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青藏高原东南缘构造旋转的古地磁学证据

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摘　要　本文在总结青藏高原东南缘近年来地质研究进展的基础上,从古地磁学的角度讨论其新生代以来的构造运动特征.结果表明:相对稳定的欧亚大陆,新生代以来山泰地块发生了约 20°～80°顺时针旋转,局部地区旋转量甚至高达 135°,且中部地区的旋转量明显高于南北地区;印支地块经历了～30°的顺时针旋转;川滇地块的顺时针旋转量沿 102°E 经度线由南向北由 30°逐渐减小;另一方面,古地磁数据还揭示出山泰地块新生代以来发生了～8°的南向滑移运动.旋转量随时间的变化表明主要构造旋转发生在始新世与中中新世之间,与哀牢山—红河断裂的左行走滑时间相一致.这表明青藏高原东南缘的新生代构造运动具有差异性和复杂性,现今国际流行的挤出逃逸、地壳缩短增厚及下地壳流模式均有其局限性.值得注意的是,青藏高原东南缘可靠的新生代古地磁数据在时空分布上的严重不足,制约了我们对印度与欧亚大陆碰撞在青藏高原东南缘的运动学响应过程的深入探讨和正确理解.因此,进一步对该地区新生代地层开展深入细致的古地磁学等综合研究,无疑具有重要的科学意义.

关键词　青藏高原东南缘,古地磁,构造旋转,走滑逃逸

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Paleomagnetic constraints on the tectonic rotation of the southeastern margin of the Tibetan Plateau

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Abstract　In this paper we present a comprehensive summary of the geological evolution of the southeastern margin of the Tibetan Plateau and a detailed reanalysis of previously published paleomagnetic data. We focus on the Cenozoic, which represents a period during which the southeastern margin of the Tibetan Plateau was one of the most active tectonic regions due to the India-Eurasia collision. Our analysis indicates that, since the Cenozoic, with respect to the stable Eurasian block, the Shantai terrane experienced a clockwise rotation of ～20°—80°, with some areas experiencing clockwise rotation by as much as 135°, and the rotation of the central part of the terrane is higher than that in the north and south of the terrane; the IndoChina terrane rotated ～30°clockwise and the rotation of the Chuandian terrane decreased from 30° along the longitude 102°E from south to north. Of the three terranes only the Shantai terrane recorded a

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~8° southward translation. The variation of rotation versus time indicates that the main rotation of the southeastern margin of the Tibetan Plateau occurred between Eocene and mid-Miocene, which is in accordance with the sinisterly slip of the Ailao Shan-Red River fault zone. This complex tectonic history, revealed by paleomagnetism, cannot be fully explained by the commonly accepted models for the formation of the Tibetan Plateau, such as crustal thickening, lateral extrusion or lower crustal flow. Reliable Cenozoic paleomagnetic data in the southeast margin of Tibetan Plateau are scarce. Therefore, to better evaluate the effects of the India-Eurasian collision on the southeastern margin of the Tibetan Plateau, additional and more detailed paleomagnetic studies of Cenozoic rocks from this region are essential.

Keywords　Southeastern margin of the Tibetan Plateau, Paleomagnetism, Tectonic rotation, Extrusion

1 引　言

青藏高原的隆升是始于古近纪初印度与欧亚大陆碰撞的结果[1-5]．这一碰撞不仅造成了亚洲大陆内部强烈的构造变形[6-8]，而且对区域甚至全球气候变化都有着深远影响[9-12]．早期研究表明，印度与欧亚大陆碰撞以来的构造缩短量达到 2600 km 左右[13-14]．而关于青藏高原构造缩短变形的端元模式主要有两种：地壳缩短增厚和走滑逃逸．地壳缩短增厚模式认为欧亚大陆地壳类似于一粘滞性薄板，碰撞所造成的构造缩短主要由地壳增厚和一系列逆冲断层所吸收，加厚的高原地壳向东扩展．早期没有物质向东逃逸，晚期尽管有物质向东运动，但其变形是一种连续的内部应变[15-16]．同时，青藏高原东部、东南缘地区因右行剪切而绕东喜马拉雅构造节发生大规模的顺时针旋转，旋转速度达到每百万年 1°～2°[17]．而走滑逃逸模式则认为印度向欧亚大陆的俯冲可简化为块体的刚性运动；块体间的汇聚由断层所围限的刚性地块的侧向走滑逃逸来调节[18-21]．首先，印支地块向东南方向走滑逃逸并伴随大规模顺时针旋转，其走滑的东、西边界分别为左行走滑的哀牢山—红河断裂和右行走滑的实皆断裂（或高黎贡走滑断裂）[22-24]．该期走滑可能造成了中国南海的扩张[18-19,25]．其次，随着印度板块不断向北挤压，青藏高原东北部和华南、华北地块开始第二期走滑．其南边界为由左行走滑转为右行正断的红河断裂，北边界为左行的阿尔金断裂带．华北地块内部山西地堑的裂开以及西伯利亚板块南缘贝加尔湖的形成等均是其远程效应[18]．

尽管上述两种变形模式均能解释青藏高原的很多地质现象，但不足之处显而易见．譬如走滑逃逸模式难以解释高原内部南北向裂谷的产生、GPS 观测到的断层走滑速率与地质推测速率之间的巨大差异[26-32]；而缩短增厚模式则很难解释大规模走滑的发生[19,25]．为此，Royden 等根据野外观测、GPS 测量和数值模拟提出了介于上述两种模式之间的下地壳流动模式[33-34]．该模式认为早第三纪时（约 50～20 Ma），青藏高原中、北部以构造挤压缩短为主，而东、东南部在印度与欧亚板块碰撞挤压和西太平洋板块俯冲弧后扩张的双重作用下向东、东南方向发生走滑逃逸．晚第三纪时（约 20～15 Ma 以后）青藏高原整体快速隆升，中部发生东西向伸展．由于西太平洋板块俯冲速度的减慢甚至停止，东向逃逸主要集中在高原东北缘地区，且多被区域性的逆冲和褶皱所吸收．此时由于高原的抬升，青藏高原的下地壳变热变软，变软的下地壳向东、东南缘发生塑性流动，而上地壳向东南的移动则被顺时针旋转和鲜水河—小江断裂的走滑所调节．

由此可见，青藏高原东南缘是全球晚新生代以来构造最活跃的地区之一，也是解决青藏高原演化的关键地区之一．因此从 20 世纪 80 年代开始，青藏高原东南缘就成为地球科学家关注的焦点．地质研究表明，青藏高原东南缘晚新生代地壳没有明显的挤压缩短，主要是以沿大型断层的走滑和块体的构造旋转为主[35-51]．而上述模型争论的焦点就是地质时期是否发生过大规模的走滑逃逸和构造旋转．古地磁研究作为定量恢复古构造运动最有效的手段而成为解决这一争论的关键．为此，近年来在该地区积累了大量的古地磁数据[52-92]．然而，由于采样位置和采样地层时代的差异、数据本身的可靠性、以及局部新构造运动的影响，不同作者所得出的结论亦存在很大差异，甚至相互矛盾．为此，本文拟在对青藏高原东南缘近年来的地质研究进展进行扼要分析的基

础上,对青藏高原东南缘晚中生代以来已有的古地磁数据进行筛选分析,依据可靠的古地磁数据,探讨青藏高原东南缘晚新生代的构造运动和其对青藏高原构造运动的启示,以及今后古地磁学研究亟待解决的关键问题.

2 区域地质构造背景

青藏高原东南缘由一系列断层所夹的次级块体拼合而成[28],主要包括川滇、山泰和印支地块三个次一级构造单元(图1).川滇地块是扬子板块的西南边缘部分,被北西—北北向的鲜水河—小江断裂与扬子板块主体隔开,其西南以哀牢山—红河断裂带为边界.山泰地块的西部边界为高黎贡—实皆断裂带;该地块可进一步划分为分属于冈瓦纳大陆的保山地体和属于特提斯的兰坪—思茅地体,二者之间由近南—北向花岗岩体组成的昌宁—孟连缝合带分开[93-95].山泰地块和印支地块由平行于Nan-Uttaradit缝合带的北东—南西向奠边府左行走滑断裂隔开[25].青藏高原东南缘大面积出露中、新生代红层,并直接覆盖于古生代地层之上[95].受新生代构造活动影响,这些红层在山泰和川滇地块内被挤压成一系列北西—北北西向的褶皱和逆冲断层[25,95].各主要边界断裂带的活动历史简介如下:

2.1 鲜水河—小江断裂

作为调节青藏高原物质向东运动和绕东喜马拉雅构造节顺时针旋转的边界[38,96],鲜水河—小江断裂带从西北向东南依次为北西—南东向的甘孜断裂、鲜水河断裂、近南—北向的安宁—则木河断裂和小江断裂[35,38,97].小江断裂向南由西向东分为绿汁江、易门、普渡河、西小江和东小江断裂,其中绿汁江断裂又称元谋断裂.许志琴等[98]在康定发现一个平行于该断裂的大型花岗岩体,认为该花岗岩体为同剪切岩浆侵入产物,其侵位年龄为鲜水河断裂的走滑开始时间.U-Pb和Rb-Sr同位素以及^{40}Ar/^{39}Ar年龄研究表明,其侵入和冷却年龄分别为10~12 Ma和5 Ma[99-101],因此很多学者认为10~12 Ma可能为鲜水河—小江断裂左旋走滑的开始时间.最近Wang等[102]通过对甘孜—玉树地区鲜水河断裂带的花岗岩进行^{40}Ar/^{39}Ar和磷灰石热年代学研究表明鲜水河—小江断裂带走滑运动分为两期,早期开始于13 Ma,切穿了宕江、甘孜、贡嘎山,到达清河—盐源地区;晚期从5 Ma到现在,断裂穿过玉树、甘孜、贡嘎山到达昆明地区.鲜水河—小江断裂甘孜段左行走滑位移量为78~100 km,其中有60 km的走滑转移至鲜水河—小江断裂上,局部地区走滑被伸展和挤压构造所吸收,但是在整个断裂带上总走滑位移量是一定的[36,38].

2.2 哀牢山—红河断裂

哀牢山—红河断裂由西北向东南依次为雪龙山、点苍山、哀牢山、Day Nui Con Voi(DNCV)四个变质带,其早期变形形式为左行走滑,后期为右行正断[19,25].目前研究较深入的是点苍山和哀牢山变质带.点苍山变质带主要由一套深变质岩组成,包括副片麻岩、眼球状片麻岩、云母片岩、角闪石片岩等[103];哀牢山变质带由西南部的低级变质带和东北部的高级变质带组成,东北的高级变质带由角闪岩-绿片岩相的副片麻岩、角闪岩、大理岩和花岗岩组成,西南的低级变质带由低绿片岩相片岩、千枚岩和板岩组成.带内岩石均经历韧性左行剪切,形成具透入性面理和线理的糜棱状片麻岩[19,25].

哀牢山—红河断裂带作为走滑逃逸模式早期挤出的东边界而成为研究焦点,但目前关于该断裂的性质、走滑时间和方式仍存在很大争议.Tapponnier等[19]认为该断裂是一岩石圈规模的大型走滑断裂,但Jolivet等[104]则认为其仅为一上地壳断裂.Harrision等、陈文寄等、李齐等[39,109-111]指出哀牢山变质带走滑具有转换拉张性质,在走滑的同时经历了穿时性的匀速扩张抬升,从东南以4.5 cm/a的速率向西北传递,与由南海磁异常条带所预测的哀牢山—红河断裂走滑速率3~5 cm/a相一致[112],支持挤出逃逸导致中国南海的扩张.而Wang and Burchfiel、Schoenbohm等[35,115]则认为哀牢山—红河断裂带为一转换压缩断裂.

Tapponnier等、Leloup等、Gilley等[19,25,103,105]认为左行走滑开始于35 Ma,主走滑时间为22~17 Ma,与断裂两侧火山岩的年龄相一致[106-108].但是,Chung等、Wang等[42,113]认为走滑时间应晚于30 Ma. Wang等[43,44]进一步通过对最东南端DNCV变质岩的^{40}Ar/^{39}Ar定年得出走滑开始于27.5 Ma,晚于南海扩张的时间(34Ma),因此南海扩张与走滑逃逸无关.Searle[114]则认为走滑开始时间甚至晚于21 Ma.

另一方面,通过断裂带两侧相关标志地质体的对比,Leloup等[25]认为左行走滑位移为700±200 km,最大位移约1150 km. Chung等[113]认为左行走滑量约为600 km.然而,Searle[114]则认为上述标志体都不可靠,哀牢山—红河断裂带左行走滑位移量仍不清

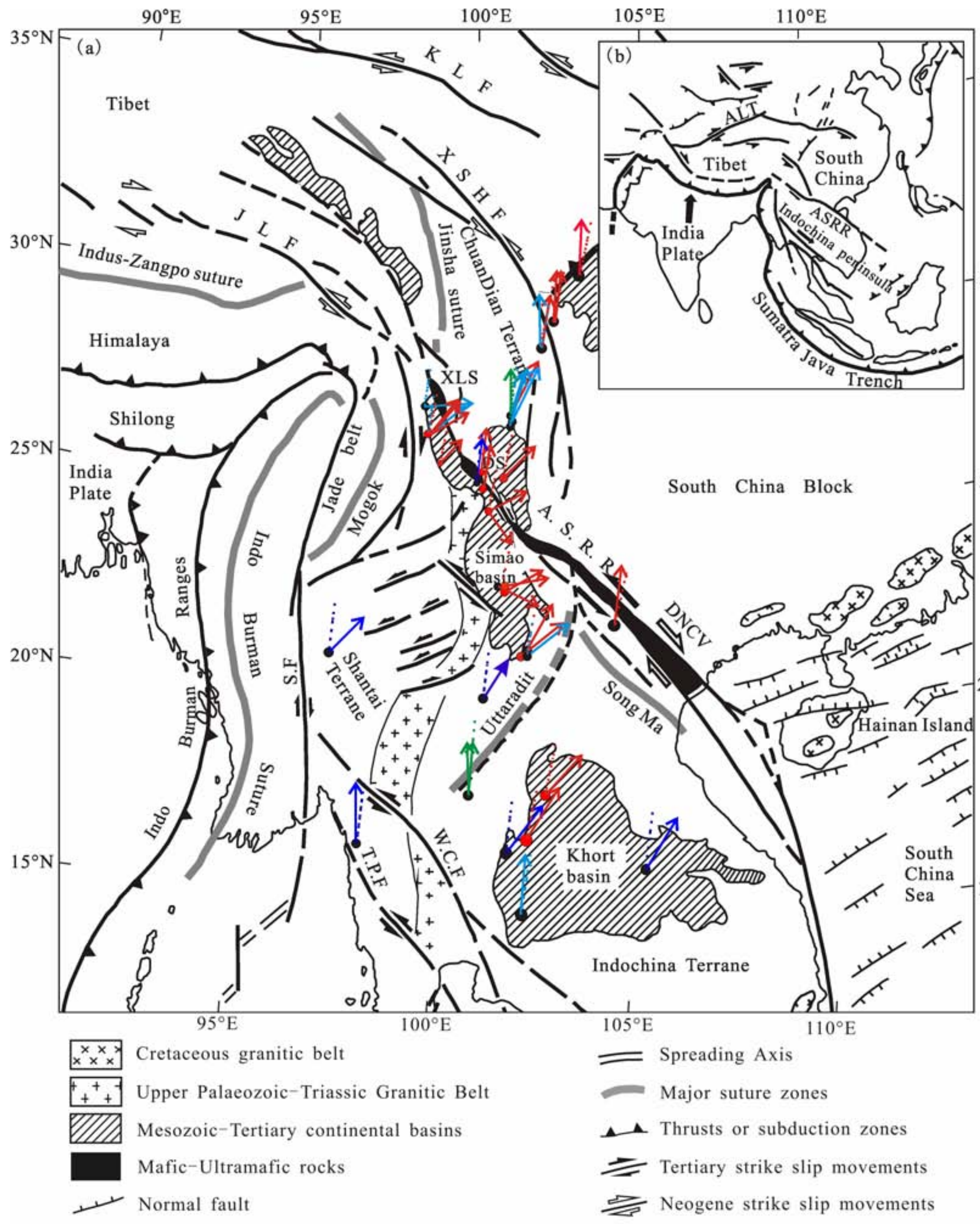

图 1　青藏高原东南缘构造图．(a) 青藏高原东南缘构造简图(修改自[25])．ASRR：哀牢山—红河剪切带；DS：点苍山变质带；XLS：雪龙山变质带；DNCV：Day Nui Con Voi 变质带；XSHF：鲜水河—小江断裂；SF：实皆断裂；KLF：昆仑断裂；JLF：嘉黎断裂；WCF：Wang Chao Fault；TPF：Three Pagodas Fault．实线箭头代表实测古地磁偏角，虚线代表以思茅(23.5°N、100.5°E)为参考点，以欧亚大陆视极移曲线为参考极所计算出的期望古地磁偏角；紫色、红色、蓝色、绿色分别代表侏罗纪、白垩纪、古近纪、新近纪；黑色(红色)实点代表古地磁所记录的向北(向南)的纬向运动．(b)走滑逃逸模式示意图[18-19]．

Fig. 1　Sketch map of the tectonic setting of the southeast margin of the Tibetan plateau. (a) Sketch map of the tectonic setting of the southeast margin of the Tibetan plateau (modified from [25]). ASSR: Ailao Shan-Red River Shear Zone; DS: Diancang Shan Shear Zone; XLS: Xuelong Shan Shear Zone; DNCV: Day Nui Con Voi Shear Zone; XSHF: Xian Shui He-Xiao Jiang Fault; SF: Sagaing Fault; KLF: Kunlun Fault; JLF: Jiali Fault; WCF: Wang Chao Fault; TPF: Three Pagodas Fault. Solid arrows represent measured paleomagnetic declination, dotted lines represent the expected paleomagnetic declination, they were calculated from the apparent polar wander path (APWP) of Eurasia as a reference pole and Simao (23.5°N, 100.5°E) as a reference site. The purple, red, blue, and green represent Jurassic, Cretaceous, Paleogene, and Neogene data, respectively. The black (red) dots represent the northward (southward) latitudinal displacement recorded by paleomagnetic data. (b) Sketch map of the extrusion model on refs [18-19].

楚.哀牢山—红河断裂在约5 Ma时由左行走滑转为右行走滑且兼具正断分量[19,25],走滑的位移量在几公里至几十公里[45,96,116],但也有学者认为转换时间可能为12或16 Ma[101].

2.3 其它走滑断裂带

除哀牢山—红河断裂带和鲜水河—小江断裂带外,青藏高原东南缘还发育实皆断裂、高黎贡山剪切带、冲山剪切带、Wang Chao断裂、Three Pagodas断裂等大型走滑剪切断裂以及南亭、孟兴、南马等小型断裂(图1).实皆断裂和高黎贡山剪切带作为印支地块逃逸的西边界,主要为右行剪切.实皆断裂的走滑与安达曼海的扩张有关,开始于15 Ma;而高黎贡断裂的走滑时间和哀牢山—红河断裂带相同[23,117].但是,高黎贡剪切带现今为一不活动剪切带,而GPS观测证实实皆断裂现今仍以18 mm/a的速度运动[118].最新研究表明,冲山剪切带为一既有左行走滑又有右行走滑的剪切带,其活动时间至少开始于34 Ma,甚至早于41 Ma,结束于17 Ma,与哀牢山—红河剪切带早期左行走滑的时间相同,这表明夹于哀牢山—红河断裂和高黎贡山剪切带之间的地块在逃逸时并不是一个刚性块体,至少被冲山剪切带分为两部分[22]. Wang Chao和Three Pagodas断裂左行走滑停止于30.5 Ma[41].南亭、孟兴、南马等小型断裂都为NE—SW走向,现今表现为左行走滑,但早期可能为右行走滑,在距今5～20 Ma时走滑形式发生反转[119]. Wang等、Schoenbohm等[38,96]认为这些小型断裂可能是鲜水河—小江断裂跨过哀牢山—红河断裂后的延伸,这一结论得到GPS观测结果的进一步证实[120].

值得注意的是,所有由野外地质观测推断出的大型走滑断裂平均走滑速率均远高于GPS观测到的走滑速率[26-32],而断层的走滑速率直接被用来约束重建青藏高原的构造演化模型[29].这一差异或表明这些断层在地质时期走滑速率比现今要大,或表明野外地质对断层走滑时间和位移量的厘定存在很大误差.由此可见,尽管前人对青藏高原东南缘走滑断裂开展了大量研究,但迄今对其走滑时间、走滑位移量及其在青藏高原构造演化中的作用还很不清楚,仍有待于多学科的进一步综合研究.

3 青藏高原东南缘已有古地磁结果

走滑逃逸模式的关键在于青藏高原东南缘在新生代沿哀牢山—红河断裂发生了大规模的南向逃逸和构造旋转.因此,自从Tapponnier等[18]提出走滑逃逸模式以来,青藏高原东南缘就成了古地磁学研究的热点. Achache等[52]首次对青藏高原周缘白垩纪和新生代已有古地磁数据进行了总结,提出青藏高原东南缘的印支地块相对于欧亚大陆存在纬向上的南移(−5.5±10.2°)和顺时针旋转(29±16.2°),支持走滑逃逸模式.然而,该数据少、误差很大,尤其是纬向运动量在古地磁误差范围内.此后的二十多年,大量学者对青藏高原东南缘新生代以来的运动模式进行了广泛的古地磁学研究.但已有数据的质量参差不齐,比如有的数据未进行系统退磁[79],有的则可能受到了重磁化的影响[53].因此,为了更好地约束青藏高原东南缘的构造运动模式,我们对迄今已发表侏罗纪以来的古地磁数据按照如下可靠性标准进行筛选:

(1)采样点大于3且经过系统退磁;

(2)α_{95}小于15°;

(3)通过褶皱检验或倒转检验或者其它检验方法.

同时,本文选用欧亚大陆200 Ma以来的视极移曲线[121]作为参考极重新计算各个地块相对于稳定欧亚大陆的构造旋转和纬向位移量;各个特定时期的参考极以10 Ma为窗口进行Fisher平均(表1).相对旋转和纬向运动计算采用Butler方法[122],误差采用Demarest方法[123],计算结果见表2和图1,以箭头表示古地磁偏角,其与由欧亚大陆视极移曲线得出的期望古地磁偏角之差代表旋转量.

3.1 山泰地块

山泰地块是青藏高原东南缘古地磁数据积累最多的地区,由符合标准、重新计算后的古地磁结果(表2)随采样点纬度的分布(图2)可以发现:除Mae Sot、景东和下关采点外,山泰地块相对欧亚大陆经历了约20°～80°顺时针旋转,局部地区旋转量甚至高达135°,且中部地区旋转量明显高于南北地区.为此,一些研究者结合区域地质背景,提出山泰地块早期整体先经历了～30°的顺时针旋转,后期由于南亭、孟兴、南马等小型断裂的活动[119],中部地区经历内部变形又发生了进一步旋转[67-69,77-78].在纬向运动方面,大部分白垩纪古地磁结果支持山泰地块白垩纪以来相对欧亚大陆经历了～8°(～900 km)的南向滑移,但侏罗纪古地磁结果却显示山泰地块自侏罗纪以来相对欧亚大陆发生大规模的北向运动,可能与特提斯洋的演化有关;同时新生代古地磁结果也显示山泰地块新生代以来相对欧亚大陆发生了

表 1　欧亚大陆的视极移曲线[121]

Table 1　The APWP of Eurasia[121]

Age(Ma)	λ(°N)	Φ(°E)	A95(°)	Age(Ma)	λ(°N)	Φ(°E)	A95(°)	Note
0	86.3	172	2.6	110	80	183.6	4.2	
10	85.4	162.5	2	120	78.2	189.4	2.4	
20	84	154.8	2.7	130	75.8	192.9	2.8	
30	82.8	158.1	3.8	140	73.8	197.6	6	
40	81.3	162.4	3.3	150	75	159.9	6.6	
50	80.9	164.4	3.4	160	72.5	144	5	
60	81.1	190.5	2.9	170	69.7	112.5	6.7	
70	80.3	204.3	3.2	180	65.5	95.9	5.6	
80	81.4	206.1	5.9	190	65.3	98.4	4.2	
90	82.2	202.1	5.2	200	63.2	106	4.3	
100	81.7	180.1	6.7					
Mean N poles	84.7	158.1	3.4					10～20Ma poles[1]
Mean P-E poles	81.7	169.3	2.6					30～60Ma poles[2]
Mean K2 poles	77	191.8	3.4					60～100Ma poles[3]
Mean K1 poles	81.5	196.8	1.7					100～140Ma poles[4]
Mean K poles	79.5	194.1	2.1					60～140Ma poles[5]
Mean J2 poles	69.7	112.5	6.7					170Ma poles[6]
Mean J1 poles	66.1	102.9	4.6					170～200Ma poles[7]
Mean J poles	70	114.7	8.1					150～200Ma poles[8]
Mean J3-K1 poles	76.7	176.6	5					100～160Ma poles[9]

注:N:晚第三纪;P-E:古新世-始新世;K2:晚白垩世;K1:早白垩世;K:白垩纪;J2:中侏罗纪;J1:早侏罗纪;J:侏罗纪;J3-K1:晚侏罗-早白垩(下同). 方括号中的数字代表表 2 中的参考极.

北向运动.

3.2　印支地块

印支地块上积累的可靠古地磁数据相对较少,同样将计算后的结果(表 2)投影在采样点纬度的坐标系上(图 3). 结果表明:除 Song Da 采样点外,侏罗纪和白垩纪的古地磁结果显示印支地块侏罗纪以来相对欧亚大陆经历了～30°的顺时针旋转,但是越南、呵叻高原以及 Mae Moh 新生代古地磁结果显示印支地块第三纪以来相对欧亚大陆无明显的构造旋转. 纬向运动方面,只有呵叻高原早白垩世和 Borikhanxay 晚侏罗-早白垩世的结果显示印支地块白垩纪以来相对欧亚大陆经历了约 6°～8°的南向滑移;而 Khorat plateau 和 Muang Phin 采点早侏罗纪的结果则显示印支地块侏罗纪以来相对欧亚大陆经历了～20°的北向漂移. 此外,Song Da 采点白垩纪古地磁结果显示该地区白垩纪以来相对欧亚大陆无明显的纬向运动;新生代古地磁结果也均显示印支地块新近纪以来相对欧亚大陆无显著纬向运动.

3.3　川滇地块

川滇地块可靠古地磁数据亦较少. 为了便于讨论,暂将鲜水河—小江断裂以北的古地磁数据也一并投影在采样点纬度的坐标系内. 从表 2 和图 4 可以看出,川滇地块相对欧亚大陆的顺时针旋转量沿 102°E 经度线由南向北由 30°逐渐减小,鲜水河—小江断裂以北转为逆时针旋转,推测可能是川滇地块受山泰、印支地块挤出拖拽影响的结果[55,74]. 纬向运动方面,除楚雄采点外,所有结果均显示川滇地块相对欧亚大陆经历了显著的北向运动,新生代结果尤为明显.

4　讨　论

古地磁结果揭示了山泰、印支、川滇地块在新生代经历了差异性顺时针旋转,这种旋转的差异性说明印度与欧亚大陆的碰撞对青藏高原东南缘不同地区产生的影响存在区域差异性,这也与青藏高原东

表 2 青藏高原东南缘古地磁结果

Table 2 Paleomagnetic results from the southeastern margin of the Tibetan plateau

Locality			Age	N	Observed direction			VGP			$R\pm\Delta R$	$\lambda\pm\Delta\lambda$	Reference pole	Test	Reference
	Lat(°N)	long(°E)			D(°)	I(°)	a95(°)	Lat(°N)	Long(°E)	A95(°)					
Chuadian block															
雅安	30.1	103	K	9	2.1	30.7	11.3	76.3	274.5	11.1	−10.0±10.7	12.8±11.3	5	F1\R	[54]
西昌	27.9	102.3	K	33	3.7	41.5	3.4	85.2	241.7	3.5	−8.1±4.1	2.9±4.1	5	F1	[72]
西昌	27.7	102.2	K2	12	5.9	45.8	4.6	84.7	193.3	—	−8.7±6.1	−0.5±?	3	Syn-folding	[83]
会理*	26.8	102.5	K1	7	22.1	37.1	3.8	69	204.6	4.3					[63]
会理	26.5	102.4	K2	18	8.1	38.8	6.6	81.5	220.9	7.1	−6.4±7.4	3.7±7.9	3	F1	[63]
会理	26.4	102.3	P—E	7	178.7	−13.7	12.1	70.6	286.1	11.6	−10.1±10.2	22.3±11.9	2	$k_s/k_g=1.7$	[63]
永仁	26.1	101.7	P、E	16	17.2	26.6	5.8	70.1	224.6	4.9	8.4±5.7	14.7±5.5	2	F2\R	[74]
元谋	25.9	101.7	K2	21	26.9	35.6	3.6	64.6	199.6	3.3	12.5±4.6	5.2±4.7	3	F1	[55]
大姚	25.8	101.5	P、E	9	25.8	28.6	5.5	64	211.2	4.3	17.0±5.5	13.7±5.0	2	F1\F2\R	[81]
大姚	25.7	101.3	P	10	16.5	31.1	4.8	72.3	218.4	4.5	7.7±5.1	11.8±5.2	2	F1\F2	[74]
楚雄	25.0	101.5	K	21	44.6	41.3	10.7	49.2	182	11.4	33.1±11.6	−0.6±11.6	5	F1	[61]
元谋	25.7	101.9	N	17	1.4	27.8	2.1	79.1	266.7	2.8	−3.6±3.6	13.4±4.4	1	R	[73]
西昌*	27.0	102.4	K2	20	12.6	46.2	6.9	78.9	186.6	4.3					[85]
西昌*	27.9	102.3	K1	11	14.2	44.5	14.5	77.4	196.2	11.5					[85]
会理*	26.4	101.9	J3	26	26.5	44	7.6	66.2	187.6	6					[85]
西昌*	26.9	102	J2	27	30.5	43.9	14.6	62.2	187	7.7					[85]
会理*	26.5	102	J1	14	25.3	41.8	11.4	69.4	192.4	5.8					[85]
雅安*	30.1	103	K	21	10.5	47.3	2.2	80.7	200.2	2.3					[86]
雅安*	30.1	103	E	15	359	51.6	3.9	88.1	75.7	4.3					[86]
路南*	—	—	E	105⋆	—	—	—	84.4	343.1	—					[87]
昆明*	—	—	E	145⋆	—	—	—	83.8	309.1	—					[87]
姚安*	25.7	101.3	E	15⋆	46.4	−44.0	6.3	—	—	—					[84]
姚安*	25.7	101.3	K	15⋆	63.8	59.3	8.9	—	—	—					[84]
大姚—永仁*	25.7	101.4	P	17⋆	43.1	41.0	16.4	—	—	—					[84]
永仁*	25.8	101.5	P	18⋆	49.9	40.3	16.0	—	—	—					[84]
昆明*	25.2	101.3	P	11⋆	76.2	36.2	6.9	—	—	—					[84]

续表 2

Locality			Age	N	Observed direction			VGP			$R\pm\Delta R$	$\lambda\pm\Delta\lambda$	Reference pole	Test	Reference
	Lat(°N)	long(°E)			D(°)	I(°)	a95(°)	Lat(°N)	Long(°E)	A95(°)					
Indochina block															
Khorat plateau	16.7	101.83	J1	8	37.2	40.1	6.6	54.4	175.6	7.3	36.6±8.4	17.7±8.6	7	F1	[58]
Khorat plateau*	16.7	101.83	J3+K1(B)	20	27.3	38.9	1.8	63.8	175.6	1.7					[58]
Khorat plateau*	16.7	101.83	J3+K1(C)	20	29.3	37.8	2.4	—	—	—					[58]
Mae Moh	18.3	99.7	N	86*	358.3	22.2	4				−6.5±4.5	9.5±4.1	1	R	[146]
Mae Moh	18.3	99.7	N	65*	4.4	37.6	3.4				−0.4±4.5	0.0±4.1	1	R	[147]
Song Da	21.0	104.4	K2	8	3.2	26.7	12.9	83.2	255.6	10.8	−10.7±11.9	6.0±11.3	3	F1\R	[70]
Song Da	22.3	103.4	K2	5	12.2	40.1	4.7	78.7	188	5.1	−1.8±5.7	−0.8±6.1	3	F1\F2	[70]
Song Daa	21.7	103.9	K2	13	6.4	32	8.5	82.9	220.7	6.9	−7.6±8.5	3.2±7.7	3		[70]
Khort plateau	17.5	103.5	K2	14	31.8	28.7	3.5	59.4	190.8	3.5				$k_s/k_g=1.01$	[76]
Khort plateau	17.0	103	K2	8	31.4	27.1	9.4	59.7	192.7	9.4				$k_s/k_g=1.1$	[76]
Khort plateau	17.0	103	K1	4	31.8	38.3	5.7	59.7	178.2	5.7	23.0±6.0	−5.8±5.9	4	F1	[76]
Borikhanxay	18.5	103.8	J3−K1	18	42.1	46.9	7.9	50.7	169.7	8.7	28.4±10.2	−7.5±10.0	9	F2	[71]
Muang phin	16.5	106	J1−2	23	30.8	39.9	3	60.5	178.6	3	27.1±8.6	13.4±8.6	8	Syn-folding	[71]
Da Lat*	11.0	108	K	21	14.5	33.3	6.3	74.2	171.1	5.9				$k_s/k_g=1.0$	[124]
Khorat plateau*	—	—	J	1	25	36	—	—	—	—					[53]
Khorat plateau*	—	—	K	7	37	32	9	—	—	—					[88][b]
Khorat plateau*	—	—	J2	14	31	41	13	—	—	—					[88][b]
Khorat plateau*	—	—	J2	16	33	35	8	—	—	—					[88][b]
Khorat plateau*	—	—	J1	16	39	36	9	—	—	—					[89][b]
Khorat plateau*	—	—	J1	15	33	29	7	—	—	—					[88][b]
Khorat plateau	14.5	102.5	N	29	4.3	28.5	6.6	85.7	171.4	5.4	−0.3±6.7	1.4±6.4	1		[90][c]
Vietnam	—	—	N	28	357.8	18.6	4.9	85.8	319.9	3.8	−6.4±5.0	7.0±5.1	1		[91][c]
Shantai block															
兰坪思茅	26.5	99.3	E	9	266.1	−39.8	11.2	14.5	169.7	10.9	77.2±12	5.3±11.2	2	F2	[68]
云龙	25.8	99.4	P	14*	50.2	31.1	13.2				41.3±12.6	11.6±8.7	2	R	[82]
景谷*	23.5	100.8	E	6	73.1	39.9	11.8	23.2	174.6	12.2					[81]
思茅*	23.5	100.7	E−O	7	84.7	38.9	7.6	13.2	209.2	—					[66]
思茅*	23.5	100.7	N	6	21.1	35.5	7.1	70	197.8	—					[66]

续表 2

Locality			Age	N	Observed direction			VGP			$R\pm\Delta R$	$\lambda\pm\Delta\lambda$	Reference pole	Test	Reference
	Lat(°N)	long(°E)			D(°)	I(°)	a95(°)	Lat(°N)	Long(°E)	A95(°)					
江城*	22.6	101.4	P	6	339.1	36.8	12.1	70.3	10.5	11.7					[81]
勐腊	21.5	101.7	E	17	51.7	33.4	8.7	41.3	185.2	8.5	43.3±8.7	5.7±8.9	2	F1\F2\R	[81]
云龙	25.8	99.4	K1	23⋆	59.7	41	11.9	36.2	178.2	11.3	50.4±12.8	0.9±11.4	4	R	[82]
云龙	25.8	99.4	K2	8	38.4	51.6	5.4	57.7	168	5.3	24.1±7.6	−8.4±6.3	3	F1\F2	[82]
云龙	25.8	99.4	K2	29	38.3	50.7	3.4	56.7	170.1	4	24.0±5.2	−7.3±5.2	3	F1\F2	[60]
云龙	25.8	99.4	K2	20	40.2	49.9	3.5	54.6	171.8	4.4	25.9±5.3	−6.3±5.6	3	F1\F2	[67]
下关	25.6	100.2	K2	9	6.9	47.7	8.6	83.6	152.7	10	−7.4±10.7	−4.8±10.6	3	F1\R	[64]
永平	25.5	99.5	K1	12	42	51.1	8.7	50.9	167.3	20.6	32.8±11.2	−9.2±20.7	4	F1	[62]
巍山	25.4	100.2	J1	5	7.3	25.3	10.4	76.3	250	10.4	5.6±10.8	35.9±11.4	7	ks/kg=2.0	[64]
景东	24.5	100.8	K2	13	8.3	48.3	7.7	81.2	145.8	8.9	−5.9±9.8	−6.9±9.5	3	F2	[78]
潞西*	24.3	98.4	J2	6	99.7	35.2	11.3	−0.5	166.6	12.2					[64]
镇沅	24.0	101.1	K2	7	61.8	46.1	8.1	34.7	172.7	8.1	47.6±9.8	−4.8±8.8	3	F2	[78]
镇沅西	24.0	101.1	K2	4	324.2	−49.4	6.4	−25.7	135.2	7.7	130±8.4	−7.2±8.4	3	F2	[78]
景谷*	23.6	100.5	J2	10	83.3	36.8	5.4	14	173.6	4.2					[64]
景谷	23.4	100.9	K2	8	79.4	43.3	9.1	18.9	170	8.9	65.3±10.5	−3.4±9.5	3	ks/kg=1.8	[64]
思茅*	23.4	100.4	K1	3	84.4	39.6	17.7	13.6	171.5	—					[66]
思茅	23.4	100.5	K1	7	295.8	−36	6.3	−13.9	161.3	—	106.7±6.4	3.6±6.3	4	F1	[66]
普洱	23.0	101	K	25	59.9	45.2	5.1	35.8	173.1	5.6	48.6±6.1	−5.2±6.0	5	F1\F2	[69]
勐腊*	21.6	101.4	K2	10	60.8	37.8	7.6	33.7	179.3	8.2					[64]
Phong saly	21.6	101.9	J3−K1	19	28.8	32.1	8.8	63.4	193.9	7.4	14.7±9.4	6.2±8.9	9	F2	[71]
勐腊南	21.4	101.6	K	13	51.2	46.4	5.6	43.6	172.1	6.1	40±6.8	−7.9±6.5	5	F2	[78]
Nan City	19.2	101	J3−J1	11	32.3	33.3	12.2	60.1	186.5	11.7	26.4±14.3	19.7±14.2	8	F2	[77]
Mae Sot	16.7	98.7	J1−2	12	359.8	31.4	5	89.7	57.7	4.2	−6.9±9.2	18.9±9.1	8	F1	[59]
Kalaw	20.7	96.5	J−K	13	44.7	23.4	6.1	47.2	190.6	4.8	30.5±6.9	10.0±6.9	9	F	[92]
West Thailand	13−18	100−102	N	24	24.4	26.2	6.9	66.4	189.5	6.2	19.7±6.8	3.5±7.1	1		[90][c]

注:Lat, Long 为采样点纬度(°N)和经度(°E). Age 为此采样点地层时代(同表 1). n 为采样点数;D,I,a95 为古地磁偏角、倾角和 95%置信区间. Test 为古地磁结果所通过稳定性检验,F1 为 McElhinny 褶皱检验[124],F2 为 McFadden 褶皱检验[125],R 为 McFadden and McElhinny 倒转检验[126]. $R\pm\Delta R$、$\lambda\pm\Delta\lambda$ 为计算出的旋转量和纬向走滑量及其误差,正(负)分别代表顺时针(逆时针)旋转和向北(南)纬向运动. Reference pole 为计算时所采用的古地磁参考极.

* 代表未通过本文筛选标准的古地磁数据;⋆代表样品的块数;a 代表两个点的平均;b 数据源自[53];c 火山岩数据.

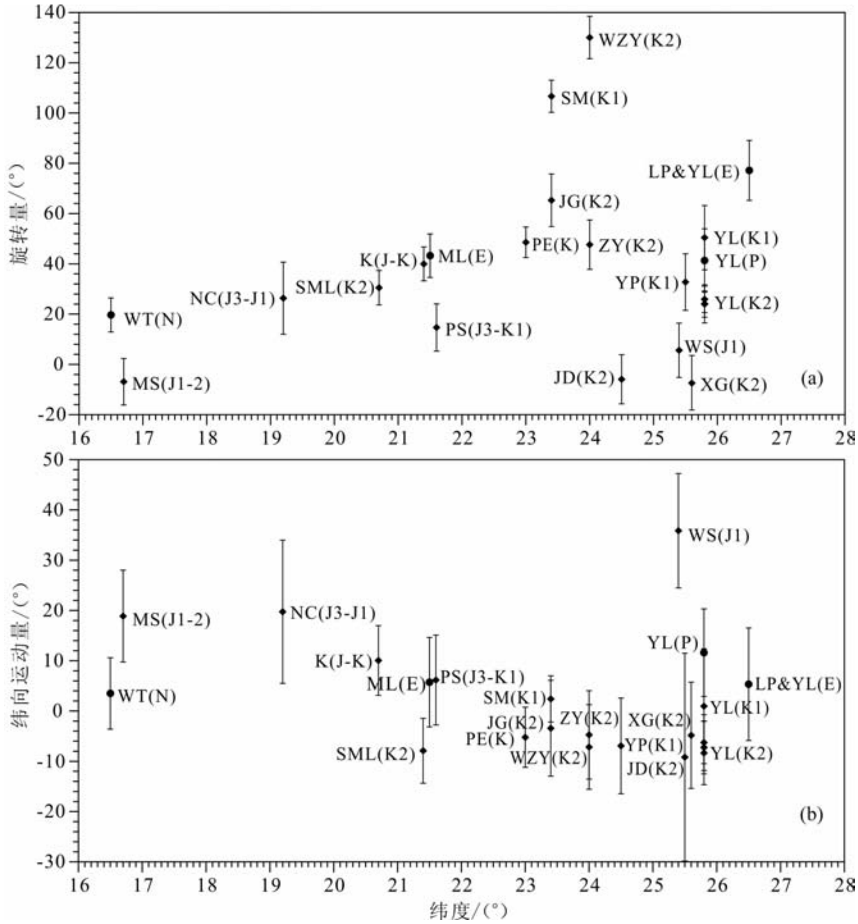

图 2　山泰地块相对欧亚大陆的旋转和纬向运动.图中菱形和实心圆圈分别代表中生代和新生代古地磁结果；条形棒代表 95%置信区间内的误差；括号外字符为采样点名称缩写，括号内为样品时代.

MS：Mae Sot；NT：泰国北部；SML：勐腊南部；ML：勐腊；PS：Phong Saly；JG：景谷；SM：思茅；ZY：镇沅；WZY：镇沅西；YP：永平；YL：云龙；JD：景东；XG：下关；L & S：兰坪及思茅. N：新近纪；P：古新世 E：始新世；K：白垩纪；K2：晚白垩世；K1：早白垩世；J：侏罗纪；J3：晚侏罗世 J2：中侏罗世；J1：早侏罗世

Fig. 2 Relative rotation and latitudinal displacement of the Shantai terrane respect to the Eurasian plate. Diamonds and circles represent Mesozoic and Cenozoic paleomagnetic results, respectively. Error bars represent 95% confidence intervals. The labels represent the abbreviation of sampling localities and ages are given in parenthesis.

MS：Mae Sot；NT：Northern Thailand；SML：Southern Mengla；ML：Mengla；PS：Phong Saly；JG：Jinggu；SM：Simao；ZY：Zhengyuan；WZY：West Zhengyuan；YP：Yongping；YL：Yunlong；JD：Jingdong；XG：Xiaguan；L& S：Lanping and Simao. N：Neogene；P：Paleocene；E：Eocene；K：Cretaceous；K2：Late Cretaceous；K1：Early Cretaceous；J：Jurassic；J3：Upper Jurassic；J2：Middle Jurassic；J1：Lower Jurassic.

南缘局部地区构造背景的差异性有关，比如思茅地体中部发育大量左行走滑断裂，而呵叻高原则相对为一刚性的整体.下关、景东、Mae Sot、Song Da 等地区古地磁结果表明其相对欧亚大陆无显著的构造旋转.进一步分析发现上述地区，古地磁采样剖面均非常靠近走滑断裂带（见图 1），其不旋转或者旋转量很小可能是受走滑断层的影响[127-128]，也有可能是这些走滑断层作为差异性旋转的解耦带，本身并没有旋转[64].

目前，仅有山泰地块白垩纪和印支地块部分白垩纪古地磁数据反映白垩纪以来其相对欧亚大陆经历了约 800 km 的南向移动，这一方面可能是印支和川滇地块白垩纪数据太少，另一方面也可能是印支地块并非作为一个整体发生走滑逃逸，只有部分地块发生了挤出逃逸的缘故；比如最新研究发现，印支地块最南端的 Kontum 块体白垩纪之后，同样相对于欧亚大陆发生了 9.2°±4.9°的南向移动[129].山泰地块的挤出边界为哀牢山—红河断裂，而印支地块的挤出边界则位于 Song Ma 断裂以西[70,130-131].这一结果表明走滑逃逸模式在适用范围上有其局限性，而完全否认走滑发生的地壳增厚模式同样也有局限性.

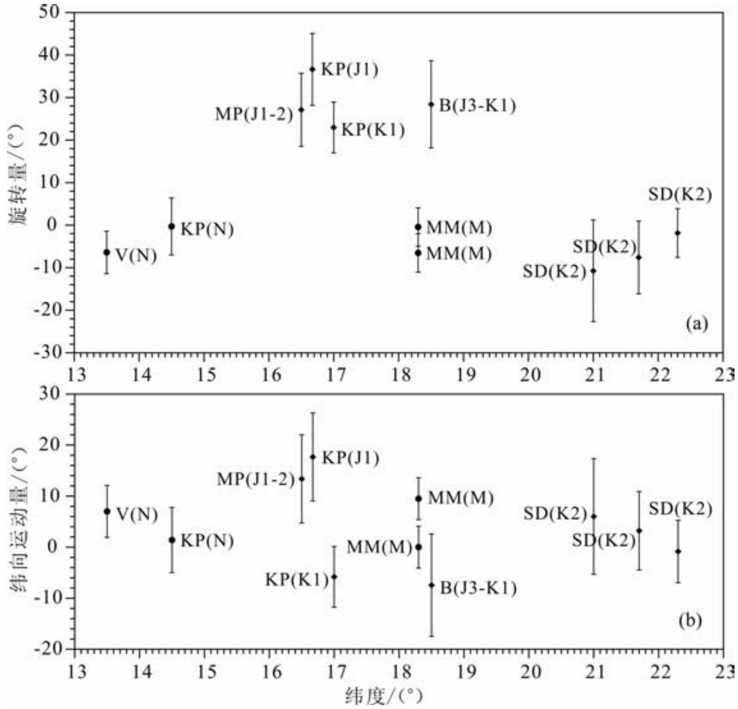

图3 印支地块相对欧亚大陆的旋转和纬向运动
KP：呵叻高原；NT：泰国北部；B：Borikhanxay；SD：Song Da；MP：Muang Phin；MM：Mae Moh；V：越南. 其余同图2.
Fig. 3 Relative rotation and latitudinal displacement of the Indochina terrane relative to the Eurasian plate. The symbols and labels are the same as in Fig. 2.

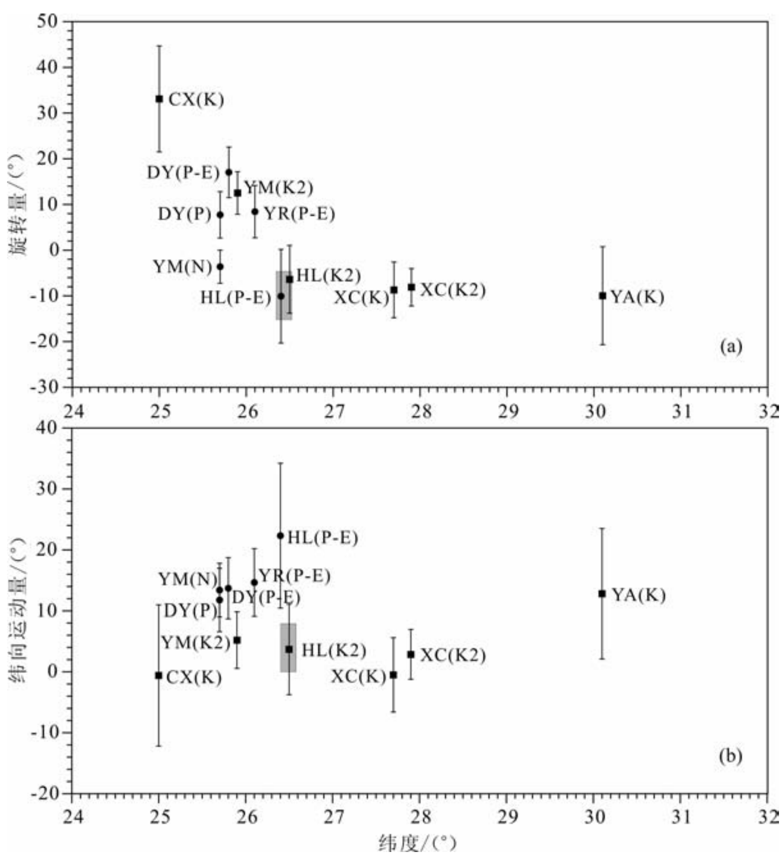

图4 川滇地块相对欧亚大陆的旋转和纬向运动. 灰色矩形框代表鲜水河—小江断裂带的位置.
CX：楚雄；DY：大姚；YM：元谋；HL：会理；YA：雅安；XC：西昌. 其余同图2.
Fig. 4 Relative Rotation and Latitude displacement of Chuandian terrane respect to the Eurasian block. The grey rectangle represents the location of XSHF.
CX: Chuxiong; DY: Dayao; YM: Yuanmou; HL: Huili; YA: Ya'an; XC: Xichang. The rest symbols and labels are the same as in Fig. 2

此外，无论是山泰地块还是印支地块，其侏罗纪和新生代古地磁结果都显示其相对欧亚大陆发生了大规模的北向运动. Achache and Courtillot[132]对呵叻高原晚三叠的古地磁研究得出印支地块晚三叠世相对欧亚大陆存在 1650±850 km 的北向位移，这与本文的结果(～15°)基本一致. 印支和山泰地块侏罗纪的北向运动有两种可能：

其一，由于印支、山泰地块和华南板块在侏罗纪以前已经碰撞拼合完毕[133]，而华南、华北板块在晚侏罗世才拼合为一个整体[134-135]，华南、华北与西伯利亚直至早白垩世才完全拼合成为一个整体[136]，所以印支、山泰地块的北向运动可能是其与华南板块一起北向运动与华北板块在晚侏罗世完成碰撞拼合，或者是印支地块与华南、华北地块一起北向运动与西伯利亚板块发生碰撞拼合.

其二，山泰地块和印支地块在侏罗纪时尚未与华南地块完全拼合，在侏罗—白垩纪时其处于拉萨和羌塘地块之间，新生代时由于印度与欧亚大陆的碰撞走滑逃逸至现今位置[56]. 目前尚没有更多的证据表明哪一种原因更有可能，因此需要更多的中生代古地磁数据以确定青藏高原东南缘各个微板块与华南大陆的拼合历史.

新生代印支、山泰和川滇地块相对欧亚大陆大规模向北运动与现有地质背景相矛盾，造成这种矛盾的原因可能有很多，但一种最可能的解释是新生代沉积物受到了倾角浅化的影响而没有实际构造意义. 事实上，新生代沉积物磁倾角浅化现象在新生代快速沉积的中亚地区非常普遍[137-144]. 可靠的新生代火山岩的古地磁资料也许是解决这一问题的关键[139,143].

另一方面，为反映青藏高原东南缘构造旋转量随时间的变化，我们把所有可靠古地磁结果投影在时间坐标系内(图 5)，发现青藏高原东南缘整体经历了 30°～40°的顺时针旋转，局部地区的旋转量高达 100°以上. 侏罗纪到古新世-始新世所记录的构造旋转量几乎没有显著区别，说明青藏高原东南缘构造旋转发生在始新世以来；同时，地层时代分别为 14.1～12.0 Ma 的 Mae Moh 盆地和～5 Ma 的元谋盆地未观察到明显的构造旋转[73,146-147]，这很可能说明青藏高原东南缘构造旋转主要发生在始新世—中中新世之间. 这一旋转时间和哀牢山—红河断裂左行走滑时间相一致，而中中新世以后无明显的构造旋转与 GPS 观测现今较低的走滑速率相一致，说明青藏高原东南缘主要的走滑逃逸和旋转发生在中中新世以前. Dupont-Nivet 等[148]对青藏高原东北缘西宁—兰州盆地古地磁研究同样得出西宁—兰州盆地的构造旋转发生在始新世—中新世之间. 如果上述结论正确的话，则意味着西宁一兰州盆地所代表的青藏高原东北缘与青藏高原东南缘在新生代拥有同样的旋转历史. 然而，这一推论正确与否仍有待于进一步研究.

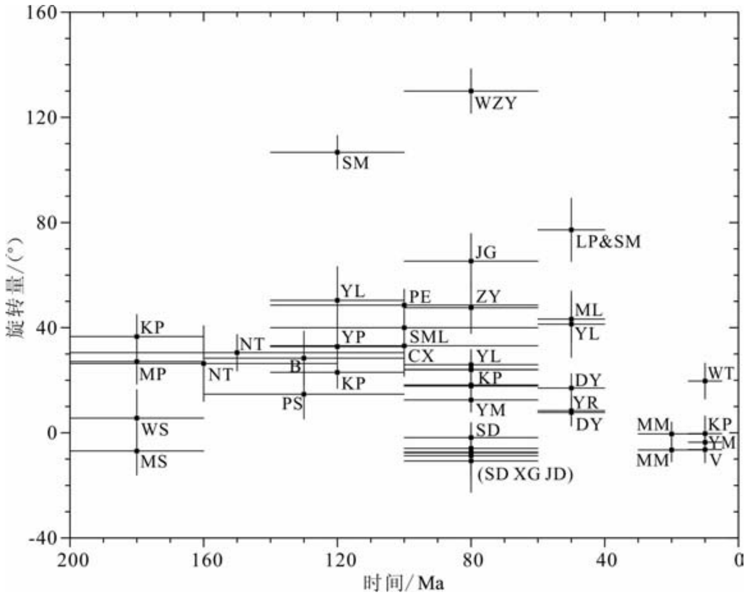

图 5　青藏高原东南缘相对欧亚大陆旋转量随采样时间的变化. 字符代表采样点名称的缩写(同图 2,3,4). 竖直和水平细线分别代表在 95%置信区间内旋转量的误差和采样地层的时间跨度范围(见表 1).

Fig. 5　Observed relative rotations of the southeastern margin of the Tibetan plateau with respect to the Eurasian block as a function of age. The labels represent the abbreviation of sampling localities (same as Figs. 2, 3 and 4). Vertical and horizontal thin lines represent 95% confidence intervals in rotation and uncertainty in age or age span (see Table 1).

首先,迄今为止仍没有地质证据表明青藏高原东北缘与东南缘在新生代具有共同的构造演化史.其次,相比于东北缘,青藏高原东南缘新生代古地磁数据还非常少.而且Mae Moh盆地和元谋盆地的古地磁结果均来自磁性地层学的结果,这些结果所揭示的构造旋转样式和旋转量能否适用于采样剖面之外的块体,仍值得进一步研究.特别是区域范围内普遍缺少始新世—中新世古地磁数据,使得上述推论缺少直接证据;此外,青藏高原东南缘新构造运动非常复杂,不仅可划分为印支、山泰和川滇等多个次级地块,而且地块内部断层交错、变形强烈,基本不具有刚性块体的特点,因而为数不多的几个采点或采样剖面很难客观地描述整个块体的运动学特征.因此,尽管到目前为止青藏高原东南缘已经积累了不少古地磁数据,但是未来对该地区的古地磁研究,尤其是新生代古地磁研究,仍然亟需加强.

5 结 论

5.1 印支、山泰、川滇地块新生代以来相对欧亚大陆发生了显著的差异性顺时针旋转;山泰地块南向运动显著.

5.2 靠近走滑断层一般没有明显的旋转,这说明走滑断层可能是差异性旋转的解耦带.

5.3 侏罗纪古地磁结果暗示欧亚大陆在晚侏罗纪以后在动力学意义上才成为一个整体;而新生代古地磁结果所揭示的青藏高原东南缘相对欧亚大陆的北向位移则可能是沉积物磁倾角浅化所致.

值得注意的是现有青藏高原东南缘古地磁数据还很匮乏,尤其是晚新生代古地磁数据.因此,进一步对新生代地层开展深入细致的古地磁学研究,对更好地理解印度与欧亚大陆碰撞对青藏高原东南缘的影响具有重要的科学意义.

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