Middle-Miocene transformation of tectonic regime in the Himalayan orogen

WANG XiaoXian¹, ZHANG JinJiang^{1*}, LIU Jiang¹, YAN ShuYu^{1,2} & WANG JiaMin¹

¹ Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, School of Earth and Space Sciences, Peking University, Beijing 100871, China;

² Petroleum Exploration and Development Research Institute, PetroChina, Beijing 100083, China

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Understanding the multiple tectonic transformations during the Himalayan orogeny is significant in evaluating the evolution of Himalayan orogen. In the Gyirong area in south Tibet, deformed leucogranitic veins in the biotite-plagioclase gneisses of Greater Himalayan crystalline complex (GHC) constitute south-vergent asymmetric folds. The reconstruction of the veins shows that they experienced two generations of deformation under different tectonic regimes: an earlier top-to-north extension and a later top-to-south thrusting, implying a tectonic transformation from N-S extension to N-S shortening. Zircons LA-ICP-MS U-Pb dating of the leucogranite shows that it was emplaced during 21.03–18.7 Ma. The data suggest that the tectonic transformation occurred after 18.7 Ma. The chronological data of South Tibet detachment system (STDS) and North-South trending rift (NSTR) from Gyirong and other areas indicate that the Himalayan orogeny was in a period of tectonic transformation from N-S extension to N-S shortening during 19–13 Ma. The transformation of tectonic regime was probably controlled by the India-Asia convergence rate. An increase in the convergence rate resulted in N-S shortening of the orogen, thrusting and folding, with coeval formation of the NSTR in Tibet. A decrease in the convergence rate led to N-S extension and reactivation of the STDS.

leucogranitic vein, south Tibet detachment system (STDS), north-south trending rift (NSTR), tectonic regime transformation, Himalayan orogen, Gyirong area

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The Himalayan orogen lies between the Yarlung Zangbo suture (YLZBS) to the north and the Main frontal Thrust (MFT) to the south, and comprises, from north to south, the Tethyan Himalaya sequence (THS), Greater Himalayan crystalline complex (GHC), Lesser Himalaya sequence (LHS) and Siwalik foreland basin sediments, separated by the south Tibet detachment system (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and the MFT respectively (Figure 1) [1–3]. In southern Himalaya, the intense orogeny formed the south Himalayan thrust system, which consists of, successively from north to south, MCT, MBT and MFT. In contrast, the northern Himalayan domain is characterized by extensional structures including STDS, the north Himalayan gneiss dome (NHGD), and the north-

south trending rift (NSTR). Recent studies have revealed that the different orogenic processes were controlled by different tectonic regimes and the resultant structural architecture [1] as follows. (1) Prior to 36–32 Ma (from late Eocene to early Oligocene), the Himalayan orogen was controlled by N-S contraction regime and experienced an early shorting and thrusting. (2) After early Oligocene, the tectonic regime transformed from N-S contraction to N-S extension. Between late Oligocene and early Miocene (28.4–16.2 Ma), the northern Himalayas experienced widespread extension, resulting in large scale extensional tectonics, such as the north-dipping STDS [4–16]. (3) In middle-Miocene (~13 Ma), the tectonic regime shifted to E-W extension [17,18], which formed the NSTR cutting the STDS, such as Yadong-Gulu rift, Nima-Dingri rift and Xainza-Dinggye rift. Although the first transformation of tectonic

*Corresponding author (email: zhjj@pku.edu.cn)

Figure 1 Sketch map of the Himalayan orogen (modified from [1,2]). YLZBS: Yarlung Zangbo suture; STDS: South Tibet detachment system; MCT: main central thrust; MBT: main boundary thrust; MFT: main frontier thrust.

regime from N-S contraction to N-S extension has been extensively studied [1,19–21], there have been no major investigations on the later transformation of tectonic regime from N-S extension to E-W extension.

In order to reveal this transformation of tectonic regime in the Himalayan orogen, we focus on the Gyirong area, where different kinds of structures related to the orogeny converge develop and intersect. This study provides a detailed structural analysis on the complexly deformed leucogranitic veins in the footwall of the STDS, and reports high-precision zircon LA-ICP-MS U-Pb ages on the veins, in an attempt to constrain the timing and geodynamic setting of the transformation of tectonic regime associated with the Himalayan orogeny.

1 Geological setting and sample description

The Himalayan orogen in Gyirong area can also be divided into five units from south to north: the GHC, the STDS, the THS, the late Cenozoic sedimentary basins and the NHGD (Figure 2) [1]. The GHC is composed of two components separated by a north-dipping fault. The southern part is composed of medium-grade metamorphic rocks, such as meta-sandstone and schist. The northern part consists of high-grade rocks, such as biotite-plagioclase gneiss, granitic gneiss and migmatite, into which leucogranitic veins intruded. The STDS in Gyirong area represents a large-scale ductile shear zone with a width of over 10 km. It consists of mylonitic granitic gneiss and foliated leucogranite [22]. The THS forms the hanging wall of the STDS, mainly Paleozoic-Mesozoic sedimentary sequence, which was metamorphosed to slates and phyllites. The Cenozoic sedimentary basins in Gyirong area include Gyirong basin, Oma basin

and some other small basins. Exposed to the north of Gyirong basin are Peiku Co and Malashan domes. These two domes are cored by two-mica granite/leucogranite and mylonitic granitic gneiss [23,24], mantled by garnet two-mica schist in the middle, and overlaid by the slate and phyllite of THS. The area of this study is located in the GHC where leucogranitic veins intruded into the gneiss (Figure 2) [1].

The leucogranite veins intruded into the biotite-plagioclase gneiss (Figure 3(a)), and occur as south-vergent asymmetric folds. The biotite-plagioclase gneiss, consisting of quartz, plagioclase, K-feldspar, biotite and muscovite, shows typical gneissic texture defined by the discontinuous alignment of biotites (Figure 3(b)). The leucogranite of sample TYC-88 is composed of quartz (45%), plagioclase (35%), K-feldspar (15%), biotite and muscovite (<5%), and minor chlorite. The quartz displays undulatory extinction and crenulated boundary (Figure 3(c)), probably caused by shearing. Some of the plagioclase grains show alternation to fine muscovite (Figure 3(d)).

2 Analytical method

We dated zircons from the leucogranitic vein from GHC in Gyirong area using LA-ICP-MS U-Pb method. The zircon grains were embedded in 25 mm epoxy discs and polished to approximately half of the grain thickness. The internal growth structure of zircons were analyzed by Cathodoluminescence (CL) imaging technique using a LEO 1450VP SEM, operating at 15 kV and 150 μ A with a scanning time 1 min, at the Institute of Geology and Geophysics, CAS. Zircon U-Pb isotopic measurements were carried out on a Laser Ablation Inductively Coupled Plasma Mass Spectrometer at the

Figure 2 Geological map of the Gyirong area in northern Himalaya (after [1]).

LA-ICP-MS laboratory of the Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, CAS, Beijing. Zircon grains were ablated with laser spots of 35 μm and ablated depths of 20–40 μm . PLE zircon (337 Ma) and NIST SRM 612 silicate were used as external standards for correcting mass fractionation and instrumental bias. Off-line isotope ratios and trace element concentrations were calculated by GLITTER_Ver4.0 [25]; U-Pb concordia diagrams, weighted mean calculations and probability density plots of U-Pb ages were made by using Isoplot/Ex_ver 3 [26].

3 Results

The CL images of representative zircons (Figure 4) show that zircons in sample TYC-88 are euhedral with prismatic shapes and size ranging from 100 to 300 μm . The zircons

show core-rim textures: the cores are dark with a spongy texture, probably caused by hydrothermal alteration, whereas the rims are bright with apparent oscillatory rings, indicating the magmatic origin [27].

Thirty-two spots were analyzed on the magmatic rim of the zircons from sample TYC-88, most of which plot well on the U-Pb Concordia (Figure 5 and Table 1). Nearly all the grains show low Th/U values (0.009–0.055). The thirty-two spots yield apparent $^{206}\text{Pb}/^{238}\text{U}$ ages from 26.8 to 18.2 Ma. In the U-Pb concordia diagram, the age data are divided into two groups: the first group consists of eleven spots with ages ranging from 21.2 to 20.9 Ma, giving a weighted mean age of 21.03 ± 0.11 Ma (MSWD=0.39); the second group includes fifteen spots with ages from 19.2 to 18.2 Ma, giving a weighted mean age of 18.70 ± 0.19 Ma (MSWD=3.6). The features of similar oscillatory rings and low Th/U ratios in rims of the two groups of zircons are consistent with magmatic zircons formed by anatexis [22]. We therefore

Figure 3 Photographs and photomicrographs of leucogranite and biotite-plagioclase gneiss from the GHC in Gyirong area. (a) Outcrops of leucogranite and the wall rock biotite plagioclase gneiss; (b) the gneissic texture defined by the discontinuous alignment of biotite; (c) mineral assemblage of leucogranite; (d) fine-grained muscovite altered from plagioclase. Qtz, Quartz; Kfs, K-feldspar; Pl, Plagioclase; Bi, Biotite; Mu, Muscovite.

consider these ages to represent the crystallization ages of the leucogranite. The range of the ages of leucogranite is in accordance with the age data from the Himalayan orogen, suggesting a long duration of anatexis [1].

4 Discussion

4.1 Multiple episodes of deformation and tectonic transformation in Gyirong area

The Himalayan orogen in Gyirong area experienced multiple episodes of deformation [1]. Based on the studies of structures and deformation of the Gyirong and the adjacent areas, Yang et al. [22] suggested three main stages of deformation: (1) an early south-directed thrusting preserved in

the THS and GHC; (2) top-down-to-north slip along STDS; and (3) E-W extension, typically represented by the NSTR. Hence a transformation of tectonic regime occurred between each two episodes of deformation.

The leucogranitic veins in this study experienced a complex deformational history and they display south-vergent asymmetric folds, indicating south-directed thrusting (Figure 6(b)). However, the reconstruction of the veins shows that they are composed of a series of asymmetric pudding or lenses which suggest a top-down-to-north shear (Figure 6(c)). These rocks thus experienced two generations of deformation in different tectonic regimes: an earlier top-down-to-north extension and a later top-to-south thrusting and thickening, clearly marking a transformation in the tectonic regime in between. Combining with the zircon U-Pb age of the leucogranite and geological history of the study area [1], we propose an evolutionary process as follows.

(1) Since ~34 to ~19 Ma, the top-down-to-north slip along STDS controlled by the regime of N-S extension resulted in the partial melting of GHC [22]. The identical age of the leucogranitic veins and STDS demonstrates the emplacement and crystallization of leucogranite was synchronous with the STDS.

(2) After 18.7 Ma, the leucogranite veins underwent continued top-down-to-north extension, which formed the asymmetric puddings or lens and the neck structure between puddings (Figure 6(c)).

(3) Subsequently, the rocks experienced top-to-south thrusting and shortening under a N-S contractional tectonic regime, which formed the south-vergent asymmetric folds (Figure 6(d)).

The leucogranitic veins are adjacent to STDS but away from the MCT; furthermore, the deformation in MCT is reflected for several kilometers in the shear zone. Therefore the south-vergent geometry of the veins was not involved in the MCT, and should have resulted through the transformation of tectonic regime. As a result, we suggest that an

Figure 4 CL images of representative zircons in sample TYC-88 from the leucogranite in GHC.

Table 1 Zircon LA-ICP-MS U-Pb analytical data of the leucogranitic vein from Gyirong

Analytical spot	Th (ppm)	U (ppm)	Th/U	Isotopic ratio								Apparent age (Ma)					
				$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	$^{208}\text{Pb}/^{232}\text{Th}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	$^{208}\text{Pb}/^{232}\text{Th}$	$\pm 1\sigma$
TYC-88-01	82.8	6718.9	0.01	0.04780	0.00086	0.02741	0.00043	0.00416	0.00003	0.00165	0.00011	26.8	0.2	27.5	0.4	33.3	2.2
TYC-88-02	35.1	1236.9	0.03	0.04697	0.00433	0.01853	0.00167	0.00286	0.00006	0.00135	0.00033	18.4	0.4	18.6	1.7	27.3	6.8
TYC-88-03	39.2	2573.4	0.02	0.04695	0.00233	0.02113	0.00101	0.00327	0.00004	0.00313	0.00031	21.0	0.2	21.2	1.0	63.1	6.2
TYC-88-04	61.2	1922.1	0.03	0.04854	0.00166	0.02094	0.00068	0.00313	0.00003	0.00173	0.00013	20.1	0.2	21.0	0.7	35.0	2.6
TYC-88-05	19.5	1838.5	0.01	0.04654	0.00175	0.02106	0.00076	0.00328	0.00003	0.00099	0.00034	21.1	0.2	21.2	0.8	20.0	6.9
TYC-88-06	45.1	1785.7	0.03	0.04751	0.00186	0.02155	0.00081	0.00329	0.00003	0.00196	0.00019	21.2	0.2	21.6	0.8	39.5	3.8
TYC-88-07	116.3	2106.6	0.06	0.04496	0.00151	0.01774	0.00057	0.00286	0.00002	0.00102	0.00006	18.4	0.2	17.9	0.6	20.6	1.3
TYC-88-08	59.1	1517.5	0.04	0.04646	0.00179	0.01853	0.00068	0.00289	0.00003	0.00157	0.00012	18.6	0.2	18.6	0.7	31.8	2.4
TYC-88-09	36.1	2238.7	0.02	0.04563	0.00143	0.02044	0.00061	0.00325	0.00003	0.00112	0.00020	20.9	0.2	20.5	0.6	22.6	4.1
TYC-88-10	25.8	1042.3	0.02	0.04614	0.00230	0.01864	0.00091	0.00293	0.00003	0.00148	0.00023	18.9	0.2	18.7	0.9	30.0	4.6
TYC-88-11	34.4	2628.0	0.01	0.04523	0.00113	0.02295	0.00053	0.00368	0.00003	0.00149	0.00018	23.7	0.2	23.0	0.5	30.1	3.6
TYC-88-12	26.2	2102.5	0.01	0.04477	0.00139	0.02037	0.00060	0.00330	0.00003	0.00172	0.00027	21.2	0.2	20.5	0.6	34.7	5.4
TYC-88-13	37.2	2666.1	0.01	0.04585	0.00126	0.02051	0.00053	0.00325	0.00003	0.00108	0.00016	20.9	0.2	20.6	0.5	21.7	3.2
TYC-88-14	46.4	1971.5	0.02	0.04728	0.00227	0.01904	0.00088	0.00292	0.00003	0.00109	0.00014	18.8	0.2	19.1	0.9	22.1	2.8
TYC-88-15	74.9	1930.6	0.04	0.04424	0.00156	0.01724	0.00058	0.00283	0.00002	0.00104	0.00009	18.2	0.2	17.4	0.6	21.0	1.8
TYC-88-16	61.9	1816.3	0.03	0.04709	0.00170	0.01901	0.00065	0.00293	0.00003	0.00112	0.00011	18.9	0.2	19.1	0.7	22.6	2.2
TYC-88-17	32.9	2139.6	0.02	0.04667	0.00141	0.02096	0.00060	0.00326	0.00003	0.00127	0.00019	21.0	0.2	21.1	0.6	25.6	3.9
TYC-88-18	70.2	1686.3	0.04	0.04501	0.00245	0.01752	0.00092	0.00282	0.00003	0.00110	0.00015	18.2	0.2	17.6	0.9	22.2	2.9
TYC-88-19	24.0	2704.1	0.01	0.04747	0.00127	0.02341	0.00059	0.00358	0.00003	0.00376	0.00032	23.0	0.2	23.5	0.6	75.9	6.4
TYC-88-20	31.8	2669.3	0.01	0.04609	0.00131	0.02087	0.00056	0.00329	0.00003	0.00137	0.00020	21.1	0.2	21.0	0.6	27.6	4.1
TYC-88-21	39.6	2165.7	0.02	0.04726	0.00154	0.02140	0.00066	0.00329	0.00003	0.00295	0.00020	21.1	0.2	21.5	0.7	59.5	4.0
TYC-88-22	81.2	2222.1	0.04	0.04556	0.00161	0.01850	0.00062	0.00295	0.00003	0.00153	0.00010	19.0	0.2	18.6	0.6	30.9	2.1
TYC-88-23	137.0	7195.0	0.02	0.04741	0.00084	0.02681	0.00042	0.00410	0.00003	0.00231	0.00008	26.4	0.2	26.9	0.4	46.6	1.6
TYC-88-24	51.0	1636.0	0.03	0.04709	0.00208	0.01925	0.00082	0.00297	0.00003	0.00093	0.00014	19.1	0.2	19.4	0.8	18.7	2.9
TYC-88-25	58.3	1737.5	0.03	0.04438	0.00197	0.01772	0.00076	0.00290	0.00003	0.00135	0.00012	18.6	0.2	17.8	0.8	27.3	2.4
TYC-88-26	75.1	2491.8	0.03	0.04633	0.00139	0.02083	0.00059	0.00326	0.00003	0.00128	0.00010	21.0	0.2	20.9	0.6	25.9	1.9
TYC-88-27	72.5	1835.9	0.04	0.04769	0.00179	0.01944	0.00070	0.00296	0.00003	0.00155	0.00011	19.0	0.2	19.5	0.7	31.3	2.3
TYC-88-28	115.9	2924.6	0.04	0.04646	0.00125	0.01915	0.00048	0.00299	0.00002	0.00095	0.00006	19.2	0.2	19.3	0.5	19.3	1.3
TYC-88-29	17.3	1007.6	0.02	0.04620	0.00232	0.01805	0.00088	0.00283	0.00003	0.00151	0.00036	18.2	0.2	18.2	0.9	30.5	7.3
TYC-88-30	23.0	914.6	0.03	0.04550	0.00272	0.01814	0.00106	0.00289	0.00003	0.00178	0.00026	18.6	0.2	18.3	1.1	36.0	5.3
TYC-88-31	38.4	2122.9	0.02	0.04691	0.00146	0.02101	0.00062	0.00325	0.00003	0.00159	0.00017	20.9	0.2	21.1	0.6	32.1	3.5
TYC-88-32	35.4	1566.4	0.02	0.04615	0.00163	0.01961	0.00066	0.00308	0.00003	0.00173	0.00016	19.8	0.2	19.7	0.7	35.0	3.3

Figure 5 U-Pb concordia diagram for zircons from sample TYC-88 of the leucogranite.

important transformation of tectonic regime from N-S extension to N-S contraction occurred after 18.7 Ma in our study area in northern Himalaya.

4.2 Middle-Miocene transformation of tectonic regime in Himalayan orogen

Based on the analysis of the structure and chronology of the leucogranite in Gyirong area, we propose that the transformation of tectonic regime from N-S extension to N-S contraction occurred after 18.7 Ma in the Gyirong area. In the Dinggye and Yadong areas of northern Himalaya, the N-S extensional STDS was cut and offset by the E-W extensional NSTRs [17,18]. All of NSTRs present the active ages of 19–7 Ma [4–10,12–17,22,28,30–48] (Figure 7), which are coeval with the south-direct thrust (<18.7 Ma) of asymmetric

Figure 6 Structures of the Himalayan orogen in Gyirong area and the reconstruction of leucogranite. (a) Cross-section across the STDS in the Gyirong area (location is seen in Figure 2); (b) leucogranitic veins forming south-vergent asymmetric folds in GHC gneiss; (c) early phase of extension; (d) later thrusting and shortening of the leucogranite.

Figure 7 Summary diagram of the ages of STDS and NSTRs in the Himalayan orogen (data from [4–10,12–17,22,28,30–48]).

folds in this study. This confirms the view that NSTR is probably the result of N-S contraction [29] and provides unequivocal evidence for the transformation of tectonic regime.

In order to accurately constrain the time of the transformation of tectonic regime from N-S extension to N-S contraction, we summarize and analyze the ages of STDS and NSTRs in Gyirong and other areas in Himalayan orogen (Figure 7) [4–10,12–17,22,28,30–48]. The result shows that the STDS was active from ca. 36 to 13 Ma with the major activity at ca. 28–13 Ma and the NSTRs were active from ca. 19 to 7 Ma with a peak ages of 19–13 Ma. All the analyses

prove that the Himalayan orogen was controlled by the regime of N-S extension from ca. 28 to 19 Ma. During ca. 19–13 Ma, it was controlled by both the N-S extension and N-S contraction regime, implying a transition from N-S extension to N-S contraction. Since 13 Ma, the regime of N-S contraction was dominant. The U-Pb/U-(Th)-Pb ages of zircon/monazite from leucogranites and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of mica from leucogranites and meta-sedimentary rocks in Himalayan orogen (Figure 8 and Table S1) [1,4–13,15–18, 22–24,30,34–83] show that the peak ages of leucogranites are roughly between 24 Ma and 13 Ma, while the peak

$^{40}\text{Ar}/^{39}\text{Ar}$ ages are around 18–13 Ma. This means the emplacement of the leucogranites culminated at the same time as the $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages during ca. 18–13 Ma, which suggests a rapid cooling at this time. The rapid cooling event was probably related to the interaction of the extension of STDS, and uplift and erosion caused by the orogeny of N-S contraction, indicating a transition and adjustment from extension and collapse to contraction and uplift. Thus we suggest the transformation of tectonic regime from N-S extension to N-S contraction occurred in middle-Miocene, i.e. the Himalayan orogen experienced a transition and adjustment from N-S extension to N-S contraction during ca. 19–13 Ma, and it was controlled by the regime of N-S contraction since 13 Ma, indicating the transformation of tectonic regime at ~13 Ma.

4.3 Geodynamic implications on the transformation of tectonic regime in the Himalayan orogen

Three categories of tectonic scenario have been proposed to interpret the transformation of tectonic regime: (1) Lateral extrusion model: the northward push of India led to the eastward extrusion of Tibet plateau in the form of eastward movement of the upper crust or “channel flow” of the middle-lower crust [84,85]. The eastward extrusion resulted in the regime of E-W extension. (2) Southward flow with a divergent radial component: the southward spreading of mid-crust in Tibet produced an E-W radial component of flow, causing the onset of the observed E-W extension and the formation of NSTR [48]. (3) Zhang et al. [1] proposed a new tectonic scenario that the transformation of tectonic regime was related to the rate of India-Asia convergence. When the convergence was slow, could the force could not sustain the thickened orogen, with the Himalayan orogen experiencing a relaxation and the northern Himalaya witnessing a mountain collapse process, i.e., the extension of the STDS. At this time, the regime of N-S extension was dominant. When the India-Asia convergence speeded up, the Himalaya experienced a rapid deformation, resulting in

the thrusting and shorting. The NSTR and south-vergent asymmetric folds formed and tectonic regime was N-S contraction.

Based on paleomagnetic data, White and Lister (2012) [86] estimated the rate of India-Asia convergence since collision. Before 20 Ma, the rate of India-Asia convergence was slow. During 19–13 Ma, it was an alternant process of speeding up and slowing down. Since 13 Ma, the convergence rate speeded up again. The tomography of Himalayan orogen reveals multiple episodes of continental subduction [87]. At 15 Ma, the breaking off of the steep subducted slab caused gentle subduction and increase in the rate of horizontal convergence [88]. The northerly moving Indian plate rotated clockwise in Miocene, which also probably altered the convergence rate and resulted in the transformation of tectonic regime [89,90]. All these features support the model proposed by Zhang et al. [1]. Integrating the structural reconstruction with above model, we suggest an evolutionary process and the transformation of tectonic regime in the northern Himalaya as follows. (1) From ca. 28 to 19 Ma, the India-Asia convergence rate was slow, when the Himalayan orogen experienced a collapse and the STDS was intensely active under a tectonic regime of N-S extension. (2) From ca. 19 to 13 Ma, the rate of India-Asia convergence changed, when the STDS and NSTR were active alternately. The tectonic regime was in a period of transition and adjustment from N-S extension to N-S contraction. (3) After ca. 13 Ma, the rapid India-Asia convergence caused intense contraction, leading to the formation of the asymmetric folds in Gyirong area and the activation of the NSTR.

5 Conclusion

(1) The leucogranite veins in the footwall of the STDS of Gyirong area, south Tibet, were emplaced at 21.03–18.7 Ma. The region experienced an earlier top-down-to-north extension and a later south-direct thrusting, indicating a tectonic transformation after 18.7 Ma.

(2) The Himalayan orogen experienced a transformation of tectonic regime from N-S extension to N-S contraction in middle-Miocene. The accomplishment of the tectonic transformation was at ca. 13 Ma.

(3) The transformation of tectonic regime in Himalayan orogen is controlled by alteration in the rate of India-Asia convergence.

Figure 8 Statistical diagram of the U-Pb/U-(Th)-Pb ages of leucogranites and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of leucogranites and metasedimentary rocks in Himalayan orogen (data from [1,4–13,15–18,22–24,30,34–83]).

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Supporting Information

Table S1 LA-ICP-MS U-Pb isotope data of zircon grains from the Penggongmiao granite and coexisting aplitic vein

The supporting information is available online at csb.scichina.com and www.springerlink.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.