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Discussion on the Cenozoic tectonic evolution and dynamics of southern Tibet*

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Abstract: Opening-closing tectonics is a new idea for exploring the global tectonics, which holds that every tectonic movement of all materials and geological bodies on earth is characterized by opening and closing. The opening-closing tectonic view can be used to explain some geological phenomena developing in continents which cannot be reasonably explained by the theory of plate tectonics. Based on the available basic geological data and combining with the opening-closing view, we analyzed the divisions and characteristics of tectonic units in South Tibet, and propose that Tibet can be divided into gravitational detachment and detachment fault zones, which are superimposed thrust fault zones and reconstructed normal fault zones, respectively. Although the mainstream opinion believed that the Tibetan Plateau is formed by collision-compression orogenesis, field investigation revealed the existence of the Rongbu Temple normal fault in the 1970s. We consider that the Rongbu Temple normal fault and the Main Central Thrust were formed earlier than the South Tibet detachment fault, and the former two faults constitute the two boundaries of the southern Tibet extrusion structure. The South Tibet detachment fault partially superimposes on the Main Central Thrust and manifests a relatively high angle in following the Rongbu Temple normal fault north of the Chomolangma. We suggest that the three fault systems are the products of different periods and tectonic backgrounds. The tectonic units, such as klippe and windows identified by previous researchers in southern Tibet, belong to thrust fault system but usually have no obvious extrusion or thrust characteristics; however, they are characterized by missing strata columns as younger strata overlapping the older ones. These klippe and windows should be the results of later gravitational decollement and must be characterized as extensions and slips, respectively. Based on opening-closing theory, we suggest that since the Cenozoic the study area had undergone multi-stage development, which can be divided into the oceanic crust expansion (opening) and subduction (closing) and the continental collision (closing) and intracontinental extension (opening) stages. Geothermal energy from the deep earth, gravitational potential energy from the earth's interior, and additional stress energy from tectonic movements, all played a key role in the multistage tectonic evolutionary process.

Keywords: South Tibet, geological structure, Cenozoic tectonic evolution, opening-closing tectonics

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Обсуждение кайнозойской тектонической эволюции и динамики Южного Тибета*

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Резюме: Новой идеей в исследовании глобальных тектонических движений является концепция тектоники открытия-закрытия, которая утверждает, что каждое тектоническое явление, преобразование вещества и формирование геологических тел на Земле – это результат чередующихся движений открытия и закрытия. Тектонический взгляд

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на открытие-закрытие может быть использован для объяснения некоторых геологических явлений, развивающихся на континентах, которые не могут быть однозначно объяснены теорией тектоники плит. Основываясь на доступных геологических данных и опираясь на концепцию открытия-закрытия, авторы проанализировали стратиграфические подразделения и тектонические единицы Южного Тибета и предложили разделить эту территорию на разломные зоны гравитационного отрыва и разломные зоны тектонического отрыва, которые накладываются друг на друга. Несмотря на широко распространенное мнение о том, что Тибетское нагорье образовано орогенезом столкновения-сжатия, полевые исследования выявили существование нормального сброса храма Жунбу в 1970-х гг. Мы считаем, что нормальный сброс храма Жунбу и Главный центральный надвиг были сформированы раньше, чем разлом Южного Тибета, а первые два разлома представляют собой две границы экструзионной структуры Южного Тибета. Разлом Южного Тибета частично накладывается на Главный центральный надвиг и, имея относительно большой угол, следует за нормальным сбросом храма Жунбу к северу от Джомолунгмы. Мы предполагаем, что три системы разломов являются продуктами разных периодов и разных тектонических процессов. Тектонические единицы, такие как клипы и окна, идентифицированные предыдущими исследователями в Южном Тибете, принадлежат к системе надвигов, но обычно не имеют явных характеристик сжатия и надвигания, в то же время они характеризуются отсутствием стратификации пластов, поскольку более молодые пласты перекрывают более старые. Эти клипы и окна, скорее всего, являются результатом более позднего гравитационного наложения и должны быть охарактеризованы как удлинение и проскальзывание соответственно. Основываясь на теории открытия-закрытия, мы предполагаем, что начиная с кайнозоя исследуемая область претерпела многоэтапное развитие, которое можно разделить на последовательное расширение (раскрытие) и субдукцию (закрытие) океанической коры, а также следующие за ними этапы континентальной коллизии (закрытие) и внутриконтинентального расширения (раскрытие). Геотермальная энергия и гравитационная потенциальная энергия из недр Земли, а также дополнительная энергия напряжения от тектонических движений – все это сыграло ключевую роль в многоступенчатом тектоническом эволюционном процессе.

Ключевые слова: Южный Тибет, геологические структуры, кайнозойская тектоническая эволюция, тектоника открытия-закрытия

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Background

The "opening-closing tectonics" hypothesis is pioneered jointly by academicians Huang Jiqing, Zhang Wenyou and Ma Xingyuan and other young scholars in the 1970s [1, 2]. Before that, the plate tectonics theory, based on marine geological survey data, had proposed a geological tectonic evolutionary model which advanced geology into a new era of lithosphere dynamics research. However, the overly idealized plate motion model encountered a series of problems in the study of continental geology. Experimental studies have proven that the continental lithosphere is not a simple rigid plate and the detachment and relative movements between various interlayers of the continental lithosphere are very common and strong. The asthenosphere that the continental lithosphere drifts on is also uneven. Expansion between continental blocks does not always form oceans but "limited ocean basins". The cracking and aggregation of continental

blocks in the geologic periods are multi-cycled, and there are also many types of orogeny movements inside the continents. Natural phenomena such as these cannot be explained by plate tectonics. The opening-closing tectonics, on the other hand, is a link connecting various earth movements and all geological disciplines, therefore, it can better explain some of these intracontinental tectonic phenomena.

The view of opening-closing tectonics emphasizes that the basic form of all earth's materials and movements is opening and closing. The opening and closing movements can be seen as approaching (opposite movement) and separation (reverse movement) in the horizontal direction, while contracting (centripetal movement) and expansion (centrifugal movement) in the vertical direction. The two are unified, that is, the opening movement (expansion) on the vertical is contemporaneous with opening (separation) on the horizontal, and the closing movement



(contraction) on the vertical corresponds to closing (approaching) on the horizontal; at the same time, the vertical (centrifugal) movement is strongly open (separation) in the horizontal direction, and vice versa. In this way, the opening and closing tectonics view unifies the vertical and horizontal movements as well as the deep and shallow structures of the earth into an organic whole. Opening and closing exist in a unified geological body. The two are interdependent, opposite and interconvertible. The spatiotemporal position of the transition point (area) of opening and closing movements has both theoretical and practical significance. The most intensive material exchange, tectonic movement, and magmatic activity occur at the transition point (area) where most orogenic belts concentrates. Meanwhile, the transition point (area) possesses the most abundance of various mineral resources and also frequent geological disasters such as earthquakes, volcanoes, mudslides and landslides.

In this paper, we compare the previously determined geological structure of the Chomolangma region in southern Tibet with traditional integrated geological maps based on the opening-closing tectonic view. We concur that although the interpretation of several basic geological phenomena in the Himalayan orogenic belt in southern Tibet is still controversial, opening-closing tectonics can reasonably explain the Cenozoic tectonic evolution process in this region. We hope this paper will draw attention of other researchers to opening-closing tectonics and offer their valuable thoughts on this subject.

Division of tectonic units in southern Tibet

The southern part of the Qinghai-Xizang Plateau is generally composed of extensional detachment and compressional nappe structural zones, where a series of parallel thrust fault zones developed. Lying from north to south are the Gangdese magmatic arc zone (GDS), the Tethys Himalayan tectonic zone (THM), the Great Himalayan tectonic zone (GHM), the Lasser Himalayan tectonic zone (LHM), and the sub-Himalaya tectonic

zone (SHM) (Siwalik Foreland Basin Sedimentary Belt). The respective boundaries between them are the India-Yarlung-Tsangpo suture zone (IYSZ), the South Tibet detachment system (STDS), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT) (Fig. 1)^{1,2}. Based on previous studies, and using the opening-closing tectonic view in combination with the dynamic tectonic unit divisional method, we summarize in this paper the geological structures, characteristics of tectonic units, and tectonic boundary attributes of the southern Tibetan Plateau.

The Main Central Thrust (MCT) was first proposed by Heim and Gansse [3] who believed that folding develops extensively on the MCT, and a set of older metamorphic rocks reverse gently overlapping the steeply dipping younger limestone. Although the MCT integrally serves as the boundary between GHM and LHM, some GHM rock formation units surrounded by the MCT are within the LHM (Figs. 2 and 3). As Harrison et al. [4] pointed out that not all shear planes are simultaneously active in shear zones. Therefore, the MCT position, as the main convergence point, has also changed over time in shear zones.

Arita [7] found abrupt changes in lithology and metamorphic grades in the MCT shear zone under a Leforte designated MCT fault [8]. Therefore, Arita named the MCT fault as MCT-I (or lower MCT) and the Leforte designated MCT fault as MCT-II (upper MCT) [8]. Consequently, later scholars often draw two MCTs in the geological map of the plateau (Fig. 4). There are three general views on the MCT: first, it has some branching characteristics, i.e., the main fault plane is straight with high-angle dipping but branching faults are undulating (Fig. 2); second, it has undulating characteristics as a whole (Fig. 3); and third, it can be divided into two faults developed in different periods (Fig. 4).

The South Tibet Detachment System (STDS), located between the Tethys Himalayan and High Himalayan tectonic zones, has been well defined by geological scholars [10, 11] and widely studied. It runs parallel to the Himalayan range for more

¹ Pan G.T., Ding J., Yao D.S. Geological map of the Qinghai-Xizang (Tibet) Plateau and adjacent areas. Chengdu: Chengdu Cartographic Publishing House, 2004.

² Ren J.S., Niu B.G., Wang J., et al. 1:5 million international geological map of Asia. Beijing: Geology Publishing House, 2013.

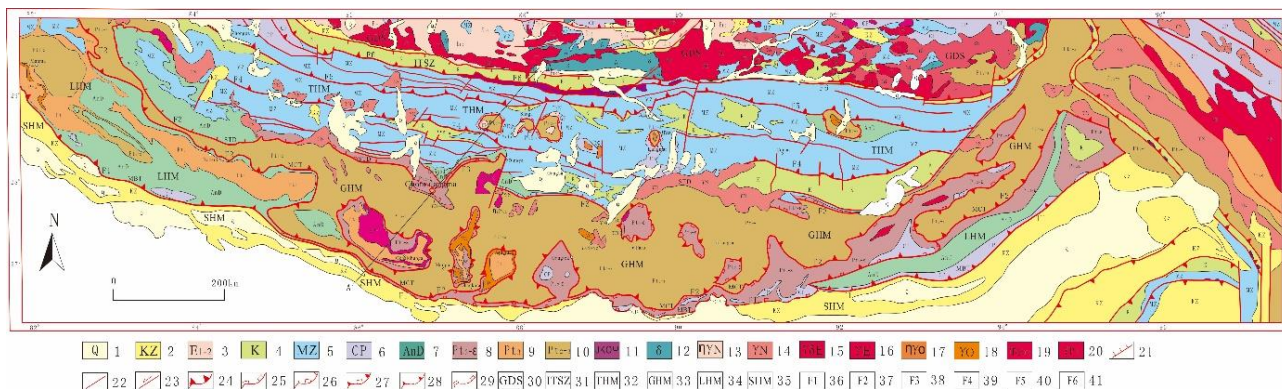


Fig. 1. Tectonic sketch map of southern Tibet (modified from)^{3,4}:

- 1 – Holocene; 2 – Cenozoic; 3 – Paleocene; 4 – Cretaceous; 5 – Mesozoic; 6 – Carboniferous-Permian (Cap 3);
7 – Pre Devonian (Cap 2); 8 – Late Proterozoic – Cambrian (Cap 1); 9 – Late Proterozoic (Cap 1);
10 – Mesoproterozoic (Basement); 11 – Ophiolitic melange; 12 – Diorite; 13 – Neogene feldspar granite;
14 – Neogene granite; 15 – Paleogene granodiorite; 16 – Paleogene granite; 17 – Ordovician feldspar;
18 – Ordovician granite; 19 – Neoproterozoic granite; 20 – Proterozoic granite; 21 – Normal fault;
22 – Unidentified fault; 23 – Strike-slip fault; 24 – Thrust fault; 25 – Detachment fault; 26 – Normal fault
superimposed and reconstructed by detachment fault; 27 – Thrust fault superimposed and reconstructed
by detachment fault; 28 – Hidden thrust fault; 29 – Hidden detachment fault; 30 – Gangdise tectonic zone;
31 – Yarlung-Tsangpo suture zone; 32 – Tethys Himalayan tectonic zone; 33 – Great Himalayan tectonic zone;
34 – Lesser Himalayan tectonic zone; 35 – Sub Himalayan tectonic zone; 36 – Main Boundary Thrust;
37 – Main Central Thrust; 38 – South Tibet detachment system; 39 – Dingri-Gangba thrust fault;
40 – Zhada-Qionduojang thrust fault; 41 – South Yarlung-Tsangpo river thrust fault

Рис. 1. Тектоническая схематическая карта Южного Тибета (с изменениями)^{3,4}:

- 1 – голоцен; 2 – кайнозой; 3 – палеоцен; 4 – мел; 5 – мезозой; 6 – каменноугольно-пермский период (покров 3);
7 – ранний девон (покров 2); 8 – поздний протерозой – кембрий (покров 1); 9 – поздний протерозой (покров 1);
10 – средний протерозой (фундамент); 11 – офиолитовый меланж; 12 – диорит; 13 – неогеновый
полевошпатовый гранит; 14 – неогеновый гранит; 15 – палеогеновый гранодиорит; 16 – палеогеновый
гранит; 17 – ордовикский полево шпат; 18 – ордовикский гранит; 19 – неопроterозойский гранит;
20 – протерозойский гранит; 21 – сброс; 22 – неидентифицированный разлом; 23 – сдвиг; 24 – надвиг;
25 – детачмент; 26 – нормальный сброс, наложенный и реконструированный по разлому детачмента;
27 – надвиг, наложенный и реконструированный; 28 – скрытый надвиг; 29 – скрытый детачмент;
30 – тектоническая зона Гангдисе; 31 – сутурная зона Ярлунг-Цангпо; 32 – Гималайская тектоническая
зона Тетиса; 33 – Великая гималайская тектоническая зона; 34 – тектоническая зона Малых Гималаев;
35 – Субгималайская тектоническая зона; 36 – Главный пограничный надвиг; 37 – Главный центральный
надвиг; 38 – Южно-Тибетская система детачмента; 39 – надвиг Тингри-Гамба;
40 – надвиг Дзанда-Цюндюцзян; 41 – надвиг реки Южная Ярлунг-Цангпо

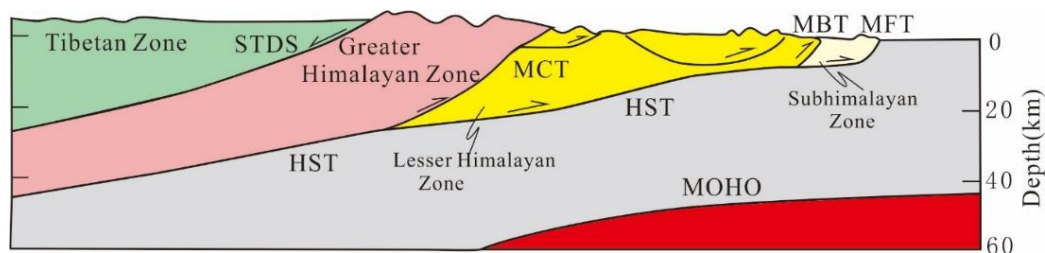


Fig. 2. Generalized cross section of the Himalayan margin of the Tibetan Plateau (adapted from [5]):

HST – Himalayan Sole Thrust; MCT – Main Central Thrust; MBT – Main Boundary Thrust;
MFT – Main Frontal Thrust; STDS – South Tibet detachment system

Рис. 2. Обобщенный разрез гималайской окраины Тибетского плато (по материалам источника [5]):

HST – надвиг подошвы Гималаев; MCT – Главный центральный надвиг; MBT – Главный пограничный надвиг;
MFT – Главный фронтальный надвиг; STDS – южно-тибетская система детачмента

³ Pan G.T., Ding J., Yao D.S. Geological map of the Qinghai-Xizang (Tibet) Plateau and adjacent areas. Chengdu: Chengdu Cartographic Publishing House, 2004.

⁴ Ren J.S., Niu B.G., Wang J., et al. 1:5 million international geological map of Asia. Beijing: Geology Publishing House, 2013.

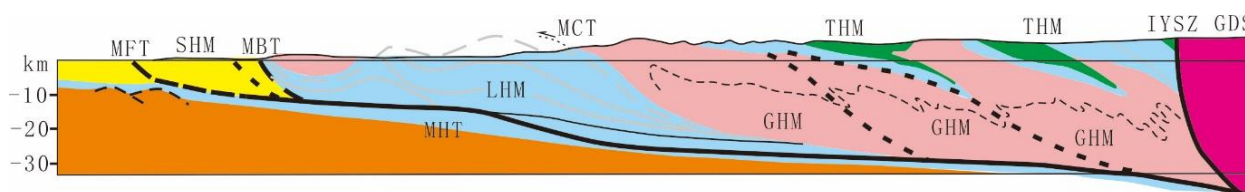


Fig. 3. Cross section of the Himalayan orogen (adapted from [6]):

MHT, MCT, MBT and MFT – see Fig. 2; IYSZ – India-Yarlung-Tsangpo suture zone;
GDS – Gangdise tectonic belt

Рис. 3. Разрез гималайского орогена (по материалам источника [6]):

MHT, MCT, MBT и MFT – см. рис. 2; IYSZ – сuture зона Индия-Ярлунг-Цангпо;
GDS – тектонический пояс Гангдисе

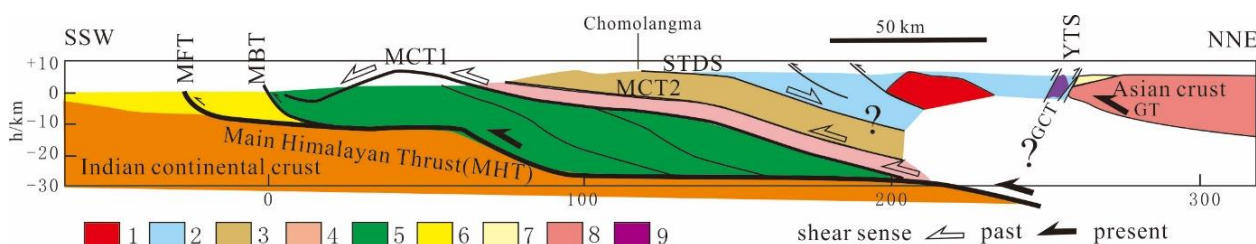


Fig. 4. Tectonic evolutionary pattern of South Tibet (adapted from [9]):

1 – North Himalayas; 2 – Tethys sedimentary rock series; 3 – Upper Himalayan crystalline sequence;
4 – Lower Himalayan crystalline sequence; 5 – Lesser Himalayan structural belt;
6 – Siwalik sedimentary rock series; 7 – Miocene molasse; 8 – Gangdese batholith; 9 – Ophiolite
YTS – Yarlung-Tsangpo suture zone; GCT – Great Counter Thrust

Рис. 4. Тектоническая модель эволюции Южного Тибета (по материалам источника [9]):

1 – Северные Гималаи; 2 – серии осадочных пород Тетиса; 3 – кристаллическая толща Верхних Гималаев;
4 – кристаллическая толща Нижних Гималаев; 5 – структурный пояс Малых Гималаев;
6 – осадочные породы серии сивалик; 7 – миоценовая моласса; 8 – гангдесийский батолит; 9 – офиолиты
YTS – сuture зона Ярлунг-Цангпо; GCT – Надвиг Большого контура

than 2000 km. The STDS is several kilometers wide and consists of some near-parallel brittle faults or ductile shear zones with complex movement patterns, such as alternate northward and southward movements [12–15]. The earlier studies have suggested that the STDS is nearly parallel to the MCT and develops between the High Himalayan range and the Laguigangri thermo-uplifting extensional zone. We believe the STDS detaches along the unconformity between the basement and the caprock and is surrounded by slip surfaces on both the south and north sides of the Chomolangma. The STDS develops not only between the high Himalayan tectonic belt and the Laguigangri thermo-uplifting extensional zone, but also in the low Himalayan tectonic belt on the south side of the Everest, and generally distributes between the MCT and the normal fault on the north side of the Laguigangri thermo-uplifting extensional zone. Due to undulation on the horizontal plane and denudation of some sections, the footwall of the basement-detachment fault can be seen from the surface.

The Main Boundary Thrust (MBT), also proposed by Heim and Gansser [3], is defined as a thrust fault that pushes the Lesser Himalayan over the sub-Himalayan Cenozoic sedimentary sequences (Figs. 2, 3 and 4). The inferred age of the MBT in the central Himalayas starts at 11 Ma based on sedimentary rate change [16], and it is still considered active after 5 Ma evidenced by the coarse-grained clastic deposits added to the Himalayan foreland basin on the MBT's hanging wall [17]. It can be seen in Fig. 1 that the partial Cenozoic stratum exposes above the MBT with the MBT and MCT largely coincidental in the middle section. One may consider that the MBT established previously is not continuous distributed in the EW direction, and the so-called MBT may be other faults.

The Main Frontal Thrust (MFT) was considered by Gansser as the thrust fault developing between the Neogene Siwalik Group and Quaternary sediments of the Indo-Ganghe Basin [18]. Figure 1, however, shows no strict boundary between the two sediments, so we believe the MFT



cannot be seen but a hidden fault in most areas. The MFT fault in Nepal causes overlaying of the two sediments, a sign of the fault's intensive activity in the Holocene [19].

The Main Himalayan Thrust (MHT) is not visible in the shallow crust, and scholars regarded it as a fault in the deep crust, formed by merging the three thrust faults (MCT, MBT, MFT) in South Tibet. Schelling and Arita [20] unified these three major Himalayan faults in eastern Nepal, South Himalaya into a low-angle fault and named it the Main Detachment Fault (MDT). But, the later results of the INDEPTH seismic reflection profiling in Southern Tibet showed that the tectonic surface lies deep in the crust of the North Himalayan tectonic zone [21]. Therefore, it is believed that the MHT only exists deep in the earth's crust, but it should still be represented by the three parallel thrust faults on the Earth's surface (Figs. 3 and 4).

Discussion of several basic geological problems in southern Tibet

Southern Tibet has relatively harsh natural conditions and quite complicated geological structure. Although a large number of experts and scholars have done research in the area, many controversial issues remains. In this paper, we shall discuss the following representative issues.

Klippe, sliding peak and the MCT in southern Tibet. Around the Himalayan arc top on both sides of the mountain summit, it occurs large scale juxtapositions of independent younger and older stratum blocks. Some researchers named this type of stratum overlay as klippe. But it is well known to all that the basic difference between klippe and sliding peak is their formation settings. That is to say the two tectonic units, klippe and window, are formed in a compressed system, while sliding peak and sliding window are formed in an extensional system (Table). Klippe and window are the two important structural units of the nappe tectonic system. The nappe tectonic system is defined in this paper as the platy or flaky mat-like blocks that undergo large-scale displacement under the compressed system, and can be divided into the folding and thrust nappe types. Generally speaking, klippe often outcrops while window develops in the frontal and trailing edges of the thrust nappe tectonic system, respectively. The sliding peak and sliding window

are the two important structural units of the slip tectonic system, which is defined in this paper as the platy or flaky sheet-like blocks that experience large-scale displacement under the extensional system. It can be divided into the extensional and gravitational slip types. We believe the Laguigangri and Kangma metamorphic core complexes, in a series of metamorphic core complex belts in northern South Tibet, are the products of extensional slipping [22], whereas the previously defined klippe and windows in the southern South Tibet should be the products of gravitational slipping.

Due to multilevel slipping, a rather complex phenomenon of summit strata stacking occur in southern Tibet, where the higher situated stratum at the mountain peak experiences greater slipping displacement. Thus one can see Carboniferous and Permian strata slipping above the basement of the Indian Craton, and Ordovician limestone strata slipping above Cambrian-Upper Proterozoic strata. As a result, the stratum column in this kind of slipping area becomes significantly thinner due to extensional and thinning actions. However, some scholars believed that the independent geological bodies bounded by the STDS in southern Tibet are klippe, and they pointed out that the klippe extend over 100 km from their northernmost outcrop toward the MCT [23]. Many other scholars also believe that these thinned independent geological bodies are klippe or windows formed by thrust compression.

We believe the movement of the detachment fault system may lead to the missing of Ordovician-Carboniferous strata in the Lasser Himalayan tectonic zone. Without sliding between the basement and caprock, the basement will uplift and occasionally with sliding peak on the basement's uplifting. The sliding peak and sliding window usually develop in the protruding region of the Himalayan arc. If they developed on the two sides of the Himalayan arc or occasionally on the basement's uplifting, they must have been formed by gravitational slip tectonics after the southern Tibet uplifting to a certain height.

The Rongbu Temple high-angle normal fault and STDS. In southern Tibet, a high-angle normal fault lies parallel to the South Tibet detachment system (STDS). This normal fault, however,



Differences between sliding and nappe structures

Различия между сдвиговыми и покровными структурами

		Nappe (Klippe)	Slip (Sliding Peak)	
			Extensional slip	Gravitational slip
Tectonic system		Compression system	Extensional system	Gravitational action in the background of uplifting
Tectonic deformation	Fault combination	Thrust faults	Normal faults	Both characteristics such as the frontal edge is more like a nappe structure, and the trailing edge is characterized by a extensional structure
	Characteristics of folds	Mainly are overturned recumbent folds with thinned and pull-off inverted limbs	The down limb is inverted limb and well preserved	
	Deformation of almonds etc.	Upright long axis with horizontal short axis, usually is upright ellipsoid	Opposite to the former, usually is flat ellipsoid	
	Deformation sequence	Old stratum overthrows young stratum. Stratigraphic duplication	Opposite to the former, strata missing	
	Deformed structures	Horizontal thinning, vertical thicken	Horizontal stretching, vertical thinning	
Deformation under the structural plane		Compression-shortened	Weak extensional deformation	Obvious extensional deformation

is often ignored or outrightly classified as part of the STDS by scholars. But in fact, the fault is quite different from the STDS. For example, on the northern slope of the Chomolangma, the fault clearly extends into the Rongbu Temple area and is a trailing-edge structure of the early extruded structure, whereas the South Tibet detachment fault is clearly formed later. As early as 1974, while conducting scientific investigation in Tibet, Guo Tieying et al. discovered a large-scale normal fault in southern Tibet, and they explicitly proposed the name Rongbu Temple normal fault. After returning from Tibet, Guo was asked by Ma Xingyuan to write an article to report this discovery, as Ma thought of the Rongbu Temple normal fault a very important manifestation of extensional structures. But Guo never wrote this article due to busy schedules. Later on, while researching in the Ali area in western Tibet, Guo saw a high-angle normal fault extending E-W in southern Ali, and he believed this normal fault was the westward extension of the Rongbu Temple normal fault as shown in Fig. 1. We believe the active period of the Rongbu Temple normal fault could have started as early as before the Neogene. The activity of the normal fault controlled the distribution and output of the later Himalayan granite pluton. After pluton cooling (about 12–17 Ma), the STDS was formed by extensional tectonic

movement occurred in southern Tibet. In the Rongbu Temple and Chomulangma areas, it can be seen clearly that the STDS traces the early Rongbu Temple normal fault with a dip of more than thirty-five degrees, while in other areas the STDS extends with a dip of no more than twenty degrees beneath the Tibetan zone.

The cross-section of the Chomolangma area consists of four parts (Fig. 5, b). The 1st part is lower Ordovician limestone containing many vertical joints developing near-horizontally on the Chomolangma summit. The 2nd part at the bottom of lower Ordovician limestone overlaps Sinian-Cambrian clastic rocks with a type of ductile shear zone as the boundary. Some mylonites develop in the ductile shear zone, indicating the presence of extensional ductile shear zones. Because of the light-yellow limestone composition, some scholars call the 2nd part the “yellow stratum”, which develops in the middle of the Chomolangma with intralayer rheological characteristics. Under the yellow stratum is the 3rd part composed of Neoproterozoic-Cambrian clastic rocks such as shallow metamorphic and unmetamorphosed sedimentary rocks. Between the 3rd and 4th parts is a low dipping detachment consisting of strongly metamorphic crystalline rock series, including Middle-Neoproterozoic schist, gneiss, plagioclase amphibole and Miocene granulite.

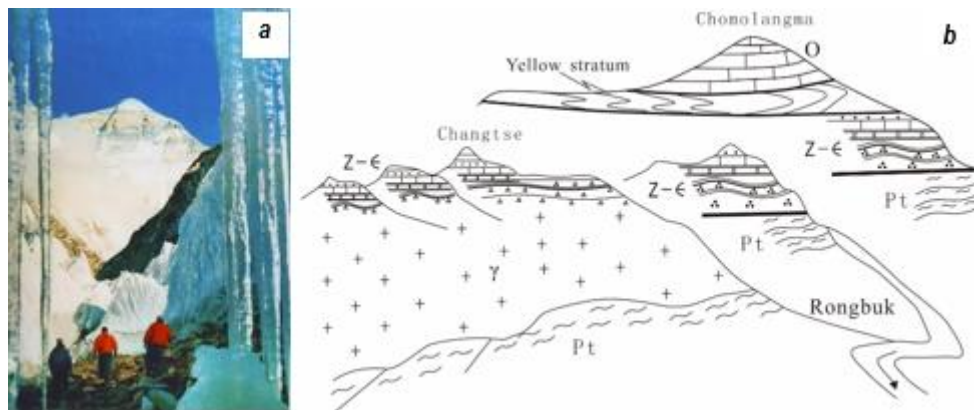


Fig. 5. A close view of the Chomolangma in 1974 (a) and geological sketch profile of the Chomolangma (b)

Рис. 5. Вид на Джомолунгму вблизи в 1974 г. (a) и геологический схематический разрез Джомолунгмы (b)

Multilevel extensional detachment faults can be seen in the Chomolangma area or elsewhere in southern Tibet. As shown in Fig. 6, an extensional slip fault develops between Upper Proterozoic-Cambrian and Upper-Middle Proterozoic strata; a second one develops between Early Paleozoic (Ordovician) and Upper Proterozoic-Cambrian strata, reconstructing the angular unconformity between the Ordovician and Precambrian representing the Pan-African movement; and a third one develops between Permian or Devonian and Silurian or Ordovician strata.

From the above description, we can make the following inferences. The Rongbu Temple normal fault paired with the MCT to form so called “horse structures” during the intercontinental collision. The uneven movements of the “horse structures”, due to different thrust velocities and amplitudes and varying degrees of severe weathering and erosion, led to the formation of two extruded tectonic belts, with very different topography to the surrounding landforms in southern Tibetan Plateau, where the extensional sliding tectonic belts developed in a later stage. The STDS is formed

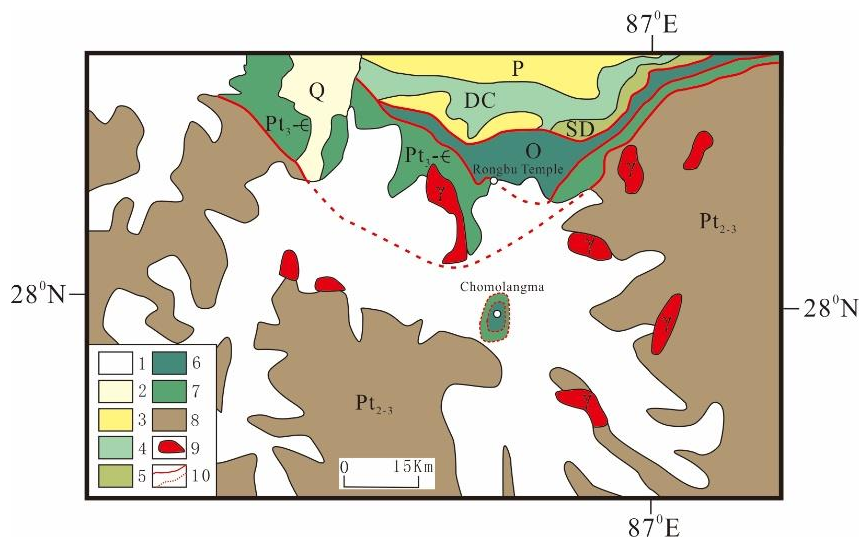


Fig. 6. Sketch map of the Chomolangma area:

1 – glacial covered area; 2 – Quaternary sediments; 3 – Permian sediments; 4 – Devonian-Carboniferous sediments; 5 – Silurian-Devonian sediments; 6 – Ordovician sediments; 7 – Upper Proterozoic-Cambrian sediments; 8 – Upper-Middle Proterozoic sediments; 9 – Neogene granite; 10 – fault or snow-covered fault

Рис. 6. Схематическая карта района Джомолунгмы:

1 – область ледникового покрова; 2 – четвертичные отложения; 3 – пермские отложения; 4 – отложения девона – карбона; 5 – отложения силура – девона; 6 – отложения ордовика; 7 – отложения верхнего протерозоя – кембрия; 8 – отложения верхнего – среднего протерозоя; 9 – граниты неогена; 10 – разлом или разлом, перекрытый снегом

in an extensional environment created by extreme compression; and the appearance of leucogranite indicates the STDS movement in an extensional setting. The STDS is huge and complex with three common detachment planes. The largest plane separates the basement (Pt₂₋₃) and caprocks of the Tibetan Plateau. The second one lies between Upper Proterozoic-Cambrian and Ordovician or Silurian strata. And the third one separates Ordovician and Devonian or Carboniferous strata. Because the STDS has detachment properties in the deep and slip-off characteristics in the shallow, it may be characterized more precisely as a detachment-slip system. The STDS is particularly developed around the Himalayan arc top with huge sliding displacement, where Carboniferous sliding stratum slides onto the basement of the Indian craton, and the sliding body (sliding surface) steps down as it makes contacts with the Rongbu Temple normal fault. Therefore, we suggest that the Rongbu Temple normal fault and the STDS are two faults of different ages and they overlap the Himalaya arc top (Fig. 1).

The following can be inferred from the above analysis:

1. The Rongbu Temple normal fault truly exists. It pairs with the MCT in the early stage to form two boundaries of lateral extruded structures

enriched with “horse structures” in southern Tibet (Fig. 7). The extrusion can be modeled by numerical simulation [24]. This lateral extruded structure is formed after the collision between the Indian and Asian-Eurasian plates, as the smaller Indian plate suddenly stopped to cause N-S compression of the bigger Asian-Eurasian plate.

2. After the lateral extruded structural is formed, the STDS became active because of the N-S extension. The STDS has a gentle dip angle across southern Tibet and a high dip angle locally in the northern Chomolangma in tracking with the early Rongbu Temple normal fault (Fig. 7). The detachment fault system, the Rongbu Temple normal fault and the thrust faults are the structures of different properties and formation ages.

The Laguigangri metamorphic core complex, STDS and MCT. In South Tibet, the Kangma, Sakya, Laguigangri and Yalaxiangbo Domes form a near W-E trending metamorphic core complex chain consisting of a core, a middle section with ductile rheology and cap rocks. Precambrian rocks (deformed granite and meta-sedimentary rocks) with high metamorphism and deformation make up the core, inside which develops multi-stage emplacement granites. The middle section is made up of low dip angle detachment faults (with ductile rheology), separating the core and

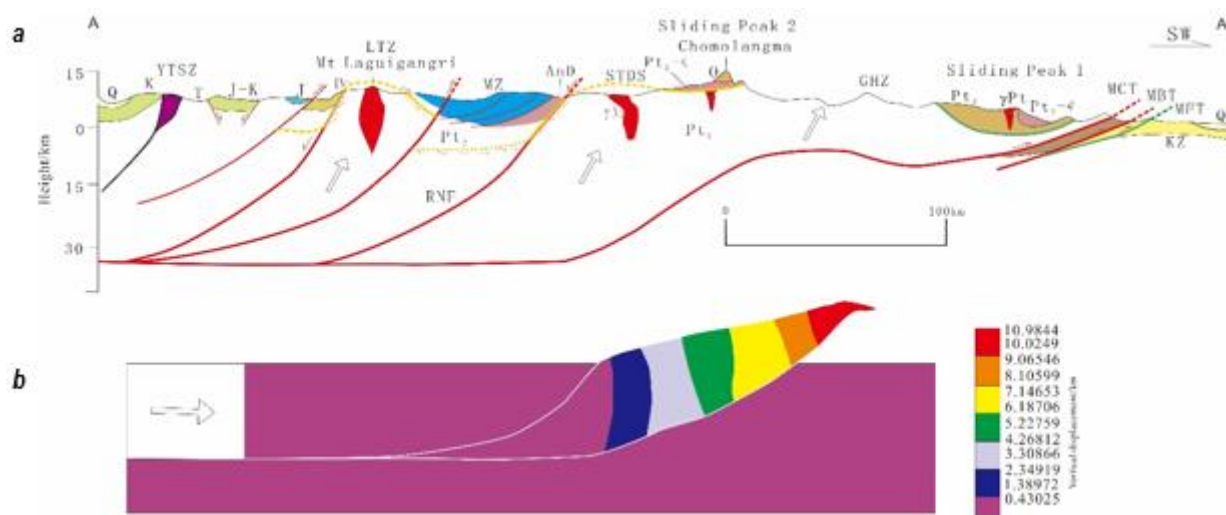


Fig. 7. Cross-section of the Chomolangma area (a); finite element modeling of the vertical extrusion of the Higher Himalayan Zone (adapted from [24]) (b):

YTSZ – Yarlung-Tsangpo suture zone; LTZ – Laguigangri tectonic zone;
RNF – Rongbu Temple normal fault; HHZ – High Himalayan tectonic zone;
STDS, MCT; MBT and MFT – see Fig. 2.

Рис. 7. Разрез в районе Джомолунгмы (a); моделирование вертикальных экструзий зоны Верхних Гималаев методом конечных элементов (по материалам источника [24]) (b):

YTSZ – сутурная зона Ярлунг-Цангпо; LTZ – тектоническая зона Лагуйганжи;
RNF – сброс храма Жунбу; HHZ – тектоническая зона Высоких Гималаев;
STDS, MCT; MBT and MFT – см. рис. 2.



cap rocks. These detachment faults, distributed in an arc shape and must be a part of the STDS, develop undulately between the basement and cap rocks. Because of the late stage fast uplifting and denudation, these detachment faults are not seen in some locations including the northern High Himalayan and northern Tethys Himalayan. Xu et al. [6] also considered the detachment fault, developed between the basement and cap rocks of the Laguigangri metamorphic dome, a part of the northward extension of the STDS and formed during 20–16 Ma. They argued that the cap rocks are the shallow metamorphic or unmetamorphic Tethys sequences, consisting of many kind of rocks including Ordovician marble and schist, Carboniferous marble, crystalline limestone, speckled slate, Permian arenaceous slate and gravel slate, metamorphic quartz sandstone, very low grade metamorphic Triassic fauxite, etc. These arc-shaped detachment faults should be part of the STDS developing in the detachment system with S-N undulating waves between the metamorphic basement and sedimentary (shallow metamorphic) cap-rock [22, 25].

Some scholars believed that the High Himalayan structural zone (HHZ), bounded by the STDS and MCT, is a vertical extrusion. However, the Laguigangri metamorphic core complex and STDS are the products of extensional structural setting, while the MCT is of compressional setting. According to the numerical modeling analysis, the STDS and MCT never merged but define respectively the top and the bottom of a channel flow of low-viscosity lower crust expelled from beneath the Tibetan Plateau [26]. Furthermore, we consider the two fault systems formed in different periods by different mechanisms. So we believe that the South Tibet detachment system couldn't pair with the MCT to form HHZ. Accompanied by Miocene granite magma activity, the Laguigangri metamorphic core complex should be formed at the same time as the STDS, and both are the products of the N-S trending thermal uplifting extension in southern Tibet.

Division and characteristics of Cenozoic multistage evolution

The formation of the Qinghai-Tibet Plateau is an important geological event in the Earth's evolutionary history. Many scholars have put forth

many ideas to explain the genesis of the plateau, including the intracontinental subduction model, oblique slice thickening-lateral extrusional escape model, bidirectional subduction with multiple driving model, tunnel flow (channel flow) model, wedge-shaped extrusion model, longitudinal extension model, lithosphere-mantle delamination model, gravitational expansion and collapse model, and so on. Although these models can offer some explanations, we believe a better explanation can come from the opening-closing view, that is, the plateau is formed by the opening and closing of different parts of the earth at different stages, or to say, by the coupling effects of opening and closing.

We believe the formation of the Himalayas and the rise of the Mt Everest are related to the disappearance of the Neo-Tethys Ocean, once located between the Indian and Asian-Eurasian Plates in the Mesozoic-Cenozoic, as a result of continuous collision and extrusion of the two plates and their extension and detachment after orogeny. And all these events are caused by crustal movements at different stages contemporaneous with multiform movements (repeated horizontal-vertical movements) and multisystem (extrusion-extension) transformation. Based on regional geological surveys and combining with previous research results, we consider the plateau experienced two evolutionary cycles of opening and closing from the formation of the Neo-Tethys Ocean to the rising of the Chomolangma to its current height after the intracontinental collision. After the Tethys ocean opening, the plateau began a strong opening-closing transitional process. The evolutionary process can generally be divided into different opening-closing cycles, manifested by different systems such as oceanic expansion (opening) and crustal sinking (conversion), intercontinental collision and compression (closing), intracontinental relaxation-collapse and extensional detachment (conversion), and sliding with thermo-uplifting and uplifting of the entire plateau (opening). In this complex and multistage evolutionary process, thermal energy (thermal matters) in the deep earth plays an important role as in the plateau uplifting process, such that molten mantle material continues to move upwards and migrates horizontally on different geospheres multiple times. That is to say, the hot



material experiences multiple vertical to horizontal transitions when it moves from the deep to the shallow part of the earth; and such movements can cause opening-closing transitions at different layers and spheres of the earth [27, 28].

The intercontinental collision (closing) stage (55–30 Ma). The formation process of the extruded structure in southern Tibet occurred in the closing stage of the Cenozoic. During this stage, the Neo-Tethys crust had disappeared; and the Indian continent, south of the Tethys ocean, began to collide with the Asian-Eurasian continent north of the Tethys ocean. Here we believe that the Indian continent at that time was quite smaller than the Eurasia continent, and because of its relatively light weight and therefore rather fast drifting speed, it became separated from the southern Gondwana. After the collision, the Indian continent developed many arc-shaped southward compressional thrusts due to extreme N-S compression; at the same time, the Himalayan area developed several lateral extrusions with “horse structures” related to corresponding magmatic activity. The bottom of the extrusions – a converging area of a series of arc-shaped thrust faults and high dip angle normal faults – should be in the middle crust at a depth of about 30–40 km. The wedge-shaped Chomolangma extrusion with large extrusion range and higher rising speed, gradually rose highest above the entire extrusion, while the HHZ-MCT extrusion reached its highest elevation and became the sliding Peak One. Due to tectonic stress in the middle and lower crust and gravitational potential energy, the southern Tibet and eastern (ES) and western (WS) syntaxes experienced increasing pressure and strain rate, so resulted in local transient high pressure. Under this condition, eclogite was formed during an ultra-high pressure metamorphic event.

Here, we believe that before the Miocene, the Chomolangma, the highest point on the topography map nowadays, was not the highest place but second to the HHZ south of the Chomolangma. Later, because of differential uplifting-descending movements of the two extrusions and northward sliding of the small dip angle extensional fault in southern Chomolangma, as well as isostatic adjustment, the Chomolangma came into being the highest place on earth, replacing

the High Himalaya Zone. Since then, affected by severe weathering and erosion, the once uplifting zone – the sliding Peak One (the High Himalaya vertical extrusion in southern Chomolangma), and the once slope caused by slippage (the missed STDS in the High Himalayan vertical extrusion), are not visible on the Earth's surface today. In fact, residual STDS still remains on the Chooyu mountain and Mount Everest. For example, the detachment fault beneath the “yellow zone” on top of the Mount Everest is just the residual STDS. But because it develops on such high elevation and covered by nowadays topographic features, it could not be seen by many scholars except mountaineers. Hence, this phenomenon is not acknowledged by some experts and scholars.

Intracontinental relaxation-collapse and extension-detachment (transition) stage (20–7 Ma). The interior and southern part of the Qinghai-Tibet Plateau began to stretch and relax accompanied by the upwelling of thermal fluid, causing new asthenospheric thermal uplifting. At the same time, the thickened lower crust softened thermally and the middle crust gathered a large number of thermal masses. So the transition stage is defined as the tectonic system in southern Tibet switching from compression (closing) to extension types (opening), followed by horizontal extensive detachment marked by ductile shear formation. It happened outside the early extrusions and the sliding Peak TWO was formed. In addition, the main detachment and sliding planes are formed with a large amount of magmatic emplacement, causing the wide distribution of the New Himalayan leucogranite dykes in the Himalaya orogeny [29, 30]. Abundant kinematic indicators are well developed in deformed leucogranites (granitic mylonites) and gneiss on both microscopic and outcropping scales (e.g., S-C fabrics, asymmetric rotational porphyroclasts, mineral-stretching lineation, dislocation of quartz, and domino structures, mica-fish fabrics, asymmetric mylonitic folds and small scale normal faults), indicating a top-to-north movement of multistage, multilayer ductile shear zones [31]. Involving a series of slippy structures in southern Tibet, the Qinghai-Tibet Plateau began to rise as a whole. At last, a series of N-S trending normal faults formed in the interior of the plateau while



the periphery of the plateau experienced outward thrust, activating some of the early thrust faults.

Sliding thermal fluid rising and the plateau overall rapid uplifting (open) stage (Since 7 Ma). In the late Miocene after the delamination and thinning of the southern Tibet lithosphere, large amounts of thermal fluids surged (vertical opening) from the asthenosphere, then isostatic adjustment happened and intra-continent began to slip (horizontal opening). The entire Qinghai-Tibet Plateau rose (open) quickly by the cooperation of mantle thermal flow and climate [32, 33]. Consequently, the periphery of the plateau experienced compression while the internal part experienced violent extension. This phenomenon was described as a "flowering bun" by Professor Guo Tieying in the early 1980s.

Overall, the upwelling of the mantle thermal fluid, the multistage multisystem crustal extension (thrust) and isostatic adjustment created the present tectonic landforms of the Everest and its surrounding areas. Due to Cenozoic detachment deformation on the north and south sides of the Everest, some basins exhibit overlaying of younger strata over the older ones; and some heat-releasing structures, such as hot springs, appear in the N-S trending grabens caused by the N-S direction thermal upwelling. So the normal fault on the north side of the Everest is a gigantic regional fault, which controls the distribution and output of magmatite in the formation of the Laguigangri and Everest thermal domes. Thus it can be certain that the magmatic and normal fault activities in this region were contemporaneous.

Fission track analysis reveals that the final cooling and exposing events in the high Himalayas mainly occurred since 7–5 Ma [34–37]. The Himalayan ES and WS syntaxes show a dramatic cooling and denudation history since 3 Ma, whereas the western tectonic nodule had an average delamination rate of 4.5 mm/a since 10 Ma, with at least 14 km materials eroded since 1 Ma [38]. Low-temperature studies show that the average erosion rate in the Nanga Bawa area was as high as 3.6 mm/a since 5 Ma [39]. Our apatite and zircon fission track analysis of the Dinggye leucogranite reveals that the cooling and erosion rates were 18.421 °C/Ma and 0.526 mm/a, respectively, in the Himalayan region since 5.7 Ma

[36]. Other studies have shown that in the Lasser Himalayan crystalline belt of Suture, India the denudation rate was 1.8 mm/a since the Pliocene epoch [40], and the Zada Basin began to sag at 5.1 Ma [41] and the submarine fan deposits in the Bay of Bengal saw increased deposition rate at about 5 Ma [42].

In the North Himalayan tectonic belt, tectonic activities since 3.6 Ma are mainly characterized by the formation of a series of near N-S graben associated thermal anomalies, while the near W-E fault structures are relatively inactive. The violent tectonic uplifting, and increase in geomorphic contrast since 3.6 Ma, are characterized by the widespread occurrence of molasses accumulation in the foothills, and by a significant increase of sedimentary rate in the basin. The sediment of the Siwalik Group in the Ganges Plain in southern Himalayas is obviously thickened with conglomerate deposits at about 3.6 Ma, when a series of near N-S graben-type basins along the northern Himalayas converted into coarse clastic conglomerate deposits, such as the Gomba conglomerate in the Gyron basin. The Asian monsoon strengthened again in the 3.6–2.6 Ma time interval [43]. The Gyron basin began to deposit the Gomba conglomerate at 2.4 Ma till 1.7 Ma as the basin shrank and ended its deposition [44]. In the southern foothills of the Himalayas, macro-conglomerate covered the Siwalik Group, while the Kashmir basin began to form in the northwestern foothills of the Himalayas [45]. Ding Lin et al. studied the fission track thermochronology of the Gangdese magma [46] in the periphery of the ES syntax of the Himalayan, and concluded that the ES syntax has a strong uplifting since 3.4 Ma and the High Himalayan tectonic belt has a strong uplifting and erosion since 3.6 Ma. Systematic zircon and apatite fission track analyses of the High Himalayan crystalline sequences all showed a good linear relationship between age and elevation, suggesting significantly accelerated cooling and denudation since 3.6 Ma.

Under the gravitational force, the sliding Peak One, the then highest peak in south of the Chomulangmo, underwent extensive gravitational collapse with southward and northward extension slipping; as a result, the Chomulangmo became the highest peak in the Pliocene epoch. What's more, the sliding Peak Two (in the Chomulangmo



area) underwent southward- and northward-directed detachments after that time, causing a large-scale stratum column thinning at the Everest summit. Thermal materials surged upward from the middle-lower crust, forming thermal anomalies such as hot springs in the N-S grabens. The tectonic and climatic factors [47] jointly restricted fast uplifting and exhumation on the southern slope of the Himalayas as well as formation of an abnormally high altitude Himalayan main ridge. The dual effects of extension and strong erosion caused by the climate have led to the formation of abnormally high-altitude mountain ranges around the peripheral plateau. After that, the strengthening of the monsoons caused the final formation of the peripheral mountain systems and mountain-basin coupling structures. To sum up, the upwelling of mantle thermal fluids, the crustal multistage and multisystem extension (thrust) and isostatic adjustment jointly create the current tectonic features of the Chomulangma and its surrounding areas.

A deeper understanding of opening-closing orogenic process requires us to concentrate our efforts more on the detailed geological record for evidence of persistent process than on the temporal evolution of geological structures and landforms. We must also examine the internal differences between the opening-closing view and the plate tectonic theory.

Conclusions

In this contribution, we use the opening-closing tectonic view to analyze several basic geological phenomena in southern Tibet and obtain some new ideas different from the plate tectonic theory. We then further analyze the Cenozoic evolutionary process of opening-closing in South Tibet and obtain the following main insights:

1. The Rongbu Temple normal fault, the MCT and other thrust faults form a lateral extrusion structure in southern Tibet. The South Tibet detachment system (STDS), the Rongbu Temple normal fault and the MCT are the products of different times and systems.

2. The klippe and windows in southern Tibet, identified by previous researchers, are formed later in an extensional setting, rather than a thrust compression setting, and belongs to the slip system.

3. The evolutionary process of southern Tibet can be divided into five different stages characterized as opening-opening-closing-opening-opening. Thermal energy and gravitational potential energy in the deep earth played a key role during this opening-closing evolutionary process. Several vertical switching movements occurred accompanied by the deep thermal matter migration from the interior to the exterior of the Earth.

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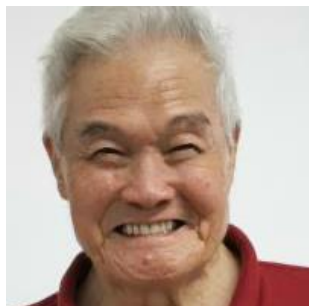
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