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印度-亚洲碰撞:从挤压到走滑的构造转换

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内容提要:印度-亚洲板块碰撞导致喜马拉雅山脉的崛起、青藏高原的生长、两倍于正常地壳厚度的巨厚陆壳体,以及大量青藏高原腹地的物质沿着大型走滑断裂朝东、东南、西的方向逃逸。印度-亚洲碰撞如何造成板块汇聚边界由挤压到走滑的构造转换对认识大陆岩石圈的变形机制具有重要意义。本文通过总结喜马拉雅造山带及青藏东南缘～55Ma以来的构造、变质、岩浆记录,发现高喜马拉雅的挤出起始于始新世加厚的喜马拉雅造山带中—下地壳的部分熔融,受控于渐新世以来同期发育的向南逆冲和平行造山带的韧性伸展,并建立了高喜马拉雅"三维挤出"构造模式。晚始新世以来,羌塘地块和拉萨地块的物质通过"岩石圈横弯褶皱和壳内解耦"的运动学机制,围绕东构造结发生顺时针旋转并向青藏高原东南缘逃逸。结合东南亚板块重建的资料,我们认为:印度-亚洲的"陆-陆碰撞"到印度洋板块-亚洲东南大陆的"洋-陆俯冲"的转换是导致从印度-亚洲主碰撞带的挤压到青藏东南缘走滑转换的根本原因。

关键词:印度-亚洲碰撞;喜马拉雅造山带;青藏高原东南缘;逆冲断层;走滑断裂;拆离层

1 序言

青藏高原经历了新元古代以来"多洋盆、多俯冲、多碰撞和多造山"长期的动力学作用过程以及(始、古、新)特提斯洋盆开启和消亡的聚散历史,最后构筑了由"阿尔金-祁连-昆仑始特提斯造山系"、"松甘-羌塘-拉萨古特提斯造山系"和"冈底斯-喜马拉雅新特提斯造山系"组成的巨型复合碰撞造山拼贴体(Xu Zhiqin et al., 2007)(图1)。因此,青藏高原的形成是地质历史过程中微板块或地体连续碰撞和拼合的结果。新特提斯洋盆的闭合导致大约60～50Ma前的印度-亚洲陆陆碰撞(Tapponnier et al., 1986, Molnar, 1988; Najman et al., 2010; Wu F Y et al., 2014; Hu X M et al., 2015)。在新元古代以来长期活动、多期造山的基础上隆升形成的、具有巨厚造山软基底的"青藏高原"被称为"造山的高原"(Orogenic Plateau)(许志琴等,2007)。

印度-亚洲陆陆碰撞之后,板块之间的汇聚并未终止,约1500km的南北向缩短量通过地壳增厚来吸收,使青藏高原成为两倍于正常地壳厚度的巨厚陆壳体(平均厚度70 km),并形成了印度板块与西伯利亚板块之间南北长2000 km、东西宽3000 km的巨大新生代陆内变形域(Molnar and Tapponnier, 1975; Yin A, 2010)。印度-亚洲碰撞导致了青藏高原的生长、喜马拉雅山脉的崛起(南北向缩短率为15～20 mm/a),物质沿着大型走滑断裂向东、东南以及向西的方向逃逸(图2)(Avouac et al., 1993; Tapponnier and Molnar, 1976; Zhang P Z et al., 2004; Gan W et al., 2007)。

青藏高原及其周缘构造演化研究中的一个关键问题是:印度-亚洲陆陆碰撞如何造成亚洲大陆的岩石圈发生"由挤压到走滑的构造转换"?我们将在本文中从三个方面阐明:①喜马拉雅造山的构造、变质、岩浆事件演化;②青藏高原物质向青藏高原东南缘逃逸的机制;③挤压到走滑构造转换的时限和运动学特征。

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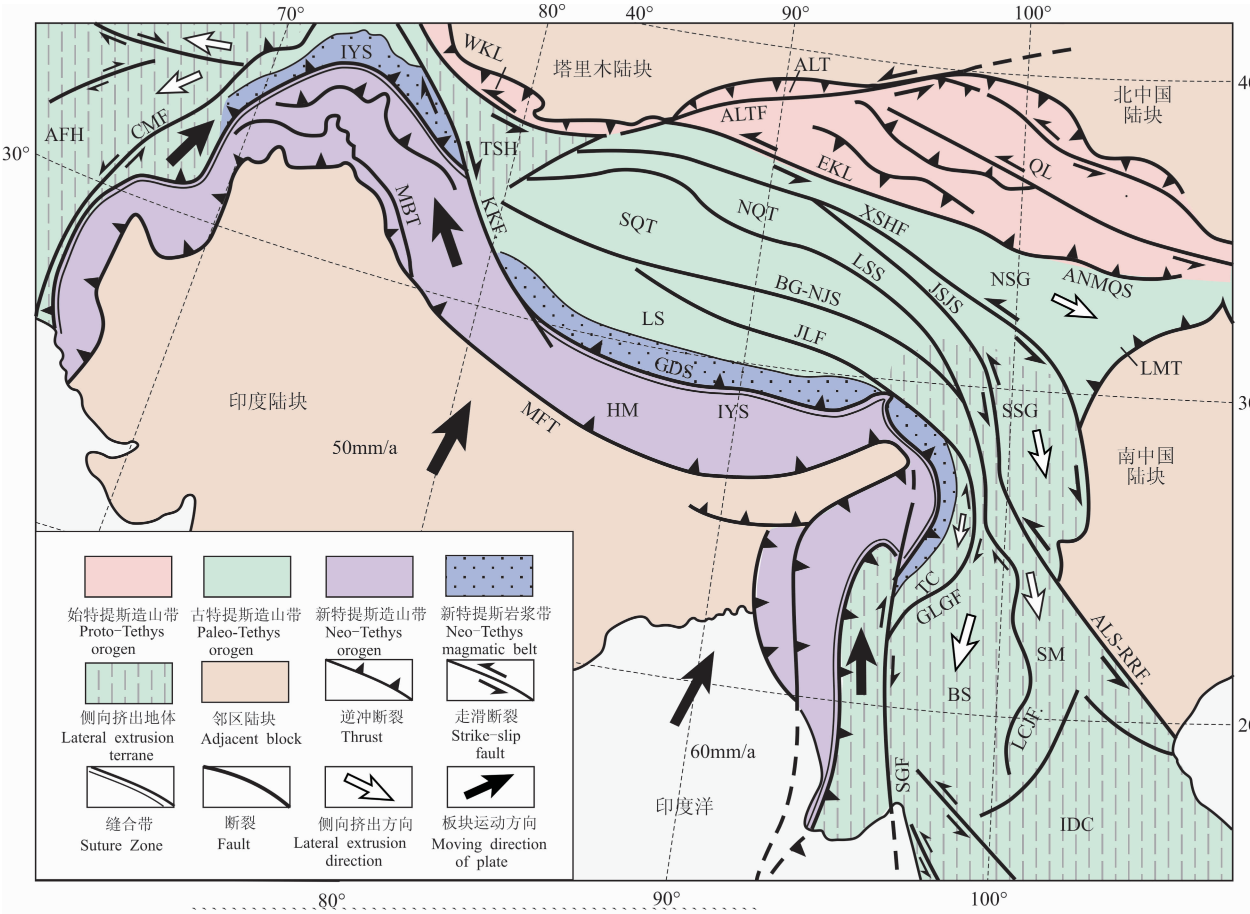

图 1 青藏高原构造构架图(据许志琴等,2011 修改)

Fig. 1 Tectonic framework of the Tibetan plateau and surrounding regions (modified from Xu Zhiqin et al., 2011)

QL—祁连地体;EKL—东昆仑地体;ALT—阿尔金地体;NSG—北松潘—甘孜地体;SSG—南松潘—甘孜地体;NQT—北羌塘地体;SQT—南羌塘地体;WKL—西昆仑地体;TSH—甜水海地体;LS—拉萨地体;TC—腾冲地体;BS—保山地体;SM—思茅地体;IDC—印度支那地体;HM—喜马拉雅地体;AFH—阿富汗地体;GDS—冈底斯地体。ANMQS—阿尼马卿缝合带;JSJS—金沙江缝合带;LSS—龙木错-双湖缝合带;BG—NJ—班公湖-怒江缝合带;IYS—印度-雅鲁藏布江缝合带;ALTF—阿尔金断裂;XSHF—鲜水河断裂;ALS—RRF—哀牢山-红河断裂;LCJF—澜沧江断裂;GLGF—高黎贡断裂;JLF—嘉黎断裂;SGF—实皆断裂;MBT—主边界冲断裂;MFT—主前锋逆冲断裂;KKF—喀喇昆仑断裂;CMF—恰曼断裂

QL—Qilian terrane; EKL—East Kunlun terrane; ALT—Aljin terrane; NSG—North Songpan Gaze terrane; SSG—South Songpan Gaze terrane; NQT—North Qiangtang terrane; SQT—South Qiangtan terrane; WKL—West Kunlun terrane; TSH—Tianshuihai terrane; LS—Lasha terrane; TC—Tengchong terrane; BS—Baoshan terrane; SM—Simao terrane; IDC—Indochina terrane; HM—Himalaya terrane; AFH—Afuhan terrane; GDS—Gangdese terrane. ANMQS—A′nyemaqen suture; JSJS—Jinshajiang suture; LSS—Longmutso-Shuanghu suture; BG—NJ—Bangonghu-Nujiang suture; IYS—Indus-Tsangbo suture; ALTF—Altyn-Tagh fault; XSHF—Xianshuihe fault; ALS—RRF Ailaoshan-Red River fault; LCJF—Lancangjaing fault; GLGF—Gaoligong fault; JLF—Jiali fault; SGF—Sagaing fault; MBT—Main Bounded fault; MFT—Main frotal fault; KKF—Karakunrun fault; CMF—Chaman fault

2 喜马拉雅的构造格架与造山机制

经过长期研究,近东西向展布、朝南突出的弧形喜马拉雅造山带的构造格架已初步奠定。喜马拉雅造山带位于印度大陆被动陆缘北侧,由特提斯喜马拉雅(Tethyan Himalayan Sequence)、高喜马拉雅(Greater Himalayan Crystalline Complex)、低喜马拉雅(Lesser Himalayan Sequence)和次喜马拉雅(Sub-Himalayan Sequence)等四个构造单元组成,各单元之间自北向南分布着藏南拆离系(South Tibet Detachment,简称 STD)、主中央逆冲断裂(Main Central Thrust,简称 MCT)、主边界逆冲断裂(Main Boundary Thrust)和主前锋逆冲断裂(Main Frontal Thrust)四条边界断裂(图 3)(Burg and Chen, 1984; Burchfiel and Royden, 1985; Burchfiel et al., 1992; Cui Junwen et al., 1992;

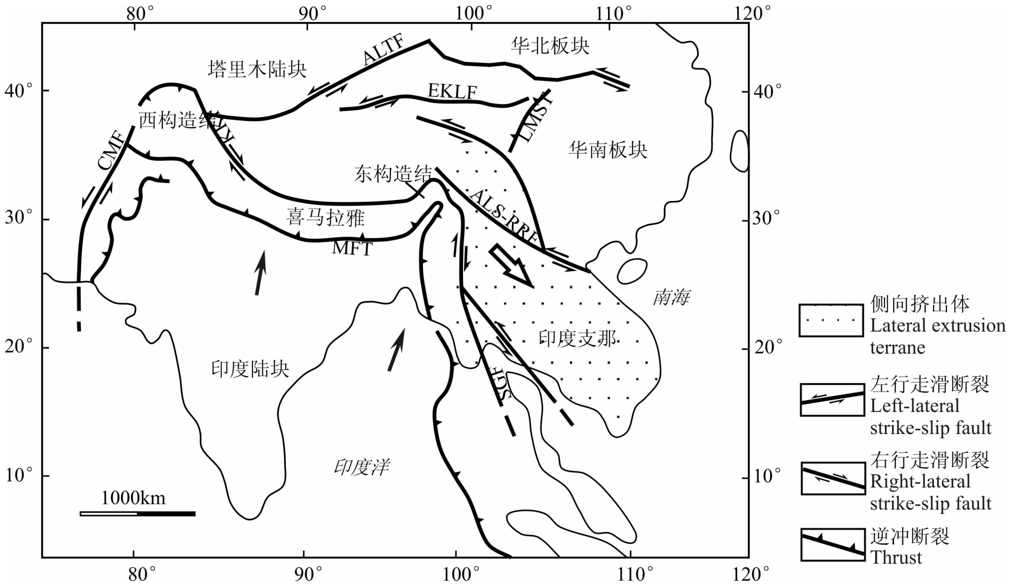

图 2　青藏高原及邻区构造示意图

Fig. 2　Schematic tectonic map of the Tibetan plateau and adjacent regions

ALTF—阿尔金断裂；EKLF—东昆仑断裂；LMST—龙门山断裂；ALS—RRF—哀牢山-红河断裂；MFT—主前锋逆冲断裂；KKF—喀喇昆仑断裂；CMF—恰曼断裂；SGF—实皆断裂

ALTF—Altyn Tagh fault; EKLF—East Kunlun faul; LMST—Longmenshan thrust; ALS—RRF—Ailaoshan -Red River fault; MFT—Main frontal thrust; KKF—Karakunrun fault; CMF—Chaman fault; SGF—Sagaing fault

Brookfield, 1993; Le Fort, 1996; Cui Junwen, 1997; Yin A and Harrison, 2000; Yin A, 2006; Xu Zhiqin et al., 2007)。国际合作青藏高原及喜马拉雅深部探测计划(INDEPTH)通过地震反射、大地电磁测深与综合探测，揭示了喜马拉雅和青藏高原的地壳结构和深部过程(Zhao W J et al., 2008)。INDEPTH 一期用近垂直深反射技术获得喜马拉雅造山带地壳精细结构，发现印度板块的向北俯冲形成了向北缓倾的主喜马拉雅逆冲断裂(Main Himalayan Thrust，简称 MHT)，可延伸到特提斯喜马拉雅之下 45 km 深度(Zhao W J et al., 1993; Hauck et al., 1998)，近年的接收函数研究验证了上述结果(Schulte-Pelkum et al., 2005)。

2.1　喜马拉雅造山带的 2D 构造模型

高喜马拉雅代表喜马拉雅造山带的变质核，其南界为主中央逆冲断裂(MCT)，北界为藏南拆离系(STD)。高喜马拉雅的拉伸线理的倾伏向总体为 N—N30°E，与 MCT 和 STD 的拉伸线理方位一致，这归结于俯冲的印度大陆北缘物质在两条剪切边界之间向南挤出(Burg J P and Chen C M, 1984; Ratschbacher et al., 1994; Catlos et al., 2004; Searle et al., 2008)。在中始新世至渐新世，由于俯冲作用(深埋/地壳增厚)的影响，高喜马拉雅的岩石经历了高角闪岩相至麻粒岩相的递进变质作用，因此被称为高喜马拉雅结晶杂岩(Searle et al., 1992; Vance and Harris, 1999; Ding L and Zhong D L, 1999; Zhang J J et al., 2011)。大量淡色花岗岩在 23～10 Ma 侵位于特提斯喜马拉雅、MCT 和 STD (Edwards et al., 1996; Edwards and Harrison, 1997; Harrison et al., 1999; Hodges et al., 1996; Leloup et al., 2010; Murphy and Harrison, 1999; Schärer et al., 1986; Searle et al., 1997; Simpson et al., 2000; Wu C et al., 1998; Wang Yinchao et al., 2005)。

MCT 具有倒转的变质作用和上盘向南的剪切指向，是一条 2～10 km 宽的韧性剪切带，使高喜马拉雅逆冲于低喜马拉雅之上(Harrison et al., 1997; Searle et al., 2008; Corrie and Kohn, 2011)。在喜马拉雅中段地区，MCT 由两个强应变带组成，分别是紧邻高喜马拉雅的上 MCT(又称为 MCT-2)(Arita, 1983)和位于低喜马拉雅的下 MCT(又称为 MCT-1)。在尼泊尔与印度西北部，MCT 具有断坪-断坡构造，并导致宽阔的褶皱(DeCelles et al., 2001; Yin A, 2006; Webb et al., 2007)。在逆冲断坪(MCT-1)上部的向斜中出露了中低级变质相的结晶板片(Lesser Himalayan

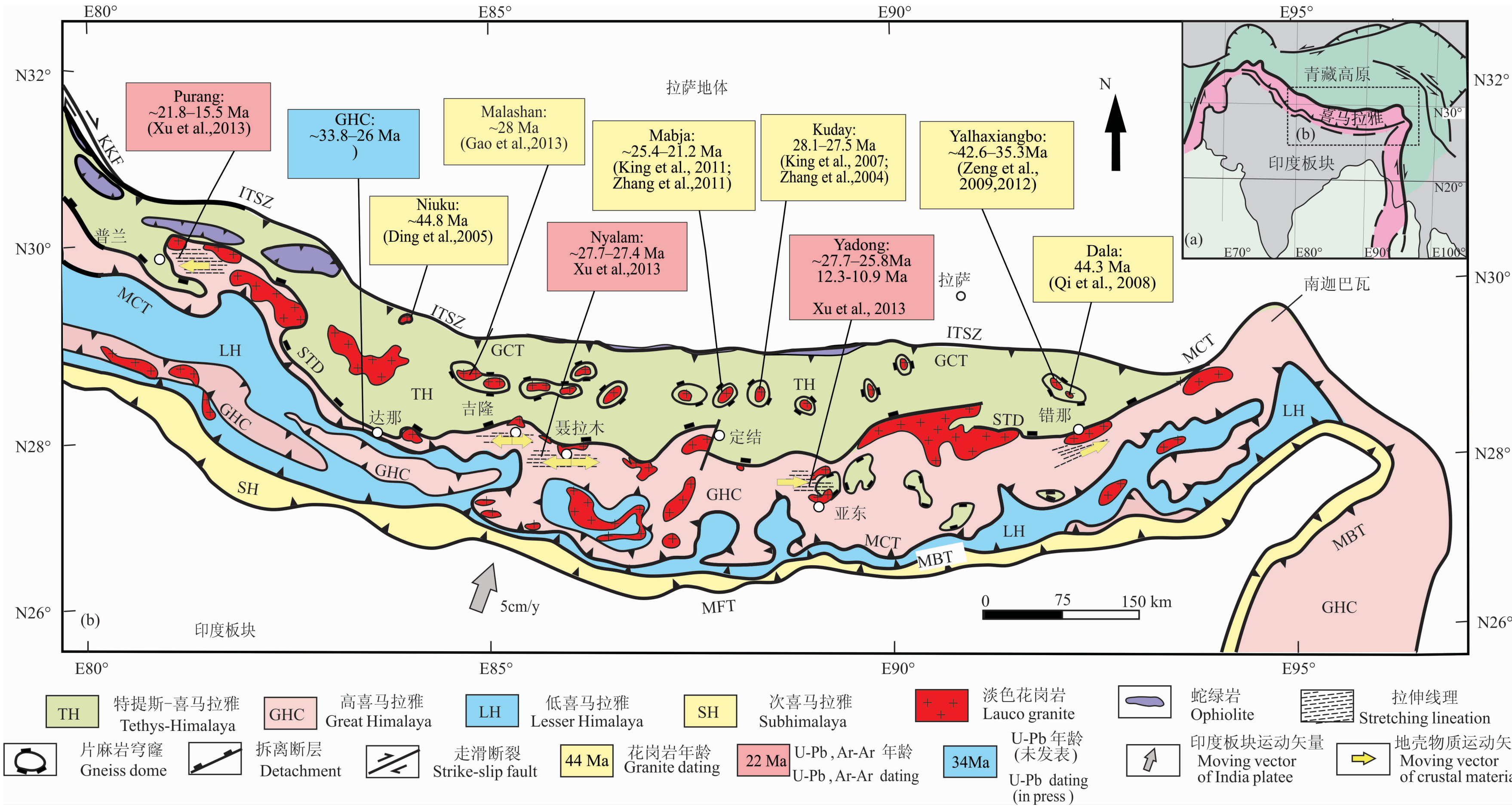

图 3 喜马拉雅造山带地质简图(修改自 DiPietro and Pogue, 2004; Yin A, 2006)

Fig. 3 Schematic geological map of the Himalayan orogen (modified from DiPietro and Pogue, 2004; Yin A, 2006)

GHC—高喜马拉雅;LH—低喜马拉雅;SH—次喜马拉雅;TH—特提斯喜马拉雅;IYS—印度-雅鲁藏布缝合带;KKF—喀喇昆仑断裂;GCT—大反转逆冲断裂;MBT—主边界逆冲断裂;MCT—主中央逆冲断裂;MFT—主前缘逆冲断裂;STD—藏南拆离系

GHC—Great Himalaya; LH—Lesser Himalaya; SH—Subhimalaya; TH—Tethys-Himalaya; IYS—Indus-Tsangbo suture; KKF—Karakunrun fault; GCT—great counter thrust; MBT—main bounded fault; MCT—main central thrust; MFT—main frotal fault; STD—South Tibetan detachment

Crystalline Nappes)，对其到底是来自于高喜马拉雅还是属于低喜马拉雅还存在争议(Upreti and Le Fort，1999；Webb et al.，2011b)。MCT 的形成时间目前尚未确定，根据角闪石的 $^{40}Ar/^{39}Ar$ 年龄和独居石的 U-Pb 测年，位于尼泊尔中部的 MCT 至少在 23～20Ma 已经开始韧性变形，并延续到上新世(Hubbard and Harrison，1989；Hodges et al.，1996；Harrison et al.，1997)。在印度东北的喜马拉雅东段，MCT 构成大型双重逆冲构造的顶板断层，其北部起始活动时间在 13Ma，而南部为 10Ma(Yin A et al.，2010)。

STD 分隔了元古宙到始新世的特提斯喜马拉雅沉积序列和高喜马拉雅结晶杂岩。通常认为向北中等倾斜的 STD 是一个上盘向北运动的低角度拆离断层，但在珠穆朗玛峰地区(Carosi et al.，1998；Murphy and Harrison，1999；Law et al.，2011)和 Annapurna-Manaslu 地区(Searle and Godin，2003)，STD 由两条叠置的拆离断层组成。虽然 STD 常被作为折返的高喜马拉雅的顶界，但是 STD 既发育了向北的正断，也记录了向南的逆冲(Hodges et al.，1996；Carosi et al.，1998，1999；Godin et al.，1999)。一些学者认为：STD 向北延伸至特提斯喜马拉雅单元之下，表现为倾向南、上盘向北的反冲断层，并在拉轨岗日变质穹隆带出露(Chen Z et al.，1990；崔军文等，1997；Li Dewei et al，2003；许志琴等，2007)。根据淡色花岗岩的侵位时间和云母的 $^{40}Ar/^{39}Ar$ 冷却年龄，STD 韧性变形的活动时间限定为－23～12 Ma(Harrison et al.，1999；Hodges et al.，1996；Vannay et al.，2004；Thiede et al.，2005；Cottle et al.，2011)。

喜马拉雅造山带是全球陆-陆碰撞造山带的典型代表，前人已提出了“楔状挤出”(wedge extrusion)、“隧道流”(channel flow)、“构造楔”(tectonic wedging)等模型，使喜马拉雅造山带成为国际地学界研究的热点。“楔状挤出”模型将高喜马拉雅看成为一个刚性的楔体，在 MCT 和 STD 的共同作用下向南挤出(图 4a)(Burchfiel and Royden，1985；Grujic et al.，1996)。“隧道流”模型假定部分熔融的低粘度中下地壳物质在高原的重力势能差异下向周缘流动(Royden，1997；Clark and Roden，2000)。MCT 和 STD 成为隧道的两个刚性边界，同时活动且剪切旋向相反，高喜马拉雅作为低粘度的中下地壳物质从一个剥蚀前峰下的隧道折返(图 4b)(Beaument et al.，2001，2004；Grujic et al.，1996，2002；Jamieson et al.，2004)。由于在印度西北和尼泊尔中部地区，高喜马拉雅逐渐尖灭，STD 和 MCT 近乎合并，“构造楔”模型认为 STD 早期为 MCT 的分支逆断层，后期才发生拆离变形，高喜马拉雅的前缘在 15～20 km 被剥蚀，使之呈楔形体出露(图 4c)(Webb et al.，2007，2011a，2011b)。Webb (2013)进一步提出构造楔-下插的演化模式，以解释早期的高喜马拉雅构造侵位和之后印度板块下插导致的喜马拉雅造山带向南的生长。构造楔模型可以解释巴基斯坦北部低喜马拉雅、高喜马拉雅和特提斯喜马拉雅地层的连续性(Pogue et al.，1999；DiPietro and Pogue，2004)，以及不丹地区高喜马拉雅和特提斯喜马拉雅的沉积接触(Long and McQuarrie，2010)。

但是，上述模型均把垂直于喜马拉雅造山带走向的南北向拉伸线理当作主要的运动矢量，为二维运动学模型，而且把造山机制归结于 MCT 和 STD 制约下的 23～10 Ma 期间高喜马拉雅的挤出，没有考虑碰撞早期的构造、变质、岩浆演化的记录。

2.2　印度-亚洲碰撞早期的变质-岩浆作用

近年来，在特提斯喜马拉雅和高喜马拉雅识别出印度-亚洲碰撞以来的早期变质-岩浆事件的记录，对于重建喜马拉雅造山过程以及东—西喜马拉雅的差异性演化，具有重要意义。

榴辉岩是基性岩石经历了高压—超高压变质作用的产物。喜马拉雅造山带的榴辉岩主要出露于西段和中段地区。在喜马拉雅西构造结南迦帕尔巴特的 Kaghan 山谷、印度的 Tso Morari 穹窿等地区都发现了含柯石英榴辉岩和榴辉岩相变质岩(Pognante and Spencer，1991；Guillot et al.，1997；Tonarini，et al.，1993；O'Brien et al.，2001)，超高压峰期变质作用($p>2.8$ GPa，$t>640°C$)在～46 Ma(Parrish et al.，2006)和 50～43 Ma(De Sigoyer et al.，2000)，表明印度大陆的西北角至少在 50～43 Ma 已下插到亚洲大陆之下并到达柯石英的稳定域。但是 Burg(2011)认为这期超高压变质作用对应于印度大陆和 Kohistan 岛弧的弧陆碰撞，而不是印度-亚洲陆陆碰撞的结果。目前在喜马拉雅中段只发现麻粒岩相的高压榴辉岩，还没有找到柯石英，峰期变质年龄从 38 Ma 到 14～15 Ma(Liu Shuwen et al.，2005；Grujic et al.，2011；Corrie et al.，2010；Kellet et al.，2014)。Wang Y et al. (2015)在喜马拉雅中段的定结地区发现了形成于 14～15 Ma 的榴辉岩，榴辉岩相峰期变质条件

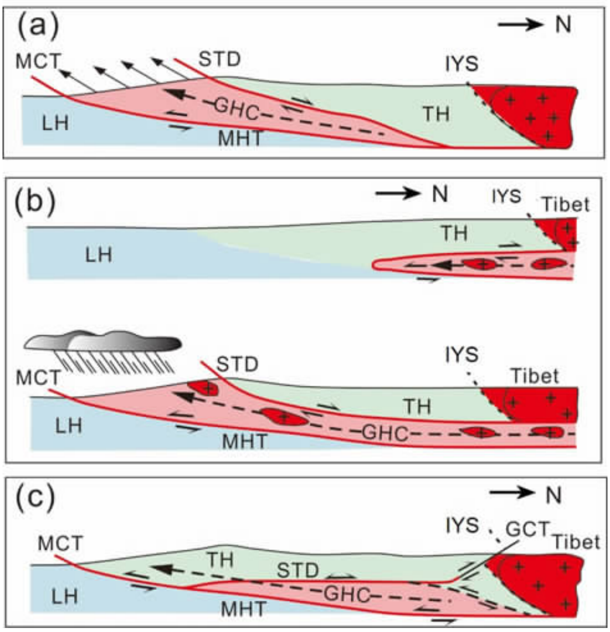

图 4 高喜马拉雅的挤出构造模式图
(据 Webb et al., 2011a)

Fig. 4 Extrusion models for the Greater Himalayan complex (after Webb et al., 2011a)

(a)—中新世早期—中期的楔形挤出模型(Burchfiel and Royden, 1985; Grujic et al., 1996);(b)—隧道流/集中剥蚀模型:始新世—渐新世的早期隧道阶段,中新世早期—中期的集中折返阶段(Royden, 1997; Beaumont et al., 2001; Hodges et al., 2001; Grujic et al., 2002);(c)—中新世早期—中期的构造楔模式(Yin A, 2006; Webb et al., 2007); GHC—高喜马拉雅,THS—特提斯喜马拉雅,LH—低喜马拉雅,MCT—主中央逆冲断裂,MHT—主喜马拉雅逆冲断裂,GCT—大反转逆冲断裂,STD—藏南拆离系,IYS—印度-雅鲁藏布缝合带。

(a)—Wedge extrusion of E. to M. Miocene (Burchfiel et al. 1992; Grujic et al. 1996); (b)—Channel flow-focused denudation involve channel stage of Eocene-Oligocene to the exhumation stage of the Greater Himalayan during E.-M. Miocene (Burchfiel and Royden 1985; Hodges et al. 2001; Beaumont et al. 2001; Grujic et al. 1996, 2001, 2002; Searle and Szulc, 2005); (c)—Tectonic wedging of E. to M. Miocene (Yin A, 2006; Webb et al., 2007); GHC—Greater Himalayan complex; THS—Tethyan Himalayan; LH—Lesser Himalayan; MCT—main central trust; MHT—Main Himalaya thrust; GCT—great corner thrust; STD—South Tibet detachment; IYS—Indus-Tsangpo suture

为 2.0～2.1GPa 和 720～760°C,经历了近等温折返并叠加了麻粒岩相退变质作用。上述数据暗示了印度-亚洲碰撞在时空上存在构造差异性。

丁林(1995)在东构造结南迦巴瓦峰发现了高压麻粒岩。张泽明等(2007)在南迦巴瓦岩群中发现产在麻粒岩相变质岩中的石榴辉石岩,认为其是榴辉岩相高压变质作用的产物(P=2.6～2.8 GPa,T=800～900℃),相当于俯冲深度 80～90 km,变质时代为 50 Ma。而东喜马拉雅构造结的麻粒岩相峰期变质作用很可能发生在 40 Ma (Ding et al.,2001) 或 37～32 Ma (Liu Y et al., 2007; Zhang Z M et al., 2010)。

特提斯喜马拉雅的花岗片麻岩穹窿中片麻岩的石榴石 Lu-Hf 同位素年龄为 54～49 Ma,表明喜马拉雅造山带的地壳在早始新世已经增厚(Smit et al., 2014))。近年来在特提斯喜马拉雅的拉轨岗日片麻岩穹窿群发现了 46～27 Ma 的淡色花岗岩,记录了多期的深熔作用(图 3)(Ding L et al., 2005; Lee and Whitehouse, 2007; Aikman et al., 2008; Zeng L et al., 2011; Hou Z Q et al., 2012; Qi Xueqiang et al., 2008; Gao Lie et al., 2009, 2013; Zhang Jinjiang et al., 2011)。增厚下地壳的角闪岩在始新世中—晚期(46～35 Ma)部分熔融,形成高 SiO_2、高 Sr/Y 比的二云母花岗岩,而淡色花岗岩和淡色花岗玢岩经历了强烈的岩浆演化后期的流体作用和钙长石结晶作用,35 Ma 以来变泥质岩发生部分熔融,随着温压条件和含水量的变化,岩体的地球化学性质差异很大(Zeng et al., 2011)。此外,在高喜马拉雅聂拉木地区,含夕线石混合岩的锆石 U-Pb 年龄为 39.7～34 Ma,代表了中地壳局部熔融的时间(Wang J M et al., 2013)。

2.3 平行造山带的近水平韧性拆离层

前人发现在高喜马拉雅上部的片麻岩和糜棱岩局部发育平行造山带走向的近东西向拉伸线理,例如:藏南聂拉木地区(Brun et al., 1985)、普兰地区(Murphy et al., 2002)、尼泊尔 Manaslu 地区(Pêcher et al., 1991)、印度 Gangotri 地区(Pêcher and Scaillet, 1989), Ama Drime 地块(Jessup et al., 2008)。Xu Z Q et al. (2013)发现高喜马拉雅上部近东西向的韧性伸展可能沿着整个造山带分布,活动时间为渐新世晚期—中新世早期,具有区域构造意义。如图 5 所示,在高喜马拉雅东段的错那-亚东地区,近 E—W 走向、向东缓倾的拆离层发育于前震旦纪变质基底(聂拉木群)富铝花岗片麻岩和寒武纪盖层之间,上盘向东的剪切变形强烈,糜棱岩厚达 1 km 以上,发育近东西向拉伸线理和剪切成因的"A"型褶皱。该拆离层糜棱岩化片麻岩的锆石的变质边年龄记录了韧性剪切开始的时间为 28～26 Ma,云母的 $^{40}Ar/^{39}Ar$ 年龄表明韧性剪切作用大概在 13～11 Ma 结束。在高喜马拉雅西段的普兰地区也发现变质基底中存在低角度的韧性剪切带,

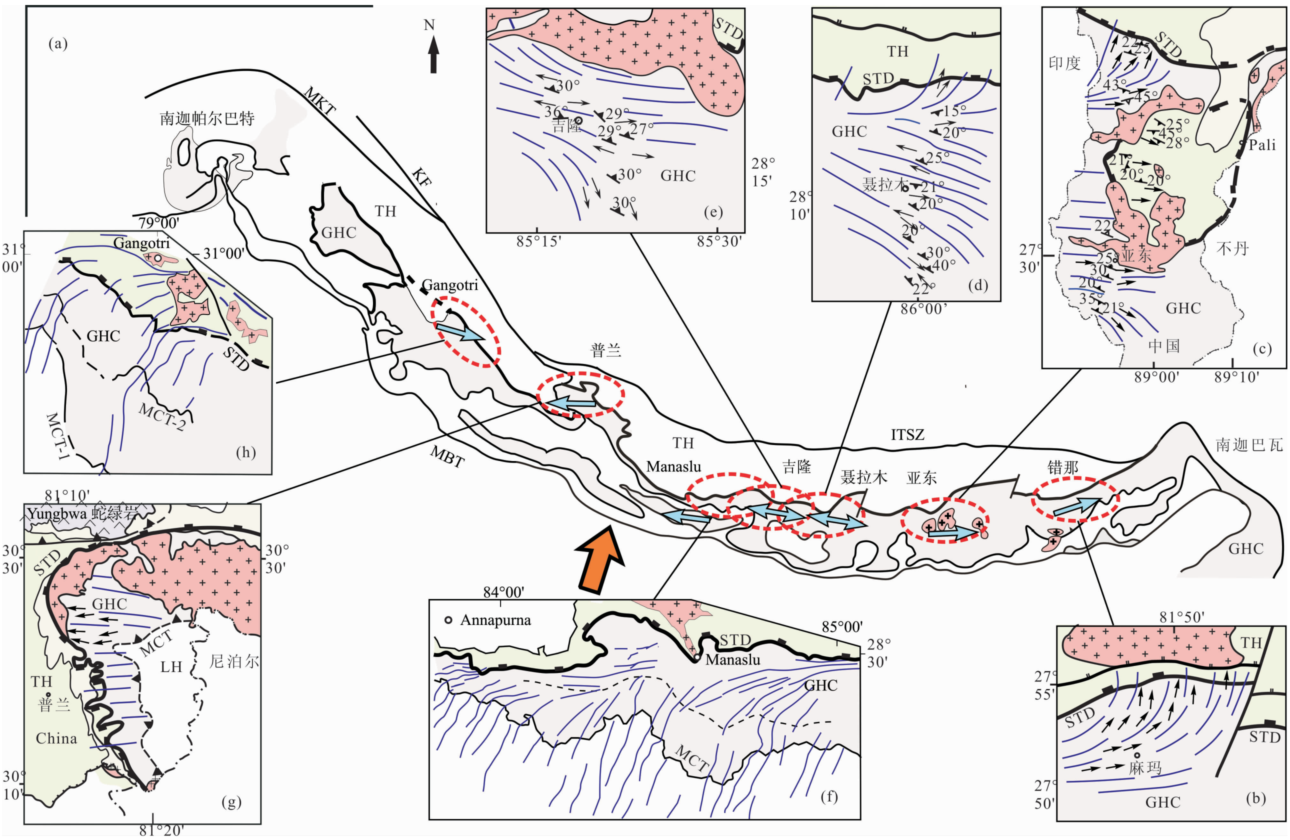

图 5　高喜马拉雅的拉伸线理模型图(修改自 Xu Z Q et al.，2013)

Fig. 5　Stretching lineation patterns in the Great Himalayas Complex(modified from Xu Z Q et al.，2013)

粉红色表示中新世淡色花岗岩，红圈表示高喜马拉雅上部的拉伸线理与造山带走向平行的区域，自东向西：(b)错那，(c)亚东，(d)聂拉木，(e)吉隆，(f)Manaslu 地区，(g)普兰，(h)Gangotri 地区. 蓝色箭头表示近水平拆离层上盘的剪切指向，橘色箭头为印度-亚洲的汇聚方向。特提斯喜马拉雅与高喜马拉雅之间的拆离导致高喜马拉雅拆离层的东部发育向东的剪切，西部发育向西的剪切，中部则两种剪切指向都存在。IYS—印度-雅鲁藏布缝合带；KKF—喀喇昆仑断裂；MBT—主边界逆冲断裂；MCT—主中央逆冲断裂；MKT—喀喇昆仑主冲带；STD—藏南拆离系。TH—特提斯喜马拉雅，GHC—高喜马拉雅

The Miocene leucogranites are shown in pink color. The red ellipses indicate areas with orogen-parallel stretching lineation in the GHC. Due to orogen-parallel gravitational collapse in the late Oligocene and Miocene，decoupling between the TH and GHC resulted in top-to-the-east shearing in the eastern Himalaya，top-to-the-west shearing in the western Himalaya，and coexistence of top-to-the-west and top-to-the-east shearing in the central Himalaya (blue arrows). The convergence direction between India and Asia is assumed to be the same as at the present (orange arrow)；ITSZ—Indus-Tsangbo suture zone；KF—Karakoram fault；MBT—main boundary thrust；MCT—main central thrust；MKT—main Karakoram thrust；STD—South Tibet detachment；TH—Tethys Himalaya；GHC—Great Himalayan Crystalline

花岗质糜棱岩和糜棱岩化副片麻岩指示了上盘向西的剪切旋向，活动时间为 22～15 Ma。此外，在高喜马拉雅中部的吉隆和聂拉木地区，近水平拆离层同时具有向东和向西的剪切指向。

因此，在高喜马拉雅上部，存在一条东起错那、亚东，经聂拉木-吉隆-Manaslu(尼泊尔)、西至普兰，大约 1800 km 长的平行造山带走向的近水平韧性拆离层，以吉隆-聂拉木地区为中心，东边上盘向东运动，西边上盘向西运动，我们将其称为高喜马拉雅拆离层(Greater Himalayan Detachement)。印度-亚洲碰撞可能导致造山带地形沿走向的差异，中部最高，喜马拉雅造山带在晚渐新世—中新世发生平行造山带走向的重力垮塌，导致变质基底(高喜马拉雅)和沉积盖层(特提斯喜马拉雅)之间发育了高喜马拉雅拆离层，这标志高喜马拉雅从地壳加厚向快速折返的转变。而印度西北 Gangotri 地区可能受到了西构造结在渐新世隆起的影响，发育了上盘向东的近水平韧性拆离层。在晚渐新世—中新世，高喜马拉雅向南挤出的同时还发育了东西向的韧性伸展，二者共同作用导致高喜马拉雅的快速折返。这表明陆陆碰撞使造山带的物质既要向上折返又要侧向逃逸，从而有效地调节地壳物质沿着应力梯度发

生塑性流动。

2.4 高喜马拉雅的高温韧性剪切系和3D构造演化

根据造山带的热结构差异，可以划分为热碰撞造山带和冷碰撞造山带两种类型。热碰撞造山带具有较高的地温梯度，岩石变形受中—下地壳的“构造-变质-岩浆”热体制控制，后期经历折返、隆升和冷却过程(Bird, 1991; Grujic et al., 1996; Beaumont et al., 2001; Cottle et al., 2015)；而冷碰撞造山带中岩石的变形处于较低的地温梯度下。Law et al.(2006)将来自地壳中—下部、又快速折返的高喜马拉雅称为“热碰撞造山带”，将特提斯喜马拉雅和低喜马拉雅称为“冷碰撞造山带”。高喜马拉雅中段的厚度可达7～9 km，由元古宙的角闪岩相-麻粒岩相(甚至榴辉岩相)变质岩组成，显示一个倒置的变质相序列(下部含石榴子石-十字石，中部蓝晶石-夕线石，顶部为混合岩化岩石)(Harrison et al., 1998; Vannay and Grasemann, 2001; Harris et al., 2004; Searle et al., 2008)，上部被2～3 km厚的花岗质岩浆侵位，说明高喜马拉雅的变质-深熔作用与MCT和STD的发育具有耦合性。一些学者提出：高喜马拉雅的变质、深熔和变形事件伴随着高喜马拉雅的折返，从44 Ma位于45 km深度，至16～13 Ma位于18 km深度(Daniel et al., 2003; Cottle et al., 2009)，暗示高喜马拉雅下部存在一条或若干条热的、低粘度的向南逆冲的韧性剪切层。

尼泊尔中部Annapura山脉以西的Benin-Jomsom剖面位于高喜马拉雅单元的中下部。我们在此发现若干条向北倾的高应变逆冲带，形成厚度达千米级的韧性逆冲剪切系。糜棱岩化片麻岩的石英组构表明该逆冲剪切系经历了高温的韧性变形(>650℃)，与广泛分布的混合岩化一致。变质锆石的U-Pb年龄揭示：该逆冲剪切系的顶部变形开始于～34 Ma，向南逐渐变年轻，至MCT顶部为26 Ma(待发表，图3)。因此，高喜马拉雅韧性逆冲剪切系的形成早于STD和MCT(～23～10 Ma)，也早于从28 Ma开始的平行造山带的高喜马拉雅拆离层。与喜马拉雅造山带地壳精细结构对比(Zhao W J et al., 1993; Hauck et al., 1998)，我们推测该高温韧性逆冲剪切系为主喜马拉雅逆冲断裂(MHT)在地表的出露部分。

根据上述研究成果，我们建立了喜马拉雅三维造山模型(图6)。喜马拉雅造山带始新世以来的深熔作用有效地弱化了中下地壳，促使高喜马拉雅在34 Ma开始向南折返并形成高温逆冲剪切系，之后造山带重力垮塌，沿高喜马拉雅拆离层发生平行造山带的伸展拆离，导致变泥质岩发生大规模的减压部分熔融，并且诱发了23 Ma以来MCT和STD的启动，促使喜马拉雅造山带的构造体制为南北向缩短增厚和东西向伸展减薄并存。

值得注意的是，主边界逆冲断裂(MBT)将低喜马拉雅推覆于第三系沉积层之上，起始时间大约在11～9.5 Ma(Meigs et al., 1995)，没有切穿第四系的沉积物。主前锋逆冲断裂(MFT)将新近纪的Siwalik群覆于印度恒河平原的第四系沉积物之上，是非常活跃的地震带(Kumer et al., 2001)。因此，喜马拉雅造山带的隆起受控于从渐新世(～34 Ma)开始向前陆运移的一系列叠瓦状逆断层，主喜马拉雅逆冲断裂为MCT、MBT、MFT收敛于深部的底板断层。

3 青藏高原东南缘的侧向逃逸

如图7所示，青藏高原东南缘由思茅-印度支那地体、保山-掸邦地体、腾冲-Mogok-西缅地体组成。这些地体的边界为大型走滑断裂带，从东向西依次为：哀牢山-红河断裂带，澜沧江断裂带，高黎贡断裂带。实皆断裂带(Sagaing fault)将腾冲-Mogok地体与西缅地体右行走滑错开约250 km。构造分析、古地磁和GPS研究均表明印度-亚洲碰撞导致青藏高原腹地的地壳物质围绕喜马拉雅东构造结作顺时针运动，向东和东南方向逃逸，造成高原东南缘的侧向生长(Zhang P S et al., 2004; Shen Z K et al., 2005; Otofuji et al., 2010; Tapponnier et al., 2011)。目前存在三种端元模型来解释青藏高原的侧向逃逸机制。①“构造逃逸”(tectonic escape)模型认为青藏高原东南缘的各刚性地块以西侧的高黎贡右行走滑断裂和东侧的哀牢山-红河断裂为边界向东南运动，变形集中在切穿岩石圈的近直立的大型走滑断裂带(Tapponnier and Molnar, 1976; Tapponnier et al., 1986; Leloup et al., 2001)。②“粘性薄板”(thin viscous sheet)模型假定青藏高原的岩石圈粘度很低，在南北向挤压应力下地壳均匀加厚，后期在地壳浅部发育走滑断裂(England and Houseman, 1986)。③“下地壳流”(lower crustal flow)模型假定青藏高原低粘度的下地壳沿一水平隧道向外流动，岩石圈垂向发生力学解耦(Clark and Royden, 2000; Royden et al., 2008)。但是，对GPS数据的模拟结果表明，青藏高原东南缘块体

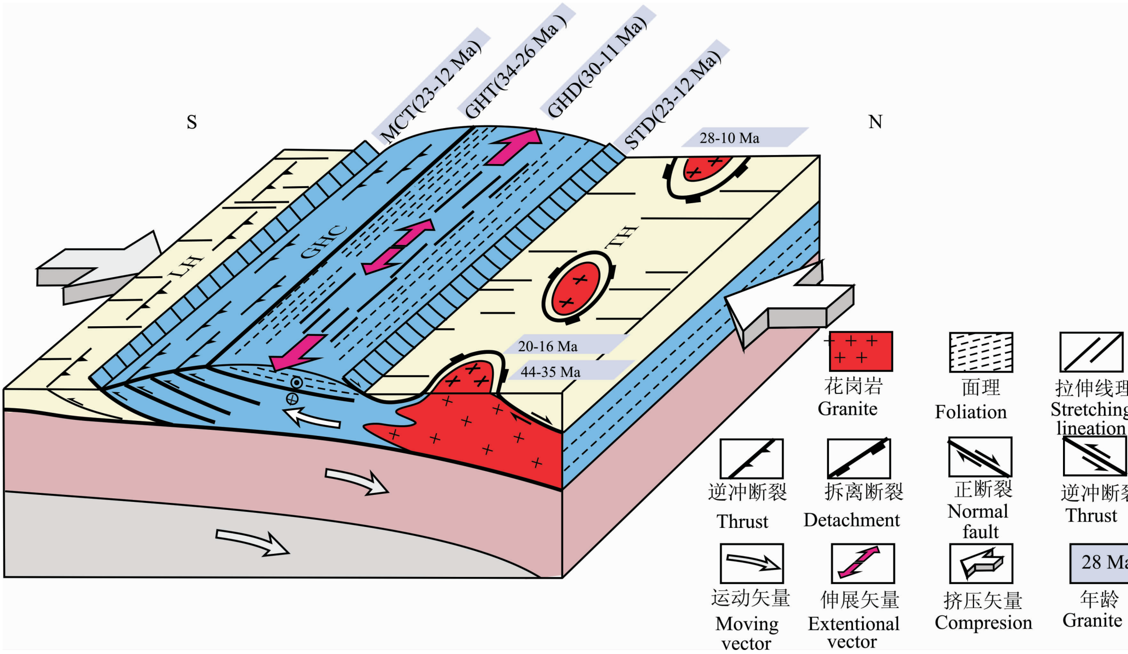

图 6　高喜马拉雅三维构造演化模型

Fig. 6　3D tectonic model of the Greater Himalayan Complex

GHC—高喜马拉雅;TH—特提斯喜马拉雅;LH—低喜马拉雅;STD—藏南拆离系;MCT—主中央逆冲断裂;GHD—高喜马拉雅拆离层;GHT—高喜马拉雅逆冲断裂

GHC—Great Himalayan Complex;TH—Tethys Himalaya;LH—Lesser Himalaya;STD—South Tibet Detachment;MCT—Main Central Thrust;GHD—Great Himalaya Detachment ;GHT—Great Himalaya Thrust

不仅沿边界断裂的发生滑移,块体内部也存在较大的应变(Thatcher, 2007; Gan W et al., 2007)。

3.1　青藏高原东南缘的走滑断裂带

青藏高原东南缘的新生代变形是在古特提斯构造体系的背景上进一步演化的。古地磁研究表明,腾冲地体、保山地体和思茅地体渐新世以来都发生了顺时针旋转,但旋转速率不同(Chen H et al., 1995; Kornfled et al., 2014a, b; Sato et al., 2001, 2007)。这些地体的边界走滑断裂带由中—高级变质岩和糜棱岩组成,经历了晚始新世—早中新世的变质作用和韧性变形,并叠加了后期的脆性变形。下面从东向西总结研究区主要走滑断裂带的演化历史。

哀牢山-红河走滑断裂带的北段大致沿晚二叠世—早三叠世金沙江-哀牢山缝合带展布,使思茅地体与北羌塘地体相连(图 8)(Fang Weixuan et al., 2002; Mo Xuanxue and Pan Guitang, 2006; Xu Zhiqin et al., 2013)。但是向南红河走滑断裂带沿着越南北部的 Phang-Si-Pang 山脉分布,位于松马缝合带的北部(Chung S L et al., 1997; Zhang R Y et al., 2013)。松马缝合带中榴辉岩的锆石 U-Pb 年龄为 230.5±8.2 Ma,记录了华南地块与印支地块之间的古特提斯洋关闭的时间(Zhang R Y et al.,2013)。$^{40}Ar/^{39}Ar$ 热年代学研究表明哀牢山-红河断裂带的左行走滑伴随两期冷却历史:在 34～27 Ma 缓慢冷却,在 27～17 Ma 快速冷却(Leloup et al., 1995, 2001; Harrison et al., 1996; Wang E C et al., 1998)。同构造石榴石的生长也记录了 34～21 Ma 的角闪岩相变质作用和左行走滑(Gilley et al., 2003)。锆石 U-Pb 年龄、云母和角闪石的 $^{40}Ar/^{39}Ar$ 年龄揭示,点苍山-哀牢山剪切带的高温韧性左行走滑在 32～25 Ma 发生在 18～25 km 深度,在 25～14 Ma 继续左行走滑并逐渐隆升至 10～15 km(Cao S Y et al., 2011a, 2011b; Liu F L et al., 2013)。16～5.5 Ma 哀牢山-红河走滑断裂带的剪切指向变为右行,在绿片岩相条件下快速冷却(Leloup et al., 2001)。

近 N—S 走向的澜沧江走滑断裂带沿着昌宁-孟连缝合带分布,向北与羌塘地体中部的龙木错-双湖缝合带相连,使保山地体与南羌塘地体相连(图 8)(Zhong Dalai, 1998; Li Cai et al., 2007; Xu Zhiqin et al., 2013;Metcalfe, 2013)。沿龙木错-双湖缝合带出露由榴辉岩、蓝片岩、蓝闪石大理岩等组成的低温高压变质带,变质峰期时间为 244～223

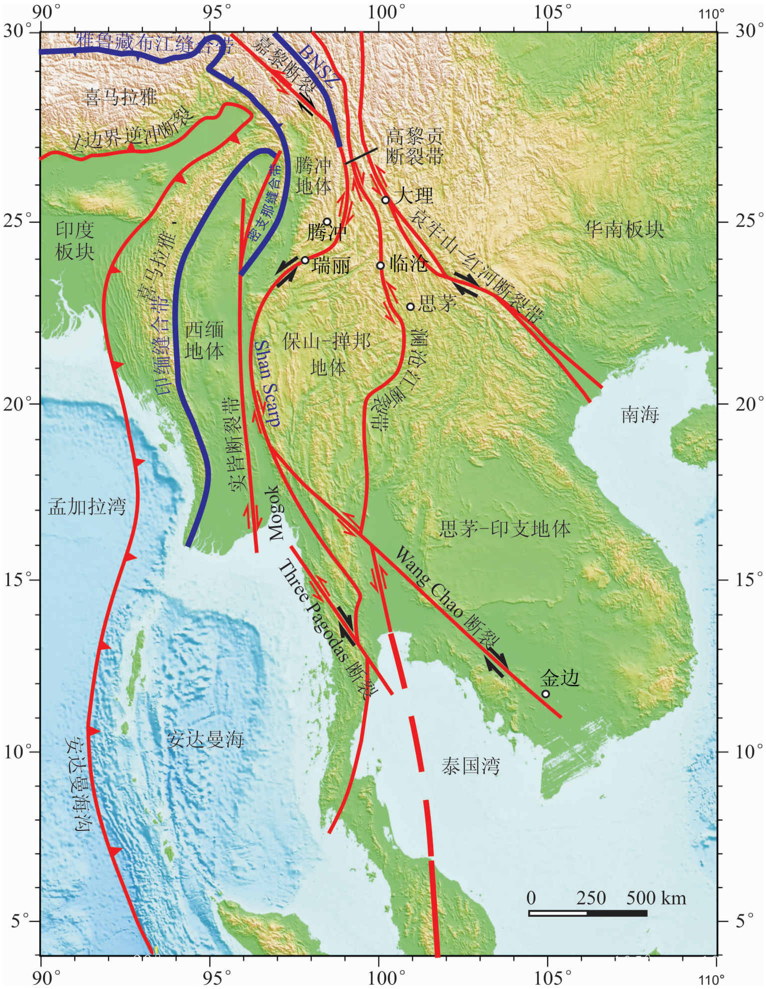

图 7 青藏高原东南缘地形和构造格架图(修改自 Leloup et al., 2001; Searle et al., 2012; Xu Z Q et al., 2015)

Fig. 7 Topography and schematic tectonic framework of SE Tibetand adjacent regions
(modified from Leloup et al., 2001; Searle et al., 2012; Xu Z Q et al., 2015)

Ma,快速折返时间为 227～203 Ma,记录了古特提洋板片在三叠纪向北羌塘地块之下俯冲消减,随后南羌塘与北羌塘发生陆陆碰撞的信息(Li Cai et al., 2006; Zhai Q G et al., 2011;Zhang Xiuzheng et al., 2014)。澜沧江走滑断裂带的北段沿碧罗雪山-崇山延伸约 250 km,由东侧片岩带和西侧片麻岩带组成,称为崇山走滑断裂带。崇山走滑断裂带的变形很复杂,在北部碧罗雪山表现为右行走滑,而到了南部崇山则表现为左行走滑为主(Socquet and Pubellier, 2005; Wang Y J et al., 2006; Akciz et al, 2008)。淡色花岗岩的独居石 U-Pb 年龄表明,崇山断裂带至少在 34 Ma 开始活动(Akciz et al, 2008),而角闪石、白云母和黑云母的 $^{40}Ar/^{39}Ar$ 年龄表明左行走滑持续到 14 Ma(Wang Y J et al., 2006; Akciz et al, 2008)。澜沧江走滑断裂带的南段从云县开始,沿临沧花岗岩体分成两支向南延伸,与南北走向的清迈-临沧变质带重合。清迈-临沧变质带在 33～30 Ma 被王朝断裂带左行错断了 120～150 km,之后经历了 29～23 Ma 的快速冷却(图 7)(Lacassin et al., 1997)。在晚渐新世—中新世,澜沧江走滑断裂带南段成为东西向伸展应力下的正断层,使变质核杂岩快速隆升,并控制了泰国裂谷盆地和泰国湾的发育(Morley et al., 2001; Macdonald et al., 2010; Nantasin et al., 2012)。

拉萨地体在白垩纪与羌塘地体沿班公-怒江缝合带碰撞,对于班公-怒江洋究竟是向北俯冲到羌塘地体之下(Yin A and Harrison, 2000; Kapp et al., 2003, 2007)还是向南俯冲到拉萨地体之下(Pan Guitang et al., 2006; Zhu D C et al., 2009, 2011; Zhang Z M et al., 2014)还存在争议。腾冲地体与拉萨地体南部的冈底斯岩浆弧具有相近的基底组成和新生代岩浆作用,可看作拉萨地体的南延部分,因

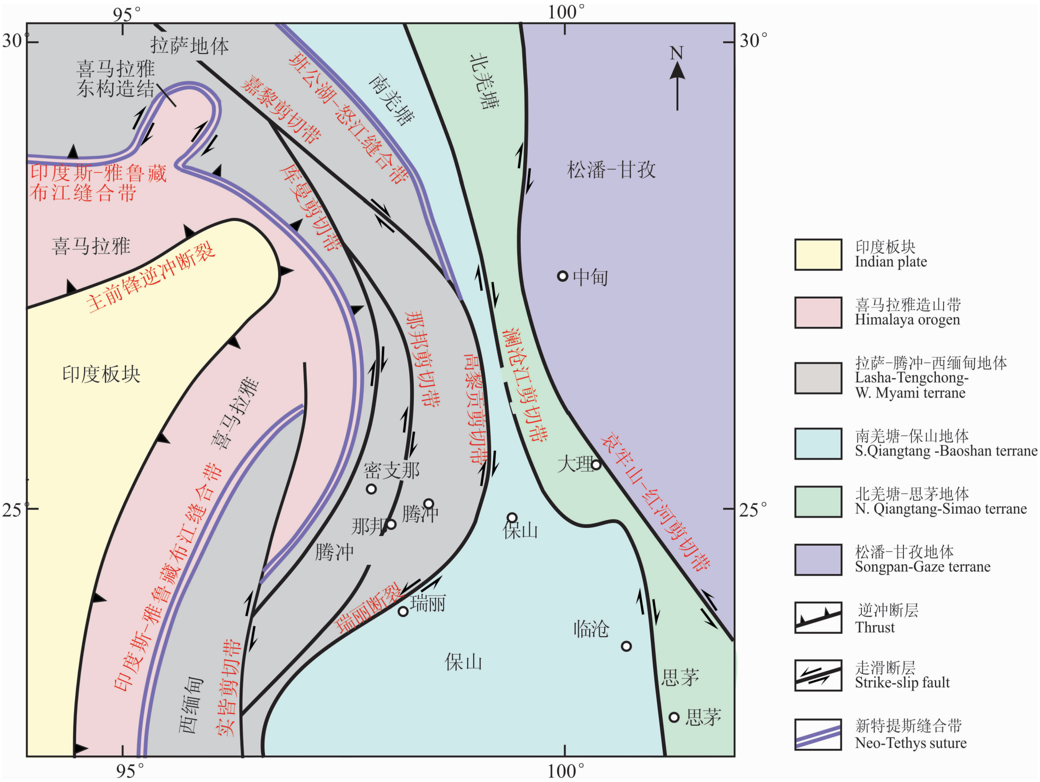

图 8　腾冲地体及其周缘的构造格架示意图(修改自 Xu Z Q et al., 2015)

Fig. 8　Simplified tectonic framework of the Tengchong terrane and adjacent regions (modified from Xu Z Q et al., 2015)

此，南北走向的高黎贡走滑断裂带与班公湖-怒江缝合带相连(图 8)(Xu Z Q et al., 2012; Xu Zhiqin et al., 2013)。$^{40}Ar/^{39}Ar$ 年代学研究表明，高黎贡右行走滑断裂带至少开始于 32 Ma，并持续到 18～10 Ma (Wang Y J et al., 2006; Zhang B et al., 2012)。位于高黎贡断裂带西北的嘉黎断裂带在 22 Ma 已开始活动，在早中新世为左行走滑断裂，但在 18～12 Ma 转变为右行走滑并与高黎贡断裂带相连(Lee H Y et al., 2003; Lin T H et al, 2009)。高黎贡断裂带的西南段在芒市附近与北东走向的瑞丽断裂相连。磷灰石裂变径迹研究表明，瑞丽断裂在 8.4～0.9 Ma 经历了左行走滑和正断，与腾冲盆地的火山活动同期(Wang G et al., 2008)。

南北走向的实皆右行走滑断裂带长 1200 km，向南连接安达曼海的弧后扩张脊(图 7)。根据金云母和白云母的 $^{40}Ar/^{39}Ar$ 年龄，实皆断裂带在 21～17 Ma 发生了右行韧性剪切(Bertrand et al., 1999)。这期变形将印度-雅鲁藏布江缝合带南段的密支那缝合带和印缅缝合带错断约 100 km，还切断了腾冲地体内部的库曼断裂和那邦断裂。滇西南那邦走滑断裂带的基性麻粒岩记录了 76～74 Ma 的麻粒岩相变质作用和 24～23 Ma 的角闪岩相退变质作用(Ji Jianqing et al., 2000)，那邦断裂带宽 3～4 km，糜棱岩、石榴石-夕线石副片麻岩、斜长角闪片麻岩发育近南北向直立面理和近水平的拉伸线理，经历了中—高温下的右行韧性剪切，锆石变质边的 U-Pb 年龄和角闪石 Ar-Ar 年龄揭示那邦右行韧性走滑的活动时间为 41～19 Ma(Xu Z et al., 2015)。

因此，高黎贡右行走滑断裂带并不是制约青藏高原东南地体挤出的西边界。印度-亚洲碰撞使印度板块的东构造犄角与拉萨地体斜向碰撞，造成腾冲-Mogok-西缅地体在 41 开始向东南挤出。澜沧江走滑断裂带与哀牢山-红河走滑断裂带的左行韧性走滑同时开始于 34 Ma，暗示了青藏高原东南缘走滑断裂系自西向东逐渐扩展。

3.2　青藏高原东南缘的壳内拆离层

虽然青藏高原东南缘的变形以大型走滑断裂带为特征，但是近年来已在越南北部的红河断裂带(Jolivet et al., 2001)、缅甸的 Mogok 变质带(Bertrand et al., 1999, 2001; Searle et al., 2007)、滇西的瑞丽和点苍山地区(Socquet and Pubellier, 2005; Liu Junlai et al., 2007)都发现了近水平的韧性剪切带。下面总结我们近年来在云南

腾冲地体(Xu Z Q et al.，2015)、保山地体和思茅地体发现的近水平韧性剪切带。这些近水平韧性剪切带作为壳内拆离层，对调节青藏高原物质向东和东南的运移发挥了重要作用。

Xu Z Q et al.(2015)发现腾冲地体内近水平韧性剪切带由糜棱岩化的花岗片麻岩和副片麻岩组成，发育于前寒武变质基底和古生代沉积盖层之间，以缓倾的面理和 NE—SW 向近水平的拉伸线理为特征，具有上盘向北东的剪切指向。腾冲地体从东向西出露了东河、古永、盈江、苏典四个片麻岩穹窿(图 9)。这些南北向拉长的片麻岩穹窿以前寒武高级变质岩和白垩纪—早始新世(126～53 Ma)花岗岩侵入体为核部，上盘向 NE 的近水平拆离层和 NE 走向的右行走滑断裂带为边部，(图 10)。我们在野外没有观察到拆离层和走滑断裂之间的切割关系，二者产状逐渐过渡。锆石变质边的 U-Pb 年龄、云母与角闪石的 $^{40}Ar/^{39}Ar$ 年龄表明：东河拆离层在角闪岩相-绿片岩相条件下的活动年龄在＞35～15 Ma，与那邦右行走滑断裂带(41～19 Ma)和高黎贡右行走滑断裂带(32～10 Ma)具有同时性，而梁河右行走滑断裂带的韧性变形在 35 Ma 结束。

此外，保山地体的元古代变质基底出露在南部西盟-勐腊一带，由上部崇山群片岩和大理岩，以及下部勐龙群的夕线石-石榴子石-斜长片麻岩和变火山岩组成。崇山群上部被早古生代海相沉积岩覆盖，发育近水平的面理和平卧褶皱，两者之间为近水平的韧性剪切带，具有上盘向南的剪切指向。

在思茅地体中，前寒武基底出露在点苍山-哀牢山一带，由夕线石-石榴子石-黑云母片麻岩和大理岩组成，经历了麻粒岩相的变质作用(700～770℃和 0.5～0.8 GPa)和角闪岩相的退变质作用(600～650℃和 0.35～0.45 GPa)(Wang Fang et al.，2011)。在点苍山地区的前寒武系基底上部发育近水平糜棱岩化的夕线石-石榴子石-黑云母片麻岩和十字石-蓝晶石-石榴子石片麻岩，以近水平面理、NW-SE 向拉伸线理以及向上盘向 SE 的剪切指向为特征，该高温韧性剪切带造成前寒武纪变质基底和中生代盖层之间的拆离。

3.3 青藏高原东南缘的逃逸机制

我们在青藏高原东南缘的腾冲地体、保山地体和思茅地体中都发现了近水平韧性剪切带，造成上盘古(中)生代沉积盖层和下盘前寒武变质基底之间的拆离。根据锆石 U-Pb 年龄、角闪石和云母 $^{40}Ar/^{39}Ar$ 年龄，这些渐新世—早中新世的壳内拆离层与青藏高原东南缘的走滑断裂带近于同时活动，二者具有运动学上的相关性。

野外构造分析、锆石 U-Pb 年龄、云母与角闪石的 $^{40}Ar/^{39}Ar$ 年龄揭示：腾冲地体的花岗岩体在侵位后快速冷却，强度很大，导致后期的韧性变形集中在花岗岩体的边界，岩体内部无变形。因此，腾冲地体的花岗片麻岩穹窿群不是传统的岩浆底辟机制，而是受韧性剪切带控制。晚始新世以来腾冲地体内的走滑断裂带和近水平拆离层的时空分布表明：腾冲地壳具有流变学的不均一，整体强度较高，应变集中于薄弱带。这不符合“下地壳流”模型中假定的广泛分布的低粘度下地壳(Clark and Royden，2000；Royden et al.，2008)。

根据力的作用方式，褶皱的形成机制分为顺层挤压(buckling)和垂层挤压(bending)。Burchfiel and Chen (2012)猜测在印度板块向北的持续挤压下，腾冲地体向外突出的弧形弯曲可看作轴面和枢纽都近于直立的倾竖褶皱，但没有给出任何运动学和年代学的证据。Xu Z Q et al. (2015)在腾冲地体中新发现的三条 NNE 走向的苏典、盈江、梁河走滑断裂带与那邦和高黎贡右行走滑断裂带具有相近的产状和剪切指向，可能都在 41 Ma 开始活动。35 Ma 之后，变形集中在那邦和高黎贡右行走滑断裂带。考虑到印度-亚洲碰撞以来印度板块在不断向北俯冲，东喜马拉雅古构造结(proto-eastern Himalayan syntaxis，缩写 PEHS)的位置应该在现今东构造结的南部。腾冲地体可能在 41 Ma 开始围绕 PEHS 通过层间滑动而弯曲，这些近直立的右行走滑断裂带就是倾竖褶皱的层间滑移面(图 11)。岩石圈横弯褶皱作用(lithospheric bending)导致腾冲地体围绕 PEHS 发生顺时针旋转并向西南挤出，不仅解释了腾冲地体走滑断裂带的时空分布和运动学特征，而且可以解释 18 Ma 之前嘉黎断裂和高黎贡断裂带的剪切指向相反的现象(Lee H Y et al.，2003；Lin T H et al.，2009)，以及古地磁研究中发现的沿雅鲁藏布江缝合带的逆时针旋转(Otofuji et al.，2010)。与此同时，壳内拆离层调节了腾冲地体旋转和挤出时的岩石圈变形，使变质基底在晚渐新世—早中新世快速折返并向西南方向挤出。因此，岩石圈横弯褶皱和壳内解耦是青藏高原东南缘物质逃逸的机制。

腾冲地体、保山地体和思茅地体的侧向挤出都受到大型走滑断裂带和壳内拆离层的共同作用。与“构造逃逸”模型相比(Tapponnier and Molnar，

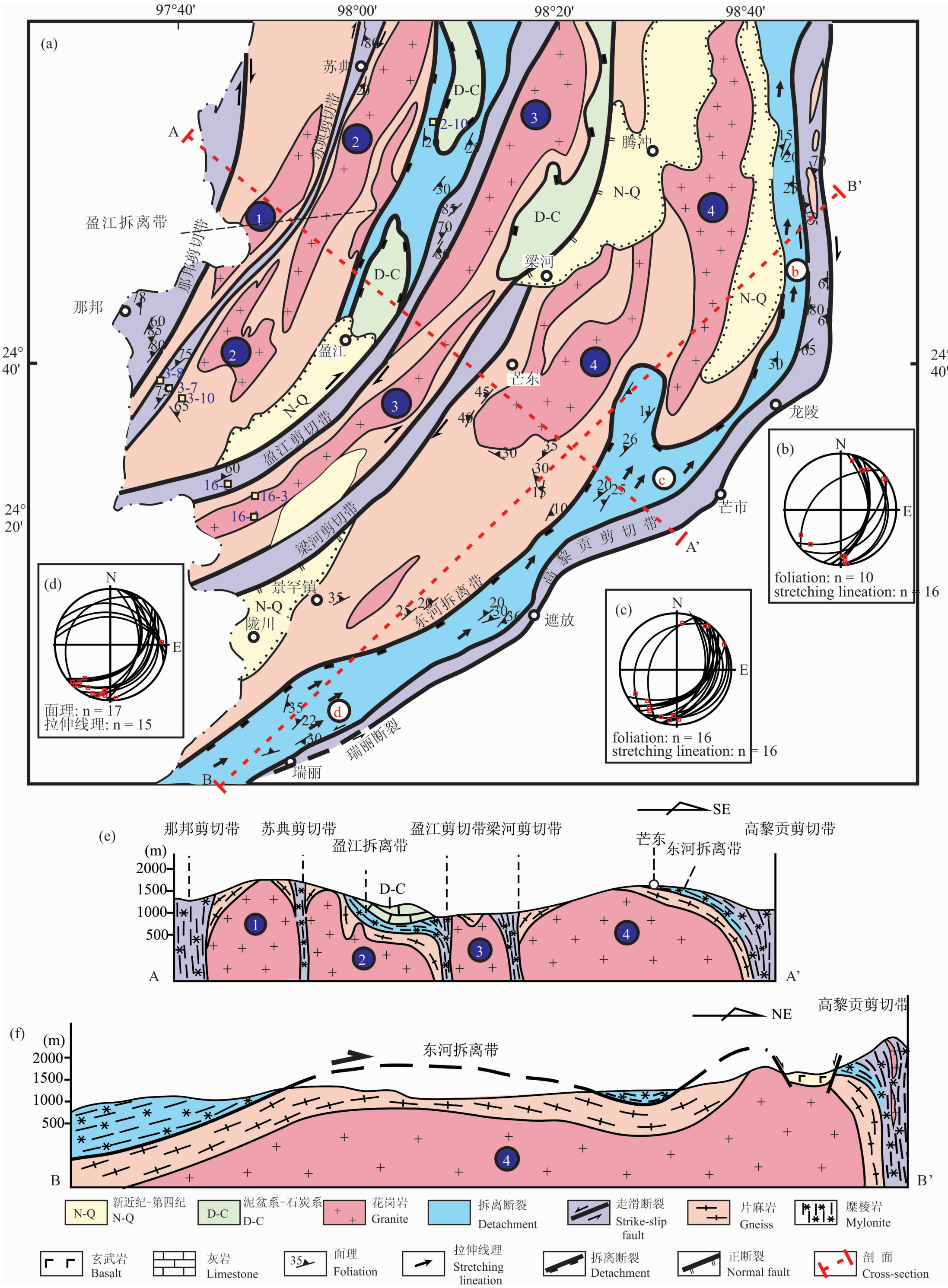

图 9　腾冲地体地质简图（据云南省地质调查局潞西幅 1∶25 万地质图，Xu Z Q et al.，2015 修改）

Fig. 9　Simplified geological map of the Tengchong terrane (modified after the 1∶250,000 geological map of the Luxi region by the Geological Survey of Yunnan Province, 2008 and Xu Z Q et al., 2015)

白色符号代表本区花岗岩岩体：1—苏典片麻岩穹窿；2—盈江片麻岩穹窿；3—梁河片麻岩穹窿；4—东河片麻岩穹窿。图 b～d 为沿东河拆离层北、中、南三个地区的面理和拉伸线理的下半球赤平投影，图 e-f 为北西、北东两个方向的地质剖面图

White numbers indicate granite plutons in this region: 1—Sudian gneiss dome; 2—Yinjiang gneiss dome; 3—Linghe gneiss dome; 4—Donghe gneiss dome; Fig b～d are lower hemisphere projection of the foliation and stretching lineation of the Donghe detachment is from (b) the northern Longling area, (c) the western Mangshi area, and (d) the northern Ruili area (labeled as b, c, d in the geological map). (e) NW-trending cross-section AA′ and (f) NE-trending cross-section BB′ in the southern Tengchong Terrane

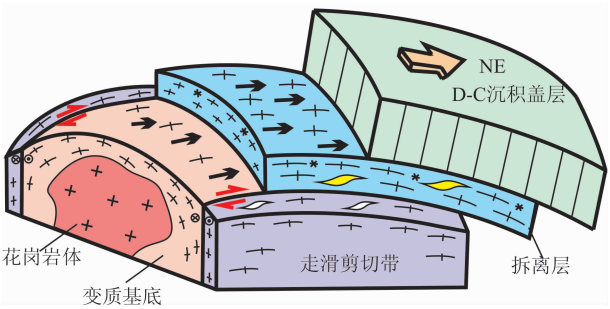

图 10 腾冲花岗片麻岩穹窿模式图(Xu Z Q et al., 2015)

Fig. 10 Schematic viewof a gneiss dome in the Tengchong Terrane (Xu Z Q et al., 2015)

本图显示以下特征:具有早白垩世—早古新世的花岗岩岩基的前寒武纪高级变质核和由向 NE 剪切指向的近水平拆离剪切带和右行走滑剪切带的幔部变质岩和上覆古生代盖层

This figure showing some features: Precambrian high-grade metamorphic core with granite plutons of the early Cretaceous to early Eocene, metamorphic mantling rocks composed of flat-lying detachments with top-to-NE shear sense and dextral strike-slip shear zones, and the overlain Paleozoic sedimentary sequences

1976; Tapponnier et al., 1986),高黎贡右行走滑断裂并不是青藏高原东南缘物质挤出的西边界,变形也没有局限在切穿岩石圈的近直立的大型走滑断裂带。因此,印度-亚洲碰撞导致的青藏高原腹地物质向南、东南的逃逸不能仅用刚性块体沿走滑断裂带的运动和旋转解释,壳内拆离是调整陆陆碰撞带岩石圈变形和物质流动的重要机制。大陆岩石圈的流变学结构不均一性是导致该变形机制的原因。

4 讨论

Xu Z Q et al. (2015) 的研究表明腾冲地体的挤出起始于 41 Ma,略晚于特提斯喜马拉雅片麻岩穹窿记录的加厚下地壳深熔事件的开始时间 46 Ma (Hou Z Q et al., 2012)。伴随着喜马拉雅造山带中下地壳部分熔融和高喜马拉雅的折返,腾冲地体围绕东喜马拉雅古构造结发生顺时针旋转和向南的挤出。值得注意的是,南海大洋扩张发生在 32～17 Ma,与哀牢山-红河断裂带的左行走滑和高黎贡断裂带的右行走滑基本同时(Gilley et al., 2003; Harrison et al., 1996; Leloup et al., 1995, 2001; Zhu M Z et al., 2009)。17～18 Ma 以来,哀牢山-红河断裂带和嘉黎断裂带都从左行走滑转变为右行走滑,暗示了晚中新世以来区域构造应力场发生了重大变化,虽然青藏高原物质向东南的逃逸仍在继续,但是岩石圈横弯褶皱已不是控制青藏高原东南缘挤出的主要变形机制。印度-亚洲陆-陆碰撞之

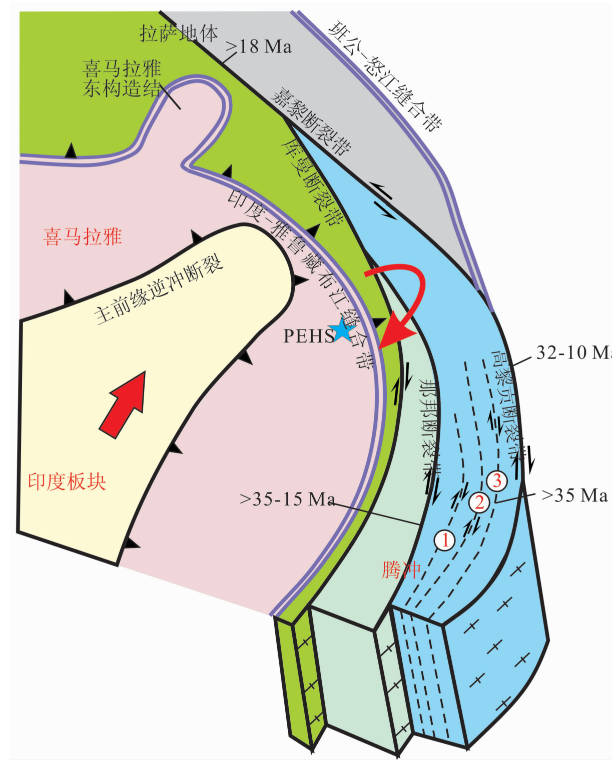

图 11 腾冲地体的岩石圈横弯褶皱模式(修改自 Xu Z Q et al., 2015)

Fig. 11 Lithospheric bending model of the Tengchong terrane in SE Tibet (modified from Xu Z Q et al., 2015)

蓝星代表 41 Ma 东喜马拉雅古构造结(proto-eastern Himalayan syntaxis,缩写 PEHS)的位置。腾冲地体围绕 PEHS 进行顺时针旋转,通过沿走滑断裂带的层间滑动形成轴面和枢纽都近于直立的倾伏倾竖褶皱,并发生顺时针旋转

A star indicates the position of the proto-eastern Himalayan syntaxis at 41 Ma. Clockwise rotation of the Tengchong Terrane around proto-eastern Himalayan syntaxis was achieved by the dextral movement along strike-slip shear zones, which separated the Tengchong Terrane into several parallel crustal slices and formed vertically plunging folds around the proto-eastern Himalayan syntaxis

后,印度板块东北角相对于欧亚大陆的汇聚速率从 45～40 Ma 期间的 118 mm/a,逐渐减小到 40～20 Ma 期间的 83 mm/a,然后在 20～10 Ma 期间急剧下降到 57 mm/a(Molnar and Stock, 2009),与目前印度-欧亚板块 36～40 mm/a 的汇聚速率接近(Zhang P Z et al., 2004)。因此,～20 Ma 是青藏高原构造演化的转折期。

从全球板块运动来看,陆-陆碰撞和洋-陆俯冲沿特提斯造山带呈交替结构,自西向东为:阿拉伯-西亚的陆-陆碰撞造成扎格罗斯造山带,阿拉伯海向中亚之下的洋-陆俯冲造成 Makran 俯冲增生杂岩

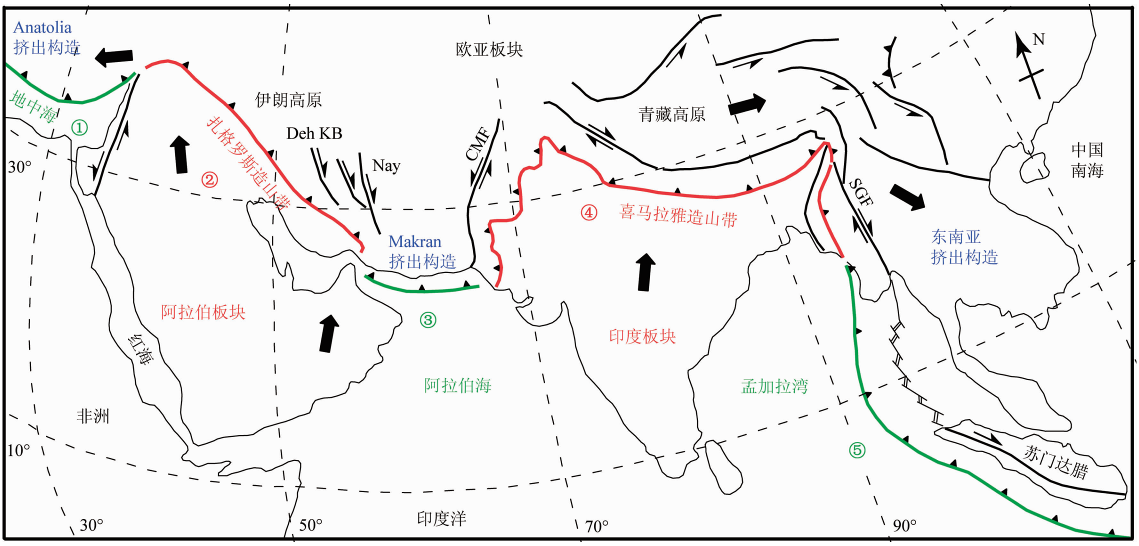

图 12　特提斯造山带陆-陆碰撞带与洋-陆俯冲带的分布(修改自 Li Z H et al., 2013)

Fig. 12　Distribution of continental-continental collision and oceanic-continental subduction in the Tethyan orogenic belt (modified from Li Z H et al., 2013)

1—地中海与欧洲的洋-陆俯冲形成 Anatolia 挤出构造；2—阿拉伯板块与西亚陆-陆碰撞形成扎格罗斯造山带；3—西印度洋(阿拉伯海)与中亚大陆的洋-陆俯冲形成 Makran 俯冲增生带；4—印藏陆-陆碰撞形成喜马拉雅造山带；5—东印度洋与东南亚的洋-陆俯冲形成苏门达腊俯冲增生带和青藏高原东南缘的挤出地体

1—Oceanic-continental subduction between the mid-terrane sea and Eourope formed the Anatolia extrusion terrane; 2—continental-continental collision between the Arab and West Asian formed the Zagross orogenic belt; 3—oceanic-continental subduction between the West Indian ocean and Central Asian continent formed the Makran accretional zone; 4—continental-continental collision between the Indian and Asian formed the Himalaya orogenic belt; 5—oceanic-continental subduction between the East Indian ocean and Southeast Asian formed the Sumantra subduction accretional zone and extrusion terrane of the SE Tibet

带，印度-亚洲的陆-陆碰撞造成喜马拉雅造山带，东印度洋向东南亚之下的洋-陆俯冲形成苏门达腊增生杂岩带(图 12)。东印度洋向东南亚的洋-陆俯冲开始于 55 Ma，主要活动时间为 30～23 Ma(Hall, 2002; Susilohadi et al., 2005)，正好对应于思茅-印度支那地体、保山-掸邦地体、腾冲-Mogok-西缅地体的侧向挤出的时间。东印度洋向东南亚的洋-陆俯冲造成的弧后扩张为青藏高原物质向东南的逃逸提供了自由空间，因此，从陆-陆碰撞到洋-陆俯冲的转换是控制印度-亚洲碰撞过程中从挤压到走滑的构造转换的根本原因。

5　结论

通过总结近年来在喜马拉雅造山带和青藏高原东南缘的研究进展，获得大约 55 Ma 以来喜马拉雅造山带的构造、变质、岩浆事件记录，建立了高喜马拉雅“三维”构造演化模型。46～35 Ma 喜马拉雅的增厚下地壳开始部分熔融，促使高喜马拉雅在 34 Ma 开始沿主喜马拉雅逆冲断裂向南折返，28 Ma 喜马拉雅造山带的重力垮塌导致沿高喜马拉雅拆离层发生平行造山带的伸展拆离，变泥质岩发生大规模的减压熔融，并且诱发了 23 Ma 以来 MCT 和 STD 的启动，促使中下地壳物质快速折返，喜马拉雅造山带的南北向缩短增厚和东西向伸展减薄并存。喜马拉雅造山带的隆升伴随着从主喜马拉雅逆冲断裂、MCT、MBT 到 MFT 一系列叠瓦状逆断层依次向前陆扩展，而且构造层次逐渐变浅，从沿主喜马拉雅逆冲断裂的高温韧性剪切变为沿 MBT 和 MFT 的脆性变形。

在腾冲地体的构造和年代学研究表明大型走滑断裂带和近水平壳内拆离层在时空上密切相关。晚始新世—早中新世，青藏高原南东南缘的物质逃逸是岩石圈横弯褶皱和壳内解耦共同作用的结果，不符合构造逃逸模型或者下地壳流模型。印度-亚洲碰撞带从挤压到走滑的构造转换受控于区域应力场的转变，是从印度－亚洲板块陆-陆碰撞到印度洋-东南亚的洋-陆俯冲的转换结果。

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Indo-Asian Collision: Tectonic Transition from Compression to Strike Slip

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Abstract

The Indo-Asian collision caused uplift of the Himalayan orogen, growth of the Tibetan plateau, a ~70－km-thick continental crust, and large amounts of materials escaping from the Tibetan plateau towards east, southeast and west along large scale strike-slip faults. How the Indo-Asian collision controlled tectonic transition from compression to strike slip in the convergent boundary is critical for our understanding of deformation mechanisms of the continental lithosphere. On the basis of structural, metamorphic and magmatic records in the Himalayan orogen and SE Tibetan margin since 55 Ma, we establish a 3D kinematic extrusion model of the Greater Himalayan Complex. Extrusion of the Greater Himalayan Complex was triggered by partial melting of the middle and lower crust of the Himalayan orogen in the Eocene, and accommodated by coeval southward thrusting and orogen-parallel ductile extension since the Oligocene. Since the late Eocene, the materials of Lhasa terrane and the Qiangtang terrane rotated clockwise around the eastern structure and escaped toward the southeastern margin of the Qinghai-Tibet plateau, which follows the kinetic theory of lithospheric bending folds and mid-crustal decoupling. In combination with data of plate reconstruction in Southeast Asia, we propose that the transition from the Indo-Asian "continent-continent collision" to the Indian Ocean-SE Asian "oceanic-continental subduction" was the preliminary cause resulting in the tectonic transition from compression of the Indo-Asian collision zone to strike slip in the SE margin of Qinghai-Tibet.

Key words: Indo-Asian collision; Himalayan orogen; SE Tibetan plateau; thrusting fault; strike-slip fault; detachment