarim basin to the north from the Qaidam basin, Kunlun Shan, and the Tibetan plateau to the south (Fig. 1). Several studies (Peltzer et al., 1989; Tapponnier et al., 1990; Meyer et al., 1998) suggested that the propagation of the Altyn Tagh fault not only controlled the uplift and denudation, but also determined the geometry of mountain belts in this area (Fig. 1). Thus, if we want to have a further understanding of the accommodation mechanism and tectonic history of this region, precise reconstruction of the thermochronological history for the propagation of the Altyn Tagh fault is needed.

Although the structural and stratigraphic evidence indicated left-lateral displacement of the Altyn Tagh fault (Molnar and Tapponnier, 1975; Molnar et al., 1987;

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Fig. 1. Illustrated geological map of Northern Tibet (modified from Cui et al., 1997; Mock et al., 1999). The stars indicate sample locations. Inset sketch map indicates the major tectonic features associated with India–Asia collision from the Himalaya belt in the south to Tian Shan in the north: NQF stands for North Qaidam fault, ATF: Altyn Tagh fault, and EKL: eastern Kunlun fault.

Gaudemer et al., 1989; Peltzer et al., 1989), no precise timing criteria were observed in the field. Folding of late Cenozoic sediments in adjacent regions, such as the Qaidam basin, implied the presence of active deformation during the Neogene (Tapponnier and Molnar, 1977). Chen et al. (1998) suggested syn-depositional thrust faulting of lacustrine sediments during Oligocene (23.7–36.6 Ma). Active folding and thrusting is evidenced at the foot of the Kunlun range and in the Qaidam basin further north. However, thrusting was also mapped in the Kunlun range south of Golmud (Mock et al., 1999), making it difficult to determine whether the contacts are actually Tertiary in age. Structural and stratigraphic evidence indicated that an active slip event occurred on the thrust fault along the northern edge of Qaidam (Molnar et al., 1987; Tapponnier et al., 1990; Wang and Coward, 1990). Several studies indicated an important change in the crustal thermal state (unroofing event) at around 20 Ma that affected the Western Kunlun range and Tarim basin along with the entire Himalayan orogen (Harrison et al., 1992, 1993). However, Mock et al. (1999) reported a cooling/unroofing event at around 30 Ma in the eastern Kunlun range. In order to clarify if this cooling event is a regional or local phenomena, a combination of $^{40}\text{Ar}/^{39}\text{Ar}$ and fission track dating on the granitoid complexes around the Qaidam basin was carried out in the present study. Current samples were obtained from the northern and the southern edges of the Qaidam basin, NW China. It is hoped that the results could provide age constraints on the onset of mountain-belt

unroofing around the Qaidam basin and also help clarify the regional tectonic history.

2. Geological setting

The Qaidam basin is a rhombic basin bounded by three fault systems: the Altyn Tagh fault zone to the northwest, the North Qaidam fault zone (NQ fault zone) to the northeast and the eastern Kunlun fault zone (EKL fault zone) to the south (Fig. 1). Among these three fault systems, the north Qaidam and eastern Kunlun fault zones are developed in the North Qaidam orogen belt, subparallel to the Qilian Shan-Nan Shan orogen belt. The northeastern border of the Qaidam basin contains Paleocene and Eocene deltaic and shallow lacustrine sandstone unconformably overlying Mesozoic strata. The basin strata reaches about 14 km thick (Wang and Coward, 1990) and consists of dark colored argillaceous deposits ranging from Middle Oligocene to late Miocene in age (Métivier, 1996) and capped by Pliocene fluvial and lacustrine facies deposits (Chen and Bowler, 1986).

Two mountain ranges surround the Qaidam basin. The 700 km long, NW–SE trending North Qaidam range, north of the Qaidam basin (Fig. 1), first formed during Paleozoic–Triassic collision, and was further deformed during the Cenozoic when India collided with Asia (Cui et al., 1999). Similarly, the Kunlun range south of the Qaidam basin (Fig. 1) is also a reactivated

Table 1
 $^{40}\text{Ar}/^{39}\text{Ar}$ analytical data

T (°C)	Cumulative ^{39}Ar	Atmospheric contamination (%)	$^{36}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	Apparent age (Ma)
NQ9901 Biotite								
500	0.058	10.18	8.64×10^{-3}	5.75×10^{-2}	2.31×10^{-2}	2.50×10^1	2.90×10^3	139.5 ± 2.2
560	0.162	3.89	3.73×10^{-3}	3.10×10^{-2}	1.99×10^{-2}	2.83×10^1	7.59×10^3	167.5 ± 2.5
640	0.297	2.77	2.72×10^{-3}	2.66×10^{-2}	1.78×10^{-2}	2.89×10^1	1.06×10^4	172.6 ± 2.8
700	0.386	4.68	4.67×10^{-3}	1.66×10^{-2}	1.96×10^{-2}	2.95×10^1	6.32×10^3	172.8 ± 2.7
760	0.447	5.72	5.73×10^{-3}	7.45×10^{-2}	2.08×10^{-2}	2.96×10^1	5.15×10^3	171.3 ± 2.5
820	0.528	5.76	5.87×10^{-3}	8.17×10^{-2}	2.13×10^{-2}	3.01×10^1	5.12×10^3	174.0 ± 2.5
900	0.703	4.04	4.04×10^{-3}	1.97×10^{-2}	1.93×10^{-2}	2.95×10^1	7.31×10^3	174.1 ± 2.5
960	0.840	6.65	6.84×10^{-3}	4.00×10^{-2}	1.94×10^{-2}	3.04×10^1	4.44×10^3	174.2 ± 2.5
1020	0.928	15.23	1.71×10^{-2}	7.03×10^{-2}	2.28×10^{-2}	3.32×10^1	1.94×10^3	173.0 ± 2.5
1100	0.975	43.72	6.69×10^{-2}	3.29×10^{-1}	3.74×10^{-2}	4.52×10^1	6.75×10^2	157.0 ± 2.6
1150	0.993	72.03	2.45×10^{-1}	3.57×10^{-1}	8.45×10^{-2}	1.00×10^2	4.10×10^2	172.6 ± 3.5
1200	1.000	98.33	9.81×10^{-1}	4.89×10^{-1}	2.42×10^{-1}	2.95×10^2	3.01×10^2	31.4 ± 8.9
Mass = 24.0 mg; J -value = $0.003578595 \pm 0.00005242$; Integrated date = 169.0 ± 2.4 Ma								
KL9901 Biotite								
500	0.035	41.43	3.00×10^{-2}	6.77×10^{-2}	2.49×10^{-2}	2.14×10^1	7.14×10^2	89.0 ± 2.4
560	0.122	12.24	7.57×10^{-3}	2.61×10^{-2}	1.79×10^{-2}	1.83×10^1	2.42×10^3	113.1 ± 1.0
640	0.323	3.65	2.23×10^{-3}	5.58×10^{-3}	1.62×10^{-2}	1.81×10^1	8.10×10^3	122.4 ± 0.2
700	0.458	5.65	3.52×10^{-3}	1.89×10^{-2}	1.71×10^{-2}	1.84×10^1	5.22×10^3	122.0 ± 0.6
760	0.532	7.62	4.83×10^{-3}	3.11×10^{-2}	1.82×10^{-2}	1.87×10^1	3.88×10^3	121.6 ± 2.1
820	0.596	12.40	7.92×10^{-3}	3.69×10^{-2}	1.93×10^{-2}	1.89×10^1	2.38×10^3	116.5 ± 1.4
900	0.736	8.69	5.47×10^{-3}	2.06×10^{-2}	1.75×10^{-2}	1.86×10^1	3.40×10^3	119.6 ± 0.5
960	0.850	16.03	1.08×10^{-2}	2.41×10^{-2}	1.87×10^{-2}	1.99×10^1	1.84×10^3	117.6 ± 0.4
1020	0.934	28.06	2.17×10^{-2}	4.20×10^{-2}	2.13×10^{-2}	2.29×10^1	1.05×10^3	115.9 ± 1.3
1100	0.982	54.17	6.26×10^{-2}	1.34×10^{-1}	3.15×10^{-2}	3.42×10^1	5.46×10^2	110.5 ± 0.4
1150	0.996	89.77	3.32×10^{-1}	4.68×10^{-1}	8.33×10^{-2}	1.09×10^2	3.29×10^2	79.6 ± 2.5
1200	1.000	93.94	1.53	5.22×10^{-1}	3.36×10^{-1}	4.80×10^2	3.15×10^2	200.2 ± 18.3
Mass = 22.0 mg; J -value = $0.00404072 \pm 0.00000400$ Integrated date = 117.6 ± 0.3 Ma								
NQ9901 K-feldspar								
450	0.001	87.00	1.06×10^{-1}	2.65×10^{-2}	1.15×10^{-1}	3.59×10^1	3.40×10^2	33.7 ± 5.5
450	0.003	87.44	9.56×10^{-2}	7.85×10^{-2}	1.68×10^{-1}	3.23×10^1	3.38×10^2	29.3 ± 5.0
500	0.004	88.49	1.20×10^{-1}	6.39×10^{-2}	1.48×10^{-1}	4.01×10^1	3.34×10^2	33.3 ± 14.2
500	0.006	83.71	7.75×10^{-2}	5.18×10^{-2}	1.01×10^{-1}	2.74×10^1	3.53×10^2	32.2 ± 4.8
550	0.008	84.83	7.77×10^{-2}	3.46×10^{-2}	9.97×10^{-2}	2.71×10^1	3.49×10^2	29.7 ± 7.8
550	0.012	79.83	4.66×10^{-2}	2.63×10^{-2}	6.32×10^{-2}	1.73×10^1	3.71×10^2	25.2 ± 3.0
600	0.015	69.00	3.68×10^{-2}	2.22×10^{-2}	5.77×10^{-2}	1.58×10^1	4.29×10^2	35.3 ± 6.1
600	0.022	54.95	2.24×10^{-2}	6.04×10^{-3}	3.06×10^{-2}	1.21×10^1	5.39×10^2	39.1 ± 1.9
650	0.029	34.42	1.35×10^{-2}	8.35×10^{-3}	2.54×10^{-2}	1.16×10^1	8.61×10^2	54.4 ± 2.2
650	0.047	20.19	7.02×10^{-3}	2.35×10^{-3}	1.89×10^{-2}	1.03×10^1	1.47×10^3	58.8 ± 1.1
700	0.063	16.49	6.75×10^{-3}	4.51×10^{-3}	1.85×10^{-2}	1.21×10^1	1.80×10^3	72.2 ± 2.0
700	0.095	7.06	3.51×10^{-3}	2.06×10^{-3}	1.60×10^{-2}	1.47×10^1	4.19×10^3	$96.9 \pm .9$
750	0.124	5.42	3.17×10^{-3}	1.42×10^{-3}	1.54×10^{-2}	1.73×10^1	5.46×10^3	115.4 ± 0.7
750	0.168	4.13	2.54×10^{-3}	1.28×10^{-3}	1.47×10^{-2}	1.82×10^1	7.17×10^3	122.7 ± 0.9
800	0.204	4.34	2.78×10^{-3}	1.23×10^{-3}	1.55×10^{-2}	1.89×10^1	6.81×10^3	127.3 ± 0.7
800	0.256	2.72	1.74×10^{-3}	1.06×10^{-3}	1.43×10^{-2}	1.90×10^1	1.09×10^4	129.5 ± 0.3
850	0.297	3.74	2.44×10^{-3}	1.77×10^{-3}	1.42×10^{-2}	1.94×10^1	7.91×10^3	130.7 ± 1.2
850	0.344	2.57	1.70×10^{-3}	1.71×10^{-3}	1.44×10^{-2}	1.95×10^1	1.15×10^4	133.3 ± 1.0
875	0.367	6.82	4.56×10^{-3}	2.11×10^{-3}	1.64×10^{-2}	1.98×10^1	4.34×10^3	129.3 ± 0.8
900	0.391	4.16	2.81×10^{-3}	2.51×10^{-3}	1.62×10^{-2}	2.00×10^1	7.12×10^3	134.4 ± 1.3
925	0.416	4.76	3.25×10^{-3}	2.78×10^{-3}	1.65×10^{-2}	2.02×10^1	6.22×10^3	135.2 ± 0.9
950	0.442	4.40	3.05×10^{-3}	2.02×10^{-3}	1.65×10^{-2}	2.05×10^1	6.72×10^3	137.6 ± 1.3
975	0.470	4.17	2.95×10^{-3}	2.26×10^{-3}	1.64×10^{-2}	2.10×10^1	7.09×10^3	140.6 ± 2.1
1000	0.498	4.69	3.40×10^{-3}	2.49×10^{-3}	1.65×10^{-2}	2.14×10^1	6.31×10^3	143.0 ± 1.6
1000	0.532	4.17	3.11×10^{-3}	2.77×10^{-3}	1.69×10^{-2}	2.21×10^1	7.09×10^3	147.6 ± 2.5
1025	0.549	7.16	5.43×10^{-3}	3.43×10^{-3}	1.52×10^{-2}	2.24×10^1	4.13×10^3	145.6 ± 0.7
1025	0.579	3.75	2.91×10^{-3}	2.86×10^{-3}	1.69×10^{-2}	2.30×10^1	7.88×10^3	154.2 ± 2.1
1050	0.602	6.44	5.07×10^{-3}	3.31×10^{-3}	1.84×10^{-2}	2.33×10^1	4.60×10^3	152.1 ± 1.8
1050	0.632	4.20	3.37×10^{-3}	1.67×10^{-3}	1.56×10^{-2}	2.37×10^1	7.05×10^3	158.5 ± 0.9
1075	0.654	5.98	4.87×10^{-3}	3.09×10^{-3}	1.77×10^{-2}	2.41×10^1	4.95×10^3	157.9 ± 1.3
1075	0.683	3.74	3.10×10^{-3}	1.92×10^{-3}	1.56×10^{-2}	2.45×10^1	7.91×10^3	164.2 ± 1.2
1100	0.705	5.28	4.45×10^{-3}	2.52×10^{-3}	1.70×10^{-2}	2.49×10^1	5.60×10^3	164.3 ± 0.8

(continued on next page)

Table 1 (continued)

T (°C)	Cumulative ^{39}Ar	Atmospheric contamination (%)	$^{36}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	Apparent age (Ma)
1100	0.733	4.22	3.62×10^{-3}	2.49×10^{-3}	1.65×10^{-2}	2.54×10^1	7.02×10^3	169.0 ± 1.5
1100	0.753	5.52	4.81×10^{-3}	2.60×10^{-3}	1.71×10^{-2}	2.58×10^1	5.36×10^3	169.2 ± 0.7
1100	0.780	4.25	3.78×10^{-3}	1.75×10^{-3}	1.61×10^{-2}	2.63×10^1	6.96×10^3	174.5 ± 1.3
1150	0.791	12.64	1.13×10^{-2}	7.24×10^{-3}	2.09×10^{-2}	2.65×10^1	2.34×10^3	161.2 ± 2.5
1200	0.818	5.34	4.98×10^{-3}	1.67×10^{-3}	1.61×10^{-2}	2.76×10^1	5.54×10^3	180.9 ± 0.6
1225	0.845	4.82	4.64×10^{-3}	3.47×10^{-3}	1.64×10^{-2}	2.85×10^1	6.13×10^3	187.2 ± 1.2
1250	0.870	5.02	4.97×10^{-3}	3.46×10^{-3}	1.72×10^{-2}	2.93×10^1	5.89×10^3	192.1 ± 1.2
1275	0.895	6.20	6.33×10^{-3}	4.07×10^{-3}	1.82×10^{-2}	3.02×10^1	4.77×10^3	195.3 ± 1.4
1300	0.924	5.89	6.17×10^{-3}	3.81×10^{-3}	1.83×10^{-2}	3.10×10^1	5.02×10^3	200.6 ± 0.7
1350	0.971	3.29	3.57×10^{-3}	8.71×10^{-4}	1.49×10^{-2}	3.21×10^1	8.99×10^3	212.9 ± 0.6
1400	0.993	5.52	5.72×10^{-3}	2.45×10^{-3}	1.65×10^{-2}	3.06×10^1	5.36×10^3	199.4 ± 0.9
1400	1.000	13.37	1.38×10^{-2}	6.57×10^{-3}	2.11×10^{-2}	3.06×10^1	2.21×10^3	183.3 ± 2.0

J -value = $0.00404072 \pm 0.00000400$; Integrated date = 147.5 ± 0.3 Ma

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450	0.002	91.80	3.27×10^{-1}	8.38×10^{-2}	1.86×10^{-1}	1.05×10^2	3.22×10^2	61.8 ± 22.7
450	0.004	88.60	6.15×10^{-1}	5.98×10^{-2}	2.09×10^{-1}	2.05×10^2	3.34×10^2	162.9 ± 14.5
500	0.005	78.08	6.08×10^{-1}	6.07×10^{-2}	1.89×10^{-1}	2.30×10^2	3.78×10^2	334.4 ± 14.3
500	0.007	84.30	5.37×10^{-1}	2.62×10^{-5}	1.39×10^{-1}	1.88×10^2	3.51×10^2	203.7 ± 12.7
550	0.008	64.75	3.43×10^{-1}	3.23×10^{-2}	9.10×10^{-2}	1.56×10^2	4.56×10^2	362.8 ± 15.6
550	0.012	78.65	2.40×10^{-1}	1.34×10^{-5}	5.98×10^{-2}	9.00×10^1	3.76×10^2	134.9 ± 4.8
600	0.015	61.21	1.56×10^{-1}	1.33×10^{-2}	4.66×10^{-2}	7.51×10^1	4.83×10^2	200.7 ± 4.2
600	0.018	82.99	1.04×10^{-1}	1.63×10^{-5}	2.89×10^{-2}	3.71×10^1	3.56×10^2	45.4 ± 6.9
650	0.029	86.05	1.08×10^{-1}	5.13×10^{-3}	2.90×10^{-2}	3.72×10^1	3.44×10^2	37.5 ± 1.7
650	0.043	76.66	6.15×10^{-2}	3.15×10^{-6}	2.66×10^{-2}	2.37×10^1	3.86×10^2	39.9 ± 1.3
700	0.055	74.56	5.01×10^{-2}	1.16×10^{-3}	2.01×10^{-2}	1.99×10^1	3.97×10^2	36.5 ± 0.5
700	0.076	67.34	3.59×10^{-2}	2.09×10^{-6}	1.90×10^{-2}	1.58×10^1	4.40×10^2	37.2 ± 0.5
750	0.096	59.02	2.65×10^{-2}	6.01×10^{-4}	1.84×10^{-2}	1.33×10^1	5.02×10^2	39.2 ± 1.2
750	0.132	56.21	2.20×10^{-2}	8.20×10^{-4}	1.60×10^{-2}	1.16×10^1	5.27×10^2	36.6 ± 0.3
800	0.163	45.90	1.57×10^{-2}	1.90×10^{-3}	1.61×10^{-2}	1.02×10^1	6.46×10^2	39.5 ± 1.2
800	0.216	47.87	1.56×10^{-2}	9.20×10^{-4}	1.52×10^{-2}	9.64	6.19×10^2	36.2 ± 0.2
850	0.259	39.07	1.16×10^{-2}	1.30×10^{-3}	1.45×10^{-2}	8.78	7.59×10^2	38.5 ± 0.5
850	0.324	40.21	1.24×10^{-2}	9.49×10^{-4}	1.46×10^{-2}	9.12	7.37×10^2	39.2 ± 0.4
875	0.357	43.65	1.42×10^{-2}	7.02×10^{-4}	1.48×10^{-2}	9.61	6.79×10^2	38.9 ± 0.5
900	0.396	38.07	1.17×10^{-2}	2.67×10^{-3}	1.44×10^{-2}	9.10	7.79×10^2	40.5 ± 0.8
925	0.440	30.83	9.32×10^{-3}	9.61×10^{-4}	1.37×10^{-2}	8.96	9.62×10^2	44.5 ± 0.3
950	0.486	29.34	9.10×10^{-3}	1.16×10^{-3}	1.46×10^{-2}	9.19	1.01×10^3	46.6 ± 0.4
975	0.531	29.35	9.58×10^{-3}	1.50×10^{-3}	1.45×10^{-2}	9.67	1.01×10^3	49.0 ± 0.5
1000	0.572	30.94	1.08×10^{-2}	1.37×10^{-3}	1.48×10^{-2}	1.04×10^1	9.58×10^2	51.4 ± 0.9
1000	0.614	41.07	1.84×10^{-2}	1.03×10^{-3}	1.64×10^{-2}	1.32×10^1	7.21×10^2	55.9 ± 0.5
1025	0.637	41.48	2.01×10^{-2}	1.99×10^{-3}	1.76×10^{-2}	1.43×10^1	7.14×10^2	60.0 ± 0.8
1025	0.665	42.89	2.47×10^{-2}	2.54×10^{-3}	1.89×10^{-2}	1.70×10^1	6.90×10^2	69.4 ± 1.2
1050	0.682	45.09	2.64×10^{-2}	3.29×10^{-4}	1.78×10^{-2}	1.73×10^1	6.56×10^2	68.0 ± 1.8
1050	0.699	45.97	3.01×10^{-2}	2.71×10^{-6}	1.76×10^{-2}	1.94×10^1	6.44×10^2	74.7 ± 2.9
1075	0.709	47.83	3.08×10^{-2}	4.17×10^{-6}	1.64×10^{-2}	1.91×10^1	6.19×10^2	71.0 ± 1.7
1075	0.723	41.32	2.89×10^{-2}	3.17×10^{-6}	1.58×10^{-2}	2.07×10^1	7.16×10^2	86.3 ± 0.7
1100	0.727	41.31	2.67×10^{-2}	9.21×10^{-4}	2.03×10^{-2}	1.91×10^1	7.16×10^2	80.0 ± 3.4
1100	0.736	39.37	2.76×10^{-2}	5.45×10^{-6}	1.45×10^{-2}	2.07×10^1	7.52×10^2	89.3 ± 3.2
1100	0.745	36.19	2.54×10^{-2}	4.91×10^{-6}	1.70×10^{-2}	2.07×10^1	8.18×10^2	93.8 ± 2.2
1100	0.756	33.73	2.44×10^{-2}	3.80×10^{-6}	1.80×10^{-2}	2.14×10^1	8.77×10^2	100.4 ± 2.0
1150	0.768	41.41	2.97×10^{-2}	1.71×10^{-3}	1.74×10^{-2}	2.12×10^1	7.15×10^2	88.4 ± 0.5
1175	0.782	35.49	2.50×10^{-2}	1.42×10^{-3}	1.76×10^{-2}	2.09×10^1	8.34×10^2	95.4 ± 2.1
1200	0.798	28.67	1.98×10^{-2}	1.78×10^{-3}	1.53×10^{-2}	2.05×10^1	1.03×10^3	103.2 ± 0.5
1225	0.816	22.16	1.51×10^{-2}	2.37×10^{-6}	1.60×10^{-2}	2.01×10^1	1.34×10^3	110.7 ± 1.3
1250	0.838	20.15	1.37×10^{-2}	3.84×10^{-4}	1.52×10^{-2}	2.01×10^1	1.47×10^3	113.1 ± 0.7
1275	0.863	18.65	1.28×10^{-2}	1.77×10^{-6}	1.57×10^{-2}	2.03×10^1	1.59×10^3	116.5 ± 0.6
1300	0.891	16.40	1.14×10^{-2}	1.59×10^{-6}	1.59×10^{-2}	2.06×10^1	1.80×10^3	121.4 ± 1.0
1325	0.922	15.85	1.13×10^{-2}	4.89×10^{-4}	1.46×10^{-2}	2.12×10^1	1.87×10^3	125.1 ± 0.8
1350	0.955	13.72	1.00×10^{-2}	1.45×10^{-4}	1.42×10^{-2}	2.16×10^1	2.16×10^3	131.0 ± 0.3
1400	0.991	23.46	2.00×10^{-2}	7.55×10^{-4}	1.60×10^{-2}	2.52×10^1	1.26×10^3	135.3 ± 0.5
1500	1.000	36.74	3.48×10^{-2}	5.18×10^{-6}	1.99×10^{-2}	2.80×10^1	8.05×10^2	124.6 ± 2.7

J -value = $0.00404072 \pm 0.00000400$; Integrated date = 68.4 ± 0.2 Ma

Note: The date calculated using the following decay constants: $\lambda_{\text{K}} = 0.581 \times 10^{-10} \text{ yr}^{-1}$; $\lambda_{\text{B}} = 4.962 \times 10^{-10} \text{ yr}^{-1}$; $\lambda = 5.543 \times 10^{-10} \text{ yr}^{-1}$; Integrated date = the date and error calculated from the sum total gas from all steps.

Paleozoic–Triassic collisional belt (Matte et al., 1996). These mountain ranges contain a sequence of nappes that originated as ramp thrusts (Chen et al., 1998) along a mid-crustal decollement beneath the basin (Burchfiel et al., 1989), and may have formed during Cenozoic India–Asia collision under northeast–southwest compression (Molnar and Tapponnier, 1978; Molnar and Chen, 1983; Armijo et al., 1986; Molnar et al., 1993).

Geological evidence indicate a left-lateral sense of displacement for the Altyn Tagh fault (Molnar and Tapponnier, 1975; Molnar et al., 1987; Gaudemer et al., 1989; Peltzer et al., 1989) that transected the Kunlun fault systems and resulted in 500 km separation of the EKL (eastern Kunlun) fault zone from the western Kunlun fault zone (Fig. 1) (Peltzer and Tapponnier, 1988). Along the Altyn Tagh fault, a number of granitoid plutons intruded into Ordovician–Permian sediments at around 120–140 Ma (biotite Rb/Sr ages), or 200 Ma (whole rock Rb/Sr ages; Harris et al., 1988). However, recent zircon U–Pb data on granitoid plutons located along the Xidatan fault (a branch of Kunlun fault zone) yield Paleozoic ages (Mock et al., 1999) suggesting that the Mesozoic Rb/Sr ages should be interpreted as a metamorphic event possibly related to accretion, rather than emplacement, of the Triassic–Jurassic Qiangtang block.

3. Geochronology

3.1. Samples and analytical methods

This study analyzed two gneissic granitoid samples: a biotite granite (NQ9901) collected from the North Qaidam range, and one biotite granite (KL9901) from the southern edge of the eastern Kunlun range (Fig. 1). Both samples exhibit gneissic textures containing almost identical mineral assemblages of biotite, muscovite, K-feldspar, plagioclase, quartz and oxides. Although micas show euhedral grains mainly aligned parallel to foliation, most feldspar grains exhibit a significant amount of fractures and weak undulose extinction along subgrain domains.

$^{40}\text{Ar}/^{39}\text{Ar}$ step-heating experiments were carried out on biotite and K-feldspar concentrates (grain sizes ranging between 100 and 180 μm) obtained from mineral separation using heavy liquids, Frantz magnetic separator, and hand picking under a microscope. Minerals were irradiated, along with the neutron flux monitor LP-6 biotite (Odin et al., 1982) at the VT-C position in the Tsing-Hua Open-Pool Reactor (THOR) at Tsing-Hua University, Taiwan, for 25 h with a fast neutron flux of $1.566 \times 10^{13} \text{ n}(\text{cm}^2 \text{ s})^{-1}$. After irradiation, the samples were degassed for 30 min. The isotopic composition was measured using a Varian-MAT GD150 mass spectrometer at National Taiwan University, Taiwan. After corrections for mass discrimination, system blanks, isotope interferences and radiometric decay, $^{40}\text{Ar}/^{39}\text{Ar}$ ages were calculated according to

$^{40}\text{Ar}^*/^{39}\text{Ar}$ ratios and the J value obtained by analyses of the monitor standards. A detailed description of analytical and data processing methods is outlined by Lo and Lee (1994). Detailed results of $^{40}\text{Ar}/^{39}\text{Ar}$ analyses are listed in Table 1. Plateau ages were calculated from adjacent ages that agreed within a range of 2σ .

For fission track (FT) analyses, two apatite separates obtained via conventional techniques were mounted in Araldite[®], polished and etched in HNO_3 (5 M) for 20 s. All samples were analyzed using the external detector method (Hurford and Green, 1983) by attaching a low-uranium mica detector to each sample mount. Samples were irradiated at the 49-2 Reactor in Beijing, China for 1 h. The neutron flux was monitored by mica detectors that were attached to CN-5 and SRM-612 glasses with apatite. After irradiation, the mica detectors were etched in 40% HF for 45 min. Mounts were counted using a Zeiss Axioplan[®] microscope with an automated stage. Age calculations were performed using the zeta-calibration approach (Hurford and Green, 1983), based on the IUGS-recommended age standards (Hurford, 1990).

Fig. 2. Age spectra and isotope correlation diagrams for biotites. The plateau ages are indicated by the arrows.

3.2. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological results

Biotite within granite NQ9901 displayed a fairly flat age spectrum with a well-defined plateau with an age of 195.5 ± 0.4 Ma over 74% of ^{39}Ar released (Table 1, Fig. 2). Similarly, biotite from KL9901 showed a very flat age spectrum with a much younger plateau age of 120.0 ± 0.3 Ma over 80% of ^{39}Ar released (Table 1, Fig. 2). These biotite plateau ages are generally consistent with previous $^{40}\text{Ar}/^{39}\text{Ar}$, and Rb/Sr age results from granitic complexes in the same range (Harris et al., 1988; Matte et al., 1996; Mock et al., 1999), which identify the thermal events during the Jurassic–Cretaceous periods.

Two K-feldspar samples (NQ9901 and KL9901) displayed age spectrum profiles characterized by a gradient with apparent ages increasing from younger at low temperature steps to older values at high temperature steps (Fig. 3). The exception of some abnormally old ages recorded for the first few steps of KL9901 is thought to reflect a small amount of excess Ar present in the sample (Fig. 3). The apparent ages for high temperature steps (~ 215 Ma for NQ9901, and ~ 138 Ma for KL9901) are generally close to, or slightly older than, their

respective biotite plateau ages (Table 1, Figs. 2 and 3). However, the minimum ages (25.2 ± 3.0 Ma for NQ9901 and 36.2 ± 0.2 Ma for KL9901) are much younger than their respective biotite plateau ages. Nevertheless, two flat portions of the K-feldspar age spectrum at the low temperature steps appear to yield ages at ~ 33.5 Ma for NQ9901 and ~ 38.4 Ma for KL9901. Similar age ranges and age spectrum profiles have also been reported by Mock et al. (1999) for granitoid samples from the eastern Kunlun range.

3.3. Fission track dating results

Results of fission track dating are shown in Table 2 and Fig. 4. Apatites from KL9901 and NQ9901 yielded concordant fission track ages at 15.8 ± 1.1 Ma (KL9901) and 16.7 ± 1.4 Ma (NQ9901). These apatite FT ages are much younger than their corresponding biotite and feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ ages (Figs. 2–4). It is not surprising to see such a difference between apatite FT and $^{40}\text{Ar}/^{39}\text{Ar}$ ages since the apatite fission track exhibit much lower blocking temperatures of which is about 110 ± 10 °C (Naeser et al., 1989) than those of argon isotope systematics in biotite and K-feldspar (~ 150 – 350 °C) (see McDougall and Harrison, 1999).

4. Thermochronological interpretation

The Mesozoic ages interpreted in this study generally agree with previous reported whole rock Rb–Sr ages (100–120 Ma and ~ 200 Ma; Harris et al., 1988) and mica $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages (128–257 Ma; Mock et al., 1999) for granitoids in the same region, suggesting that the thermal events are related to the accretion of the Lhasa block in Tibet (Allegre et al., 1984). The $^{40}\text{Ar}/^{39}\text{Ar}$ age ranges and age spectrum profiles of K-feldspars are also generally consistent with reported ages for granitoids in the eastern Kunlun range (Mock et al., 1999). Using the multi-domain diffusion (MDD) modeling method (Lovera et al., 1989, 1991), Mock et al. (1999) suggested a Tertiary rapid cooling/unroofing event in the eastern Kunlun range. By considering the sample locations and similarities of $^{40}\text{Ar}/^{39}\text{Ar}$ age ranges and K-feldspar age spectrum features between the present study and Mock et al. (1999), we suggest that this Tertiary rapid cooling/unroofing event is also identified in the present samples.

The validity of the MDD model has been questioned due to complex microstructures preserved within K-feldspar (Parsons et al., 1999; Reddy et al., 1999, 2001) and the potential influence from other diffusion mechanisms (Lee, 1995). In order to compare our results with those in previous studies, the MDD model and the basic assumption for argon diffusion in K-feldspar (such as volume diffusion in a plane slab) used in previous studies, were utilized. A slab diffusion geometry is thought to be justified because argon loss from K-feldspar during in vacuo step-heating experiments can be

Fig. 3. Age spectrum diagrams for K-feldspars. Please refer to Fig. 2 and the text for further explanation.

Table 2
Fission track analytical results

Sample	Lithology	N_c	$\rho_s(N_s)$ ($\times 10^5 \text{ cm}^{-2}$)	$\rho_i(N_i)$ ($\times 10^6 \text{ cm}^{-2}$)	$\rho_d(N_d)$ ($\times 10^6 \text{ cm}^{-2}$)	P (χ^2)%	Uranium content (ppm)	r	Fission track age (Ma $\pm 1\sigma$)	ML ($\pm$ std error) (μm)	Std. dev. (μm)
KL9901	Bt granite	30	0.7687 (244)	1.3090 (4160)	1.5550 (3908)	100	10.4	0.909	15.8 ± 1.1	12.23 ± 0.27	2.00
NQ9901	Bt granite	29	1.0730 (154)	1.7510 (2512)	1.5700 (3953)	88.2	13.7	0.922	16.7 ± 1.4	11.80 ± 0.23	2.00

Note: N_c = number of apatite crystals analyzed; ρ_d = induced fission-track density calculated from muscovite external detectors used with SRM612 dosimeter; N_d = total number of fission tracks counted in ρ_d ; ρ_s = spontaneous fission-track density on the internal surfaces of apatite crystals analyzed; N_s = total number of fission tracks counted in ρ_s ; ρ_i = induced fission-track density on the muscovite external detector for crystals analyzed; N_i = total number of fission tracks counted in ρ_i ; $P(\chi^2)$ = chi-squared probability that all single-crystal ages represent a single population of ages where degrees of freedom = $N_c - 1$ (Galbraith, 1981); r = correlation coefficient between N_s and N_i ; N_j = number of horizontally confined fission-track lengths measured; ML = mean track length.

best described by volume diffusion in a slab geometry (Lovera et al., 1997). After appropriate adjustment of the various model parameters, a model age spectrum can be obtained that closely matches the experimental results as shown in Fig. 5. The best-fit modeling parameters, such as the activation energy (E), size (ρ), percentage of released gas (ϕ), and closure temperature (T_c) of K-feldspar are summarized in Tables 3 and 4. The modeling results are shown graphically in Figs. 5 and 6. Although it may not be necessarily unique, the modeled cooling histories appear to be consistent with the biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages and apatite fission-track ages for the same sample (Figs. 5 and 6). It is shown that the granitoid (NQ9901) in the northern edge of

the Qaidam basin may have been emplaced much earlier (240–250 Ma) than the southern edge (150 Ma; KL9901). After the Mesozoic thermal event, both experienced slow cooling until the Oligocene (Figs. 5 and 6). Starting in the Oligocene, both samples exhibit a very similar cooling path where the cooling rate increases dramatically to about $\sim 7.5\text{--}10.7^\circ\text{C}/\text{Ma}$ (Figs. 5 and 6). These cooling patterns are similar to those of the eastern Kunlun region (Fig. 7; Mock et al., 1999) (The cooling paths parallel to each other and inflect at the same time during the Oligocene–Miocene). The similarity of the cooling patterns may suggest that the Tertiary fast cooling event not only affected the eastern Kunlun range, but also

Fig. 4. Apatite Fission track data for NQ9901 and KL9901. The histograms of fission track ages give the age distribution in grains analyzed and the radial plots show the single grain age. The histograms of track length show the distribution of track length in grains analyzed.

Fig. 5. Experimental and MDD modeling diagrams for NQ9901 K-feldspar age spectrum: (a) Arrhenius plot calculated from the experimental results assuming a plane slab diffusion geometry from measured $^{39}\text{Ar}_\text{K}$ loss during step-heating. (b) $\text{Log}(r/r_0)$ plot with theoretical fit for single activation assumption. (c) Experimental and theoretical age spectra. The theoretical age spectrum was calculated by using the diffusion parameters and cooling history shown in (a), (b) and (d). (d) Proposed cooling path.

extended to the North Qaidam range around the Qaidam basin (Figs. 1 and 7).

5. Discussion

Tapponnier et al. (1990) and Meyer et al. (1998) suggested that most of the parallel mountain ranges in northeastern Tibet resulted from sediment accumulation

(basin infilling) between rising blocks of large-scale ramp anticlines, with south-dipping thrust faults splaying from the sinistral slip of the Altyn Tagh fault (Fig. 1). Indeed, rapid cooling of metamorphic/plutonic complexes often reflect the increased rate of denudation due to uplift of the mountain ranges. Sustained uplifting of a mountain range could also accelerate river incision and erosion that leads to the formation of a foreland flexural depression (basin). Consequently, increasing denudation could also result in increased sedimentation in the basin. In other words, uplift of a mountain range and basin formation could be co-dependent.

Table 3
Parameters (activation energy E , 'size' $\log(D_0/\rho^2)$, percentage of released gas ϕ , and closure temperature T_c) used for K-feldspars' Arrhenius modeling

Sample	Number of domains	E (kcal/mol)	$\log(D_0/\rho^2)$ (s^{-1})	ϕ (fraction $^{39}\text{Ar}\%$)	T_c ($^{\circ}\text{C}$)
NQ9901	7	42	4.90	7.03	182
		42	4.46	16.81	191
		42	3.74	14.06	198
		42	2.57	11.14	238
		42	2.38	17.88	244
		42	1.66	23.92	260
KL9901	3	42	1.63	9.16	265
		35	2.42	40.83	157
		35	1.75	24.56	174
		35	0.17	34.61	217

T_c was calculated following Dodson's formula (Dodson, 1973) and using a cooling rate of 10 $^{\circ}\text{C}/\text{Ma}$.

Table 4
Age (Ma), cooling rate ($^{\circ}\text{C}/\text{Ma}$) and temperature ($^{\circ}\text{C}$) parameters used for the modeling of the K-feldspar cooling history

Sample	Age 1–Age 2 (Ma)	Cooling rate ($^{\circ}\text{C}/\text{Ma}$)	Temperature 1–Temperature 2 ($^{\circ}\text{C}$)
NQ9901	240–225	1.7	425–400
	225–110	2.0	400–168
	110–36	0.12	168–159
	36–30	1.5	159–150
	30–16.7	3.0	150–110
	16.7–2	7.5	110–0
KL9901	150–80	1.71	300–180
	80–30	0.2	180–170
	30–20	2.0	170–150
	20–5	10.0	150–0

Fig. 6. Experimental and MDD modeling diagrams for KL9901 K-feldspar: (a) Arrhenius plot. (b) $\log(r/r_0)$ plot. (c) Age spectra. (d) Modeled cooling path.

Many of these Oligocene deformations in northeastern Tibet appear to be coeval with significant strike slip motion of the Altyn-Tagh fault (Tapponnier et al., 1990; Meyer et al., 1998). Wang (1997) claimed several Tertiary back-thrusts branched from the mid-crustal decollement formed by continuous northeastward propagation of the Altyn Tagh fault, and produced northwest–southeast trending basement wedges along the North Qaidam range. These basement wedges were then uplifted by thrusting, and possibly underwent denudation around 30 My ago (Wang, 1997). This idea is supported by thermochronological evidence from the fault slip (East Kunlun fault) in the eastern Kunlun range, which also started at around 30 Ma (Mock et al., 1999). It is also note worthy that the North Qaidam fault branched from the Altyn Tagh fault through an oblique, more easterly striking splay (Fig. 1). As discussed above, the North Qaidam range was uplifted rapidly during the mid-Oligocene–Miocene, which implies that the North Qaidam fault was also active during that time. Thus, we conclude that the slip and thrusting of the North Qaidam

fault and the Eastern Kunlun fault may have occurred in association with movement of the Altyn Tagh fault during mid-Oligocene–Miocene time.

Previous studies showed that sedimentation rate in the Qaidam Basin increased from 0.017 mm/Ma during the Late Mesozoic–Early Tertiary, to more than 0.07 mm/Ma after 36.6 Ma due to variation in the rate of slip along the Altyn Tagh fault and northeastward-extension of this region (Fig. 8) (Xu, 1985; Chen et al., 1998; Métivier, 1996; Cui et al., 1999). As discussed above, the mountain ranges (North Qaidam and Kunlun) around the Qaidam Basin experienced similar rapid uplift starting from the mid-Oligocene, which occurred almost simultaneously with increased sedimentation in the Qaidam Basin (Fig. 8). Such a temporal concordance reinforces the notation that there was a close interplay between uplift of the mountain ranges

Fig. 7. Compilation of the cooling history of orogenic belts around the Qaidam Basin, data modified from Mock et al. (1999) and the present study.

Fig. 8. Diagram showing the changes of sedimentation rate in the Qaidam Basin, the slip rate of the Altyn Tagh fault, and the regional northeastward-extension rate of northeastern Tibet. Data modified from Métivier (1996) and Cui et al. (1999).

Fig. 9. Schematic diagram showing the possible denudation scenario of the mountain ranges around the Qaidam Basin (Modified from Meyer et al., 1998; Cui et al., 1999). The faults on the northern and southern edges of the Qaidam Basin made were thrusts from south to north, resulting in uplift and denudation of this area starting in the mid-Oligocene (~ 30 Ma).

(Kunlun and North Qaidam), slip propagation along the Altyn Tagh Fault, and development of the Qaidam Basin (Figs. 1, 8 and 9) (Tapponnier and Molnar, 1977; Tapponnier et al., 1990; Chen et al., 1998; Meyer et al., 1998; Cui et al., 1999).

6. Conclusion

$^{40}\text{Ar}/^{39}\text{Ar}$ and fission track thermochronological results from two granitoid suites collected from mountain ranges along the northern and southern edges of the Qaidam basin suggest that these granites may have been emplaced during separate events, but experienced similar rapid cooling during the Oligocene–Miocene. This pattern is observed widely in mountain ranges around the Qaidam Basin. By examining the spatial and temporal relationship of fault slips, terrain uplift and basin sedimentation, it is suggested that significant strike-slip motion along the Altyn Tagh fault, starting from the mid-Oligocene, may have led to crustal thickening and uplift of the mountain ranges around the Qaidam basin. This reinforces the idea that the India–Asia collision was mainly accommodated by lateral extrusion along major strike-slip faults during the Cenozoic, and that the Altyn Tagh fault was indeed active and propagating along the northern edge of Tibet since the mid-Oligocene.

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