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“V”型共轭走滑断裂:特征、形成机制及其对青藏高原东南缘晚新生代变形的启示

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摘要:“V”型共轭走滑断裂是指共轭角为钝角的共轭走滑断裂,其“V”型开口方向为锐角且指示最大拉伸方向。前人开展了大量关于“V”型共轭走滑断裂发育背景及动力学机制的研究,但是目前未有针对“V”型共轭断裂几何学、运动学有关的综述。归纳已有“V”型共轭走滑断裂的几何学、运动学特征,总结现存的“V”型共轭走滑断裂的动力学机制,并选取青藏高原东南缘“V”型共轭走滑断裂,进行实例分析。分布于美国西部、欧亚板块中西部和西藏中部的“V”型共轭走滑断裂特征揭示共轭角大小与断裂滑动速率及断裂长度均呈负相关关系。“V”型共轭走滑断裂的成因主要有:(1)断裂剪切面的后期旋转,(2)断裂形成于先存构造薄弱带,(3)断裂遵循对偶一般剪切模型,(4)断裂遵守最大有效力矩法则。基于地球物理数据、地形高差对比以及几何特征的分析,认为青藏高原东南缘川滇块体内部的巴塘—理塘共轭走滑断裂和得荣—乡城共轭走滑断裂的成因机制符合对偶一般剪切模型中的重力扩展,这为理解青藏高原东南缘下地壳连续变形的动力学机制提供了重要启示。

关键词:“V”型共轭走滑断裂;几何学;运动学;成因机制;青藏高原东南缘;构造地质学。

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V-Shaped Conjugate Strike-Slip Faults: Characteristics, Formation Mechanisms and Implications for the Late Cenozoic Deformation in the Southeastern Tibetan Plateau

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Abstract: The V-shaped conjugate strike-slip fault system is defined as strike-slip faults with obtuse conjugate angles, whose opening side has an acute angle between the V-shaped faults, pointing to the direction of maximum extension. Previous studies on V-shaped conjugate strike-slip faults mostly focused on their development background and associated dynamic mechanisms. However, few literatures exist to comprehensively review the geometry and kinematics of V-shaped conjugate strike-slip faults. Here, we firstly summarize previous findings on the geometry, kinematic characteristics and formation mechanisms of existing V-shaped conjugate strike-slip faults, and then select the V-shaped conjugate strike-slip faults in the southeastern Tibetan Plateau for a case analysis. The characteristics of V-shaped conjugate strike-slip faults in the western United States, central and western Eurasian plate and central Tibet show a negative relation among conjugate angles and corresponding fault slip rates and fault lengths. The four formation mechanisms of the V-shaped conjugate strike-slip faults are 1) the fault planes experienced rotation after their formation, 2) the faults were reactivated along preexisting structurally weak zones, 3) the faults followed the paired general shear model and 4) the fault evolved according to the maximum-effective-moment criterion. Integrating analyses of geophysical data, elevation difference and geometric characteristics, we infer that the development of V-shaped conjugate strike-slip faults (Batang-Litang and Derong-Xiangcheng faults) in the Chuan-Dian block in the southeastern Tibetan Plateau, is consistent with gravitational spreading of the Tibetan lithosphere under the paired general shear model. This provides important insights for understanding the continuum crustal deformation in the southeastern Tibetan Plateau.

Key words: V-shaped conjugate strike-slip faults; geometry; kinematics; formation mechanism; southeastern Tibetan Plateau; structural geology.

0 引言

走滑断裂作为3种主要断裂类型(逆冲、正断和走滑)之一,可以协调块体之间以及块体内部构造变形及运动,如土耳其的安纳托利亚断裂、青藏高原内部上千千米级别的大型走滑断裂(阿尔金、海原、昆仑、甘孜—鲜水河—小江、红河、缅甸实皆断裂等)、美国的圣安德烈斯断裂、阿富汗的查曼断裂以及新西兰的阿尔卑斯断裂等(Şengör and Kidd, 1979; Xu *et al.*, 2003; 李海兵等, 2006; Molnar and Dayem, 2010; 许志琴等, 2011; Norris and Toy, 2014; Dixon and Xie, 2018; Chen *et al.*, 2022)。

在走滑断裂的几何学分类中,“V”型共轭走滑断裂是一种特有的类型。不同于安德森模式所预测的锐角,“V”型共轭走滑断裂面向最大主压应力方向的夹角为钝角(如 Leedal and Walker(1954)测得了苏格兰右旋走滑断裂和左旋走滑断裂之间角度为 132°),而“V”型开口方向为锐角,指示最大拉伸方向。其在碰撞造山带广泛发育,例如阿尔卑斯山东部、土耳其、阿富汗、西藏、蒙古、印支半岛和泰国湾(Yin and Taylor, 2011)。相似的构造也出现在俯冲带,如委内瑞拉—安第斯共轭断裂(Yin and Taylor, 2011)。对于一些发育尚不成熟的断裂,在断裂内部所发生的地震主震和余震序列在空间上也可能显示出非安德森模式的几何形态,如发生在2019年美国加利福尼亚 Ridgecrest 地区的 $M_w 7.1$ 主震和 $M_w 6.7$ 前震所控制的地表破裂(DuRoss *et al.*,

2020; Fialko and Jin, 2021)以及2014年5月泰国清莱 $M_w 6.2$ 主震和余震序列(Pananont *et al.*, 2017)在空间上均显示出“V”型的几何形态。虽然“V”型共轭走滑断裂的运动学及成因机制对了解区域构造变形及区域动力学机制有着重要作用,但是对这种特殊的断裂组合类型还未引起足够的重视。

本文将对“V”型共轭走滑断裂的特征、分布及构造背景、成因机制做出归纳总结,并引入青藏高原东南缘“V”型共轭走滑断裂实例,即以巴塘—理塘共轭走滑断裂为主的两组共轭走滑断裂,分析它们的几何形态及构造变形,试图从成因机制的角度探讨“V”型共轭走滑断裂对于青藏高原东南缘区域构造动力学的启示意义。

1 “V”型共轭断裂的特征

1.1 共轭走滑断裂的定义

共轭走滑断裂是在同一应力场下同时活动并相交的两条走滑断裂形成的共轭体系(Fossen, 2016)。在运动学上,共轭走滑断裂形成于水平方向上的纯剪切,其中最大主应力(σ_1)方向上的缩短通过与其正交方向上最小主应力方向(σ_3)的延伸进行补偿(图1)。在这个理想模型中,中间主应力方向(σ_2)不发生伸展或压缩(Fossen, 2016)。共轭走滑断裂符合库伦破裂准则,断裂面与最大主应力方向(σ_1)之间的夹角 θ_0 的大小,即剪切角取决于岩石内部的摩擦系数,一般小于 45° (Fossen, 2016)。由共

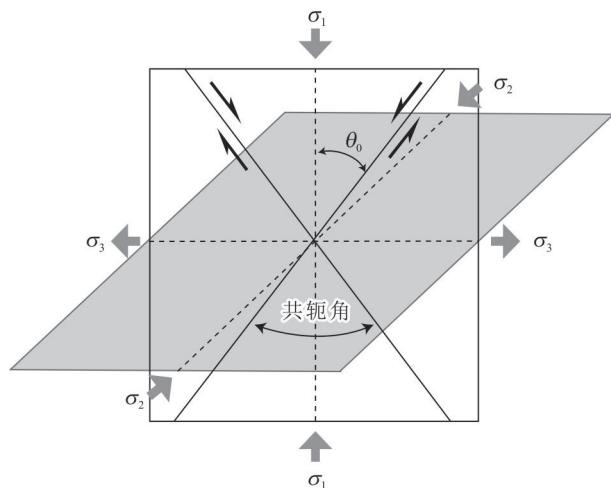


图1 纯剪切共轭走滑断裂模型(据Fossen, 2016修改)

Fig.1 Pure shear conjugate model for the formation of strike-slip faults (modified from Fossen, 2016)

黑色实线表示断裂面；黑虚线表示主应力方向； σ_1 为最大主应力方向； σ_2 为中间主应力方向； σ_3 为最小主应力方向； θ_0 为剪切角

轭剪切带(或断裂)之间包含最大主应力的夹角，即共轭角，总是锐角(Jaeger and Cook, 1979).

1.2 “X”型共轭走滑断裂特征

在平面上呈现“X”型样式的称为“X”型共轭断裂.“X”型共轭走滑断裂的形成符合摩尔—库伦破裂准则(Jaeger and Cook, 1979; Thatcher and Hill, 1991).其共轭角为锐角，剪切角小于45°.剪切角的大小可以根据摩尔—库伦破裂准则计算得出.当断裂面上的剪切应力等于断裂滑动摩擦力时，断裂开始发生滑动.断裂面上剪切应力与滑动摩擦力的关系式(Thatcher and Hill, 1991):

$$\tau = \tau_0 + \mu(\sigma_n - P), \quad (1)$$

式中： τ 为断裂面上的剪切应力； τ_0 为抗纯剪断裂极限，也称岩石的内聚力； μ 为岩石的内摩擦系数； σ_n 为作用于该剪切面上的正压力； P 为孔隙压力.在发生破裂或滑动时，两个共轭断裂面垂直于包含最大主应力和最小主应力(σ_1 和 σ_3)的平面，相交于中间主应力(σ_2)，两个断裂面与 σ_1 的交角为± θ_0 (图1). θ_0 (剪切角)的大小表达式如公式(2)

$$\theta_0 = 45^\circ - \frac{1}{2} \tan^{-1} \mu, \quad (2)$$

式中：岩石内摩擦系数 μ 为正数，因此 θ_0 剪切角永远小于45°.而实验室推导岩石内摩擦系数 $\mu=0.6\sim0.9$ (Byerlee, 1978)，表明 $\theta_0\approx25^\circ\sim30^\circ$ ；只有当岩石的内摩擦系数为0或在韧性材料中，剪切角才可等于45°(Liang *et al.*, 2021).

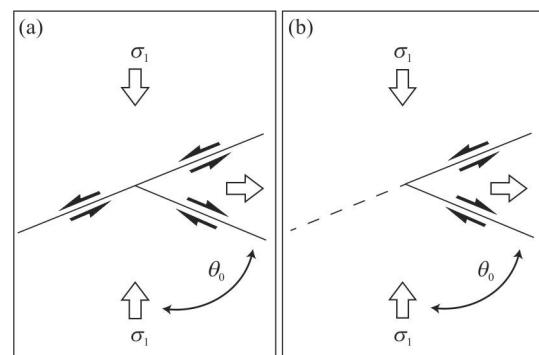


图2 “V”型共轭走滑断裂的几何形态

Fig.2 Geometry of the V-shaped conjugate strike-slip faults
a.两条共轭断裂合并,滑动在合并断裂上继续发生;b.两条共轭断裂运动终止于“V”字型尖端.黑色实线为走滑断裂, σ_1 为最大主应力,箭头指示应力方向; θ_0 为剪切角

1.3 “V”型共轭走滑断裂特征

与“X”型共轭走滑断裂比较而言，“V”型共轭走滑断裂的剪切角 θ_0 大于45°，共轭角为钝角，而其开口方向为锐角且指示最大拉伸方向，在平面上呈现“V”型.主要表现为两种几何形态(图2):第1种为两条走滑断裂在交汇点合并，滑动在合并的断裂上继续发生(图2a)，代表性例子为美国的圣安德烈斯—加洛克断裂；第2种为两条共轭断裂的运动终止于断裂的合并点，即“V”型尖端(图2b)，一个典型的例子为西藏中部共轭走滑断裂.

2 典型“V”型共轭走滑断裂的几何学、运动学特征

已有研究开展了大量关于“V”型共轭走滑断裂发育背景及成因机制的研究，认为“V”型共轭走滑断裂主要分布在碰撞造山带，在协调大陆构造逃逸变形中起着重要作用.但是目前未有针对“V”型共轭断裂几何学、运动学有关的综述.这里作者选取几个典型的代表分别对其构造背景、几何学及运动学特征予以阐述，它们分别位于美国西部、欧亚板块中西部和西藏中部.

2.1 圣安德烈斯与加洛克“V”型断裂系

在美国加利福利亚地区南部，右旋走滑的圣安德烈斯断裂(San Andreas Fault)和左旋走滑的加洛克断裂(Garlock Fault)呈“V”型相交，被认为是一组共轭的活动断裂(Platt and Passchier, 2016)，在区域上适应南北向缩短和东西向拉伸(图3a)(Hill and Dibblee, 1953; Wellman, 1954; Freund, 1970).

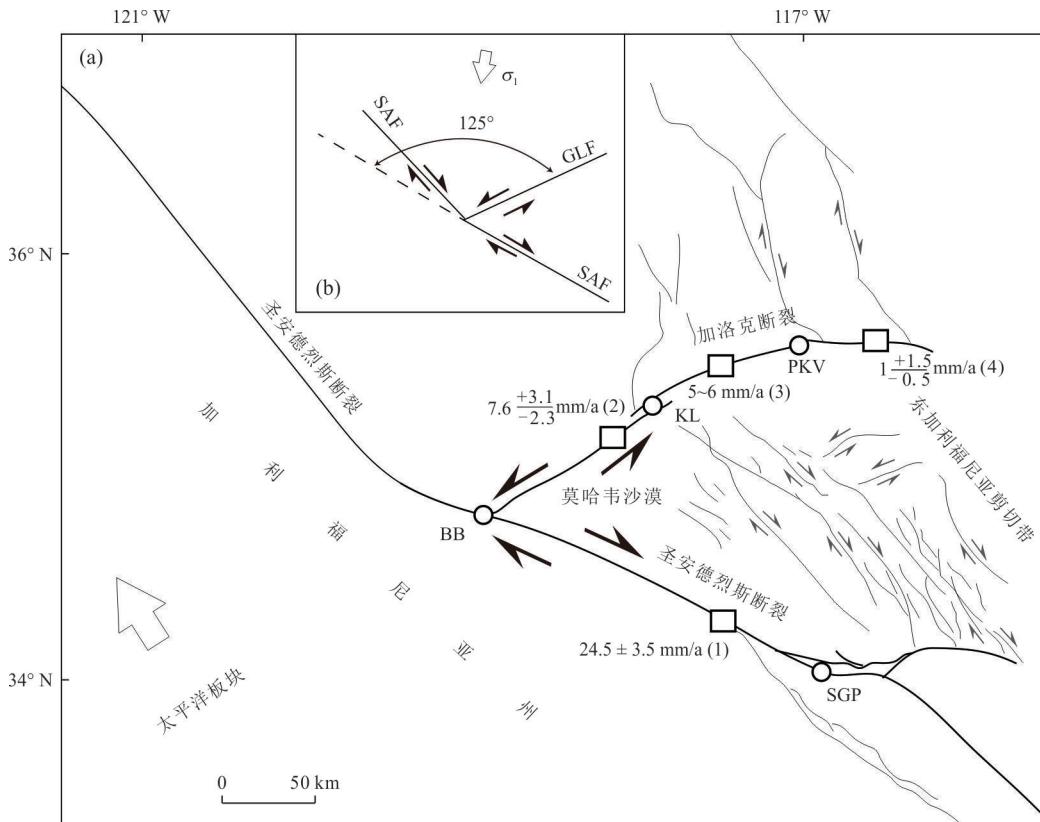


图3 圣安德烈斯—加洛克共轭走滑断裂示意图(a)及其轭角示意图(b)(改自 Hatem and Dolan, 2018)

Fig.3 Sketch map of the San Andreas-Garlock conjugate strike-slip fault system (a) and the conjugate angle (b) (modified from Hatem and Dolan, 2018)

BB.“大弯曲”;GLF. 加洛克断裂;KL. Koehn 湖;PKV. Pilot Knob 山谷;SAF. 圣安德烈斯断裂;SGP. 圣戈尔戈尼奥山口;白色方框为前人晚第四纪滑动速率(mm/a)位置:(1) Cooke and Dair (2011);McGill *et al.* (2013). (2) McGill *et al.* (2009). (3) McGill and Sieh (1993); Ganev *et al.* (2012);Crane (2014);Dolan *et al.*(2016). (4) Crane (2014)

圣安德烈斯断裂与加洛克断裂所加持的莫哈韦块体(Mojave Block)从太平洋—北美板块沿着圣安德烈斯断裂受阻弯曲部位向东侧向挤出(McGill *et al.*, 2009)。从遥感影像上看,圣安德烈斯—加洛克断裂共轭角为 125° (图3b)。

在几何运动学上,右旋走滑的圣安德烈斯断裂从美国—墨西哥边境附近延伸到加利福尼亚州门迪西诺角西北部,作为转换断裂以协调西南部太平洋板块和东北部北美板块的相对运动(Catchings, 2002)。圣安德烈斯断裂全长 1100 km ,以“大弯曲”(Big Bend)为界,分为北段和东南段。本文主要讨论断裂东南段与加洛克断裂共轭的部分。该段全长 250 km ,走向NW-SE,以“大弯曲”(Big Bend)和圣戈尔戈尼奥山口(San Gorgonio Pass)为边界(图3a)。自 16 Ma 以来,圣安德烈斯断裂岸上部分累计滑动位移约为 $315 \pm 10\text{ km}$ (Dickinson and Wernicke, 1997)。在滑动速率方面,圣安德烈斯断裂东

南段晚第四纪滑动速率为 $24.5 \pm 3.5\text{ mm/a}$ (Cooke and Dair, 2011;McGill *et al.*, 2013),现今滑动速率为 $16.3 \pm 0.8\text{ mm/a}$ (Loveless and Meade, 2011)。圣安德烈斯断裂的东南段在历史上(250年以来)未有大地震发生,研究认为断裂的东南段可能正处于地震周期震间阶段(Fialko, 2006)。

加洛克断裂是全长约 255 km 的左旋走滑断裂,横跨加利福尼亚州一半的长度(Hatem and Dolan, 2018)。断裂沿其走向被分为3段:西段长约 100 km ,从加洛克断裂与圣安德烈斯断裂的交汇点延伸至Koehn湖,走向 $\sim 60^\circ$;中段长约 90 km ,从Koehn湖延伸至Pilot Knob山谷东端,走向 $70^\circ \sim 80^\circ$;东段长约 65 km ,从Pilot Knob山谷东端延伸至加洛克断裂末端(Hatem and Dolan, 2018)。断裂开始滑动时间在 $17 \sim 10\text{ Ma}$ 之间(Burbank and Whistler, 1987; Loomis and Burbank, 1988;Monastero *et al.*, 1997; Andrew *et al.*, 2015;Dolan *et al.*, 2016)。根据基岩

位错量,加洛克断裂累计位移48~64 km(George, 1962; Davis and Burchfiel, 1973).在滑动速率方面,沿着断裂走向,断裂西部晚第四纪西部滑动速率为 $\sim 7.6 \frac{+3.1}{-2.3} \text{ mm/a}$ (McGill *et al.*, 2009),中部滑动速率为5~6 mm/a(McGill and Sieh, 1993; Ganey *et al.*, 2012; Crane, 2014; Dolan *et al.*, 2016),东部滑动速率为 $\sim 1 \frac{+1.5}{-0.5} \text{ mm/a}$ (Crane, 2014).古地震学研究结果表明,加洛克断裂产生了震级较大的全新世晚期地表破裂地震(Dawson *et al.*, 2003).因此,综合上述总结对比发现,圣安德烈斯断裂与加洛克断裂在滑动速率上差异显著.

2.2 北安纳托利亚与东安纳托利亚“V”型断裂系

新生代以来,阿拉伯板块相对于欧亚板块向北运动与之发生碰撞,导致安纳托利亚块体(Anatolian Block)沿着北安纳托利亚断裂(North Anatolian Fault)和东安纳托利亚断裂(East Anatolian Fault)向西逃逸(Sylvester, 1988),形成具有大陆岩石圈尺度的“逃逸楔”.从图4a上看,北安纳托利亚断裂和东安纳托利亚断裂在安纳托利亚块体东北部组成共轭走滑断裂系(Barka and Kadinsky-Cade,

1988; Khalifa *et al.*, 2018).其交汇位置为卡尔勒奥瓦三联点(Karliova Triple Junction),在三联点的西侧发育的卡尔勒奥瓦盆地,被认为是伸展作用的结果(Chorowicz *et al.*, 1999).该共轭走滑断裂系(图4b)的共轭角为135°(Zheng *et al.*, 2011).

在几何运动学上,北安纳托利亚断裂主要表现为右旋走滑特征(Köküm and İnceöz, 2018),以调节安纳托利亚块体和黑海板块之间的相对运动.在空间上,该断裂从卡尔勒奥瓦三联点延伸至希腊大陆,全长约1 200~1 500 km,并沿断裂走向呈现不连续的几何特征(Tatar *et al.*, 2012).总体来说,北安纳托利亚断裂从东向西逐渐变宽,本次研究仅探讨北—东安纳托利亚断裂共轭部分,即卡尔勒奥瓦三联点至塔绍瓦地区(Tasova)之间(图4a),该段长度约340 km.该断裂的启动时间范围在晚中新世—上新世(Ketin, 1969; Barka and Hancock, 1984; Şengör *et al.*, 1985),断裂走滑位移为15~120 km.北安纳托利亚断裂的滑动速率体现为:百万年尺度上为6.5 mm/a(Hubert-Ferrari *et al.*, 2002),晚第四纪时间尺度上为 $18.6 \pm 3.5 \text{ mm/a}$ (Kozaci *et al.*, 2009),而现今大地测量分析所得滑动速率更高,为20~24 mm/a(Wright *et al.*, 2001; Tatar *et al.*,

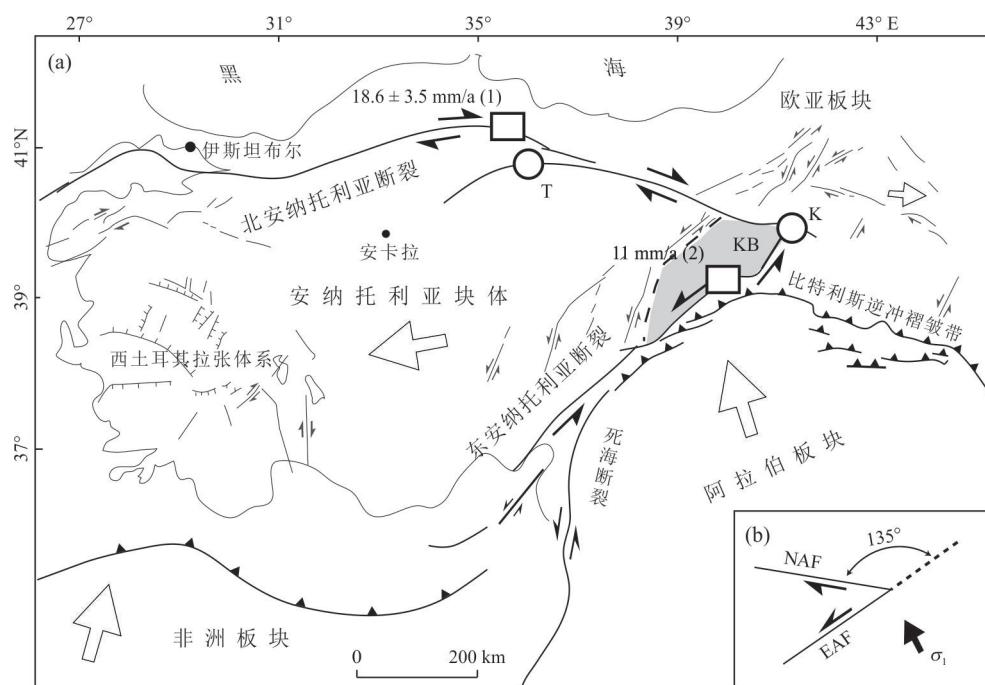


图4 安纳托利亚块体及邻区主要构造单元(改自Barka and Kadinsky-Cade, 1988)

Fig.4 Major tectonic elements of Anatolian block and adjacent area(modified from Barka and Kadinsky-Cade, 1988)

a.北安纳托利亚断裂和东安纳托利亚断裂交汇在卡尔勒奥瓦三联点(K),西侧为卡尔勒奥瓦盆地(KB.Karliova Basin).白色方框为前人晚第四纪滑动速率(mm/a)位置:(1) Kozaci *et al.* (2009);(2) Cetin *et al.* (2003);b.北—东安纳托利亚共轭走滑断裂共轭角为135°.EAF.东安纳托利亚断裂;NAF.北安纳托利亚断裂;T.塔绍瓦地区

2012; Walters *et al.*, 2014).滑动速率表现出逐渐增大的趋势.在 1939—1967 年之间,该断裂的活动产生了 6 次大型地震,形成了埃尔津坎(Erzincan)到西部穆杜努谷(Mudurnu Valley)($39.5^{\circ}\text{E} \sim 31^{\circ}\text{E}$)的连续地表破裂,沿该断裂的震源机制大都显示纯右旋走滑解(Ketin, 1969; Ambraseys, 1970; Barka and Kadinsky-Cade, 1988).

东安纳托利亚断裂表现为左旋走滑特征,它调节了安纳托利亚块体与阿拉伯板块的相对运动.在空间上,该断裂从卡尔勒奥瓦三联点延伸至地中海,全长 400 km,并由一系列不连续的断裂段组成(Khalifa *et al.*, 2018; Köküm and İnceöz, 2018).断裂的启动时间被认为是上新世(Arpat and Saroglu, 1972),总位移在 22~27 km.东安纳托利亚断裂在滑动速率方面,晚第四纪滑动速率为 11 mm/a(Ce-tin *et al.*, 2003),现今 GPS(Global Position System)及 InSAR(Interferometric Synthetic Aperture Radar)数据分析所得滑动速率为 8~13 mm/a(Walters *et al.*, 2014; Aktug *et al.*, 2016).大地测量学和地质学方法得到的滑动速率具有一致性.

北—东安纳托利亚共轭断裂在启动时间上相近,而北安纳托利亚断裂在位移规模与滑动速率上稍大于东安纳托利亚断裂.从滑动速率上看,北安纳托利亚断裂的大地滑动速率与地质滑动速率具有不一致性,而东安纳托利亚断裂在这两种尺度的滑动速率上则体现出一致性.

2.3 赫拉特与查曼“V”型断裂系

印度板块和欧亚板块的碰撞塑造了中亚地区现今的构造格局,并形成了跨越阿富汗的一系列大型走滑断裂,以调整印度板块与阿拉伯板块北向欧亚板块的挤压变形(Shnizai *et al.*, 2020).其中,赫拉特右旋走滑断裂(Herat Fault)与查曼左旋走滑断裂(Chaman Fault)在阿富汗北部组成一组共轭走滑断裂系(图 5a),共同调节印度—欧亚板块的碰撞运动.两者交角的锐角指向拉伸方向,在平面上呈现开口向西的“V”字型特征(Yin and Taylor, 2011),其共轭角大小为 130° (图 5b).

赫拉特断裂是一条主要的大陆缝合线,将北部相对稳定、轻微变形的欧亚大陆与南部广泛变形的地台分割.在几何运动学上,赫拉特断裂北起与查曼断裂的交汇点喀布尔东北侧,向西延伸至伊朗边界,全长 730 km,在阿富汗北部地台向西挤压的过程中扮演着重要角色(Boyd *et al.*, 2007; Ruleman

et al., 2007).分布在断裂周缘狭长的渐新世—中新世沉积物表明断裂在这一时期仍处于活跃阶段.中新世后,沉积物没有发生明显的位移,表明该断裂在现阶段可能不再活跃,虽然断裂在第四纪地貌中仍有明显的表现,但 Tapponnier *et al.*(1981)认为目前的右旋位移仅发生在赫拉特断裂北部与之相互平行次级断裂.赫拉特断裂地质滑动速率为 2~3 mm/a(Mohadjer *et al.*, 2016),大地测量滑动速率为 <2 mm/a(Mohadjer *et al.*, 2010).

查曼断裂是中亚最大和最活跃的走滑断裂之一,显示出左旋走滑的特征,吸收了阿富汗西南部和巴基斯坦地区由于板块碰撞引起的地壳变形(Shnizai *et al.*, 2020).查曼断裂全长 860 km,走向 $N10^{\circ}\text{--}35^{\circ}\text{E}$,标志着卡塔瓦兹(Katawaz)盆地、蛇绿岩带、喀布尔地块和阿富汗中部的边界(Shnizai *et al.*, 2020).在滑动速率方面,百万年尺度上,Lawrence *et al.*(1992)测得查曼断裂自 25~20 Ma 开始滑动以来的滑动速率为 19~24 mm/a. Shnizai *et al.*(2020)通过位错的冲积扇测得查曼断裂北段的更新世滑动速率为 3.5~4.5 mm/a. 现今尺度上,Mohadjer *et al.*(2010)使用 GPS 和 InSAR 测得断裂北段的滑动速率为 18 ± 1 mm/a. 查曼断裂大地测量滑动速率和地质测量滑动速率显示出较大的差异性.且晚第四纪滑动速率从西南向东北方向逐渐降低的趋势,北部较低的滑动速率可能是由于左旋剪切运动被断裂北部的次级断裂所吸收.对比而言,在滑动速率方面,查曼断裂相对于赫拉特断裂较大.

2.4 西藏中部多组“V”型断裂系

新生代以来,印度板块与欧亚板块的持续碰撞造成了青藏高原的隆升及青藏高原内部的大规模陆内变形(Tapponnier *et al.*, 1986).在西藏中部,分布着一个宽 200~300 km、长 1 500~1 800 km,并由一系列共轭走滑断裂组成的断裂带(Yin and Taylor, 2011).所有共轭断裂沿班公—怒江缝合带相交或合并,在班公—怒江缝合线以北,由北东向左旋走滑断裂(布木错断裂、日干配错断裂、和懂错断裂)组成;在该缝合带以南,由北西向右旋走滑断裂(拉木错—纳屋错断裂、格仁错断裂、崩错断裂)组成(Taylor *et al.*, 2003).并且,这些共轭走滑断裂与其北部或南部的南北向裂谷相连,开口均为锐角,指向东侧,对应最大拉伸应力方向 σ_3 ,在区域上调节同时代的东西向伸展和南北向收缩(Taylor *et al.*, 2003),这些断裂的共轭角大小在 $125^{\circ}\text{--}150^{\circ}$ 之间.

图5 欧亚板块中部区域构造图(改自 Shnizai *et al.*, 2020)Fig.5 Regional tectonic map of the central Eurasian plate (modified from Shnizai *et al.*, 2020)

a.赫拉特—查曼共轭走滑断裂图;白色方框为前人晚第四纪滑动速率(mm/a)位置:(1) Mohadjer *et al.*(2016);(2) Shnizai *et al.*(2020). b.赫拉特—查曼共轭走滑断裂共轭角大小

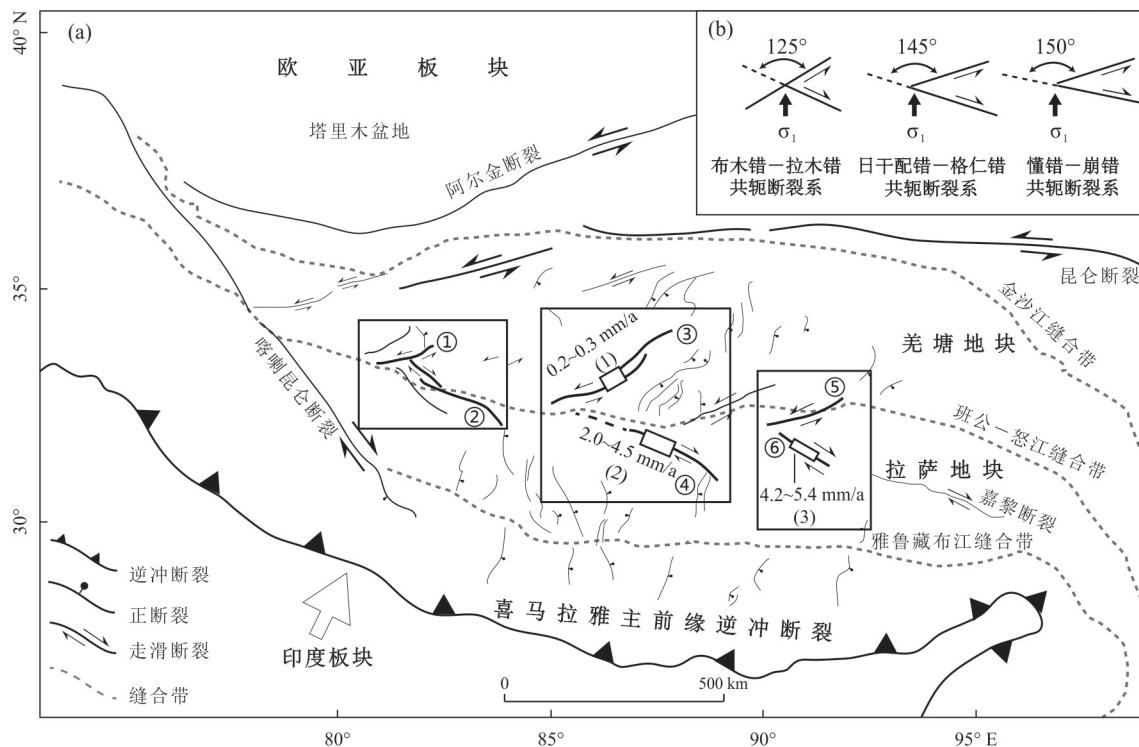
(图6)(Yin and Taylor, 2011).

在几何运动学上, Taylor *et al.*(2003)通过第三纪逆冲断裂和古生代—中生代岩性单元的位错, 得到这些共轭走滑断裂单个断裂的平均走滑位错为 12 km. 由于这些共轭走滑断裂运动学上与南北向的裂谷相连, 以裂谷的起始时间 15~5 Ma(Bian *et al.*, 2020)作为这些断裂走滑运动的起始时间. 本文主要由西向东对其中 3 组共轭走滑断裂系进行总结.

布木错—拉木错—纳屋错共轭走滑断裂系位于西藏中部共轭断裂系的西侧. 布木错断裂走向 N70°E, 为共轭走滑断裂系的北支, 显示出明显左旋走滑特征(Taylor *et al.*, 2003), 全长 120 km. 目前对

于布木错断裂左旋滑动速率的研究缺乏较好的约束(Taylor and Peltzer, 2006). 共轭走滑断裂系的南支是拉木错—纳屋错断裂, 其走向为 N55°W, 具有右旋走滑的特征. 空间上, 拉木错—纳屋错断裂由两段组成: 北段拉木错断裂走向 N50°W, 长约 45 km. 南段纳屋错断裂在卫星地图上呈现曲线状, 长约 170 km, 错断了东西走向的侏罗纪地层(Taylor *et al.*, 2003). InSAR 数据分析得出拉木错—纳屋错断裂的右旋走滑速率为 2~4 mm/a(Taylor and Peltzer, 2006; Wang *et al.*, 2019).

日干配错—格仁错共轭走滑断裂系位于西藏中部共轭断裂系的中部. 从卫星地图上看, 日干配错断裂向南与拉萨块体北部的格仁错右旋走滑断

图 6 西藏中部区域构造图(改自 Taylor *et al.*, 2003)Fig.6 Regional tectonic map of the central Tibet (modified from Taylor *et al.*, 2003)

a.西藏中部共轭走滑断裂系; b.共轭断裂系共轭角大小. ①布木错断裂; ②拉木错—纳屋错断裂; ③日干配错断裂; ④格仁错断裂; ⑤懂错断裂; ⑥崩错断裂. (1)刘富财等 (2022); (2) Shi *et al.* (2014); Wang *et al.* (2021); (3) Hollingsworth *et al.* (2010); Li *et al.* (2022).白色方框为前人晚第四纪滑动速率(mm/a)位置

裂合并. 日干配错断裂为依布茶卡断裂带的南支, 走向 N60°~70°E, 从缝合带附近洞错与扎西错之间延伸至恰岗错, 总长约 360 km (Taylor and Peltzer, 2006; 刘富财等, 2022). 该断裂总位移约为 7~14 km (Taylor *et al.*, 2003). 滑动速率方面, 日干配错断裂晚更新世以来走滑速率为 0.2~0.3 mm/a (刘富财等, 2022), InSAR 数据测得走滑速率为 2.0~6.6 mm/a (Taylor and Peltzer, 2006; Wang *et al.*, 2019). 该共轭断裂系南侧, 格仁错断裂长约 250 km, 走向为 N70°W. 格仁错断裂晚第四纪走滑速率为 2.0~4.5 mm/a (Shi *et al.*, 2014; Wang *et al.*, 2021), 现今大地测量数据为 1~4 mm/a (Wang *et al.*, 2019). 日干配错断裂与格仁错断裂在滑动速率上具有一致性.

懂错—崩错共轭走滑断裂系位于西藏中部共轭走滑断裂系的东部. 懂错断裂位于共轭断裂的北侧, 走向 NE-SW, 具有左旋走滑特征. 懂错断裂活动性较小, InSAR 数据测得懂错断裂的滑动速率为 0.5~2.5 mm/a (Garthwaite *et al.*, 2013; Li *et al.*, 2020). 崩错断裂位于共轭断裂系的南侧, 具有右旋

走滑特征. 其晚第四纪滑动速率为 4.2~5.4 mm/a (Hollingsworth *et al.*, 2010; Li *et al.*, 2022), InSAR 数据显示现今的滑动速率为 1~5 mm/a (Garthwaite *et al.*, 2013; Li *et al.*, 2020). 1951 年和 1952 年, 沿崩错断裂和附近的亚东—吉露裂谷分别发生了 M_w 8.0 和 M_w 7.5 大地震 (Li *et al.*, 2020). 总体来看, 西藏中部共轭断裂系南部断裂的滑动速率稍大于北部断裂的滑动速率.

2.5 “V”型共轭走滑断裂几何学及运动学特征小结

通过对上述 4 个区域共轭走滑断裂系的构造背景、共轭角度及滑动速率总结, 笔者发现这些“V”型共轭断裂系共轭的两支断裂均处在相同的构造应力场下, 启动时间相近, 但在滑动速率上具有不一致性. 上述的“V”型共轭走滑断裂系主要分布在板块碰撞带, 与块体的侧向挤出相关, 包括构造逃逸 (构造楔的水平运动驱动力由施加在其边界的外力驱动) 和伸展塌陷 (重力从造山带的地形高点向外扩散) (Ratschbacher *et al.*, 1991). 对于板块边缘断裂, 如分布在欧亚板块中西部的“V”型共轭断裂系, 数量少但规模大, 断裂延伸长, 并且均与块体逃逸

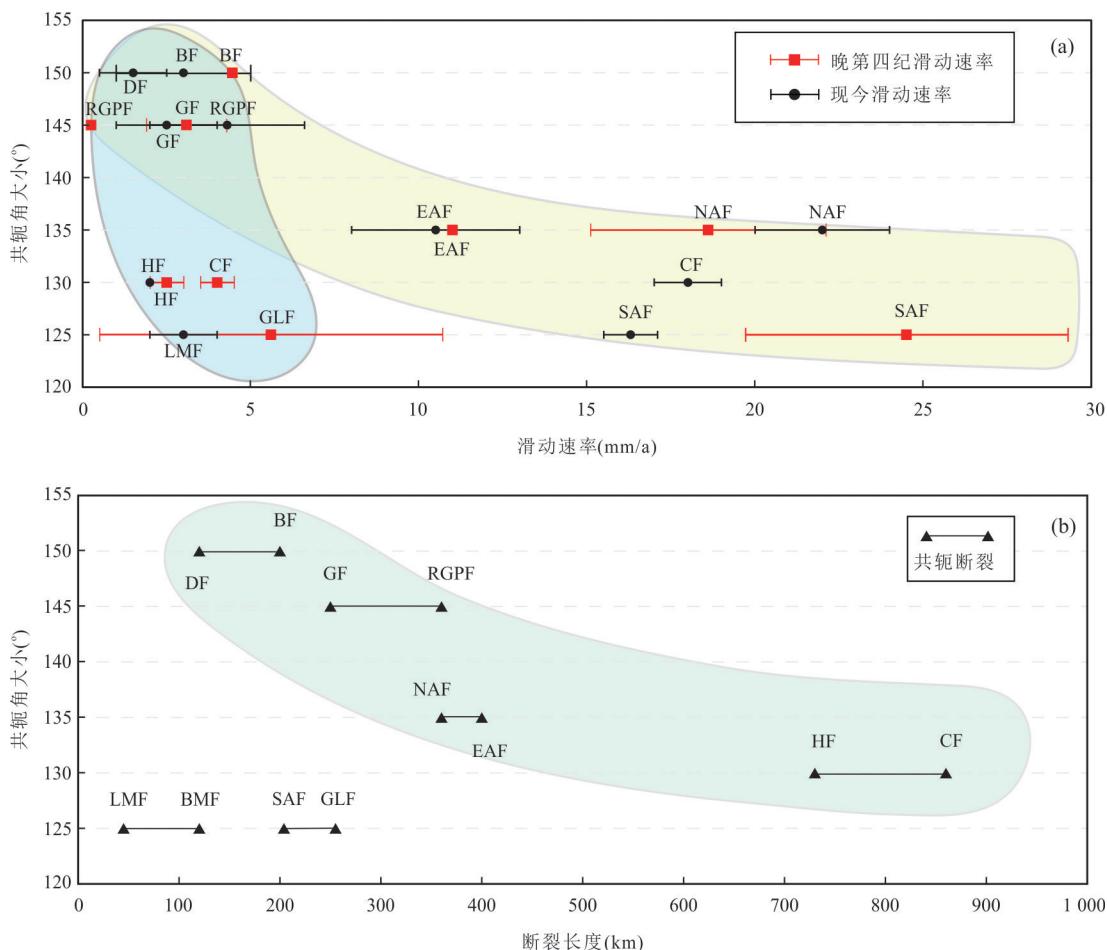


图7 共轭角大小与断裂滑动速率和断裂长度的关系

Fig.7 Relationships between the conjugate angle and the fault slip rate (a) or fault length (b)

a. 共轭角大小与滑动速率关系图；b. 共轭角大小与断裂长度关系图。BF. 崩裂断裂；CF. 查曼断裂；DF. 懂错断裂；EAF. 东安纳托利亚断裂；GF. 格仁错断裂；GLF. 加洛克断裂；HF. 赫拉特断裂；LMF. 拉木错—纳屋错断裂；NAF. 北安纳托利亚断裂；RGPF. 日干配错断裂；SAF. 圣安德烈斯断裂

有关，东安纳托利亚—北安纳托利亚共轭断裂系与安纳托利亚块体逃逸有关，查曼—赫拉特共轭断裂的形成则与北阿富汗地台逃逸有关（Ruleman *et al.*, 2007）；对比而言，分布在板块内部的断裂，如西藏中部的共轭断裂系数量多，但断裂延伸范围较小，无坚硬地台发生逃逸。Yin and Taylor(2011)已有研究推测西藏中部的侧向挤出构造可能与下地壳的连续变形有关。

通过对共轭断裂系的几何学与运动学参数初步分析发现：“V”型共轭走滑断裂共轭角大小与断裂滑动速率呈负相关关系（图7a）。这种关系尤其在断裂滑动速率 $<5\text{ mm/a}$ 时最明显，此时共轭角的变化幅度较大；在滑动速率大于 $\sim 5\text{ mm/a}$ 后，共轭角的角度变化幅度较小。此外，通过图7b发现，共轭角大小与断裂规模也呈现出负相关关系。对于规模较

大的断裂如圣安德烈斯断裂和北安纳托利亚断裂，其断裂规模选取共轭部分的长度。需要指出的是，目前笔者收集的数据量仍较有限，无法精确地表示共轭角大小与断裂滑动速率及断裂规模之间的关系，后续有关研究可通过物理模拟实验来进一步分析。

3 “V”型共轭断裂的成因机制

关于“V”型共轭断裂的成因机制，前人提出了很多观点，主要分为以下4种类型：(1) 断裂剪切面的后期旋转；(2) 断裂形成于先存构造薄弱带；(3) 断裂遵循对偶一般剪切模型；(4) 断裂遵守最大有效力矩法则。

3.1 断裂剪切面的后期旋转

Cloos(1955)提出，“V”型共轭走滑断裂共轭角

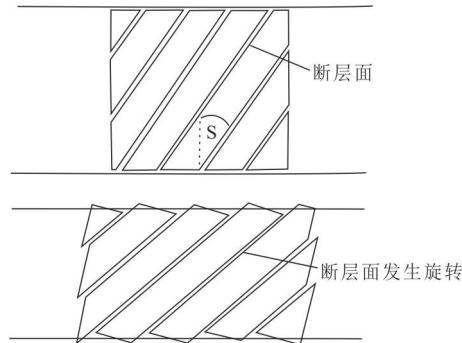


图 8 断层面的旋转(改自 Freund, 1970).

Fig.8 The rotation of fault planes (modified from Freund, 1970)

的钝角由走滑断裂的垂直轴旋转所造成。前提假定:(1)一块材料在一个方向缩短,在与之垂直的方向拉伸,无体积变化;(2)变形是沿着与缩短方向初始夹角为S的断裂面进行的;(3)断裂一旦形成,块体的变形主要是沿着断裂的运动,而形成断裂的材料长度和宽度均保持不变;(4)块体的主应力方向和主轮廓不发生旋转,被断裂切割的块体和断裂必须通过几何旋转远离缩短的方向(图8)。

Cloos(1955)在粘土模拟实验中发现,两组走滑断裂的初始共轭角为 $55^{\circ}\sim 60^{\circ}$.最初形成的一些小型走滑断裂位移及延伸长度逐渐增大,最终旋转造成 90° 或更大的夹角.Freund(1970)认为Cloos(1955)的实验证明,共轭角的增大是由于剪切面发生了旋转,纯剪切变形中剪切面的旋转是一种几何特性.这种几何特性取决于所涉及材料的物理特性.Freund(1970)提出了断裂旋转前后的几何关系.图9显示了旋转角(r)、位移(d),相邻断裂之间的宽度(w)和剪切角(s)之间的关系.其中:

$$b = \frac{w}{\cos s}, \quad (3)$$

$$\frac{d}{b} = \frac{\sin r}{\cos(s+r)}, \quad (4)$$

$$d = \frac{w \sin r}{\cos s \cos(s+r)}. \quad (5)$$

只有在预变形的方向平行于最大拉伸方向时,旋转的角度才等于 r ,否则,真实旋转的角度可能会大于或小于 r . d 、 w 和 $s+r$ 的大小可以直接测得,但是由于受到压缩, w 可能稍小于初始宽度.

3.2 断裂形成于先存构造薄弱带

先存薄弱带与先存断裂有利于断裂的形成与连接生长,其不仅制约了断裂后期的发育与分布,而且影响断裂的生成机制(邬光辉等,2021).在野

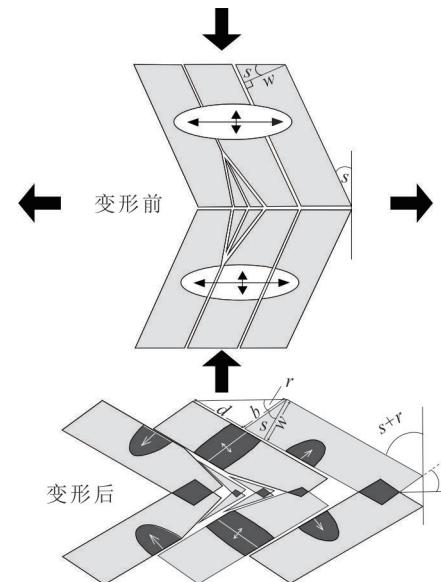


图 9 断层面旋转之后的几何模型(改自 Freund, 1970)

Fig.9 A geometrical model of the restoration of the strike-slip faults (modified from Freund, 1970)
r. 旋转角; d. 位移; w. 相邻断裂之间的宽度; s. 剪切角

外,岩石绝大多数是非均质的,一般裂隙分布在各种方向.当岩石中存在某种微裂隙,岩石受力后优先沿着这个软弱面发生断裂.因此,当地壳介质和结构极不均一时,断裂可能在先存脆弱面上发育,由此形成的共轭断裂就可以是锐角,也可以是钝角(郑友福, 1981; 万天丰, 1984).

3.3 断裂遵循对偶一般剪切模型

断裂的形成不仅取决于应力状态,还取决于通常被忽略的应变状态(Yin and Taylor, 2011).当应变状态为同轴时,会形成符合库伦剪切破裂准则的共轭断裂.相反地,尽管也受库伦剪切破裂准则的调节,当应变状态为非共轴时,可能会形成更加复杂的剪切断裂模式(Tchalenko, 1970; Wilcox et al., 1973).Naylor et al.(1986)表明里德尔剪切可以在综合简单剪切和纯剪切的一般剪切条件下形成.对偶一般剪切模型(Yin and Taylor, 2011)是指,在一般剪切流下,在两个相邻平行且具有相反剪切方向的剪切带中,发育在两组剪切带中的里德尔剪切相交,从而形成表面上所看到的“V”型共轭走滑断裂(图10).Yin and Taylor(2011)通过沙箱模拟实验证明了在下地壳或地幔的基底剪切作用或岩石圈的重力扩展作用下均可以形成“V”型共轭走滑断裂.基底剪切模拟实验得到的“V”型共轭走滑断裂具有以下特点:(1)如果基底剪切通道宽度过

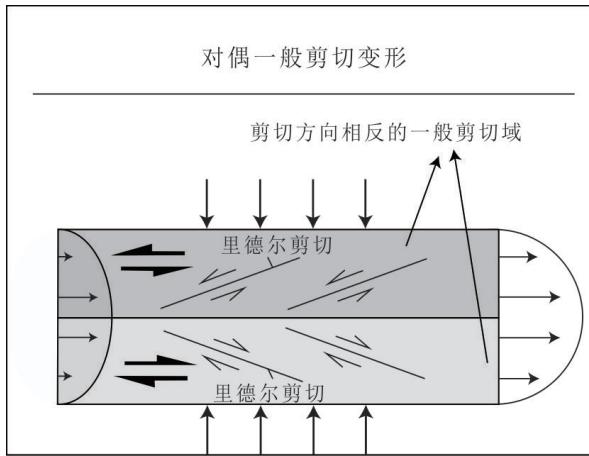


图 10 对偶一般剪切模型(改自 Yin and Taylor, 2011)

Fig.10 Paired General Shear deformation model (modified from Yin and Taylor, 2011)

窄，则无变形发生；(2)里德尔剪切先在通道的边缘形成，然后向内扩展，两个里德尔剪切汇合点形成面向基底剪切滑动方向的正断层；(3)滑移量在基底滑动方向的前端最大，向后之间减小；(4)每组共轭断裂先在基底滑动方向的前端形成，依次向后扩展；(5)最早形成的里德尔剪切向外旋转的角度最大；(6)位移沿基底滑动方向呈抛物线分布，最大位移量沿着基底滑动方向增大。重力扩展模拟得到的“V”型共轭走滑断裂的特点是：里德尔剪切与最大拉伸方向的角度从中间向边缘逐渐减小，该变形序列与基底剪切模拟相反；共轭断裂在基底滑动方向的后端先形成，依次向基底滑动方向扩展。因此，共轭断裂沿流动通道形成的先后次序可以作为“V”型共轭走滑断裂适用于哪种机制的判别依据。

3.4 断裂遵守最大有效力矩 (Maximum-Effective-Moment) 法则

共轭脆性剪切断裂和共轭韧性剪切带之间的本质区别是前者最大压应力方向断裂交角是锐角(通常为 60°)，后者为钝角(通常为 110°)。剪切带(White *et al.*, 1980)、伸展褶皱带(Platt and Vissers, 1980)和扭折带(Anderon, 1964)是应力作用下岩石局部变形的结果。它们的共同特征就是变形带中先存平面的旋转或偏转。旋转和力矩直接相关，变形的方向与最大力矩方向相关度最高。利用矩量法，Zheng *et al.*(2011)提出了有关韧性变形的最大有效力矩法则(Maximum-Effective-Moment Criterion)，其在数学上表示为：

$$M_{\text{eff}} = \frac{1}{2}(\sigma_1 - \sigma_3)L \sin 2\alpha \sin \alpha \quad (6)$$

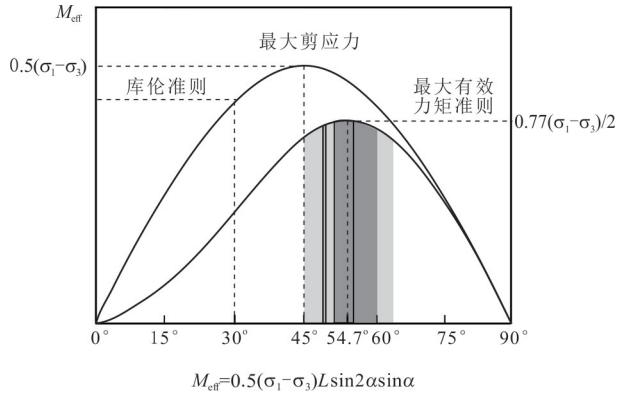


图 11 库伦准则和最大有效力矩准则(改自 Zheng *et al.*, 2011)

Fig.11 Coulomb criterion and the maximum effective moment criterion (modified from Zheng *et al.*, 2011)

$\sigma_1 - \sigma_3$ 材料的屈服强度； α ， σ_1 和剪切面之间的角度； L ，单位长度；灰色的区域显示了从实验到野外观测得的数据；深灰色的区域涵盖了 Gómez-Rivas and Carreras(2008)实验中提供的数据；4个垂直线代表 Kurz and Northrup(2008)在自然界中测量的4个共轭角

式中： M_{eff} 是最大有效力矩， $(\sigma_1 - \sigma_3)$ 代表材料或岩石的屈服强度， L 表示 σ_1 方向的单位长度， α 表示破裂面与 σ_1 之间的交角，其图形表示如图 11。该图表明，当 α 为 54.7° 时，力矩达到最大。这是形成韧性剪切带最有利的角度，同时也表示当共轭断裂形成时，面向 σ_1 的共轭角为 109.4° 。

最大有效力矩法则的物理意义如下：(1)如果存在差异应力，则存在最大力矩方向。一旦应力差达到材料的屈服强度，剪切带将会在一个或两个方向上同时形成。当差异应力小于岩石的屈服强度，剪切带不会形成；(2)无论材料是均质的还是非均质的，各向同性的还是各向异性的，晶体取向是什么样的，韧性剪切带的方向均趋向于平行最大有效力矩方向。因此 σ_1 方向初始共轭角 109.4° 与材料无关，并且在应变达到~50%之前，角度不会随应变的增大而增大；(3)由于最大有效力矩法则的尺度范围在 $10^{-7} \sim 10^8$ m, 109.4° 的大小不受构造尺度的限制；(4)由于杠杆效应，最大有效力矩方向的变形比滑移线理论、莫尔—库伦准则和零伸展法则更加节省能量。

实验表明，材料的性能取决于温度、围压和应变率等主要因素(Ranalli, 1995)。岩石通常在低温、低围压和高应变率的条件下表现出脆性行为，而在高温、高围压和低应变率的条件下表现出韧性行为。根据库伦—莫尔破裂准则，共轭剪切走滑断裂的锐角始终平分最大主压应力。然而，在高温、高围压和

低应变率条件下,共轭剪切断裂的共轭角 $>45^\circ$ 的情况会出现.

4 实例分析:青藏高原东南缘“V”型共轭走滑断裂

位于青藏高原东南缘的川滇地块是以鲜水河—小江断裂带和红河—哀牢山断裂带为边界的菱形块体(Xu *et al.*, 2003).该地区地壳受到近W-E向挤压和近N-S向伸展,且经历了青藏高原内部向东部的挤出逃逸和沿喜马拉雅东构造结的顺时针旋转(Tapponnier *et al.*, 1986),因此位于该地区的走滑断裂具有多重变形起源(Su *et al.*, 2012).

在川滇地块内部,发育着两组走向的活动走滑断裂.这两组走滑断裂剪切方向相反,显示出相似的地质和地貌特征,并被解释为活动共轭剪切,组成共轭走滑断裂系(Su *et al.*, 2012).一组走向为NE-SW,具有右旋走滑位移,包括九龙断裂、巴塘断裂和得荣断裂;另一组走向为NW-SE,具有左旋走滑位移,包括理塘断裂、乡城断裂、中甸断裂(Su *et al.*, 2012).这些走滑断裂相互相交,W-E向开口的夹角在 $100^\circ\sim140^\circ$.巴塘—理塘共轭走滑断裂(周荣军等,2005;Zheng *et al.*, 2011)和乡城—得荣共轭走滑断裂位于川滇块体的中心部位,这两组共轭断裂相互平行排列,线性特征显著,是川滇块体内部变形的重要组成部分.本文通过分析巴塘—理塘共轭走滑断裂和乡城—得荣共轭走滑断裂的变形特征,同时结合前文所述“V”型共轭走滑断裂的成因机制,来探讨青藏高原东南缘川滇块体内部的变形机制.

4.1 巴塘—理塘共轭走滑断裂特征

巴塘—理塘共轭走滑断裂由一系列平行断裂组成(图12).理塘断裂走向NW-SE,具有左旋走滑特征;巴塘断裂走向NE-SW,具有右旋走滑特征(Su *et al.*, 2012).Wilson *et al.*(2006)通过古应力重建,指出在义敦观察到的NW向左旋走滑断裂和NE向右旋走滑断裂共轭群,反映了巴塘断裂和理塘断裂大规模共轭几何特征.周荣军等(2005)结合地球物理场、震源机制解、GPS测量等资料,分析了巴塘—理塘断裂带现今地壳运动的总体态势及其所导致的块体运移规律,指出1989年巴塘6.7级震群的成因,是由于NNE向巴塘断裂和NW向理塘断裂共轭剪切所派生的近EW向正断裂的张性破裂所致,指出巴塘断裂与理塘断裂为共轭剪切走滑断裂.

巴塘—理塘共轭断裂面向S的“V”型开口角度为 80° ,E-W向共轭角为 100° (Su *et al.*, 2012).

在几何运动学方面,巴塘断裂北起于巴塘县莫西附近,向南延伸至澜沧江边,全长约200 km,总体走向N30°E,倾向NW.全新世以来,水平滑动速率 $3\sim4$ mm/a(周荣军等,2005).理塘断裂是一条与鲜水河断裂近于平行展布全新世走滑断裂带(周荣军等,2005).前人对于理塘断裂带的空间展布具有很大的争议.断裂长度从165 km至400 km不等(Zhang *et al.*, 2015; Chevalier *et al.*, 2016; Zeng *et al.*, 2020).滑动速率方面,理塘断裂晚第四纪滑速速率为 $2.3\sim4.0$ mm/a(Xu *et al.*, 2005; Zhou *et al.*, 2007; Chevalier *et al.*, 2016).现今GPS测量所得理塘断裂的左旋走滑速率为 4.4 ± 1.3 mm/a,拉张速率为 2.7 ± 1.1 mm/a(Wang *et al.*, 2008).因此,从滑动速率来看,巴塘断裂与理塘断裂在晚第四纪的走滑速率具有一致性.

4.2 得荣—乡城共轭走滑断裂特征

得荣断裂和乡城断裂交汇于雅鲁藏布江大拐弯处,构成一组共轭走滑断裂系(图13),其E-W向开口共轭角大小为 110° (Su *et al.*, 2012).得荣断裂由3条不连续的断裂组成,走向NE-SW,断裂长度为100 km.从地质和地貌特征来看,断裂具有右旋走滑特征.断裂深切定曲、麦曲、玛曲河谷.麦曲和定曲分别被位错8 km和14 km(Su *et al.*, 2012).乡城断裂在义敦弧内走向NW-SE,延伸长度约为170 km,具有左旋走滑特征.野外观测和卫星影像均显示较好的线性特征.沿着断裂,金沙江的两条支流分别被左旋位错15 km和13 km.

4.3 青藏高原东南缘成因机制探讨

对上述川滇地块内部共轭断裂系的分析可以为研究青藏高原东南缘运动学机制提供有益参考.GPS数据显示,地壳物质从青藏高原内部开始,围绕喜马拉雅东构造结,向东南方向流动,最后在东南缘形成扇形锋(Gan *et al.*, 2007).然而,目前关于青藏高原东南缘如何调节物质挤出和地壳变形仍存在争议.主要论点集中在两个端元模型,“刚性块体挤出”模型(Tapponnier *et al.*, 1982)和“下地壳流”模型(Royden *et al.*, 1997; Clark *et al.*, 2005).“刚性块体挤出”模型认为大规模的刚性块体沿大型走滑断层侧向挤出逃逸,并伴随挤出块体的地壳缩短,而“下地壳流”模型则认为高原地壳深部物质向高原边缘进行塑性流动导致地壳增厚,形成连续

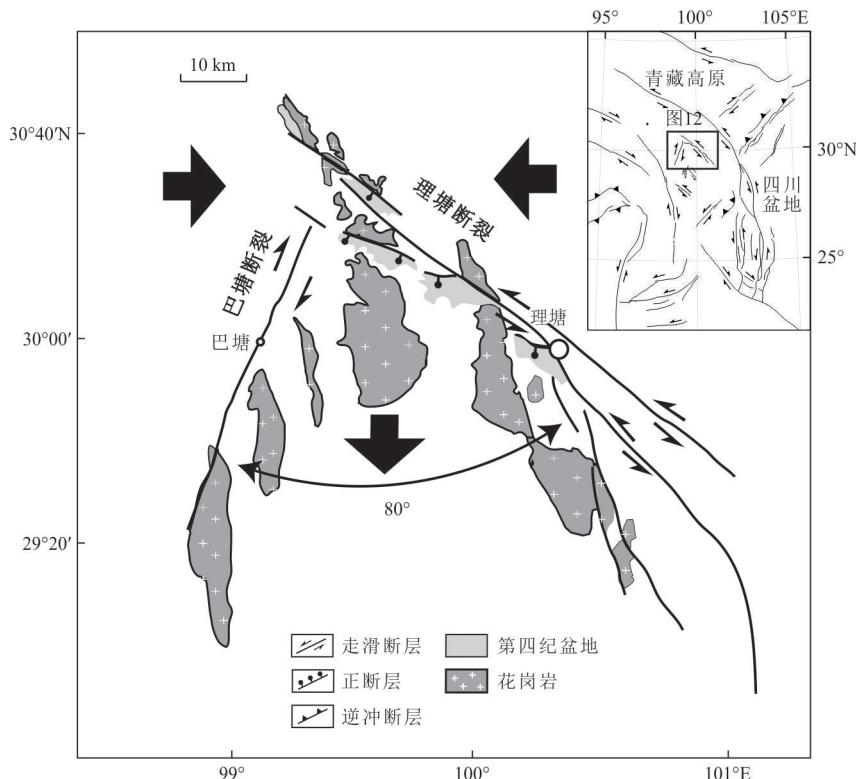


图12 巴塘—理塘共轭走滑断裂示意图(改自 Su et al., 2012)

Fig.12 Sketch map of the Batang-Litang conjugate strike-slip fault system (modified from Su et al., 2012)

巴塘—理塘断裂面最大拉伸方向角度为 80° ,共轭角大小为 100°

平缓的高海拔低起伏地形。上述位于川滇块体内部的两组共轭走滑断裂,巴塘—理塘共轭走滑断裂和得荣—乡城共轭走滑断裂,相互平行展布,受到E-W向的压缩和N-S向的伸展。“V”字型开口指向物质流出的方向即最大拉伸方向,共轭角均为钝角。两组共轭断裂的走滑活动在交汇处停止,均为第四纪活动走滑断裂。Freund(1970)在断裂剪切面后期旋转模型中指出断裂的位错(d)与旋转的角度(r)和断裂间距(W)成正相关。巴塘—理塘断裂和得荣—乡城断裂之间间距在 $80\sim110$ km之间, 20° 的旋转需要 >49 km的滑动距离,远超目前所观察到的15 km。Yin and Taylor(2011)提出对偶一般剪切模型,在一般剪切流下,两个相邻且剪切方向相反的一般剪切域中形成的里德尔剪切组成一对共轭断裂系。在沙箱模拟指出,这样的一般剪切流可以由基底剪切和重力扩展作用的提供,两者可由共轭断裂在通道形成的先后次序来区分。在几何结构上,巴塘—理塘断裂和得荣—乡城断裂与Yin and Taylor(2011)所提出的“V”型共轭断裂一致,但共轭角度略小。推测原因可能是受到川滇块体物质向东南方向旋转的原因。He et al.(2021)通过Lg波层

析成像指出,川滇块体地壳下部存在强烈的Lg衰减,同时结合前人研究得到的川滇地区中下地壳低 Q_{Lg} 值,高泊松比、低速率和高导电率,认为川滇块体中下地壳存在部分熔融(Xu et al., 2007; Zhou et al., 2008; Zhang et al., 2012; Chen et al., 2014; 杨文采等,2022)。这为川滇块体下地壳一般剪切流的存在提供了条件。已有研究证明青藏高原东南缘在9~13 Ma发生快速剥露,河流开始快速下切(Clark et al., 2005)。Zhang et al.(2015)通过低温热年代研究认为理塘断裂的启动时间在7~5 Ma。在时间上与青藏高原东南缘晚中新世大范围隆起相匹配。得荣—乡城断裂面向地壳物质流动方向的夹角小于巴塘—理塘断裂面向地壳物质流动方向的夹角。这表明从构造形成次序上看,巴塘—理塘断裂先形成,这与Yin and Taylor(2011)重力扩展沙箱模拟中共轭断裂形成的次序相同。川滇块体北部的海拔高于其南部约2 000 m(从4 000 m下降到2 000 m),高度差为重力势能提供了条件。综上,中新世以来,青藏高原东南缘的地形生长与扩展与下地壳物质在重力扩展作用下连续变形非常相关,当然理塘缝合带所指示的先存薄弱带性质也可能

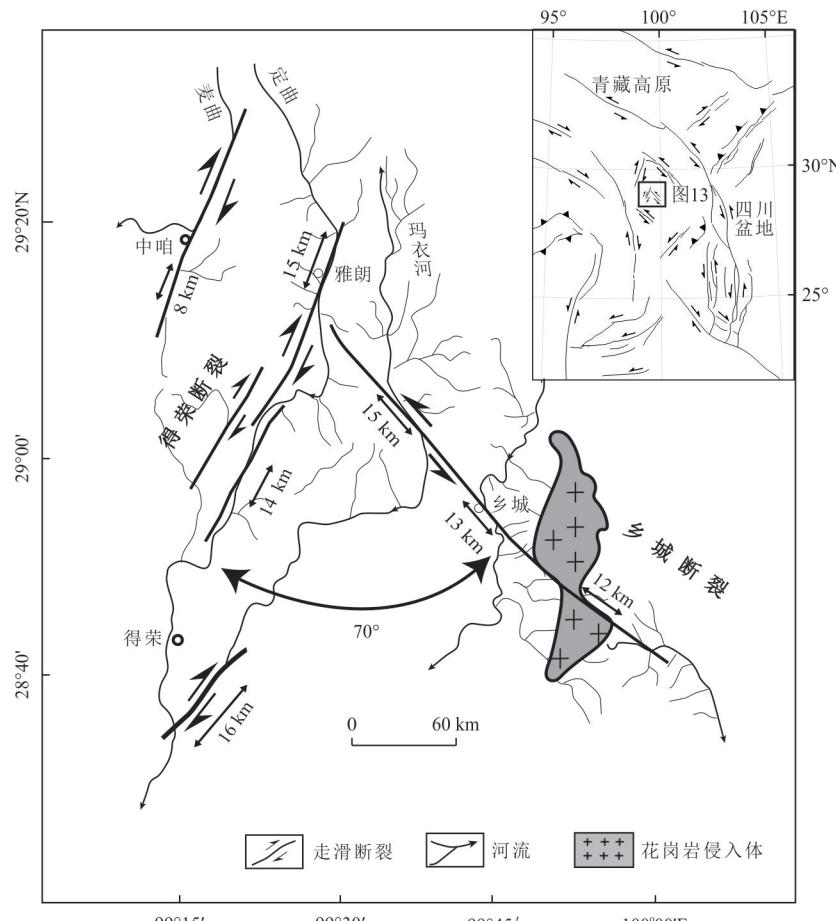
图 13 得荣—乡城断裂的地貌位错图(改自 Su *et al.*, 2012)

Fig.13 Geomorphic displacement along the Derong-Xiangcheng conjugate strike-slip faults (modified from Su *et al.*, 2012)
得荣—乡城断裂面最大拉伸方向角度为 70° ,其轭角大小为 110°

提供了有利条件(Reid *et al.*, 2005),也不排除其他机制在不同时间和空间所起到的作用。

5 总结与展望

通过总结现存的“V”型共轭走滑断裂的几何特征以及运动学特征,探讨“V”型共轭走滑断裂的发育背景及其共轭角大小与断裂几何特征和运动学特征之间的联系,取得如下几点认识:

(1)“V”型共轭走滑断裂一般发育在板块碰撞造山带,通常与侧向挤出构造有关;

(2)“V”型共轭走滑断裂共轭角大小与断裂滑动速率呈负相关关系。这种关系尤其在断裂滑动速率 $<5 \text{ mm/a}$ 时最明显,此时共轭角的变化幅度较大;在滑动速率 $>\sim 5 \text{ mm/a}$ 后,共轭角的角度变化幅度较小,趋于稳定;

(3)“V”型共轭走滑断裂共轭角的大小与断裂长度呈负相关关系。

“V”型共轭走滑断裂的成因,主要有(1)断裂剪切面的后期旋转;(2)断裂形成于先存构造薄弱带;(3)断裂遵循对偶一般剪切模型;(4)断裂遵守最大有效力矩法则等4种机制。通过对位于青藏高原东南缘川滇块体内部的两组共轭走滑断裂(巴塘—理塘断裂和得荣—乡城断裂)的分析,结合其共轭角大小、地球物理数据以及川滇地块地形高差数据,认为这两组断裂的成因机制遵循对偶一般剪切模型,可能与中中新世以来川滇地块下地壳的重力扩展作用相关。

目前对于“V”型共轭走滑断裂成因机制的研究仅局限于共轭角度,而对于其共轭关系、断裂的可塑性或延展性以及断裂启动时间的同步性或非同步性问题仍亟待今后的研究中给予重视。

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