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Collision Tectonics between the Tarim Block (Basin) and the Northwestern Tibet Plateau: New Observations from a Multidisciplinary Geoscientific Investigation in the Western Kunlun Mountains

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Abstract New results from deep seismic reflection profiling, wide-angle reflection-refraction profiling and broadband seismic experiments reveal that a series of south-dipping reflectors occur on the southern margin of the Tarim block (basin). However, it is these south-dipping structures that are intercepted by another series of north-dipping reflectors at depths from 30 to about 150 km beneath the foreland of the W Kunlun Mountains. No evidence from the above geophysical data as well as geochemical and surface geological data indicate the southward subduction of the Tarim block beneath the W Kunlun Mountains (NW Tibet plateau), forming the so-called "two-sided subduction" model for the Tibet plateau as proposed by previous studies. So the authors infer that the tectonic interaction between the Tarim block and the W Kunlun block was chiefly affected by a "horizontal compression in opposite directions", which brought about "face-to-face contact" between these two lithospheric blocks and led to the thickening, shortening and densifying of the lithosphere. Hence a "delamination" was formed due to the gravitational instability created by the thickening and densifying; then alkaline basic volcanic rocks (mainly shoshonite series) was erupted along the northern margin of the Tibet plateau owing to the delamination. This inference for the formation of the alkaline basic volcanics has been confirmed by recent geochemical and petrological studies in Tibet, indicating that different contacts control different magmatic activities: the alkali basalts are always developed in the "horizontal shortening boundary (contact)" on the northern margin of the Tibet plateau, while the muscovite granite and two-mica granite (leucogranite) in the "subductional contact" on the southern margin of the Tibet plateau.

Key words: collision tectonics, deep structure, NW Tibet plateau

1 Introduction

A multidisciplinary geoscientific investigation (MGI) was carried out in 1997–1999, which was a key project jointly supported by State Project 305 of the Xinjiang Uygur Autonomous Region (XUAR), the former Ministry of Geology and Mineral Resources (MGMR) of China and the National Natural Science Foundation of China (NNSFC). The responsible organization was the Institute of Geology, Chinese Academy of Geological Sciences (CAGS), and the main participating organizations were the Institute of Earth Sciences, Academia Sinica (Taipei), China University of Geosciences (Beijing), Geological Institute of the State Seismological Bureau of China, the 6th Geophysical Prospecting Party of the MGMR and the 562 Geological Research Party of the CAGS.

The tectonic relationship between the Indian plate and Tibet proper has been relatively extensively studied in the past several decades. However, NW Tibet, especially the W Kunlun and Karakorum Mountains, lacks the multidisciplinary geoscientific investigation and also has seldom been described in the literature, so the purpose of the project is to study the tectonics of the western Tibet plateau and approach the formation of the northwestern boundary of the Tibet plateau and its dynamic relation with the collision of the Indian and Eurasian plates.

The MGI includes the wide-angle reflection-refraction profile, deep seismic reflection profile and broadband seismic experiment and gravity survey, combined with geochemical and geological reconnaissance. Because of rugged topography and difficult logistic, our study area was limited to the road and its vicinity (Fig. 1).

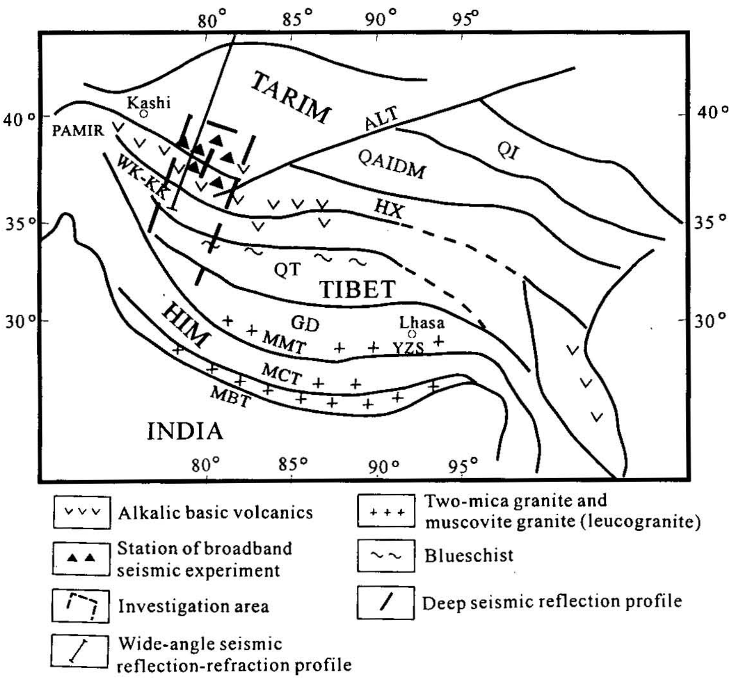


Fig.1 Schematic map showing the geological and geophysical investigation area
ALT: Altun strike-slip fault; GD: Gangdise; QL: Qilian Mts.; HIM: Himalayas; HX: Hoh Xil; YZS: Yarlung Zangbo Suture; MBT; Main Boundary Thrust; MCT: Main Central Thrust; MMT: Main Mantle Thrust

2 Geophysical Properties and Its Geological Interpretation

2.1 The Moho—Variation of the crustal thickness

The Moho depth obtained from the wide-angle reflection-refraction profile is, from north to south, 50 km in the Tarim basin (block) and 60 km in the north of the W Kunlun Mountains, i.e. the Moho of the Tarim basin dips gently to the south (Fig. 2). The deep seismic reflection profile and the broadband seismic experiment also show a clear Moho represented by the nearly horizontal strong reflectors at depths of 45–55 km (17–18 s) beneath the Tarim basin and the northern margin of the W Kunlun Mountains (Figs. 5 and 6), which may correspond to the Moho given in the wide-angle reflection-refraction profile.

2.2 Low-velocity layer in the upper crust

A low-velocity layer occurs at depths of 15–20 km in the wide-angle reflection-refraction profile (Fig. 2), with a thickness of around 5–10 km. The velocity ranges from 6.0 km/s–5.9 km/s. The magnetolluric sounding (MT) also shows a low-resistivity (high-conductivity) layer of about 4.4–9.7 Ω·m, at depths of 15–25 km (Fig. 3), which corresponds to the low-velocity layer in the wide-angle reflection-refraction profile. It may have acted as the "décollement", constraining the south-dipping thrust sheets occurring on the surface.

2.3 Concealed structures

In the deep seismic reflection profile, two nearly vertical strike-slip faults (cf. in Figs. 4 and 5) revealed by the obvious variation of the reflectors (Figs. 4 and 5) extend from the middle of the upper crust down to the Moho and most probably correspond to the WNW-NW strike-slip fault system on the surface between the W Kunlun Mountains and Tarim basin. It is noticed that the two concealed strike-slip faults are most likely the main inducing structure of the recent earthquakes in the southwestern Tarim basin.

3 Deep Structure and Collision Tectonics between the NW Tibet Plateau and the Tarim Block (Eurasian plate)

The deep seismic reflection profile extends from the southern Tarim basin southwards into the W Kunlun Mountains, totalling about 100 km long, cutting across their contact. From the seismic data, we have the following primary understanding of the deep structure:

The most prominent feature of the deep seismic reflectors of the north-dipping band beneath the W Kunlun Mountains was observed to extend from 8 s (24 km) to 20s (60 km), while the reflectors of the south-dipping band observed beneath the southern Tarim basin (Fig. 4). The broadband seismic experiment also indicates the existence of strong north-dipping reflectors beneath the W Kunlun Mountains and the south-dipping ones beneath the southern margin of the Tarim basin (Fig. 6), but the north-dipping reflectors in the W Kunlun Mountains become obscure and significantly weaker when they enter the foreland between the Kunlun Range and the Tarim basin (Kao et al., 1999). All of the deep seismic images indicate that there is no evidence to ascertain a prominent southward

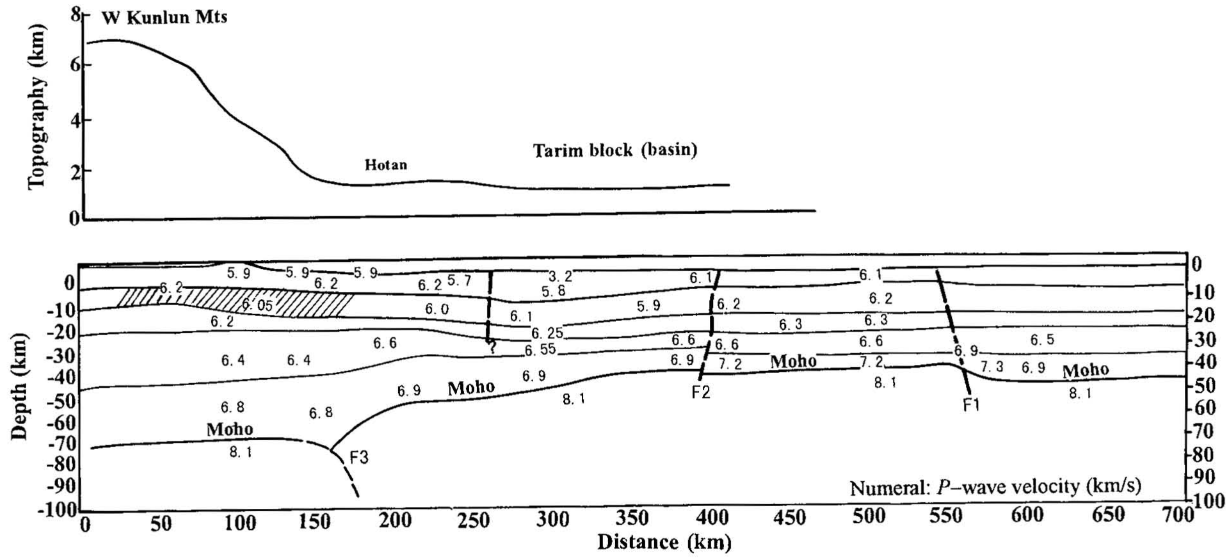


Fig. 2 Wide-angle reflection-refraction profile showing the P-wave velocity (km/s) across the boundary between the W Kunlun Mts. and Tarim block.

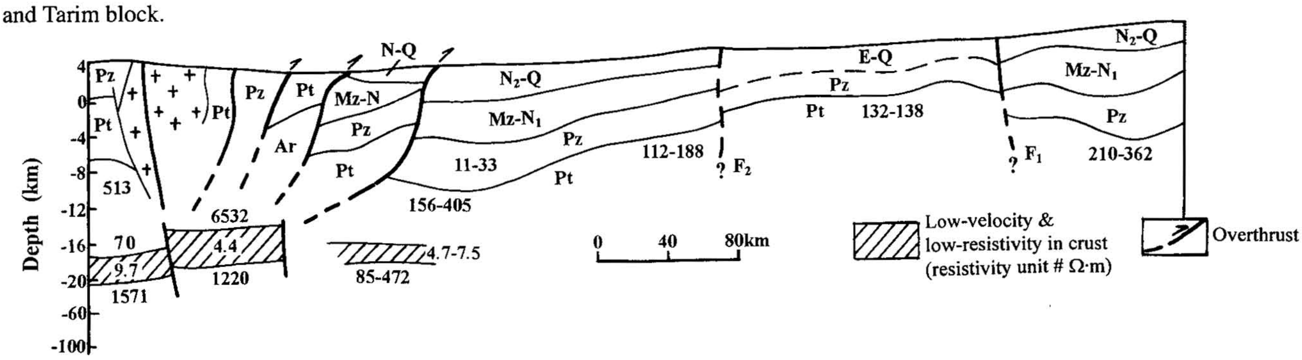


Fig. 3 Magnetotelluric interpretation section across the boundary between the W Kunlun Mts. and Tarim block (basin) (after Ding Daogui et al., 1996)

subduction from the Tarim basin to the W Kunlun Mountains as suggested by many geoscientists. In the mid-1980s a "two-sided subduction" model was proposed for the Tibet orogenic system (Lyon-Caen and Molnar, 1984; Willett and Beaumont, 1994; Deng, 1995; Matte et al., 1996). It suggests that, in addition to the northward subduction of India beneath southern Tibet, the Tarim block in the north also was subducted southwards beneath northern Tibet. Many geoscientists (Arnaud et al., 1992; Deng, 1995) have given an account of the southward plunging of the Eurasian continent (Tarim basin) down to the Tibet plateau along its northern margin on the basis of their research on the young alkali basalts in the north of Tibet that are the product of the southward subduction of the Tarim block towards the Tibet plateau. However, our deep seismic profiling and broadband seismic experiment mentioned above give no evidence of a full-scale subduction of one block beneath another, but the co-existence of both the north- and south-dipping structures is observed (Figs. 5 and 6).

Judging from the above geophysical data, we suggest an alternative interpretation model that the tectonic interaction between the W Kunlun Mountains and Tarim basin was mainly affected by a "horizontal compression in opposite directions", which brought about a "face-to-face contact" of the two lithospheric blocks and led to the thickening, shortening and densifying of the lithosphere. Then, the lower part of the lithosphere was detached and sunk into the asthenosphere, forming the "delamination" due to the gravitational instability created by the densified lithosphere, and losing the balance between the horizontal compression and the buoyancy, hence a rapid uplift and extensional fractures were brought about on the surface. Heating from the asthenosphere caused partial melting to produce alkaline basic volcanics, the shoshonite series (Fig. 7), which erupted along the

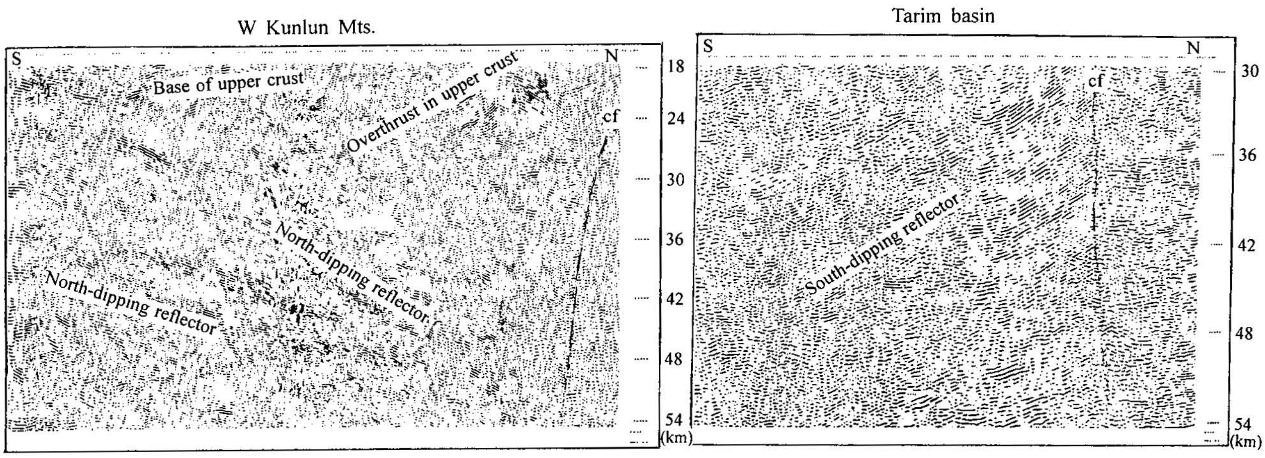


Fig. 4 Deep seismic reflection profile from the W Kunlun Mts. to the southern margin of the Tarim basin

Left: North-dipping reflectors in the foreland of the W Kunlun Mts. Right: South-dipping reflectors on the southern margin of the Tarim basin

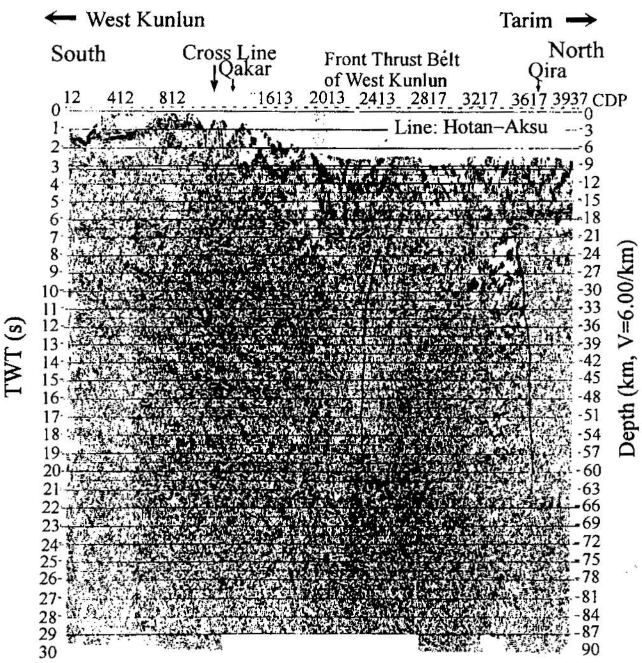


Fig.5. Deep seismic reflection profileshowing north-dipping reflectors beneath the northern margin of the W Kunlun Mts. (NW Tibet plateau) and south-dipping reflectors beneath the southern margin of the Tarim basin

extensional fractures in northern Tibet, where we have not yet found Cenozoic leucogranite. This inference of the formation of the shoshonite series has been confirmed by recent geochemical and experimental petrological studies in Tibet (Deng et al., 1996; Lai, 1999), indicating that different contacts may control the variation of magmatic activities: the alkaline basic volcanics is always developed in the "horizontal compression contact" along the northern margin of Tibet, while muscovite granite and two-mica granite (leucogranite) developed in the "subductional contact" in the southern margin of Tibet (Fig. 8, lower right and left).

4 Petrological and Geochemical Evidence of the Collision Tectonics between the NW Tibet Plateau and the Tarim Block

Detailed studies for estimating the magma-generating pressures and depths on the basis of experimental petrology at high pressures and temperatures and mineral-melt equilibrium thermodynamics have been completed by Lai (1999) and Deng et al. (1996), indicating that the primary or approximately primary magma of the Cenozoic alkaline basic volcanics on the northern margin of Tibet may have originated from the upper mantle-lower crust at depths from 74.3–85.1 km (Table 1, Lai, 1999) by delamination in the lower lithosphere, which is consistent with the "horizontal compression contact" model (Figs. 7 and 8); while the Cenozoic muscovite granite and two-mica granite (leucogranite) on the southern margin of Tibet originated from the middle-upper crust at depths from 25–40 km in a "subduction contact" (Deng, 1996; Lai, 1999) (Fig. 8).

The values of Mg′, δEu, La/Yb and $^{87}Sr/^{86}Sr$ are important indicators for identifying the primary magma type (Frey et al., 1978, Deng et al., 1996, Turner et al., 1996, Lai, 1999). The Mg′ values of the primary

Table 1 Source depths and pressures of the Cenozoic volcanics on the northern margin of the Qinghai-Tibet Plateau

Area	Lithologic features	SiO_2 (%)	Mg′	P (10^8Pa)	Depth (km)
W. Kunlun	Potassic basic volcanics (shoshonite series)	43.17	0.62	25.8	85.1
Dahongliutan, W Kunlun	Potassic basic volcanics (shoshonite series)	44.89	0.65	22.5	74.3
Lixian, Gansu	Potassic basic volcanics (shoshonite series)	38.65	0.65	33.0	108.9

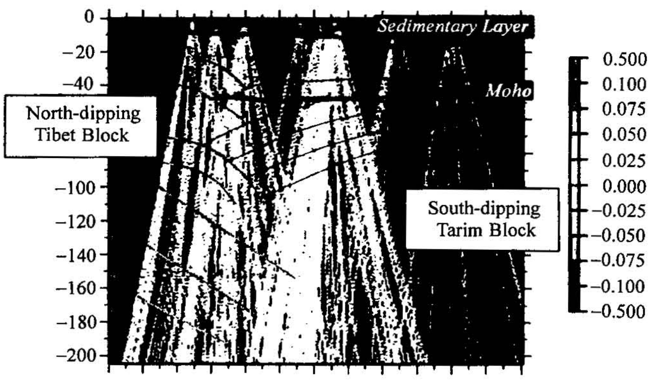


Fig.6. Broadband seismic experiment showing north-dipping reflectors beneath the northern margin of the W Kunlun (NW Tibet Plateau) and south-dipping reflectors beneath the southern margin of the Tarim basin.

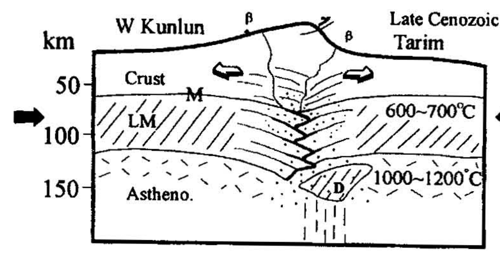


Fig. 7 Speculative model showing the delamination, extensional fractures and magma generation on the northwestern margin of Tibet.
LM: Lithospheric mantle Astheno: Asthenosphere D: Delamination
Alkalic basic volcanics

magma for the alkaline basic volcanics should be 0.68–0.75 (Frey et al., 1978) or 0.65–0.75 (Deng et al., 1996). The Mg′ values given from the alkaline basic volcanics on the northern margin of Tibet, used for pressure and depth estimation, are 0.62–0.68 (Lai et al., 1999). So they are ascribed to the primary magma or low evolution-degree magma type.

The δEu and Eu anomalies are also the indicators for identifying the primary magma type. Most of the alkaline basic volcanics on the northern margin of Tibet have high δEu (>0.7) and low or no negative Eu anomaly (Deng et al., 1996; Lai, 1999), implying that the primary magma lacks plagioclase, i.e., it originated in the deepest crust or lithospheric mantle.

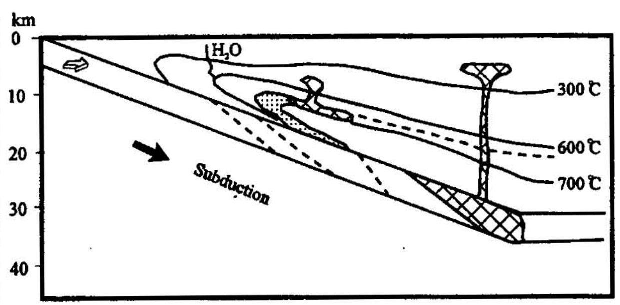
It is notable that deep-seated mantle xenoliths, such as spinel lherzolite and spinel harzburgite, have been recently found from Cenozoic alkaline basalt in the Kangxiwar area, western Kunlun Mountains (Luo et al., 2000). The spinel belongs to spinel-chromitite series with the ratio of (Cr)/(Cr+Al)=25%–8%. According to the thermobarometer of Webb and Wood (1984), the pressure and depth of these peridotites are 1.6 GPa and about 60 km respectively (Luo et al., 2000), so the Cenozoic alkaline basalt carrying these peridotite xenoliths originated from the area around the lithospheric mantle.

Based on the data mentioned above, we can make a list of discrimination of the tectonic interaction and evolution on the southern and northern margins of the Tibet plateau (Fig. 8).

5 Conclusions

No evidence from our deep seismic sounding has revealed the southward subduction of the Tarim block beneath the W Kunlun Mountains in the NW Tibet Plateau. So, we think that the "two-sided subduction" model proposed by many geoscientists may be modified. Judging from the above-mentioned geophysical, geochemical and geological data, the continental collisions of the southern margin and the northern margin of the Tibet plateau are different. In the former case, the intracontinental collisional orogeny and crustal thickening may have resulted from the underthrusting or subduction of the Indian continent, which caused the intrusion of muscovite granite and two-mica granite. In the latter case, the "horizontal compression in opposite directions", i.e. the compression of the Tarim block from the north and the Indian continent from the south resulted in thickening and densifying of the lower part of the lithosphere; thus delamination occurred owing the gravitational instability: the thickened and densified lithosphere was detached and sunk into the asthenosphere. A rapid

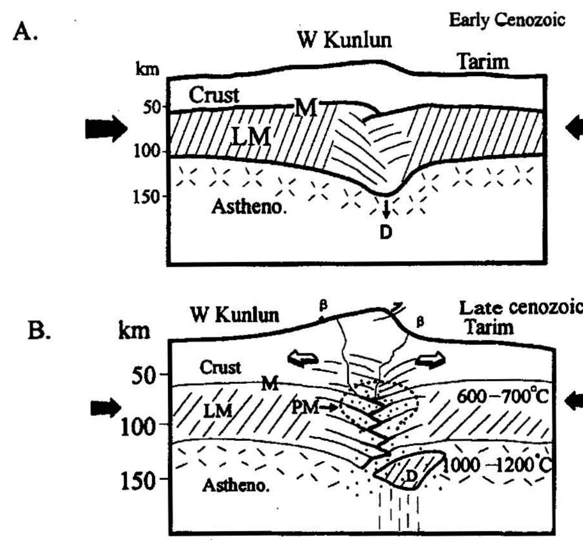
Region	S margin of Tibet	NW margin of Tibet
Type of contact	Subductional contact	Horizontal shortening (fractured) contact
Magmatic activities	Muscovite granite, two-mica granitic rock and calc-alkaline igneous rocks	High-potassium basic volcanics (mainly shoshonite series)
Main geochemical indicators	Low Mg (Mg'<0.25), low La/Yb, negative Eu anomaly, high $^{87}Sr/^{86}Sr$ (0.742–0.765)	High Mg and K (Mg'>0.60), high La/Yb, no negative Eu anomaly, low $^{87}Sr/^{86}Sr$ (0.7080–0.7120)
Deep structure	Detachment in crust by subduction	Delamination (D) due to thickening and densifying of the lithosphere
Magmatic origin	Differentiation from the upper part of the subducted slab (at depths of 20−35 km)	Partial melting (PM) of the lithospheric mantle-lower crust (at depths of 74−85 km)



Speculative model showing the subductional contact and magma generation on the southern margin of Tibet (After Deng Jinfu et al., 1996)

Original magma chamber of leucogranite

Migamatite front of leucogranite



Speculative model showing the horizontal shortening contact (A) and magma generation (B) on the northwestern margin of Tibet

Fig. 8 Discrimination of the tectonic interaction on the southern margin and northern margin of the Tibet plateau uplift occurred at the surface following the delamination, and subsequent alkaline volcanic rocks, the extensive shoshonite, formed by partial melting, erupted along the extensional fractures.

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