2019年1月 地 球 学 报 Jan. 2019
第40卷 第1期: 55-75 Acta Geoscientica Sinica Vol.40 No.1: 55-75
www.cagsbulletin.com

帕米尔弧形构造带的构造过程与地貌特征

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摘 要: 帕米尔弧形构造带是印度-欧亚板块碰撞变形最强烈的地区之一, 是研究构造过程、地貌演化以及气候变化及其相互作用的理想场所。本文基于前人的研究成果, 对帕米尔弧形构造带新生代构造单元、地貌特征和动力学演化模型进行了总结归纳, 包括: 主要构造单元的活动起止时间、活动量及活动速率; 帕米尔弧形构造带现今的地貌特征(水系和冰川的分布); 帕米尔弧形构造带6种主要的地球动力学演化模型的主要样式、优点及限制。论文提出了帕米尔弧形构造带晚新生代构造研究的三个重要的科学问题: 精细厘定构造带内部的不同断裂带运动学特征和相互关系; 深部地质过程与浅部响应相结合, 探讨构造带形成的深部地质过程控制; 将构造过程、气候特征与地貌演化作为一个耦合系统开展研究。

关键词: 帕米尔弧形构造带; 新生代; 构造过程; 地貌特征; 地球动力学模型

中图分类号: P534.6; P54; P931 **文献标志码:** A **doi:** 10.3975/cagsb.2018.092603

The Tectonic Processes and Geomorphic Characteristics of Pamir Salient

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Abstract: Pamir salient is one of the intensest deformation zones caused by India-Eurasia collision, and is an ideal region to study tectonic processes, geomorphic characteristics, climate changes and their interactions. On the basis of previous research results, the Cenozoic tectonic units, geomorphic characteristics and geodynamic evolution models of the Pamir salient are synthesized in this paper, which include the onset and stop timing, motion magnitude and rates of the main tectonic units; the present geomorphic characteristics of the Pamirs salient (distribution of river systems and glaciers); and the main configuration, advantages and limitations of six geodynamic evolution models of the Pamir salient. We propose three key scientific issues in the study of late Cenozoic tectonic processes in Pamir salient, i.e., precise determination of kinematic characteristics and relationships of different faults; combining deep geological processes with surface responses so as to explore the control of deep geological processes on the formation of Pamir salient; and taking the tectonic processes, climatic characteristics and geomorphic evolution as a coupling system.

Key words: Pamir salient; Cenozoic; tectonic processes; geomorphic characteristics; geodynamic models

帕米尔弧形构造带(Pamir salient)位于喜马拉雅—青藏高原的西北部, 主要由北帕米尔、中帕米尔和南帕米尔3个地体在晚古生代—中生代拼贴而成(图1)(Angiolini et al., 2013; Robinson, 2015), 由于印度-欧亚板块的持续汇聚, 其在晚新生代整体向北弧形突进了约280 km(Burtman and Molnar, 1993; Cowgill, 2010; Sobel et al., 2011, 2013)。帕米尔强烈的向北扩展, 导致地壳厚度由前新生代的25~30 km(Burtman and Molnar, 1993)增加至现今的55 km以上, 局部地区甚至达到70 km(Beloussov et

本文由国家自然科学基金重点基金项目(编号: 41330207)、重点国际合作项目(编号: 41720104003)、国家科技重大专项(编号: 2017ZX05008-001; 2016ZX05003-001)和国家重点研发计划(编号: 2016YFC0601004)联合资助。
收稿日期: 2018-09-04; 改回日期: 2018-09-25; 网络首发日期: 2018-09-27。责任编辑: 闫立娟。
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al., 1980; Mechie et al., 2012; Schneider et al., 2013), 并使得地壳物质被大规模垂向挤出(Robinson et al., 2004, 2007; Stübner et al., 2013a)、剥蚀(Lukens et al., 2012; Carrapa et al., 2014; Fuchs et al., 2014)和俯冲断离(Negredo et al., 2007; Schneider et al., 2013; Sippl et al., 2013b)。帕米尔的扩展也使得塔里木盆地西南缘被强烈改造，使这一地区成为新生代构造变形最强烈的地区之一(陈汉林等, 2010, 2014; 程晓敢等, 2011, 2012; 廖林等, 2012; Wang et al., 2013, 2016a; 李康, 2014; Cheng et al., 2016, 2017; Wang et al., 2016b)。

随着新都库什和喀喇昆仑山脉的隆升，印度夏季风在晚第四纪几乎不能为帕米尔提供水气，而西风带所带来的水气大部分降落在帕米尔西缘，从而造成帕米尔中—东部地区的半干旱—干旱化(Fuchs et al., 2013, 2014)，并使得公格尔山—慕士塔格峰和塔什库尔干冰川消退(Seong et al., 2009a, b; Owen et al., 2012)。而构造活动和气候影响造就了帕米尔现今的地貌特征，导致帕米尔高原西缘发育深切河谷，在高原的中-东部发育公格尔山—塔什库尔干谷地、卡拉库尔谷地等，并接受新生代沉积(Brookfield, 2008)。同时，地貌演化也影响了构造活动，帕米尔东北缘公格尔山穹窿在 3–1 Ma 的快速剥露是对作用于穹窿的冰川作用和盖孜河的侵蚀作用的响应，而河流的侵蚀和冰川作用则是对伸展构造的反馈(Cao et al., 2013a)。

因此，帕米尔弧形构造带是研究构造过程、地貌演化以及气候变化及其相互作用的理想场所。

1 帕米尔弧形构造带的构造过程

印度板块与欧亚板块~50 Ma 以来的持续碰撞，造成了中亚地区强烈的陆内变形和帕米尔高原的隆升，同时形成了帕米尔弧形构造带(Molnar and Tapponnier, 1975; Rowley et al., 1996)。帕米尔弧形构造带周缘以一系列逆冲、走滑和走滑逆冲断层带为界，内部则以发育了一系列与伸展相关的构造为特征(图 1)。南缘为科依斯坦—拉达克弧及向北俯冲的印度板块；北缘为向北逆冲的主帕米尔逆冲断层(Main Pamir Thrust, MPT)和帕米尔前缘逆冲断层(Pamir Frontal Thrust, PFT)；东缘为喀喇昆仑断层(Karakorum Fault, KKF)、喀拉喀什断层(Karakax Fault, KXF)和喀什—叶城走滑系统

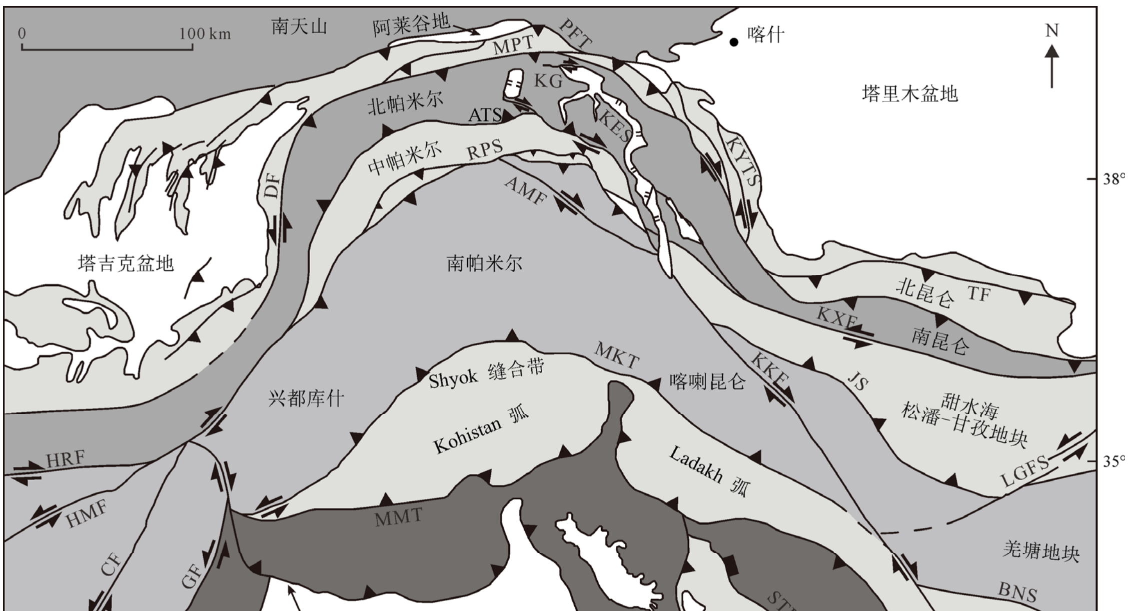

图 1 帕米尔弧形构造带构造纲要图(据 Robinson et al., 2004; Cowgill, 2010)

Fig. 1 Tectonic outline of the Pamir Arcuate Tectonic Belt (modified after Robinson et al., 2004; Cowgill, 2010)

AMF-Aksu–Murgab 断层; ATS-Akbaytal–Tanymas 缝合带; BNS-班公—怒江缝合带; CF-恰曼断层; DF-达瓦孜断层; GF-Gardez 断层; HMF-Helmand 断层; HRF-Herat 断层; JS-金沙江缝合带; KES-公格尔山伸展系统; KG-卡拉库尔地堑; KKF-喀喇昆仑断层; KXF-喀拉喀什断层; KYTS-喀什—叶城转换系统; LGFS-龙木错—郭扎错断层系统; MBT-主边缘逆冲断层; MCT-主中央逆冲断层; MKT-主喀喇昆仑逆冲逆冲断层; MMT-主地幔逆冲断层; MPT-主帕米尔逆冲断层; PFT-帕米尔前缘逆冲断层; RKF-Rangkul 断层; RPS-Rushan–Pshart 缝合带; STDS-藏南拆离系; TF-铁克里克断层

AMF-Aksu–Murgab falut; ATS-Akbaytal–Tanymas suture; BNS-Bangong–Nujiang suture; CF-Chaman fault; DF-Darvaz fault; GF-Gardez fault; HMF-Helmand fault; HRF-Herat fault; JS-Jinsha suture; KES-Kongur Shan extensional system; KG-Karakul graben; KKF-Karakoram fault; KXF-karakax fault; KYTS-Kashgar–Yecheng transfer system; LGFS-Longmu Co–Guoza Co fault system; MBT-main boundary thrust; MCT-main central thrust; MKT-main Karakoram thrust; MMT-main mantle thrust; MPT-main Pamir thrust; PFT-Pamir frontal thrust; RKF-Rangkul fault; RPS-Rushan–Pshart suture; STDS-south Tibetan detachment system; TF-Tiklik fault

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(Kashgar–Yecheng Transfer System, KYTS)；西缘为达瓦孜断层(Darvaz Fault, DF)和恰曼断层(Chaman Fault, CF)；内部则主要发育与伸展相关的公格尔伸展系统(Kongur Shan Extensional Sysem, KES)、卡拉库尔地堑(Karakul Graben, KG)和新生代穹窿。

1.1 南缘印度板块的俯冲历史

~50–25 Ma，印度-欧亚大陆的碰撞导致了亚洲岩石圈的逐步增厚(Klootwijk et al., 1992; Najman et al., 2010)。古地磁重建、地质平衡恢复和全球层析成像结果显示，在印度克拉通岩石圈与欧亚板块碰撞之前，印度克拉通北缘的被动大陆边缘(~1 350 km 宽)已经发生了俯冲，称为 Greater India(Van der Voo et al., 1999; Guillot et al., 2003; Van Hinsbergen et al., 2011)。持续的 N–S 向汇聚作用导致了帕米尔内部的强烈缩短和地壳的增厚。

25–20 Ma，由于印度克拉通板块浮力大、厚且稳定，加之亏损的岩石圈地幔(Kumar et al., 2001)，可能阻止了俯冲，导致了 Great India 板片沿着其与印度克拉通岩石圈之间的过渡带发生了断离(图 2)(DeCelles et al., 2002; Negredo et al., 2007; Stearns et al., 2013, 2015)。之后，汇聚模式由俯冲变为下插(Kufner et al., 2016)，速度从~44 km/Ma 减少到~34 km/Ma(Molnar and Stock, 2009)。持续向北下插的印度克拉通岩石圈地幔与帕米尔地壳耦合，增加了造山带的边界挤压应力。

~12 Ma，~N–S 向的重力垮塌在中帕米尔终止，重力垮塌导致重力势能减弱，使得亚洲地壳的应力由拉张变为挤压，变形向前陆传播，造成了北帕米尔与南天山之间的加速缩短。~11 Ma，深部持续向北的印度克拉通岩石圈与亚洲克拉通岩石圈发生碰撞，导致了亚洲克拉通板片的拆沉和后撤(Kufner et al., 2016)，也形成了帕米尔之下的地震带(Sippl et al., 2013a)。

1.2 北缘正向逆冲

帕米尔北缘发育南倾的主帕米尔逆冲断层(MPT)、帕米尔前缘逆冲断层(PFT)及其两者之间的乌泊尔背驮盆地(Wupoer Piggyback Basin)，并以此与北侧的阿莱山谷和南天山分界(图 1)。

1.2.1 主帕米尔逆冲断层(MPT)

MPT 是向北后撤的俯冲亚洲板片在地表的投影(Sobel et al., 2013)，近 EW 向展布的 MPT 由多条向北逆冲的叠瓦状断层组成，位于 MPT 南侧的 Trans Alai 山脉沿 MPT 逆冲到北侧的阿莱谷地之上(陈杰等, 2011)。

MPT 的活动时间可能起始于 20–25 Ma(Thomas et al., 1994, 1996; Sobel and Dumitru, 1997; Bershaw et al., 2012; Cao et al., 2013b, Thompson et al., 2015)或者中始新世(Yin et al., 2002)。晚中新世后，其活动速率明显下降(Sobel et al., 2011)。Coutand et al.(2002)利用平衡剖面法估算出阿莱谷地 25 Ma 以来的缩短速率为 0.7~0.8 mm/a。Arrowsmith and Strecker(1999)通过对位于阿莱山谷的 Syrinadjar 河中被错断阶地的分析，计算出 MPT 中段(阿莱谷地南缘)全新世的倾滑速率为≥6 mm/a。GPS 数据显示 MPT 在阿莱盆地南缘现今仍以 10~15 mm/a 的速率吸收南北向的缩短(Zubovich et al., 2010; Ischuk et al., 2013)，但这一断层在帕米尔东北缘可能已不再活动(陈杰等, 2011)。

1.2.2 帕米尔前缘逆冲断层(PFT)

PFT 位于 MPT 以北~30 km，是帕米尔弧形构造带最前缘最新的变形带，其前缘逆断层又称乌帕尔断层带(陈汉林等, 2010)，且具有明显的右旋走滑分量(肖安成等, 2000)。PFT 由多个向北逆冲的次级推覆体及其间的横向撕裂断层组成(刘胜等, 2005; 陈汉林等, 2010; 陈杰等, 2011)，由西向东包括卡巴加特断层、吉勒格由特断层、托姆洛安断层、木什背斜和乌帕尔压扭断层(陈杰等，1997; 尚新璐等, 2004; 陈汉林等, 2010)。其形成可能与乌拉根古隆起的存在有关(Wang et al., 2016a)。

6–3.5 Ma，帕米尔前缘逆冲断层开始活跃(Arrowsmith and Strecker 1999; Fu et al., 2010; Thompson et al., 2015)。Thompson et al.(2015)通过生长地层及磁性地层学研究，认为 FPT 于~5–6 Ma 开始活动。FPT 几乎吸收了帕米尔北缘晚第四纪以来的所有变形，~0.35 Ma 以来的平均缩短率为 6~8 mm/a(Li et al., 2012b)。野外露头及磁性地层学数据显示 PFT 现今最小缩短量为 2.1 km，最小缩短速率约为 6.2 mm/a(陈杰等, 2011)。Zubovich et al.(2016)通过 GPS 数据分析，认为 PFT 现今倾滑速率至少在(5.6±0.8) mm/a，缩短速率在(92.2±0.8) mm/a。潘家伟等(2009)根据乌帕尔断裂带造成的水系错断量，计算出该断层的右旋走滑速率为 4.0~6.8 mm/a，活动时间为>2.2–3.0 Ma。

1.3 东缘右旋-走滑逆冲

帕米尔东缘发育三条主要的走滑断层，从西向东依次为喀喇昆仑断层(KKF)、喀拉喀什断层(KXF)和喀什-叶城转换系统(KYTS)(图 1)，并以此与东侧的甜水海地块、西昆仑和塔里木盆地分隔(Burtman and Molnar, 1993; Cowgill, 2010)，这三条断层都有可能参与了帕米尔相对于西昆仑向北的运动(陈杰等, 2011)。

1.3.1 喀喇昆仑断层(KKF)

KKF 总体走向 NW–SE，长约 1 200 km，自青藏高原东南端的冈仁波齐山脉一直延伸到中帕米

万方数据

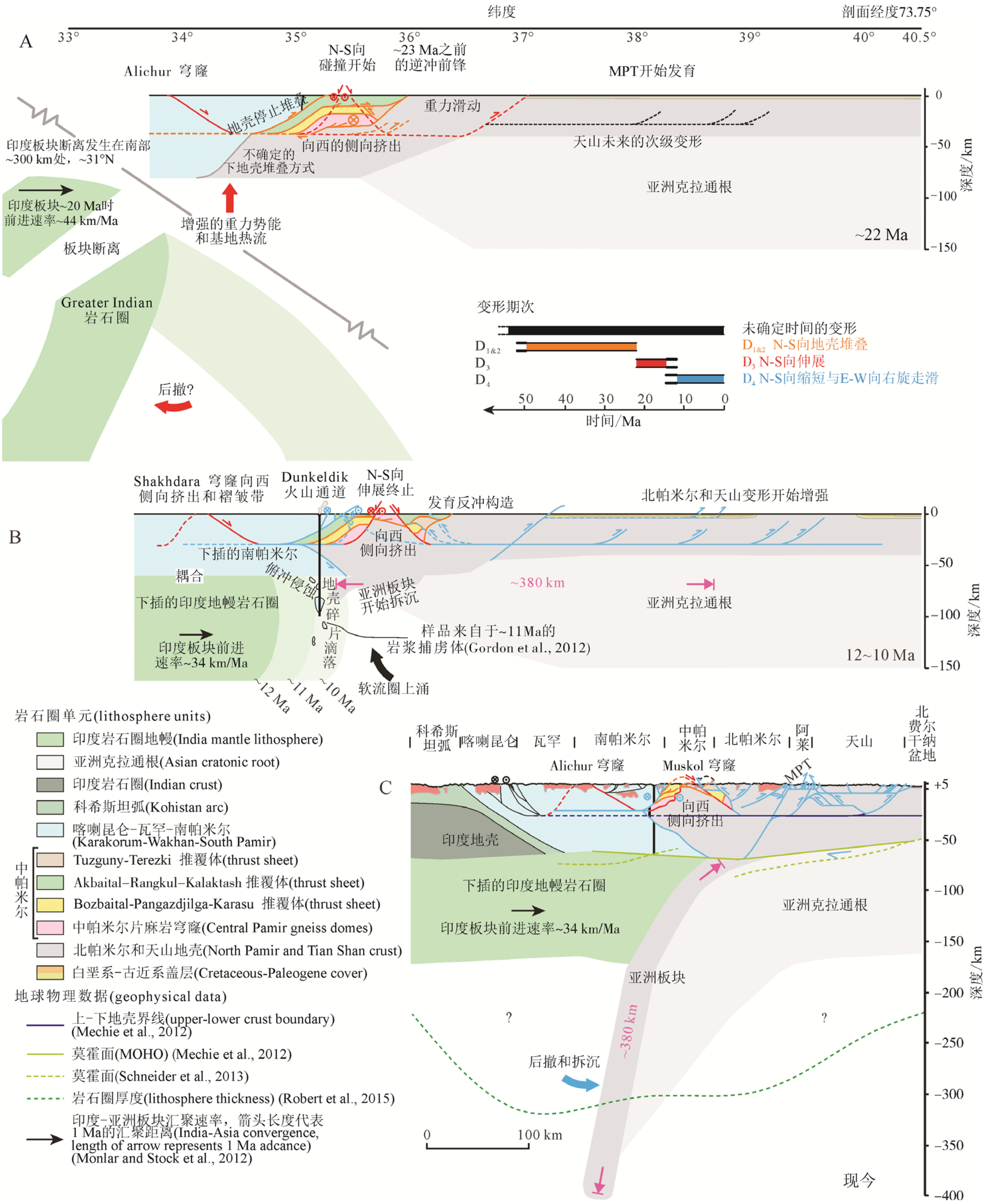

图 2 帕米尔深部构造过程及其浅部响应剖面示意图(据 Rutte et al., 2017b)

Fig. 2 Schematic sections through Pamir Arcuate Tectonic Belt illustrating the spatiotemporal relationships between crustal and mantle processes (after Rutte et al., 2017b)

A- ~22 Ma：始于~37 Ma 的逆冲推覆体褶皱堆叠使中帕米尔地壳强烈增厚，北帕米尔地壳表现为下插。部分地壳物质向西侧向挤出。Greater India 岩石圈在~25–20 Ma 发生断离，引发重力坍塌，在中、南帕米尔发生了广泛的 N–S 向伸展作用，北帕米尔与天山之间开始发生汇聚；B- ~12–10 Ma：板块断离之后，印度岩石圈地幔由俯冲变为下插，且与南帕米尔地壳耦合，近 N–S 向的伸展作用停止，变为 N–S 向的挤压作用。南帕米尔地壳岩石由于俯冲侵蚀作用，地壳碎片滴落至地下 100 km 深，之后作为捕虏体被从 Dunkeldik 岩浆通道喷发至地表。~11 Ma：印度岩石圈地幔与亚洲克拉通岩石圈发生碰撞，导致了亚洲克拉通板片的拆沉和后撤。C-现今：亚洲板片的拆沉仍在继续，地壳发生了 N–S 向的缩短和地壳物质向西的侧向挤出，以及 E–W 向的伸展作用

A- ~22 Ma: starting prior ~37 Ma thrust sheets and fold nappes thickened the Central Pamir (and South Pamir, not shown), tripling the upper crust; North Pamir crust is underthrusting. Part of the crust is extruding laterally (westward). Greater Indian lithosphere breakoff at ~25–20 Ma triggered gravitational collapse, i.e., ~N–S extension in the South and Central Pamir. Dominant top-to- ~ N sliding initiated contraction in the North Pamir and possibly the Tian Shan; B- ~12–10 Ma: after breakoff, Indian mantle lithosphere has been underthrusting Asia and coupling with the Pamir crust, ending ~N–S collapse and resuming N-S shortening (in the Central Pamir at ~12 Ma). Through a combination of subduction erosion and transient dripping, South Pamir rocks are buried to depth ≤100 km and erupted as xenoliths in the Dunkeldik volcanic pipes. ~11 Ma: Indian mantle lithosphere impinged on the southern edge of the Asian cratonic root (Tarim and Tajik basin lithosphere) and forced its delamination; C-recent: Delamination of the Asian slab is ongoing. Crust experiences dominant ~N–S shortening and westward extrusion through dextral wrenching and ~E–W extension (not displayed)

万方数据

尔，构成了帕米尔高原东南部的边界(Peltzer and Tapponnier, 1988)。对于KKF在调节印度和欧亚板块之间变形中所起的作用，有两种不同的观点：(1)KKF新生代调节了南帕米尔向北~300 km的位移量，并造成了地壳的显著增厚，形成了~70 km的陆壳(Tapponnier et al., 1982; Peltzer and Tapponnier, 1988; Armijo et al., 1989; Hamburger et al., 1992; Burtman and Molnar, 1993; Lacassin et al., 2004; 李海兵等, 2007); (2)KKF作为转换系统在连接帕米尔的逆冲带和青藏高原西缘之间所起的作用有限(Burtman and Molnar, 1993; Searle, 1996; Seeber and Pecher, 1998; Murphy et al., 2000; Wright et al., 2004; Robinson et al., 2007; Searle and Phillips, 2007; Robinson, 2009a; Wang et al., 2012)。

KKF走滑活动可能起始于13~15 Ma(Murphy et al., 2000; Murphy et al., 2002; Phillips et al., 2004; Phillips and Searle, 2007)或者(23±1) Ma (Lacassin et al., 2004; Valli et al., 2008)。Brookfield et al.(2017)通过花岗岩中锆石结晶年龄，认为KKF活动时间在~12 Ma。

Robinson(2015)和Robinson et al.(2016)通过测试穿过KKF北段主干而未变形的宽谷阶地中次生碳酸盐岩帽的年龄和穿过其北段分支未被错动的冰期沉积物的年龄，认为KKF北段至少~200 ka以来已不再活动。Robinson(2009a, b)通过对遥感影像的解译，认为KKF北段活动的停止可能与~3 Ma龙木错—郭扎错左旋走滑断裂的活动有关。对于KKF北段的延伸，有学者认为KKF走滑量向北被帕米尔内部的RPZ和Aksu-Murgab断层系所吸收并终止，并未传到北部的KES和MPT(Burtman and Molnar, 1993; Strecker et al., 1995; Robinson et al., 2007)。而Chevalier et al.(2016)认为KKF北段在第四纪仍有活动，且向北与公格尔伸展系统连接成为同一个断裂体系。

断层北段右旋走滑量为149~167 km，平均滑动速率为6.9~10.8 mm/a(Robinson, 2009a)。而其南段走滑量只有~65 km(Murphy et al., 2000; Wang et al., 2012)。

1.3.2 喀拉喀什断层(KXF)

KXF又名康西瓦断层，位于KKF以东，走向近NWW，延伸近700 km，可能为阿尔金断裂的西延部分，为一左行走滑断层(Peltzer et al., 1989; Tapponnier and Molnar, 1997; 刘栋梁等, 2011)。Avouac and Peltzer(1993)认为左旋走滑的ATF在其西南端分为SW走向的龙木错—郭扎错左旋走滑断层和NWW走向的KXF。且由于龙木错—郭扎错左旋走滑断层的位移量只有25~30 km(Raterman et al., 2007)，所以Cowgill et al.(2003)推测ATF的大部分走滑量可能被KXF和向南逆冲的甜水海逆冲带所吸收。

早期的研究认为，KXF的左旋走滑速率为20~30 mm/a(Peltzer et al., 1989; Ryerson et al., 1997)。而付碧宏等(2006)根据不同年代地表地貌特征的左旋错位距离，估算出康西瓦断层晚第四纪以来的长期走滑速率为8~12 mm/a。Li et al.(2012a)和Gong et al.(2017)的研究认为KXF晚第四纪的平均走滑速率为分别为6.5 mm/a和(7.8±1.6) mm/a，这与GPS观测结果(7±3) mm/a相一致(Shen et al., 2001)。

1.3.3 喀什-叶城转换系统(KYTS)

KYTS走向NNW，长约350 km，宽约50 km，由四条近平行的右旋走滑断层组成，自西向东有库斯拉甫断层、库姆塔格断层、叶尔羌断层和阿尔塔什断层。

Sobel and Dumitru(1997)通过采自5个剖面的AFT数据的分析，识别出从晚渐新世—早中新世时期存在一期与KYTS的活动有关的隆升剥蚀和冷却，认为KYTS于20 Ma之前开始活动。Cowgill(2010)认为Yin et al.(2002)文章中阿尔塔什剖面37 Ma的快速沉降是KYTS开始活动的标志，且该转换系统是分割东帕米尔和西昆仑—塔里木块体的主要边界右旋压扭断裂带，吸收调节了北帕米尔相对于西昆仑—塔里木块体向北的运动量；晚新生代以来的累积右旋断错量约为280 km，平均滑动速率为7~8 mm/a。Cao et al.(2013b)通过对采自克孜勒陶河河谷的样品的AFT年龄分析，结合野外剖面的调查，认为KYTS启动时间在~50 Ma，但此时的断裂系比现在的要窄，直到~10–6 Ma才形成与现在规模相当的断裂系。

Sobel et al.(2011)通过对采自塔什库尔干—叶尔羌河的碎屑样品的热年代学分析，认为KYTS中的库斯拉甫断层和库姆塔格断层至少在5~3 Ma以来已停止活动，而最东缘的阿尔塔什断层在5~3 Ma以来的走滑速率仅为1.7~5.3 mm/a。这一现象表明晚中新世或上新世以来，帕米尔东缘与塔里木板块近乎作为一个整体向北运动(Sobel et al., 2011)。

1.4 西缘左旋逆冲

帕米尔西缘发育两条主要的左行走滑断层：达瓦孜断(DF)和西南端的恰曼断层(CF)(图1)。

1.4.1 达瓦孜断层(DF)

NNE走向的DF是帕米尔与塔吉克盆地的分界，其启动时间未被确定，推测可能与MPT、KYTS一致。根据全新世和晚更新世的地貌，尤其是早全新世的阶地和冲积扇的错断距离，推测该断层左旋走滑速率为10~15 mm/a(Kuchai and Trifonov, 1977;

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Trifonov, 1978)。Mohadjer et al.(2010)根据 Khorog (MANM)和 Shaartuz(SHTZ)两观测站所记录的 GPS 速度数据，通过计算其在 DF 走向上的速度分量，得出 DF 的最大左旋剪切速率为(11.4±2) mm/a。Ischuk et al.(2013)通过 GPS 数据得出帕米尔西缘与塔吉克盆地之间的左旋剪切速率为~10 mm/a，但由于 GPS 测点零散的的分布使得不能很好地限定其分布和位置。Tomas et al.(1994)结合已有的地震和地质资料，认为 DF 存在向西的逆冲分量。

1.4.2 恰曼断层(CF)

CF 位于帕米尔高原西南端，是印度板块与亚欧板块的分界，走向 NE，南北长约~1 000 km，东西宽约 20~30 km，南端连接麦克兰(Makran)增生汇聚带，北端与喜马拉雅汇聚带相连(Lawrence et al., 1981; Tapponnier et al., 1981; Dewey et al., 1988; 许志琴等, 2011)。

CF 开始活动时间为~25–20 Ma，总的位移量为(460±10) km，早中新世以来的平均走滑速率为 24~35 mm/a(Beun et al., 1979; Lawrence et al., 1992)。GPS 数据显示 Chaman-Gardiz-Konar System 北部现今的左旋剪切速率为(18±1) mm/a(Mohadjer et al., 2010)。合成孔径雷达干涉测量技术(InSAR)对北部的现今滑移速率进行分析得到了一个相对较低的滑动速率~8 mm/a(Furuya and Satyabala, 2008), Fattahi and Amelung(2016)利用该方法也得到了相似的结果(~8.1±2) mm/a；对 CF 的中部和南部，Barnhart(2017)通过InSAR分析，得出走滑速率的峰值为 9~12 mm/a。在 CF 中南部的 Spinatizha 地区北部的 GPS 数据显示了(~8–10) mm/a 的走滑速率(Crupa et al., 2017)。

1.5 内部伸展作用

帕米尔弧形构造带内部，晚新生代的构造活动主要表现为片麻岩穹窿的剥蚀和伸展系统的扩展。其中，北帕米尔主要发育与东西向的伸展作用，且在其东北缘发育与之相关的公格尔伸展系统和公格尔—慕士塔格穹窿；中、南帕米尔主要发育南北向伸展作用和之相关的穹窿。

1.5.1 EW 向伸展构造

在新生代，帕米尔内部的 EW 向伸展构造主要为卡拉库尔地堑(Karakul Graben, KG)和公格尔伸展系统(Kongur Shan Extensional System, KES)以及除了 KES 以外的公格尔—慕士塔格穹窿边界的断层(图 1)。

(1)卡拉库尔地堑(KG)

在北帕米尔中部，发育了近 NNE–SSW 走向的卡拉库尔地堑(图 1)，内部形成了卡拉库尔盆地。KG 北部以 NW–SE 走向的右旋走滑 Markansu 断层带为界，南部以 NW–SE 走向的右旋走滑 Aksu-Rangkul 断层带为界(Strecker et al., 1995)。

如果拉张只沿东西两侧的边界正断层发育，KG 的 EW 向总拉张量<3 km，考虑拉张速率为~0.5–1 mm/a，则推算出 KG 的 EW 向扩张可能开始于~9–3 Ma(Amidon and Hynek, 2010)。同时，沿地堑的拉张还伴随着左旋走滑分量，加之南北两侧边界的右旋走滑断层，该地区除了受到 EW 向拉张之外，还收到了 NNW–SSE 向的挤压(Strecker et al., 1995)。

(2)公格尔伸展系统(KES)

KES 走向 NW–SE，延伸约 250 km，由北向南依次为木吉断层、公格尔山正断层、塔合曼断层和塔什库尔干正断层(Robinson et al., 2007)。KES 东西向的伸展量在木吉断层为 30 km，在公格尔山附近最大，约 34 km，向南减少至慕士塔格山附近的 20 km，最南边的塔什库尔干正断层只有<3 km(Robinson et al., 2004, 2007)，总体上呈北宽南窄。

KES 北部活动时间较早，为 8~7 Ma(Robinson et al., 2004)；南部略晚，为 6.2~5 Ma(Robinson et al., 2007; Sobel et al., 2011; Cao et al., 2013a)。Robinson et al.(2004)对采自北部 Qimugang 山谷地区和公格尔山附近KES下盘的样品进行了独居石U-Pb年龄、云母 $^{40}Ar/^{39}Ar$ 年龄和钾长石多重扩散域 MDD (Multi-diffusion Domain, MDD)模式分析，表明断层下盘 8~7 Ma 以来发生了快速稳定隆升。而公格尔正断层在墓士塔格山附近的起始活动时间则为 6.2~5 Ma(Robinson et al., 2007; Sobel et al., 2011; Cao et al., 2013a)。第四纪的断层陡坎和地震活动表明公格尔正断层现今仍然在活动(Seong et al., 2009b; 李文巧等, 2011)。

木吉断层位于KES最北段，为具有拉张分量的右旋走滑断层，木吉断层下盘 8~7 Ma 以来自地下 10 km 深处发生了快速而稳定的冷却，其剥蚀速率为 1.3~1.4 mm/a(Robinson et al., 2004)，木吉断层的右旋走滑速率为(4.5±0.2) mm/a 到(11.1±0.9) mm/a 之间，或≤~7 mm/a，但后者要求垂向移动速率为~0.3–0.5 mm/a(Chevalier et al., 2011)。

公格尔山正断层下盘自 8~7 Ma 以来，在 Qimugang 山谷总剥蚀厚度为 10~11 km，在公格尔山附近剥蚀厚度为 29 km(Robinson et al., 2004)；自 7.5~5 Ma 以来，在慕士塔格山附近剥蚀量约 9 km(Robinson et al., 2007)。Robinson et al.(2010)基于热对流和断层几何特征的模拟计算表明公格尔山附近自约 7 Ma 以来，断层下盘剥蚀速率为 4.2 mm/a，倾滑速率约 6.5 mm/a。若假定断层倾角为 40°，则垂直滑动速率约 4.2 mm/a，近 EW 向拉张

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速率 5.0 mm/a(陈杰等，2011)。慕士塔格山附近自 7.5~5 Ma 以来下盘剥蚀速率约为 1.2~1.8 mm/a，近 EW 拉张速率约为 3 mm/a(Robinson et al., 2007)。

塔合曼断层位于塔什库尔干谷地北缘，是公格尔山正断层和塔什库尔干正断层之间的调节断层(Robinson et al., 2007)。长约 20 km，总体走向 NNE，北部约 2/3 走向 N25°E，南部约 1/3 走向 N5°E，倾向 W–NW，倾角近直立(Robinson et al., 2004)。Robinson et al.(2007)通过对断层下盘的 $^{40}Ar/^{39}Ar$ 热年代学研究，认为断层活动时间在 10~8 Ma。

塔什库尔干断层位于塔什库尔干谷地的西侧，处于 KES 的最南端，长约 75 km。断层走向 N–NNW，倾向东，倾角近直立。断层北部下盘在东西向伸展过程中的剥蚀量≤5 km。陈杰等(2011)通过库孜滚地区断层错断的两期冰碛堤及其表面暴露年龄，计算出断层的垂直滑动速率为 1 mm/a。陈沈强(2016)通过采自塔什库尔干断层上、下盘样品的热年代学分析，认为塔什库尔干断层初始活动时间为 8~6 Ma，断层下盘 6 Ma 以来的剥蚀速率为 0.9 mm/a，剥蚀量达 5.4 km。

(3)库科正断层(Kuke Fault)

KF 位于库科西鲁克乡附近，是公格尔—慕士塔格片麻岩穹窿(Kongur–Muztaghata gneiss domes)的东南边界，宽 1~2 km，北段走向近 N–S，南段走向 NE–SW，向东倾 65°~80°，北接盖孜断层，南接辛迪断层(Cai et al., 2017)。Robinson et al.(2007)依据采自断层其上、下盘的黑云母 $^{40}Ar/^{39}Ar$ 年龄、锆石(U-Th)/He 年龄和磷灰石裂变径迹年龄，认为其活动时间为 12~6 Ma。Cai et al.(2017)利用 U-Pb 和 ^{40}Ar-^{39}Ar 定年，结合之前的地质年代学和热年代学数据，认为 KF 的剪切作用发生在 12~8 Ma。

库科正断层与卡拉吉勒正断层、盖孜断层、和南侧的辛迪断层共同组成了公格尔—慕士塔格穹窿的东部边界。为一系列正断层或右旋走滑断层，这些断层都是东帕米尔剪切带(Eastern Pamir shear zone)的组成部分(Robinson et al., 2007)。

1.5.2　帕米尔内部穹窿

在帕米尔地区，发育着许多新生代片麻岩穹窿，约占帕米尔总面积的 30%(图 3)。由于帕米尔内部的伸展作用，这些穹窿共造成了~30~40 km 厚的地壳

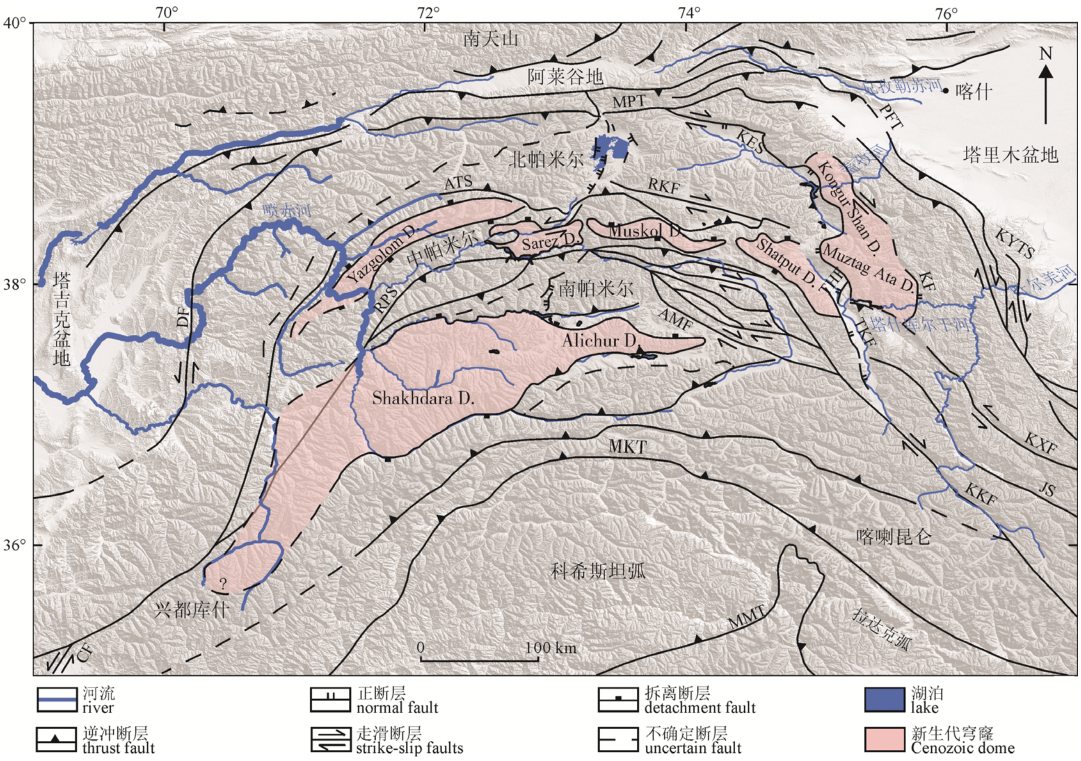

图 3　帕米尔弧形构造带新生代穹窿和水系分布图(据 Thiede et al., 2013; Fuchs et al., 2014; Komatsu, 2016)

Fig. 3　Domes and river system distribution map of the Pamir Arcuate Structural Belt (after Thiede et al., 2013; Fuchs et al., 2014; Komatsu, 2016)

AMF-Aksu–Murgab 断层; ATS-Akbaytal–Tanymas 缝合带; CF-恰曼断层; DF-达瓦孜断层; JS-金沙江缝合带; KES-公格尔山伸展系统; KF-库科正断层; KKF-喀喇昆仑断层; KXF-喀拉喀什断层; KYTS-喀什-叶城转换系统; MKT-主喀喇昆仑逆冲逆冲断层; MMT-主地幔逆冲断层; MPT-主帕米尔逆冲断层; PFT-帕米尔前缘逆冲断层; RKF-Rangkul 断层; RPS-Rushan–Pshart 缝合带

AMF-Aksu–Murgab falut; ATS-Akbaytal–Tanymas suture; CF-Chaman fault; DF-Darvaz fault; JS-Jinsha suture; KES-Kongur Shan extensional system; KF-Kuke fault; KKF-Karakoram fault; KXF-Karakax fault; KYTS-Kashgar–Yecheng Transfer System; MKT-Main Karakoram Thrust; MMT-Main Mantle Thrust; MPT-Main Pamir Thrust; PFT-Pamir Frontal Thrust; RKF-Rangkul fault; RPS-Rushan–Pshart suture

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物质的剥蚀(Schwab et al., 2004; Robinson et al., 2004; Schmidt et al., 2011; Stübner et al., 2013a)。

(1)北帕米尔穹窿

在帕米尔东北缘，主要发育公格尔山穹窿(Kongur Shan dome)和慕士塔格峰穹窿(Muztaghata dome)。

公格尔山穹窿在 9 Ma 仍处于进变质作用(Robinson et al., 2004)，于 7~5.5 Ma 开始剥露(Robinson et al., 2010; Thiede et al., 2013; Cao et al., 2013a)，并持续至今，平均剥露速率为 4.2 mm/a(Robinson et al., 2010)或>2~3 mm/a(Thiede et al., 2013)，剥露量达到 29 km(Robinson et al., 2004)，其在 3~1 Ma 可能发生了加速剥露(Arnaud et al., 1993; Cao et al., 2013a, b)。

慕士塔格峰穹窿在 30~20 Ma 发生进变质作用，原岩被埋深至 30~35 km，并于 14 Ma 发生了片岩的部分熔融，而退变质作用开始于 10~8 Ma，表明该穹窿处于第一期剥露(Robinson et al., 2007)；该穹窿的第二期剥露则开始于 6.2~5 Ma(Robinson et al., 2007; Cao et al., 2013b)，但剥露速率明显比第一期时小，仅为(1±0.5) mm/a(Thiede et al., 2013)。

(2)中、南帕米尔穹窿

中帕米尔的 Yazgolom、Sarez、Muskol、Shatput 穹窿在 35~20 Ma 处于进变质作用(Schmidt et al., 2011; Stearns et al., 2013; Smit et al., 2014)，于 20~16 Ma 开始剥露(Rutte et al., 2013; Stearns et al., 2013, 2015)，并持续至 10 Ma(Schmalholz, 2004; Cao et al., 2013b)。

南帕米尔的 Shakhdara-Alichur 穹窿是帕米尔内部出露面积最大的晚新生代片麻岩穹窿，被 Turumtai 地堑分割成 Shakhdara 和 Alichur 穹窿(Stübner et al., 2013a)；这两个穹窿的进变质作用发生在 37~20 Ma，于 20 Ma 开始发生退变质作用，即开始剥露(Schmidt et al., 2011; Smit et al., 2014; Stearns et al., 2015)，并持续至 2 Ma(Stübner et al., 2013b)。

(3)帕米尔内部东西走向穹窿的形成机制与演化

Stearns et al.(2015)则提出了一种针对南北向伸展作用的解释方案，认为俯冲的印度板片在 32~20 Ma 发生后撤和拆离，导致帕米尔地壳由挤压转为伸展，中下地壳的物质被快速剥露，形成 Yazgolom、Sarez、Muskol、Shatput 及 Shakhdara-Alichur 穹窿。本文依据此模型，对帕米尔内部穹窿的演化史进行总结。

>37– ~22 Ma，由于印度板块的向北汇聚，在中、南帕米尔形成了大范围的褶皱和逆冲推覆体，加之与造山带平行的物质侧向挤出(Ratschbacher et al., 1991)，导致了中、南帕米尔广泛的 N–S 向缩短、地壳增厚和进变质作用的发生。由于中帕米尔逆冲断层和褶皱推覆体的堆叠，阻止了变形继续向北传播，变形没有传到北帕米尔(Rutte et al., 2017b)。

~23–20 Ma，由于地壳增厚和 Greater India 板块~25 Ma 的拆离，加之软流圈物质的上涌促使基底的热流值增加，导致岩石圈强度的减弱，引起了中、南帕米尔厚、热且高海拔的地壳的重力垮塌(图 2)，造成了中、南帕米尔的 N–S 向的伸展和退变质作用的发生(Stearns et al., 2013, 2015)，在中、南帕米尔地区形成了变质核杂岩(Rey et al., 2010; Rutte et al., 2017a)。中、南帕米尔的重力垮塌也可能造成了北帕米尔的变形，变形前锋从中帕米尔移动到了北帕米尔。由于重力垮塌、北帕米尔缩短和侵蚀作用的增强，造成了北帕米尔中部~25~16 Ma 的加速剥蚀(Amidon and Hynek, 2010)。

20–12 Ma，双向(南倾和北倾)的剪切带沿中、南帕米尔穹窿的南北边界发育，且主要的伸展作用发生在穹窿北缘(Rutte et al., 2017a)。

12 Ma 至今，由于重力势能的衰减和印度克拉通的下插和向北传播，导致了亚洲克拉通板片~11 Ma 的拆沉和后撤(Kufner et al., 2016)，中、南帕米尔 N–S 向伸展作用及其相关的穹窿剥露停止，N–S 向的挤压作用沿着双向的褶皱逆冲带发育(图 2)。Schurr et al.(2014)通过帕米尔的地震构造学研究，认为帕米尔高原西缘持续的重力垮塌和地壳物质向西部塔吉克盆地的侧向挤出，导致了一系列的构造变形，发育了 S–N 向的缩短、E–W 向与造山带平行的伸展作用和右旋走滑。

1.6 帕米尔隆升历史

基于低温热年代学研究，帕米尔弧形构造带新生代共经历了四次隆升，分别在~50–40 Ma，~25–16 Ma，~10–7 Ma 和<5 Ma (Robinson et al., 2004, 2007; Amidon and Hynek, 2010; Wang et al., 2011; Sobel et al., 2011, 2013; Cao et al., 2013a, b; Carrapa et al., 2014)。

~50–40 Ma，帕米尔发生了初始隆升，这一隆升是对印度与 Kohistan-Ladakh 弧在~55–47 Ma 碰撞的响应(De Sigoyer et al., 2004; Leech et al., 2005; Guillot et al., 2008)。帕米尔弧形构造带东北缘奥依塔格剖面沉积物的氧同位素分析结果显示，帕米尔的初始隆升使得其在始新世—渐新世时期已达到可以阻挡大气环流的高程(Bershaw et al., 2012)。

万方数据

Amidon and Hynek(2010)通过卡拉库尔地堑的磷灰石和锆石的(U/Th)‑He 年龄分析，认为该地区在~50–40 Ma 发生了与隆升有关的加速剥蚀。在此阶段，帕米尔西北缘发生了逆时针旋转，帕米尔东北缘和内部发生了顺时针旋转(Liu et al., 2017)。

~25–16 Ma，帕米尔发生了第二次隆升，与欧亚板块向南的俯冲作用有关(陈汉林等, 2014)。Sobel et al.(2011)通过总结帕米尔东缘已发表的热年代学数据，认为 KYTS 在渐新世至早—中中新世发生过显著的构造活动。Amidon and Hynek(2010)分析了帕米尔北缘卡拉库尔地堑的磷灰石和锆石的(U/Th)‑He 年龄，认为该地区在~25–16 Ma 发生过新的一期构造隆升，并认为此次构造隆升可能与 Greater India 板块在 25 Ma 的拆离或者 KKF 初期的活动有关。Hubbard et al.(1999)认为帕米尔西南部的22–17 Ma 的冷却年龄，反映了与构造隆升相关的剥蚀。这一隆升在帕米尔弧形构造带相邻的盆地内部有着很好的记录，帕米尔北缘山前阿莱谷地和塔吉克盆地的挠曲及沉积盆地的加速发生于早中新世(Leith et al., 1985; Coutand et al., 2002); 塔西南新生代沉积物的同位素物源的研究，表明西昆仑在此阶段发生了第一次隆升(Blayney et al., 2016); Clift et al.(2017)通过对塔克拉玛干沙漠西南部新生代沉积地层的研究，认为 Pamir 在 24 Ma 之前已经发生了隆升，早于北昆仑的 17 Ma。

~10–7 Ma，帕米尔发生了第三次隆升。Carrapa et al.(2014)通过对采自塔吉克斯坦盆地和帕米尔河流的沉积物样品进行了磷灰石裂变径迹测试，发现帕米尔在中新世—上新世发生了一期造山带尺度的强烈剥蚀。公格尔山伸展系统下盘的热年代学数据显示，公格尔山和慕士塔格山分别在在~8–7 Ma 和~9–7.5 Ma 发生了快速剥蚀(Robinson et al., 2004, 2007)。帕米尔东缘~10–6 Ma 的磷灰石裂变径迹年龄，结合 KYTS 的野外调查表明帕米尔在此时期发生了一次强烈的逆冲和与之相关的剥蚀冷却(Cao et al., 2013b)。

<5 Ma，帕米尔发生了第四次隆升。塔西南的西域砾岩和生长地层记录了此次隆升事件(Chen et al., 2002; Heermance et al., 2007)。帕米尔东缘山前在~5–4 Ma 开始发育褶皱冲断带(程晓敢等, 2012; 李康, 2014)，乌帕尔背驮盆地的物源及古水流的变化(Robinson et al., 2004; Thiede et al., 2013; Cao et al., 2013b; Sobel et al., 2013)，都记录了帕米尔在上新世至今的隆升和剥蚀。这次事件导致了帕米尔东北缘的山前变形带由 MPT 向北迁移到 PFT(李康, 2014; Thompson et al., 2015)。

2　帕米尔弧形构造带现今地貌特征

帕米尔高原平均高程约 4 000 m，东北部公格尔山和慕士塔格峰的高程分别达到 7 719 m 和 7 546 m(崔之久, 1960; Brunel et al., 1994)。西帕米尔主要为起伏的山脉、深切峡谷和大型山谷冰川，帕米尔西南缘的山峰平均海拔为~5 000~6 000 m，而谷地的平均海拔为~2 000~3 000 m(Stübner et al., 2017)。而东帕米尔为整体地势较高但更为平缓的山脉，且被大量堆积物覆盖，仅有少量山脉被冰川覆盖(Abramowski et al., 2006)。帕米尔整体地形的起伏变化较小，反映了宽阔的谷地和有限的河流下切作用(Fuchs et al., 2013)。

2.1　水系分布

帕米尔内部被萨雷阔勒岭分隔为东、西两大流域系统，其中的东部流域系统主要由盖孜河和塔什库尔干河—叶尔羌河组成，西部流域系统则由喷赤河及其支流组成(图 3)(Brookfield, 2008; Komatsu, 2016)。水系的补给皆主要来源于冰川融水和上游山区降水(Kayumov and Rajabov, 2010)。

盖孜河大致流向为NE向，上游有NW–SE向展布的支流木吉河和康西瓦河，于布伦口水库汇流，之后折向 NE 穿过山谷，流入喀什平原西部地区，最终消失于东北部的沙漠里(图 3)。盖孜河上游的北西支为木吉河，其源头为萨雷阔勒岭，其两侧有沿着东西向展布的冰川，但分布并不集中；南东支为康西瓦河，源头冰川十分发育，接受慕士塔格峰和公格尔冰川的融水补给，发源于慕士塔格的峡谷之中，出谷后补给喀拉库勒湖，而后流至布伦口水库与木吉河汇流(蒲健辰等, 2003; 再努尔, 2010)。喀拉库勒湖是帕米尔高原中国境内面积最大的天然湖泊，形成于早全新世，属于冰碛堰塞湖，面积约 4.59 km^2，呈三角形，平均水深约 15 m，湖面海拔 3 656 m(Seong et al., 2007)。

盖孜河流域总面积为 11 029 km^2，山区流域面积占总面积的98.2%，为10 827 km^2，平原流域面积占总面积的 1.8%，为 202 km^2。盖孜河全长 347 km，其中，山区河长 184 km，平原区河长 163 km(李燕等, 2003; 再努尔, 2010)，盖孜河多年平均径流量为 9.78 亿 m^3(Su and Wang, 1998)。

叶尔羌河是东帕米尔最长的河流，发源于喀喇昆仑山北坡的喀喇昆仑山口，地理坐标 74°28’–80°54’E, 34°50’–40°31’N，叶尔羌河全长1 097 km，多年平均径流量 66.3 亿 m^3(凌红波等, 2012)。流域总面积 9.89 万 km^2，山区面积 6.08 万 km^2，占流域总面积 61.5%，平原区面积 3.81 万 km^2，占 38.5%(孙本国等, 2006)。叶尔羌河主要支流有上游

万方数据

的克勒青河，中游的塔什库尔干河和山口以外汇入的提兹那甫河等。

塔什库尔干河是叶尔羌河最大的支流，位于74°28'–76°13'E，37°11'–38°13'N，由明铁盖河和红其拉甫河汇流而成，发源于喀喇昆仑山脉萨雷阔勒岭(周聿超, 1999)。红其拉甫河发源于红其拉甫附近海拔 5 852 m 的喀喇昆仑山塔木太开山达板，流向SW–NE，明铁盖河发源于海拔 5 844 m 的喀喇昆仑山中国与阿富汗交界的瓦赫吉尔山口，流向近E–W。塔什库尔干河流向 NNW，在塔合曼村与发源于慕士塔格峰南侧的塔合曼河汇流后向东流，之后在阿克陶县境内的盖里克处汇入叶尔羌河。塔什库尔干河干流全长 298 km，流域面积 9 980 km^2，常年流量>30 m^3/s ,丰水期流量>30 m^3/s ,洪水期流量 200~500 m^3/s(巴合提瓦尔等，2008；仝晓霞等，2017)。

喷赤河发源于东南帕米尔，流经帕米尔南缘和西缘，最终留向西部的塔吉克盆地。喷赤河上游及其支流为东向西展布向西流动，经阿富汗Eshkashem 地区折向北，与达瓦孜断层平行，且穿过了 Shakhdara 和 Yazgulom 穹窿(Fuchs et al., 2013)；之后在帕米尔西北缘转向西南流入塔吉克盆地。喷赤河全场 2 540 km，流域面积达 46.5 万 km^2，河口地区多年平均流量达 1 330 m^3/s，年径流量 430 亿 m^3(鲜丽菊, 2017)。

水系的发育受到了帕米尔晚新生代构造活动的控制，盖孜河和塔什库尔干河的上游沿公格尔山伸展系统发育而呈南北向展布，喷赤河的上游及其支流则沿 Yazgolom、Sarez、Muskol、Shatput 和Shakhdara-Alichur 穹窿的边缘呈东西向展布(图3)(Komatsu，2016)。河流的下切速率反映了流经地区的构造隆升速率，如喷赤河在过去 26 ka 的平均下切速率为~5.6 mm/a，流经 Shakhdara 穹窿处的下切速率约为 7.3 mm/a，在 Yazgolom 穹窿的下游为~4~5 mm/a，在 Shakhdara 和 Yazgolom 穹窿的南部边界仅为 2~3 mm/a，在达瓦孜断层上游则为~6 mm/a(Fuchs et al., 2014)。塔什库尔干河在慕士塔格峰穹窿南缘的全新世下切速率为(6.3±1.2) mm/a，可能与慕士塔格峰的快速隆升或第四纪冰川作用有关(刘进峰等, 2011)。公格尔山—慕士塔格峰现今的地貌特征则与公格尔—慕士塔格峰穹窿的剥露，该地区的岩性、气候特征和第四纪冰川作用等因素有关(Schoenbohm et al., 2014)。

2.2 冰川分布

整个帕米尔的冰雪覆盖面积在 12 078 km^2 (Dolgushin and Osipova, 1989)，冰川主要分布在其东北缘和西北缘。

(1)帕米尔东北缘

帕米尔东北缘山峰海拔高度大，雪线在4 800~5 200m 之间。海拔超过 6 000 m 的山峰共有85座，在慕士塔格山主峰周围有32座，公格尔山主峰周围有 53 座(苏珍等，1989)。巨大的山顶和高耸的山峰，是冰川发育的良好场所，加之高大的山体阻挡了西风带，使西风所携带的水汽得以补给该区(苏珍等, 1989)。因此，帕米尔东北缘地区得以发育巨大规模的冰川。

帕米尔东北缘冰川的主要类型是山谷冰川，其形态是从山谷向外呈辐射状延伸(上官冬辉等，2005)。据中国科学院兰州冰川冻土研究所的相关数据，东帕米尔共有现代冰川 466 条，冰川面积898.08 km^2，冰川储量 95.662 7 km^3。其中，大小公格尔山共有现代冰川 327 条，冰川面积 640.15 km^2，冰川储量 69.667 5 km^3；号称“冰川之父”的慕士塔格山有现代冰川 139 条，冰川面积 257.93 km^2，冰川储量 25.995 2 km^3(Su and Wang, 1989)。

公格尔—慕士塔格冰川经历了至少三次大冰期和至少 10 次小的冰进(Seong et al., 2007)。Yao et al.(2012)年对青藏高原及其周边冰川状态的研究，指出过去 30 年中青藏高原及其周边的冰川一直处于急剧的退缩状态。上官冬辉等(2005)基于 ASTER影像和已有的冰川编目数据，解译了冰川从1962/1966 年到 2001 年的变化特征，整体上是西北侧呈前进趋势，而其他大部分都有不同程度的退缩；其中，东南坡退缩比例最大，东北坡退缩量最大，而西南坡的退缩比例和退缩量均最小(曾磊等，2013)。略微增加的降雨量无法补偿冰川的消融量(Khromova et al., 2006)。东帕米尔、天山和兴都库什连续的冰川范围的减小对应了中亚日益增长的干旱(Fuchs et al., 2014)。

(2)帕米尔西北缘

中帕米尔是塔吉克斯坦境内最大的冰川区，冰川面积为 2 473 km^2 (Schetinnikov, 1998)。Fedchenko冰川是帕米尔高原上最大的冰川，也是北半球中纬度地区最大的高山树枝状冰川之一(38°15'N，72°15'E)(Aizen et al., 2009)。Fedchenko 冰川由一些堆积区的小支流盆地和一个山谷冰川舌组成，总面积 649 km^2，长 77 km，高程在 2 900~300 m，雪线在~4 700~4 800 m(Dolgushin and Osipova, 1989)，冰川总体积在 124 km^3 左右(Schetinnikov, 1998)。1958年的地震和重力调查显示，冰川厚度在冰川舌处为~200~250 m，在海拔~4 750~4 850 m 的冰川中部为800 m，在海拔 5 000 m 处厚度则达到 1 000 m

万方数据

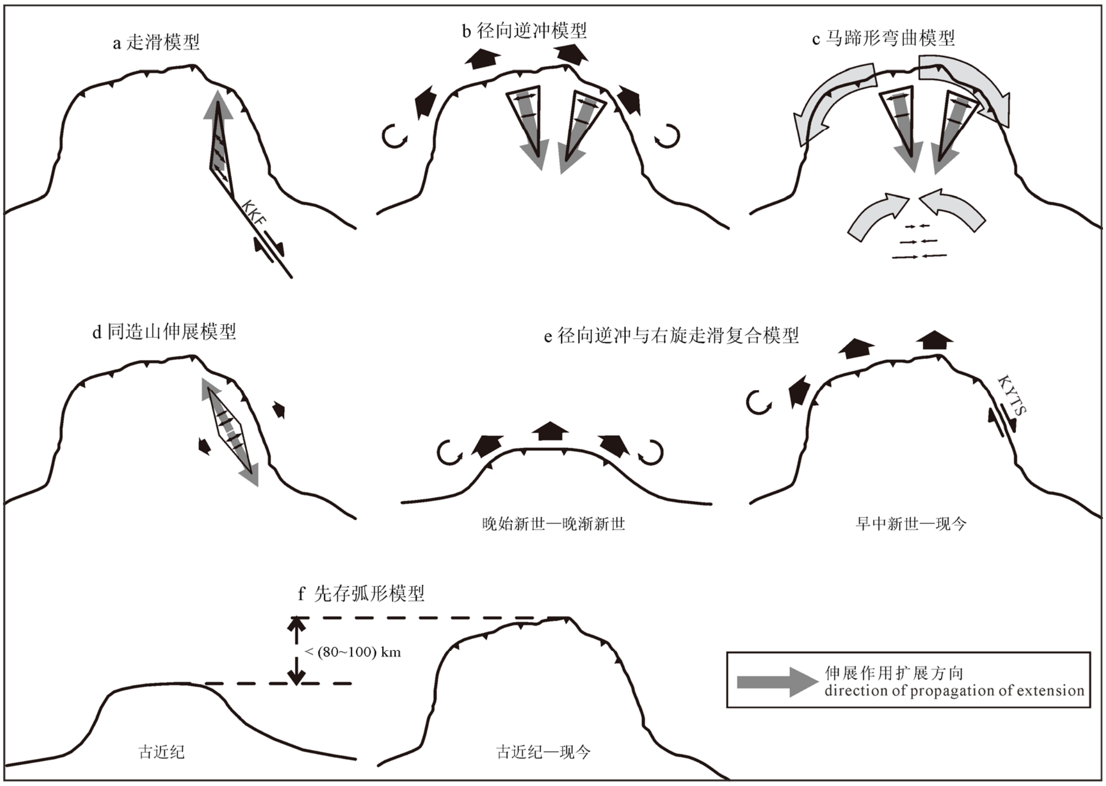

图 4　帕米尔弧形构造带演化动力学模型
(据 Robinson et al., 2004; Cowgill, 2010; Bosboom et al., 2014; Chen et al., 2018)
Fig. 4　Models for the evolution of the PamirArcuate Structural Belt
(modified after Robinson et al., 2004; Cowgill, 2010; Bosboom et al., 2014; Chen et al., 2018)

(Berzon et al., 1962)。两次冰川历史调查显示 Fedchenko 冰川在现今仅发生了小面积的变化，冰川主体并未发生大的变化(Regensburger, 1963)。

3　帕米尔弧形构造带的动力学模型

关于帕米尔弧形构造带形成的动力学模型有走滑模型、径向逆冲模型、马蹄形弯曲模型、径向逆冲与右旋走滑复合模型、同造山模型和先存弧形模型 6 种(图 4)。其中，走滑模型、径向逆冲模型和马蹄形弯曲模型可解释帕米尔弧形构造带的形成和东西向的伸展作用，径向逆冲与右旋走滑复合模型很好地解释帕米尔弧形构造带东西段形成的差异性，而同造山模型可解释帕米尔内部东西向和南北向的伸展作用。前五种模型都是基于帕米尔在新近纪以来的逐渐向北突进，而先存弧形模型则提出构造带的弧形形态在古近纪之前已经形成，之后由于印度-欧亚板块的碰撞再次向北突进。

3.1　走滑模型

走滑模型认为帕米尔弧形构造带的形成可能受控于西缘的达瓦孜左行走滑断层(DF)、东缘的喀什—叶城右行走滑系统(KYTS)和喀喇昆仑右行走滑断层(KKF)(Peltzer et al., 1988; Murphy et al., 2000; Bershaw et al., 2012)，并认为喀喇昆仑断层(KKF)在新生代的持续向北扩展导致了帕米尔内部发生东西向的伸展(Strecker et al., 1995; Murphy et al., 2000; Chevalier et al., 2011)。但是该模型要求伸展作用最先开始于公格尔伸展系统(KES)的南端，之后逐渐向北扩展，且最大伸展量在南部(Robinson et al., 2004)，事实上公格尔伸展系统(KES)总体上北宽南窄(Robinson et al., 2004, 2007)，而且这一模型也很难解释帕米尔西缘发生的逆时针旋转。

3.2　径向逆冲模型

径向逆冲模型是基于帕米尔西缘塔吉克盆地在新生代发生了逆时针旋转(Bazhenov et al., 1994; Thomas et al., 1994)而被提出，这一模型认为帕米尔弧形构造带沿主帕米尔逆冲断层(MPT)呈放射状逆冲，并使帕米尔内部发生东西向的伸展作用(Strecker et al., 1995)。该模型要求伸展作用最先开始于公格尔伸展系统(KES)的北部，之后逐渐向南扩展，最大伸展量在北部(Robinson et al., 2004)。虽然这与公格尔伸展系统(KES)总体上北宽南窄的状况(Robinson et al., 2004, 2007)相符，但是无法解释帕米尔弧形构造带东缘的塔里木盆地西南部中新世以来未发生了大角度的顺时针旋转以及喀什—叶城走滑系统(KYTS)的大规模右旋走滑。

3.3　马蹄形弯曲模型

马蹄形弯曲模型是用于解释同时发生在南迦

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帕尔巴特(Nanga Parbat)的挤压缩短作用和帕米尔内部东西向的伸展作用，并认为左旋走滑的恰曼断层控制着帕米尔的弧形造山过程(Yin et al., 2001)。该模型的伸展变形机制与径向逆冲模型不同，但二者所揭示的帕米尔内部东西向伸展作用的运动学模式是相同的。

3.4 同造山伸展模型

同造山伸展模型认为主帕米尔逆冲断层(MPT)持续逆冲，使得上盘的公格尔山—慕士塔格峰穹窿不断隆升，并在穹窿的西侧形成公格尔伸展系统(KES)(Arnaud et al., 1993; Brunel et al., 1994)。Thiede et al.(2013)和 Sobel et al.(2013)对公格尔伸展系统(KES)的形成提出了新的动力学机制解释方案，认为沿着阿莱俯冲板片的东边界存在一条俯冲边界转换断层，大量的热沿着该断层上涌，导致帕米尔东缘公格尔伸展系统(KES)的发生。该模型要求伸展作用最先开始于公格尔伸展系统(KES)的中部，再逐渐向南北两端扩展，且最大伸展量在中部，这与公格尔伸展系统(KES)总体上北宽南窄的现象(Robinson et al., 2004, 2007)不符。前文中提到的 Stearns et al.(2015)针对南北向伸展作用的解释方案，认为俯冲的印度板片在 23~20 Ma 发生后撤和拆离，导致帕米尔地壳由南北向挤压转为南北向伸展，中下地壳的物质被快速剥露，形成 Yazgolom、Sarez、Muskol、Shatput 及 Shakhdara-Alichur 穹窿。

3.5 径向逆冲与右旋走滑复合模型

径向逆冲与右旋走滑复合模型是为了更好地匹配帕米尔东、西缘构造活动的差异性，认为帕米尔弧形构造带的形成过程可能分为 2 个阶段，即在始新世—渐新世，以径向逆冲为主；而从早中新世开始，帕米尔东缘以右旋走滑为主，西缘则一直为径向逆冲(Cowgill, 2010; Bosboom et al., 2014)。但该模型未对造成帕米尔东、西缘不同演化形式、东缘从径向逆冲转为右旋走滑和内部发生东西向伸展的机制作出解释。

3.6 先存弧形模型

该模型提出弧形构造带的弧形形态不完全是在新近纪以来形成，弧形形态在古近纪之前已经形成，在新近纪由于印度-欧亚板块的碰撞再次向北突进(Chen et al., 2018)。

Chen et al.(2018)总结了帕米尔东北缘前陆地区 12 个沉积剖面的地层学特征，发现了三套由隆升所造成的古近纪冲积砾岩层：(1)早古新世，新特提斯洋闭合时亚洲板块南缘阿尔卑斯型大陆边缘的弧后变形；(2)晚古新世—早始新世，对印度-帕米尔碰撞的即时响应；(3)中始新世—渐新世，印度-亚洲板块的持续汇聚。这些古近纪的冲积砾岩最大粒径在 5~10 cm，这种粒径的沉积物从扇根最多只能被搬运 60 km 远(Shukla et al., 2001)，而结构分析发现这些砾岩在渐新世—中新世向北位移了 20~50 km(Coutand et al., 2002; Cheng et al., 2016; Chapman et al., 2017)。所以认为，在古近纪，帕米尔位于现今位置以南 80~110 km，即在帕米尔新生代向北位移之前有一个先存的向北突出的弧形形态。这个先存的弧形形态可能是古生代—中生代印度-亚洲板块碰撞之前，欧亚板块南缘一系列的块体拼合所造成的。

以上这些模型基本上是从某一个侧重面提出来的端元性模型，但是帕米尔弧形构造带在新生代时期经历了复杂的构造演化过程，并遭受了强烈的剥蚀作用，构造带内部的很多记录被强烈改造或消失。因此，需要将造山带与盆地相结合、深部过程与浅部响应相结合及其空间变化与时间演化相结合开展系统研究，提出更为合理的动力学模型。

4 帕米尔弧形构造带构造过程与地貌演变研究的关键科学问题

综合前述研究现状分析，前人对帕米尔弧形构造带的晚新生代的构造过程开展了系统的研究，并提出不同的扩展模型。而这些模型的提出很重要地依赖于帕米尔弧形构造带内部不同性质的断裂带的运动学特征分析，而这些断裂带的发育特征很可能是受控于深部的地质过程，它们是深部地质过程在浅部的响应。同时，构造过程决定了地貌的演化和气候的变化，帕米尔弧形构造带特殊的构造过程造就了帕米尔独特的地貌特征和水系的变迁；而地貌的演化和气候的变化也制约了构造的形成，通过对帕米尔水系和地貌演化过程的分析，可以获知某些断裂带或某区域的构造活动特征，从而进一步限定帕米尔弧形构造带晚新生代的演化模型。

综上分析帕米尔弧形构造带晚新生代构造研究，有以下 3 个方面的科学问题值得进一步关注。

(1)问题一：帕米尔弧形构造带内部不同性质的断裂带在弧形构造带的扩展过程中扮演了十分重要的角色，要建立合理的扩展过程与动力学模型，如何系统厘定构造带内部主要断裂带的运动学特征及其相互关系是关键。

帕米尔弧形构造带内部发育大量不同性质的断裂带(图 1)，前人对帕米尔弧形构造带周缘的主帕米尔逆冲断层(MPT)、帕米尔前缘逆冲断层(PFT)、喀什—叶城右行走滑系统(KYTS)、达瓦孜左行走滑断层(DF)，以及对应于片麻岩穹窿剥露的公格尔山断层、南帕米尔剪切带等拆离断层得到了一定程度的研究，这些断层的启动时间、运动量、

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平均运动速率等得到揭示。但是, 这些数据多来自断层的一个部位, 不能简单地将其代表整条断层的活动特征, 如主帕米尔逆冲断层(MPT)在阿莱盆地的南缘现今仍以 10~15 mm/a 的速率吸收南北向的缩短作用(Zubovich et al., 2010; Ischuk et al., 2013), 但这一断层在帕米尔东北缘已不活动(陈杰等, 2011)。对于帕米尔弧形构造带的形成过程, 特别是构造带的东部, 现有的单一模型都无法完美地解释, 不同时期的演化模型可能不同(Bosboom et al., 2014), 但不同阶段演化模型的转换时间、转换机制等问题的解决需要对构造带内部的不同断裂带运动学特征和相互关系的精细厘定。

(2)问题二: 帕米尔弧形构造带的形成不仅受水平方向上差异性的控制, 而且还受控于垂向上的变化, 也就是深部地质过程对构造带形成的控制, 因此将深部结构与浅部构造相结合、深部地质过程与浅部响应相结合开展研究, 探讨构造带形成的深部地质过程控制, 也是揭示帕米尔弧形构造带形成机制的关键。

Stearns et al.(2015)认为帕米尔弧形构造带中—南部的南北向伸展作用可能与印度俯冲板片的后撤和拆离有关, 但其与俯冲板片后撤和拆离的具体关系仍有待研究。Sobel et al.(2013)和 Thiede et al.(2013)提出帕米尔东部公格尔山伸展系统(KSE)的形成则可能与一条存在于帕米尔东缘深部的俯冲边界转换断层有关, 但是还缺少足够的地球物理证据来支撑这一观点。另外, 帕米尔东南部塔什库尔干杂岩体和 Dunkeldik 火山岩的形成机制也仍存争议, 二者可能与印度俯冲板片的拆离(Jiang et al., 2012; Stearns et al., 2015)或俯冲边界转换断层的存在(Sobel et al., 2013)有关。同样, Sippl et al.(2013b)认为欧亚板块向南俯冲于帕米尔之下, 且有中—上地壳的物质滞留在 80~100 km 深处, 这些物质的滞留或折返与片麻岩穹窿剥露的关系仍有待研究。因此, 要揭示帕米尔弧形构造带形成机制, 必须将深部结构与浅部构造相结合、深部地质过程与浅部响应相结合开展研究, 探讨构造带形成的深部地质过程控制。

(3)问题三: 作为一个现今还在活动的弧形构造带, 构造过程对地貌演化和气候变化起到重要的控制作用, 要揭示帕米尔弧形构造带地貌演化及其对气候变化的影响, 必须将构造过程、气候特征与地貌演化作为一个耦合系统开展研究。

作为一个现今还在活动的弧形构造带, 目前对其地貌特征的研究相对比较缺乏, 讨论构造过程、气候特征与地貌演化之间的关系则更少。Schoenbohm et al.(2014)认为帕米尔东北缘公格尔山—慕士塔格峰的地貌主要受控于公格尔—慕士塔格峰穹窿的剥露和第四纪冰川作用; 塔什库尔干谷地西侧南萨雷阔勒岭的地貌受控于塔什库尔干断层的构造活动, 其地貌特征反映出该断层至少在晚第四纪具有中段构造活动强度大于南、北两段的特征。但是帕米尔弧形构造带还有大量的地貌演化的问题, 例如叶尔羌河主河道的形态是否反映了帕米尔东缘的右旋走滑? 盖孜河在公格尔山段是先存河流还是其溯源侵蚀后形成的(Brookfield, 2008)? 这些问题的解决必须依赖于公格尔—慕士塔格峰穹窿的剥露速率、公格尔山断层的活动特征和/或第四纪冰川作用等的研究成果。

Acknowledgements:

This study was supported by National Natural Science Foundation of China (No. 41330207), Key International Cooperation Projects (No. 41720104003), National Science and Technology Major Project (Nos. 2017ZX05008-001 and 2016ZX05003-001) and National Key Research and Development Plan (No. 2016YFC0601004).

参考文献:

巴合提瓦尔·马苏尔, 熊凤英, 哈德尔·阿布都哈力, 沈永平. 2008. 新疆塔什库尔干河冰雪水文特征与水能开发潜力[J]. 冰川冻土, 30(6): 1073-1077.

陈汉林, 陈沈强, 林秀斌. 2014. 帕米尔弧形构造带新生代构造演化研究进展[J]. 地球科学进展, 29(8): 890-902.

陈汉林, 张芬芬, 程晓敢, 廖林, 罗俊成, 师骏, 王步清, 杨长福, 陈立峰. 2010. 帕米尔东北缘地区构造变形特征与盆山结构[J]. 地质科学, 45(1): 102-112.

陈杰, 李涛, 李文巧, 袁兆德. 2011. 帕米尔构造结及邻区的晚新生代构造与现今变形[J]. 地震地质, 33(2): 241-259.

陈杰, 曲国胜, 胡军, 冯先岳. 1997. 帕米尔北缘弧形推覆构造带东段的基本特征与现代地震活动[J]. 地震地质, 19(4): 301-312.

陈沈强. 2016. 帕米尔东南部塔什库尔干断层的构造活动[D]. 杭州: 浙江大学.

程晓敢, 黄智斌, 陈汉林, 杜治利, 李康, 师骏. 2012. 西昆仑山前冲断带断裂特征及构造单元划分[J]. 岩石学报, 28(8): 2591-2601.

程晓敢, 雷刚林, 陈汉林, 杜治利, 廖林, 罗俊成, 师骏. 2011. 西昆仑山前甫沙-克里阳地区新生代变形特征及油气控制作用[J]. 石油学报, 32(1): 83-89.

崔之久. 1960. 慕士塔格-公格尔冰川的某些特点及其开发利用的条件[J]. 地理学报, 26(1): 35-44, 74.

付碧宏, 张松林, 谢小平, 石许华, 王世锋. 2006. 阿尔金断裂系西段-康西瓦断裂的晚第四纪构造地貌特征研究[J]. 第四纪研究, 26(2): 228-235.

李海兵, VALLI F, 刘敦一, 许志琴, 杨经绥, ARNAUD N, TAPPONNIER P, ROBIN L, 陈松永, 戚学祥. 2007. 喀喇昆

万方数据

仑断裂的形成时代: 锆石 SHRIMP U-Pb 年龄的制约[J]. 科学通报, 52(04): 438-447.
李康. 2014. 帕米尔东北缘晚新生代构造与沉积演化[D]. 杭州: 浙江大学: 145.
李文巧, 陈杰, 袁兆德, 黄明达, 李涛, 余松, 杨晓东. 2011. 帕米尔高原 1895 年塔什库尔干地震地表多段同震破裂与发震构造[J]. 地震地质, 33(2): 260-276.
李燕, 李红斌, 王连有. 2003. 喀喇昆仑山盖孜河水文水资源特性分析[J]. 干旱区研究, 20(4): 272-275.
廖林, 王步清, 程晓敢, 雷刚林, 陈汉林, 姚琪. 2012. 帕米尔东北缘冲断带新生代构造变形特征及油气控制作用[J]. 中国矿业大学学报, 41(5): 776-782.
凌红波, 徐海量, 张青青, 刘新华, 傅荩仪, 白元. 2012. 叶尔羌河年径流量与降水量的集中性及相关性分析[J]. 中国沙漠, 32(6): 1757-1764.
刘栋梁, 李海兵, 潘家伟, CHEVALIER M L, 裴军令, 孙知明, 司家亮, 许伟. 2011. 帕米尔东北缘-西昆仑的构造地貌及其构造意义[J]. 岩石学报, 27(11): 3499-3512.
刘进峰, 陈杰, 王昌盛. 2011. 新疆叶尔羌河上游全新世阶地的释光年代与河流下切速率[J]. 地震地质, 33(2): 421-429.
刘胜, 邱斌, 尹宏, 李建立, 翟胜敏, 李文华. 2005. 西昆仑山前乌泊尔逆冲推覆带构造特征[J]. 石油学报, 26(6): 16-19.
潘家伟, 李海兵, VAN DER WOERD J, 孙知明, 裴军令, 司家亮, 邱祝礼. 2009. 青藏高原西北部帕米尔东北缘构造地貌与活动构造研究[J]. 第四纪研究, 29(3): 586-598.
蒲健辰, 姚檀栋, 段克勤. 2003. 慕士塔格峰洋布拉克冰川消融的观测分析[J]. 冰川冻土, 25(6): 680-684.
上官冬辉, 刘时银, 丁永建, 丁良福, 沈永平, 张世强, 鲁安新, 李刚, 蔡迪花, 张勇. 2005. 利用 ASTER 影像对慕士塔格-公格尔山冰川解译与目录编制[J]. 冰川冻土, 27(3): 344-351.
尚新璐, 陈新卫, 吴超, 罗金海. 2004. 塔里木盆地西部喀什地区的新生代冲断构造[J]. 地质科学, 39(4): 543-550, 603.
苏珍, 刘时银, 王志超. 1989. 慕士塔格山和公格尔山的现代冰川[J]. 自然资源学报, 4(3): 241-246.
孙本国, 毛炜峄, 冯燕茹, 常涛, 张丽萍, 赵玲. 2006. 叶尔羌河流域气温、降水及径流变化特征分析[J]. 干旱区研究, 23(2): 203-209.
仝晓霞, 马武明, 孙兴乐. 2017. 新疆帕米尔高原塔什库尔干地区冰川融水锶同位素特征及其环境意义[J]. 环境化学, 36(4): 830-838.
鲜丽菊. 2017. 气候变化对喷赤河径流过程的影响研究-以塔吉克斯坦典型流域为例[D]. 乌鲁木齐: 新疆农业大学: 14.
肖安成, 杨树锋, 陈汉林, 贾承造, 魏国齐. 2000. 西昆仑山前冲断系的结构特征[J]. 地学前缘, 7(S2): 128-136.
许志琴, 李海兵, 唐哲民, 戚学祥, 李化启, 蔡志慧. 2011. 大型走滑断裂对青藏高原地体构架的改造[J]. 岩石学报, 27(11): 3157-3170.
再努尔. 2010. 盖孜河流域地表水资源特性分析[J]. 吉林水利, (8): 14-15, 27.
曾磊, 杨太保, 田洪阵. 2013. 近 40 年东帕米尔高原冰川变化及其对气候的响应[J]. 干旱区资源与环境, 27(5): 144-150.
周聿超. 1999. 新疆河流水文资源[M]. 乌鲁木齐: 新疆科技卫生出版社.

References:

ABRAMOWSKI U, BERGAU A, SEEBACH D, ZECH R, GLASER B, SOSIN P, KUBIK P W, ZECH W. 2006. Pleistocene glaciations of Central Asia: results from ^{10}Be surface exposure ages of erratic boulders from the Pamir (Tajikistan), and the Alay-Turkestan range (Kyrgyzstan)[J]. Quaternary Science Reviews, 25(9-10): 1080-1096.
AIZEN V B, MAYEWSKI P A, AIZEN E M, JOSWIAK D R, SURAZAKOV A B, KASPARI S, GRIGHOLM B, KRACHLER M, HANDLEY M, FINAEV A. 2009. Stable-isotope and trace element time series from Fedchenko glacier (Pamirs) snow/firn cores[J]. Journal of Glaciology, 55(190): 275-291.
AMIDON W H, HYNEK S A. 2010. Exhumational history of the north Central Pamir[J]. Tectonics, 29: TC5015.
ANGIOLINI L, ZANCHI A, ZANCHETTA S, NICORA A, VEZZOLI G. 2013. The Cimmerian geopuzzle: new data from South Pamir[J]. Terra Nova, 25(5): 352-360.
ARMIJO R, TAPPONNIER P, TONGLIN H. 1989. Late Cenozoic right-lateral strike–slip faulting in southern Tibet[J]. Journal of Geophysical Research, 94(B3): 2787-2838.
ARNAUD N O, BRUNEL M, CANTAGREL J M, TAPPONNIER P. 1993. High cooling and denudation rates at Kongur Shan, Eastern Pamir (Xinjiang, China) revealed by ^{40}Ar/^{39}Ar alkali feldspar thermochronology[J]. Tectonics, 12(6): 1335-1346.
ARROWSMITH J, STRECKER M. 1999. Seismotectonic range-front segmentationand mountain-belt growth in the Pamir-Alai region, Kyrgyzstan(India-Eurasia collision zone)[J]. GSA Bulletin, 111(11): 1665-1683.
AVOUAC J, PELTZER G. 1993. Active tectonics in southern Xinjiang, China: Analysis of terrace riser and normal fault scarp degradation along the Hotan-Qira Fault system[J]. Journal of Geophysical Research, 98(B12): 21773-21807.
BARNHART W D. 2017. Fault creep rates of the Chaman fault (Afghanistan and Pakistan) inferred from InSAR[J]. Journal of Geophysical Research: Solid Earth, 122(1): 372-386.
BAZHENOV M L, PERROUD H, CHAUVIN A, BURTMAN V S, THOMAS J C. 1994. Paleomagnetism of Cretaceous red beds from Tadzhikistan and Cenozoic deformation due to India-Eurasia collision[J]. Earth and Planetary Science Letters, 124(1-4): 1-18.
BELOUSSOV V V, BELYAEVSKY N A, BORISOV A A, VOLVOVSKY B S, VOLKOVSKY I S, RESVOY D P, TALVIRSKY B B, KHAMRABAEV I K, KAILA K L, NARAIN H, MARUSSI A, FINETTI J. 1980. Structure of the lithosphere along the deep seismic sounding profile: Tien Shan-Pamirs-Karakorum-Himalayas[J]. Tectonophysics, 70(3-4): 193-221.
BERSHAW J, GARZIONE C N, SCHOENBOHM L, GEHRELS G, LI Tao. 2012. Cenozoic evolution ofthe Pamir plateau based on stratigraphy, zircon provenance, and stable isotopes of

万方数据

foreland basin sediments at Oytag (Wuyitake) in the Tarim Basin (west China)[J]. Journal of Asian Earth Sciences, 44: 136-148.

BERZON I S, PAK V A, YAKOVLEV V N. 1962. Stroenie lednika Fedchenko po geofizicheskim dannim (seismo-razvedka, gravimetriya)[Structure of Fedchenko Glacier by geophysical data (seismic and gravimetric surveys)][J]. Mater. Glyatsiol., (6): 90-96.

BEUN N, BORDET P, CARBONNEL J P. 1979. First quantitative results related to the sliding of the Chaman fault (eastern Afghanistan)[J]. Academie des Sciences, Paris, Comptes Rendus Hebdomadaires des Seances, Serie D: Sciences Naturelles, 288(11): 931-934.

BLAYNEY T, NAJMAN Y, DUPONT-NIVET G, CARTER A, MILLAR I, GARZANTI E, SOBEL E R, RITTNER M, ANDO S, GUO Zhao-jie, VEZZOLI G. 2016. Indentation of the Pamirs with respect to the northern margin of Tibet: Constraints from the Tarim basin sedimentary record[J]. Tectonics, 35(10): 2345-2369.

BOSBOOM R, DUPONT-NIVET G, HUANG Wen-tao, YANG Wei, GUO Zhao-jie. 2014. Oligocene clockwise rotations along the eastern Pamir: Tectonic and paleogeographic implications[J]. Tectonics, 33(2): 53-66.

BROOKFIELD M E, CHUNG Sun-lin, SHELLNUTT J G. 2017. Mid-Miocene (post 12 Ma) Displacement along the Central Karakoram Fault Zone in the Nubra Valley, Ladakh, India from Spot LA-ICPMS U/Pb Zircon Ages of Granites[J]. Journal Geological Society of India, 89(3): 231-239.

BROOKFIELD M E. 2008. Evolution of the great river systems of southern Asia during the Cenozoic India-Asia collision: Rivers draining north from the Pamir syntaxis[J]. Geomorphology, 100(3-4): 296-311.

BRUNEL M, ARNAUD N, TAPPONNIER P, PAN Y, WANG Y. 1994. Kongur Shan normal fault: Type example of mountain building assisted by extension (Karakoram fault, eastern Pamir) [J]. Geology, 22(8): 707-710.

BURTMAN V S, MOLNAR P. 1993. Geological and geophysical evidence for deep subduction beneath the Pamir[J]. Geological Society of America Special Paper, 281(2): 248-251.

CAI Zhi-hui, XU Zhi-qin, CAO Hui, ROBINSON A C, LI Guang-wei, XU Xiao-yin. 2017. Miocene exhumation of northeast Pamir: Deformation and geo/thermochronological evidence from western Muztaghata shear zone and Kuke ductile shear zone[J]. Journal of Structural Geology, 102: 130-146.

CAO Kai, BERNET M, WANG Guo-can, VAN DER BEEK P, WANG An, ZHANG Ke-xin, ENKELMANN E. 2013a. Focused Pliocene-Quaternary exhumation of the Eastern Pamir domes, western China[J]. Earth and Planetary Science Letters, 363: 16-26.

CAO Kai, WANG Guo-can, VAN DER BEEK P, BERNET M, ZHANG Ke-xin. 2013b. Cenozoic thermo-tectonic evolution of the northeastern Pamir revealed by zircon and apatite fission-track thermochronology[J]. Tectonophysics, 589(2): 17-32.

CARRAPA B, MUSTAPHA F S, COSCA M, GEHRELS G, SCHOENBOHM L M, SOBEL E R, DECELLES P G, RUSSELL J, GOODMAN P. 2014. Multisystem dating of modern river detritus from Tajikistan and China: Implications for crustal evolution and exhumation of the Pamir[J]. Lithosphere, 6(6): 443-455.

CHAPMAN J B, CARRAPA B, BALLATO P, DECELLES P G, WORTHINGTON J, OIMAHMADOV I, GADOEV M, KETCHAM R. 2017. Intracontinental subduction beneath the Pamir Mountains: constraints from thermokinematic modeling of shortening in the Tajik fold-and-thrust belt[J]. Geological Society of America Bulletin, 129(11-12): 1450-1471.

CHEN Han-lin, CHEN Shen-qiang, LIN Xiu-bin. 2014. A review of the Cenozoic Tectonic evolution of Pamir syntax[J]. Advances in Earth Science, 29(8): 890-902(in Chinese with English abstract).

CHEN Han-lin, ZHANG Fen-fen, CHENG Xiao-gan, LIAO Lin, LUO Jun-cheng, SHI Jun, WANG Bu-qing, YANG Chang-fu, CHEN Li-feng. 2010. The deformation features and basin-range coupling structurein the northeastern Pamir tectonic belt[J]. Chinese Journal of Geology, 45(1): 102-112(in Chinese with English abstract).

CHEN Jie, BURBANK D W, SCHARER K M, SOBEL E R, YIN Jin-hui, RUBIN C, ZHAO Rui-bin. 2002. Magnetochronology of the Upper Cenozoic strata in the Southwestern Chinese Tian Shan: rates of Pleistocene folding and thrusting[J]. Earth and Planetary Science Letters, 195(1-2): 113-130.

CHEN Jie, LI Tao, LI Wen-qiao, YUAN Zhao-de. 2011. Late Cenozoic and present tectonic deformation in the Pamir salient, northwestern China[J]. Seismology and Geology, 33(2): 241-259(in Chinese with English abstract).

CHEN jie, QU Guo-sheng, HU Jun, FENG Xian-yue. 1997. Arcuate thrust tectonics and its contemporaryseismicity in the eastern section ofthe external zone of the Pamir[J]. Seismology and Geology, 19(4): 301-312(in Chinese with English abstract).

CHEN Shen-qiang. 2016. Tectonic activity of the Tashkurgan fault, SE Pamir[D]. Hangzhou: Zhejiang University(in Chinese with English abstract).

CHEN Xin-wei, CHEN Han-lin, LIN Xiu-bin, CHENG Xiao-gan, YANG Rong, DING Wei-wei, GONG Jun-feng, WU Lei, ZHANG Feng-qi, CHEN Shen-qiang, ZHANG Yao, YAN Jia-kai. 2018. Arcuate Pamir in the Paleogene? Insights from a review of stratigraphy and sedimentology of the basin fills in the foreland of NE Chinese Pamir, western Tarim Basin[J]. Earth-Science Reviews, 180: 1-16.

CHENG Xiao-gan, CHEN Han-lin, LIN Xiu-bin, WU Lei, GONG Jun-feng. 2017. Geometry and kinematic evolution of the Hotan-Tiklik segment of the Western Kunlun thrust belt: constrained by structural analyses and apatite fission track thermochronology[J]. The Journal of Geology, 125(1): 65-82.

CHENG Xiao-gan, CHEN Han-lin, LIN Xiu-bin, YANG Shu-feng, CHEN Shen-qiang, ZHANG Fen-fen, LI Kang, LIU Ze-lin. 2016. Deformation geometry and timing of theWupoer thrust belt in the NE Pamir and its tectonic implications[J]. Frontiers

万方数据

of Earth Science, 10(4): 751-760.
CHENG Xiao-gan, HUANG Zhi-bin, CHEN Han-lin, DU Zhi-li, LI Kang, SHI Jun. 2012. Fault characteristics and division of tectonic units of the thrust belt in the front of the West Kunlun Mountains[J]. Acta Petrologica Sinica, 28(8): 2591-2601(in Chinese with English abstract).
CHENG Xiao-gan, LEI Gang-lin, CHEN Han-lin, DU Zhi-li, LIAO Lin, LUO Jun-cheng, SHI Jun. 2011. Cenozoic structural deformation of the Fusha-Keliyang area in the piedmont of thewestern Kunlun Mountains and its control on hydrocarbon accumulation[J]. Acta Petrolei Sinica, 32(1): 83-89(in Chinese with English abstract).
CHEVALIER M L, LELOUP P H, LI Hai-bing. 2016. Comment on “No late Quaternary strike-slip motion along the northern Karakoram fault” published by Robinson et al. in EPSL, 2015[J]. Earth and Planetary Science Letters, 443: 216-219.
CHEVALIER M, LI Hai-bin, PAN Jia-wei, PEI Jun-ling, WU Fu-yao, XU Wei, SUN Zhi-ming, LIU Dong-liang. 2011. Fast slip-rate along the northern end of the Karakorum fault system, western Tibet[J]. Geophysical Research Letters, 38(22): L22309.
CLIFT P D, ZHENG Hong-bo, CARTER A, BÖNING P, JONELL T N, SCHORR H, SHAN Xin, PAHNKE K, WEI Xiao-chun, RITTENOUR T. 2017. Controls on erosion in the western Tarim Basin: Implications for the uplift of northwest Tibet and the Pamir[J]. Geosphere, 13(5): 1747-1765.
COUTAND I, STRECKER M R, ARROWSMITH J R, HILLEY G, THIEDE R C, KORJENKOV A, OMURALIEV M. 2002. Late Cenozoic tectonicdevelopment of theintramontane Alai Valley, (Pamir-Tien Shanregion, central Asia): An example of intracontinental deformationdue to the Indo-Eurasia collision[J]. Tectonics, 21(6): 1053.
COWGILL E, YIN A, HARRISON T. 2003. Reconstruction of the Altyn Tagh fault based on U-Pb geochronology: Role of back thrusts, mantle sutures, and heterogeneous crustal strength in forming the Tibetan Plateau[J]. Journal of Geophysical Research-Solid Earth, 108(B7): 2346.
COWGILL E. 2010. Cenozoic right-slip faulting along the eastern margin of the Pamir salient, northwestern China[J]. GSA Bulletin, 122(1-2): 145-161.
CRUPA, W E, KHAN S D, HUANG Jing-qiu, KHUN A S, KASI A. 2017. Active tectonic deformation of the western Indian plate boundary: A case study from the Chaman Fault System[J]. Journal of Asian Earth Sciences, 147: 452-468.
CUI Zhi-jiu. 1960. Some features and development conditions of Muztaghata and kongur glacier[J]. Acta Geographica Sinica, 26(1): 35-44, 74(in Chinese with English abstract).
DE SIGOYER J, GUILLOT S, DICK P. 2004. Exhumation of the ultrahigh-pressure Tso Morari unit in eastern Ladakh (NW Himalaya): a case study[J]. Tectonics, 23(3): TC3003.
DECELLES P G, ROBINSON D M, ZANDT G. 2002. Implications of shortening in the Himalayan fold-thrust belt for uplift of the Tibetan Plateau[J]. Tectonics, 21(6): 1062.
DEWEY J F, SHACKLETON R M, CHENGFA C, SUN Yi-yin. 1988. The tectonic evolution of the Tibetan Plateau[J]. Philosophical Transactions of the Royal Society of London Series A, mathematical and Physical Sciences, 327(1594): 379-413.
DOLGUSHIN L D, OSIPOVA G B. 1989. Ledniki (Glaciers), Second edition[M]. Moscow: Mysl Publishers (in Russian).
FATTAHI H, AMELUNG F. 2016. InSAR observations of strain accumulation and fault creep along the Chaman Fault system, Pakistan and Afghanistan: Strain Accumulation at Chaman Fault[J]. Geophysical Research Letters, 43(16): 8399-8406.
FU Bi-hong, NINOMIYA Y, GUO Jian-ming. 2010. Slip partitioning in the northeast Pamir-Tian Shan convergence zone[J]. Tectonophysics, 483(3-4): 344-364.
FU Bi-hong, ZHANG Song-lin, XIE Xiao-ping, SHI Xu-hua, WANG Shi-feng. 2006. Late Quaternary tectono-geomorphic features along the Kangxiwar Fault, Altyn Tagh Fault System, northern Tibet[J]. Quaternary Sciences, 26(2): 228-235(in Chinese with English abstract).
FUCHS M C, GLOAGUEN R, KRBETSCHEK M, SZULC A. 2014. Rates of river incision across the main tectonic units of the Pamir identified using optically stimulated luminescence dating of fluvial terraces[J]. Geomorphology, 216: 79-92.
FUCHS M C, GLOAGUEN R, POHL E. 2013. Tectonic and climatic forcing on the Panj river system during the Quaternary[J]. International Journal of Earth Sciences, 102(7): 1985-2003.
FURUYA M, SATYABALA S P. 2008. Slow earthquake in Afghanistan detected by InSAR[J]. Geophysical Research Letters, 35(6): L06309.
GONG Zhi-jun, SUN Ji-min, ZHANG Zhi-liang, FU Bi-hong, JIA Ying-ying. 2017. Optical dating of an offset river terrace sequence across the Karakax fault and its implication for the late Quaternary leftlateral slip rate[J]. Journal of Asian Earth Sciences, 147: 415-423.
GUILLOT S, GARZANTI E, BARATOUX D, MARQUER D, MAHEO G, DE SIGOYER J. 2003. Reconstructing the total shortening history of the NW Himalaya[J]. Geochemistry Geo-physics Geosystems, 4(7): 1064.
GUILLOT S, MAHÉO G, DE SIGOYER J, HATTORI K H, PECHER A. 2008. Tethyan and Indian subduction viewed from the Himalayan high- to ultrahigh-pressure metamorphic rocks[J]. Tectonophysics, 451(1-4): 225-241.
HAMBURGER M W, SAREWITZ D R, PAVLIS T L, POPANDOPULO G A. 1992. Structural and seismic evidence for intracontinental subductionin the Peter, the First Range Central Asia[J]. Geological Society of America Bulletin, 104(4): 397-408.
HEERMANCE R V, CHEN J, BURBANK D W, WANG Chang-sheng. 2007. Chronology and tectonic controls of Late Tertiary deposition in the southwestern Tian Shan foreland, NW China[J]. Basin Research, 19(4): 599-632.
HUBBARD M S, GREW E S, HODGES K V, YATES M G, PERTSEV N N. 1999. Neogene cooling and exhumation of upper-amphibolite-facies ‘whiteschists’ in the southwest Pamir Mountains, Tajikistan[J]. Tectonophysics, 305: 325-337.
ISCHUK A, BENDICK R, RYBIN A, MOLNAR P, KHAN S F, KUZIKOV S, MOHADJER S, SAYDULLAEV U, ILYASOVA

万方数据

Z, SCHELOCHKOV G, ZUBOVICH A V. 2013. Kinematics of the Pamir and Hindu Kush regions from GPS geodesy [J]. Journal of Geophysical Research: Solid Earth, 118(5): 2408-2416.

JIANG Y H, LIU Z, JIA R Y, LIAO S Y, ZHOU Q, ZHAO P. 2012. Miocene potassic granite-syenite association in western Tibetan Plateau: Implications for shoshonitic and high Ba-Sr granite genesis[J]. Lithos, 134: 146-162.

KAYUMOV A, RAJABOV I. 2010. Glacier-Water resources of Tajikistan in condition of the climate change[R]. Dushanbe.

KHROMOVA T E, OSIPOVA G B, TSVETKOV D G, DYURGEROV M B, BARRY R G. 2006. Changes in glacier extent in the eastern Pamir, Central Asia, determined from historical data and ASTER imagery[J]. Remote Sensing of Environment, 102: 24-32.

KLOOTWIJK C T, GEE J S, PEIRCE J W, SMITH G M, MCFADDEN P L. 1992. An early India-Asia contact: Paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121[J]. Geology, 20(5): 395-398.

KOMATSU T. 2016. Geomorphic features of the eastern Pamirs, with a focus on the occurrence of intermontane basins[J]. Advances in Asian Human-Environmental Research, 55-68.

KUCHAI V K, TRIFONOV V G. 1977. Young left-lateral strike slip along the zone of the Darvaz-Karakul' fault (in Russian)[J]. Geotektonika, (3): 91-105.

KUFNER S-K, SCHURR B, SIPPL C, YUAN Xiao-hui, RATSCHBACHER L, AKBAR A S M, ISCHUK A, MURODKULOV S, SCHNEIDER F, MECHIE J, TILMANN F. 2016. Deep India meets deep Asia: Lithospheric indentation, delamination and break-off under Pamir and Hindu Kush (Central Asia)[J]. Earth and Planetary Science Letters, 435: 171-184.

KUMAR M R, SAUL J, SARKAR D, YUAN Xiao-hui, RATSCHBACHER L, AKBAR A S M, ISCHUK A, MURODKULOV S, SCHNEIDER F, MECHIE J, TILMANN F. 2001. Crustal structure of the Indian shield: new constraints from teleseismic receiver functions[J]. Geophysical Research Letters, 28(7): 1339-1342.

LACASSIN R, VALLI F, ARNAUD N, LELOUP P H, PAQUETTE J L, LI Hai-bing, TAPPONNIER P, CHEVALIER M L, GUILLOT S, MAHEO G, XU Zhi-qin. 2004. Large-scale geometry, offset and kinematic evolution of the Karakorum fault, Tibet[J]. Earth and Planetary Science Letters, 219(3-4): 255-269.

LAWRENCE R D, KHAN S H, NAKATA T. 1992. Chaman Fault, Pakistan-Afghanistan[J]. Annales Tectonicae, 6(Suppl.): 196-223.

LAWRENCE R D, YEATS R S, KHAN S H, FARAH A, DEJONG K. 1981. Thrust and strike slip fault interaction along the Chaman transform zone, Pakistan[J]. Geological Society, London, Special Publications, 9(1): 363-370.

LEECH M L, SINGH S, JAIN A K, KLEMPERER S L, MANICKAVASAGAM R M. 2005. The onset of India–Asia continental collision: Early, steep subduction required by the timing of UHP metamorphism in the western Himalaya[J]. Earth and Planetary Science Letters, 234(1-2): 83-97.

LEITH W. 1985. A mid-Mesozoic extension across central Asia[J]. Nature, 313: 567-570.

LI Hai-bing, VALLI F, LIU Dun-yi, XU Zhi-qin, YANG Jing-sui, ARNAUD N, TAPPONNIER P, ROBIN L, CHEN Song-yong, QI Xue-xiang. 2007. The formation age of the Karakoram Fault: constrain from zircon SHRIMP U-Pb age[J]. Chinese Science Bulletin, 52(04): 438-447(in Chinese with English abstract).

LI Hai-bing, VAN DER WOERD J, SUN Zhi-ming, SI Jia-liang, TAPPONNIER P, PAN Jia-wei, LIU Dong-liang, CHEVALIER M L. 2012a. Co-seismic and cumulative offsets of the recent earthquakes along the Karakax left-lateral strike-slip fault in western Tibet[J]. Gondwana Research, 21: 64-87.

LI Kang. 2014. Late Cenozoic tectonic and sedimentary evolution of the NE Pamir[D]. Hangzhou: Zhejiang University: 145(in Chinese with English abstract).

LI Tao, CHEN Jie, THOMPSON J A, BURBANK D W, XIAO Wei-peng. 2012b. Equivalency of geologic and geodetic rates in contractional orogens: new insights from the Pamir Frontal Thrust[J]. Geophysical Research Letters, 39(15): L15305.

LI Wen-qiao, CHEN Jie, YUAN Zhao-de, HUANG Ming-da, LI Tao, YU Song, YANG Xiao-dong. 2011. Coseismic surface ruptures of multi segments and seismogenic fault of the Tashkorgan earthquake in Pamir, 1895[J]. Seismology and Geology, 33(2): 260-276(in Chinese with English abstract).

LI Yan, LI Hong-bin, WANG Lian-you. 2003. Analysis on the Hydrology and Water Resources of Gez River in Karakorum Mountain[J]. Arid Zone Research, 20(4): 272-275(in Chinese with English abstract).

LIAO Lin, WANG Bu-qing, CHENG Xiao-gan, LEI Gang-lin, CHEN Han-lin, YAO Qi. 2012. Cenozoic structural deformation of the thrusting zone and its control on hydrocarbon accumulation in northeastern Pamir[J]. Journal of China University of Mining & Technology, 41(5): 776-782(in Chinese with English abstract).

LING Hong-bo, XU Hai-liang, ZHANG Qing-qing, LIU Xin-hua, FU Jin-yi, BAI Yuan. 2012. Analysis on Concentration and Correlation of Runoff and Precipitation in the Yarkand River Basin[J]. Journal of Desert Research, 32(6): 1757-1764(in Chinese with English abstract).

LIU Dong-liang, LI Hai-bing, PAN Jia-wei, CHEVALIER M L, PEI Jun-ling, SUN Zhi-ming, SI Jia-liang, XU Wei. 2011. Morphotectonic study from thenortheastern margin of the Pamir to the West Kunlun range and its tectonic implications[J]. Acta Petrologica Sinica, 27(11): 3499-3512(in Chinese with English abstract).

LIU Dong-liang, LI Hai-bing, SUN Zhi-ming, CAO Yong, WANG Lei-zhen, PAN Jia-wei, HAN Liang, YE Xiao-zhou. 2017. Cenozoic episodic uplift and kinematic evolution between the Pamir and Southwestern Tien Shan[J]. Tectonophysics, 737-736: 438-454.

LIU Jin-feng, CHEN Jie, WANG Chang-sheng. 2011. Optical dating of the Holocene terrace sediments and the incision rate in

万方数据

the upper reach of the Yarkant River in Xinjiang[J]. Seismology and Geology, 33(2): 421-429(in Chinese with English abstract).

LIU Sheng, QIN Bin, YIN Hong, LI Jian-li, ZHAI Sheng-min, LI Wen-hua. 2005. Structural characteristics of Wuboer thrust belts in theforeland of West Kunlun Mountain[J]. Acta Petrolei Sinica, 26(6): 16-19(in Chinese with English abstract).

LUKENS C E, CARRAPA B, SINGER B S, GEHRELS G. 2012. Miocene exhumation of the Pamir revealed by detrital geothermochronology of Tajik rivers[J]. Tectonics, 31(2): TC2014.

MANSIRIK B, XIONG Feng-ying, ABDUHALIK H, SHEN Yong-ping. 2008. Glacier-Snow Hydrological Processes and Potential Hydropower Resources in Taxkorgan River Basin , Eastern Pamir Plateau[J]. Journal of Glaciology and Geocryology, 30(6): 1073-1077(in Chinese with English abstract).

MECHIE J, YUAN Xiao-hui, SCHURR B, SCHNEIDER F, SIPPL C, RATSCHBACHER L, MINAEV V, GADOEV M, OIMAHMADOV I, ABDYBACHAEV U, MOLDOBEKOV B, ORUNBAEV S, NEGMATULLAEV S. 2012. Crustal and uppermost mantle velocity structure along a profile across the Pamir and southern Tien Shan as derived from project TIPAGE wide-angle seismic data[J]. Geophysical Journal International, 188(2): 385-407.

MOHADJER S, BENDICK R, ISCHUK A, KUZIKOV S, KOSTUK A, SAYDULLAEV U, LODI S, KAKAR D M, WASY A, KHAN M A, MOLNAR P, BILHAM R, ZUBOVICH A V. 2010. Partitioning of India-Eurasia convergence in the Pamir-Hindu Kush from GPS measurements[J]. Geophysical Research Letters, 37(4): L04305.

MOLNAR P, STOCK J M. 2009. Slowing of India's convergence with Eurasia since 20 ma and its implications for Tibetan mantle dynamics[J]. Tectonics, 28: TC3001.

MOLNAR P, TAPPONNIER P. 1975. Cenozoic tectonics of Asia: Effects of a continental collision[J]. Science, 189: 419-426.

MURPHY M A, YIN A, KAPP P, HARRISON T M, MANNING C E, RYERSON F J, LIN Ding, GUO Jing-hui. 2002. Structural evolution of the Gurla mandhata detachment system, southwest Tibet: Implications for the eastward extent of the Karakoram fault system[J]. Geological Society of America Bulletin, 144(4): 428-447.

MURPHY M A, YIN An, KAPP P, HARRISON T M, LIN Ding, GUO Jing-hui. 2000. Southward propagation of the Karakoram fault system, southwest Tibet: timing and magnitude of slip[J]. Geology, 28(5): 451-454.

NAJMAN Y, APPEL E, BOUDAGHER-FADEL M, BOWN P, CARTER A, GARZANTI E, GODIN L, HAN Jing-tai, LIEBKE U, OLIVER G, PARRISH R, VEZZOLI G. 2010. Timing of India-Asia collision: Geological, biostratigraphic, and palaeomagnetic constraints[J]. Journal of Geophysical Research-Solid Earth, 115: B12416.

NEGREDO A M, REPLUMAZ A, VILLASE A, GUILLOT S. 2007. Modeling the evolution of continental subduction processes in the Pamir-Hindu Kush region[J]. Earth and Planetary Science Letters, 259(1): 212-225.

OWEN L A, CHEN JIE, HEDRICK K A, CAFFEE M W, ROBINSON A C, SCHOENBOHM L M, YUAN Zhao-de, LI Wen-qiao, IMRECKE D B, LIU Jin-feng. 2012. Quaternary glaciation of the Tashkurgan Valley, Southeast Pamir[J]. Quaternary Science Reviews, 47: 56-72.

PAN Jia-wei, LI Hai-bing, VAN DER WOERD J, SUN Zhi-ming, PEI Jun-ling, SI Jia-liang, QIU Zhu-li. 2009. Tectonic geomorphology and active tectonics in north eastern Pamir, northwest margin of Qinghai-Tibet Plateau[J]. Quaternary Sciences, 29(3): 586-598(in Chinese with English abstract).

PELTZER G, TAPPONNIER P, ARMIJO R. 1989. magnitude of late Quaternaryleft lateral displacement along the north edge of Tibet[J]. Science, 246: 1285-1289.

PELTZER G, TAPPONNIER P. 1988. Formation and evolution of strike-slip faults, rifts, and basins during the India-Asia collision: An experimental approach[J]. Journal of Geophysical Research, 93: 15085-15117.

PHILLIPS R J, SEARLE M P. 2007. Macrostructural and microstructural architecture of the Karakoram Fault: Relationshipbetween magmatism and strikes-slip faulting[J]. Tectonics, 26: TC3017.

PHILLIPSA R, PARRISH R, SEARLE M. 2004. Age constraints on ductile deformationand long-term slip rates along the Karakoram fault zone, Ladakh[J]. Earth and Planetary Science Letters, 226: 305-319.

PU Jian-chen, YAO Tan-dong, DUAN Ke-qin. 2003. An Observation on Surface Ablation on the YangbarkGlacier in the Muztag Ata, China[J]. Journal of Glaciology and Geocryology, 25(6): 680-684(in Chinese with English abstract).

RATERMAN N S, COWGILL E, LIN D. 2007. Variable structural style along the Karakoram Fault explained using triple-junctionanalysis of intersecting faults[J]. Geosphere, 3(2): 71-85.

RATSCHBACHER L, FRISCH W, LINZER H G, MERLE O. 1991. Lateral extrusion in the eastern Alps, Part 2: Structural analysis[J]. Tectonics, 10(2): 257-271.

REGENSBURGER K. 1963. Comparative measurements on the Fedtschenko Glacier[J]. International Association of Scientific Hydrology Bulletin, 8(1): 57-61.

REY P F, TEYSSIER C, WHITNEY D L. 2010. Limit of channel flow in orogenic plateau[J]. Lithosphere, 2(5): 328-332.

ROBINSON A C, OWEN L A, CHEN Jie, SCHOENBOHM L M, HEDRICK K A, BLISNIUK K, SHARP W D, IMRECKE D B, LI Wen-qiao, YUAN Zhao-de, CAFFEE M W, MERTZ-KRAUS R. 2016. Response to comment on "No late Quaternary strike-slip motion along the northern Karakoram fault"[J]. Earth and Planetary Science Letters, 443: 220-223.

ROBINSON A C, YIN A, MANNING C E, HARRISON T M, ZHANG Shuan-hong, WANG Xiao-feng. 2007. Cenozoic evolution of the eastern Pamir: implications for strain-accommodationmechanisms at the western end of the Himalayan–Tibetan orogen[J]. Geological Society of America Bulletin, 119(7-8): 882-896.

万方数据

ROBINSON A C, YIN An, LOVERA O M. 2010. The role of footwall deformation and denudation in controlling cooling age patterns of detachment systems: an ap-plication to the Kongur Shan extensional system in the Eastern Pamir, China[J]. Tectonophysics, 496(1-4): 28-43.

ROBINSON A C, YIN An, MANNING C E, HARRISON T M, ZHANG Shuan-hong, WANG Xiao-feng. 2004. Tectonic evolution of the northeastern Pamir: Constraints from the northern portion of the Cenozoic Kongur Shan extensional system, western China[J]. GSA Bulletin, 116(7/8): 953-973.

ROBINSON A C. 2009a. Geologic offsets across the northern Karakorum fault: implications for its role and terrane correlations in the western Himalayan-Tibetan orogeny[J]. Earth and Planetary Science Letters, 279(1-2): 123-130.

ROBINSON A C. 2009b. Evidence against Quaternary slip on the northern Karakorum Fault suggests kinematic reorganization at the western end of the Himalayan-Tibetan orogen[J]. Earth and Planetary Science Letters, 286(1-2): 158-170.

ROBINSON A C. 2015. Mesozoic tectonics of the Gondwanan terranes of the Pamir plateau[J]. Journal of Asian Earth Sciences, 102: 170-179.

ROWLEY D. 1996. Age of initiation of collision between India and Asia: Areview of stratigraphic data[J]. Earth and Planetary Science Letters, 145: 1-13.

RUTTE D, RATSCHBACHER L, KHAN J, STUBNER K, HACKER B R, STEARNS M A, ENKELMANN E, JONCKHEERE R, PFANDER J A, SPERNER B, TICHOMIROWA M. 2017b. Building the Pamir-Tibetan Plateau-Crustal stacking, extensional collapse, and lateral extrusion in the Central Pamir: 2. Timing and rates[J]. Tectonics, 36(3): 385-419.

RUTTE D, RATSCHBACHER L, SCHNEIDER S, STUBNER K, STEARNS M A, GULZAR M A, HACKER B R. 2017a. Building the Pamir-Tibetan Plateau—Crustal stacking,extensional collapse, and lateral extrusion in the Central Pamir: 1. Geometry and kinematics[J]. Tectonics, 36(3): 342-384.

RUTTE D, STEARNS M, RATSCHBACHER L. 2013. The eastern Central Pamir Gneiss Domes: temporal and spatial geometry of burial and exhumation[R]. EGU General Assembly Conference: 6090.

RYERSON F J, FINKEL R C, MERIAUX A S, CAFFEE M W, PELTZER G, FARR T, CHADWICK O, CLARKE D H. 1997. Rapid slip on the Altyn Tagh Fault; Karakax Valley segment [A]//Geological Society of America 1997 Abstracts with Programs. Salt Lake City: 143.

SCHETINNIKOV A S. 1998. Morfologiya i rezhim lednikov Pamiro-Alaya (Morphology and regime of the Pamir-Alai glaciers)[M]. Tashkent: Central Asia Hydrometeorological Institute.

SCHMALHOLZ M. 2004. The amalgamation of the Pamirs and their subsequent evolution in the far field of the India-Asia collision[M]. Tubingen: Universitat Tubingen: 103.

SCHMIDT J, HACKER B R, RATSCHBACHER L, STÜBNER K, STEARNS M, KYLANDER-CLARK A, COTTLE J M, ALEXANDER A, WEBB G, GEHRELS G, MINAEV V. 2011. Cenozoic deep crust in the Pamir, Earth Planet[J]. Earth and Planetary Science Letters, 312(3-4): 411-421.

SCHNEIDER F M, YUAN X, SCHURR B, MECHIE J, SIPPL C, HABERLAND C, MINAEV V, OIMAHMADOV I, GADOEV M, RADJABOV N, ABDYBACHAEV U, ORUNBAEV S, NEGMATULLAEV S. 2013. Seismic imaging of subducting continental lower crust beneath the Pamir[J]. Earth and Planetary Science Letters, 375: 101-112.

SCHOENBOHM L M, CHEN Jie, STUTZ J, SOBEL E R, THIEDE R C, KIRBY B, STRECKER M R. 2014. Glacial morphology in the Chinese Pamir: Connections among climate, erosion, topography, lithology and exhumation[J]. Geomorphology, 221: 1-17.

SCHURR B, RATSCHBACHER L, SIPPL C, GLOAGUEN R, YUAN Xiao-hui, MECHIE J. 2014. Seismotectonics of the Pamir[J]. Tectonics, 33(8): 1501-1508.

SCHWAB M, RATSCHBACHER L, SIEBEL W, MCWILLIAMS M, MINAEV V, LUTKOV V, CHEN Fo-kun, STANEK K, NELSON B, FRISCH W, WOODEN J L. 2004. Assembly of the Pamirs: Age and origin of magmatic belts from the southern Tian Shan to the southern Pamirs and their relation to Tibet[J]. Tectonics, 23(4): TC4002.

SEARLE M P, PHILLIPS R J. 2007. Relationships between right-lateral shear along the Karakoram fault and metamorphism, magmatism, exhumation and uplift: evidence from the K2-Gasherbrum-Pangong ranges, north Pakistan and Ladakh[J]. Journal of the Geological Society of London, 164: 439-450.

SEARLE M P. 1996. Geological evidence against large-scale pre-Holocene offsets along the Karakoram Fault: implications for the limited extrusion of the Tibetan plateau[J]. Tectonics, 15(1): 171-186.

SEEBER L, PECHER A. 1998. Strain partitioning along the Himalayan arc and the Nanga Parbat antiform[J]. Geology, 26(9): 791-794.

SEONG Y B, OWEN L A, YI C. 2007. Late Quaternary glaciation of Muztag Ata and Kongur Shan in the semi-arid region of northwestern Tibet[J]. Geological Society of America Bulletin, 121(3-4): 348-365.

SEONG Y B, OWEN L A, YI Chao-lu, FINKEL R C, SCHOENBOHM L. 2009a. Geomorphology of anomalously high glaciated mountains at the northwestern end of Tibet: Muztag Ata and Kongur Shan[J]. Geomorphology, 103(2): 227-250.

SEONG Y B, OWEN L A, YI Chao-lu, FINKEL R C. 2009b. Quaternary glaciation of Muztag Ata and Kongur Shan: Evidence for glacier response to rapid climate changes throughout the Late Glacial and Holocene in westernmost Tibet[J]. Geological Society of America Bulletin, 121(3-4): 348-365.

SHANG Xin-lu, CHEN Xin-wei, WU Chao, LUO Jin-hai. 2004. Cenozoic thrust structures in the Kashi area, western Tarim Basin[J]. Chinese Journal of Geology, 39(4): 543-550, 603(in Chinese with English abstract).

SHANGGUAN Dong-hui, LIU Shi-yin, DING Yong-jian, DING Liang-fu, SHEN Yong-ping, ZHANG Shi-qiang, LU An-xin,

万方数据

LI Gang, CAI Di-hua, ZHANG Yong. 2005. Monitoring Glacier Changes and Inventory of Glaciers in Muztag Ata KongurTagh, East Pamir, China Using ASTER Data[J]. Journal of Glaciology and Geocryology, 27(3): 344-351(in Chinese with English abstract).

SHEN Zheng-kang, WANG Min, LI Yan-xing, JACKSON D D, YIN An, DONG Dan-an, FANG Peng. 2001. Crustal deformation along the Altyn Tagh fault system, western China, from GPS[J]. Journal of Geophysical Research-Solid Earth, 106(B12): 30607-30621.

SHUKLA U K, SINGH I B, SHARMA M, SHARMA S. 2001. A model of alluvial megafan sedimentation: Ganga megafan[J]. Sedimentary Geology, 144(3-4): 243-262.

SIPPL C, SCHURR B, TYMPEL J, ANGIBOUST S, MECHIE J, YUAN Xi-chun, SCHNEIDER F M, SOBOLEV S V, RATSCHBACHER L, HABERLAND C. 2013b. Deep burial of Asian continental crust beneath the Pamir imaged with local earthquake tomography[J]. Earth and Planetary Science Letters, 384: 165-177.

SIPPL C, SCHURR B, YUAN Xi-chun, MECHIE J, SCHNEIDER F M, GADOEV M, ORUNBAEV S, OIMAHMADOV I, HABERLAND C, ABDYBACHAEV U, MINAEV V, NEGMATULLAEV S, RADJABOV N. 2013a. Geometry of the Pamir-Hindu Kush intermediate-depth earthquake zone from local seismic data[J]. Journal of Geophysical Research-Solid Earth, 118(4): 1438-1457.

SMIT M A, RATSCHBACHER L, KOOIJMAN E, STEARNS M A. 2014. Early evolution of the Pamir deep crust from Lu-Hf and U-Pb geochronology and garnet thermometry[J]. Geology, 42(12): 1047-1050.

SOBEL E R, CHEN Jie, SCHOENBOHM L M, THIEDE R, STOCKLI D F, SUDO M, STRECKER M R. 2013. Oceanic-style subduction controls late Cenozoic deformation of the Northern Pamir orogen[J]. Earth and Planetary Science Letters, 363: 204-218.

SOBEL E R, SCHOENBOHM L M, CHEN Jie, THIEDE R, STOCKLI D F, SUDO M, STRECKER M R. 2011. Late Miocene-Pliocene deceleration of dextral slip between Pamir and Tarim: Implications for Pamir orogenesis[J]. Earth and Planetary Science Letters, 304(3-4): 369-378.

SOBEL E, DUMITRU T. 1997. Thrusting and exhumation around the marginsof the western Tarim Basin during the India-Asia collsion[J]. Journal of Geophysical Research, 102(B3): 5043-5063.

STEARNS M A, HACKER B R, RATSCHBACHER L, LEE J, COTTLE J M, KYLANDER-CLARK A. 2013. Synchronous Oligocene-Miocene metamorphism of the Pamir and the north Himalaya driven by plate-scale dynamics[J]. Geology, 41(10): 1071-1074.

STEARNS M A, HACKER B R, RATSCHBACHER L, RUTTE D, KYLANDER-CLARK A. 2015. Titanite petrochronology of the Pamir gneiss domes: implications for mid-deep crust exhumation and titanite closure to Pb and Zr diffusion[J]. Tectonics, 34: 784-802.

STRECKER M R, FRISCH W, HAMBURGER M W, RATSCHBACHER L, SEMILETKIN S, SAMORUYEV A, STURCHIO N. 1995. Quaternary deformation in the Eastern Pamirs, Tadzhikistan and Kyrgyzstan[J]. Tectonics, 14(5): 1061-1079.

STÜBNER K, GRIN E, HIDY A J, SCHALLER M, GOLD R D, RATSCHBACHER L, EHLERS T. 2017. Middle and Late Pleistocene glaciations in the southwestern Pamir and their effects on topography[J]. Earth and Planetary Science Letters, 466: 181-194.

STÜBNER K, RATSCHBACHER L, RUTTE D, STANEK K, MINAEV V, WIESINGER M, GLOAGUEN R. 2013a. The giant Shakhdara migmatitic gneiss dome, Pamir, India-Asia collision zone: 1. Geometry and kinematics[J]. Tectonics, 32(4): 948-979.

STÜBNER K, RATSCHBACHER L, WEISE C, CHOW J, HOFMANN J, KHAN J, RUTTE D, SPERNER B, PFANDER J A, HACKER B R, DUNKL I, TICHOMIROWA M, STEARNS M A. 2013b. The giant Shakhdara migmatitic gneiss dome, Pamir, India-Asia collision zone: 2. Timing of dome formation[J]. Tectonics, 32(5): 1404-1431.

SU Z, WANG Z C. 1988. Glacier water resources and its utilization [A]//SU Z, XIE Z C, WANG Z C, eds. Glaciers and Environment of the Karakorum-Kunlun Mountains (in Chinese). Beijing: Science Press: 119-123.

SU Zhen, LIU Shi-yin, WANG Zhi-chao. 1989. Modern glacier of MT. Muztagata and MT. Kongur[J]. Journal of Natural Resources, 4(3): 241-246(in Chinese with English abstract).

SUN Ben-guo, MAO Wei-yi, FENG Yan-ru, CHANG Tao, ZHANG Li-ping, ZHAO Ling. 2006. Study on the Change of Air Temperature, precipitation and Runoff Volume in the Yarkant River Basin[J]. Arid Zone Research, 23(2): 203-209(in Chinese with English abstract).

TAPPONNIER P, MATTAUER M, PROUST F, CASSAIGNEAU C. 1981. Mesozoic ophiolites, sutures, and arge-scale tectonic movements in Afghanistan[J]. Earth and Planetary Science Letters, 52(2): 355-371.

TAPPONNIER P, MOLNAR P. 1977. Active faulting and tectonics in China[J]. Journal of Geophysical Research, 82(20): 2905-2930.

TAPPONNIER P, PELTZER G, LEDAIN A Y, ARMIJO R, COBBOLD P. 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine[J]. Geology, 10(12): 611-616.

THIEDE R C, SOBEL E R, CHEN Jie, SCHOENBOHM L M, STOCKLI D F, SUDO M, STRECKER M R. 2013. Late Cenozoic extension and crustal doming in the India-Eurasia collision zone: New thermochronologic constraints from the NE Chinese Pamir[J]. Tectonics, 32(3): 763-779.

THOMAS J C, CHAUVIN A, GAPAIS D, BAZHENOV M L, PERROUD H, COBBOLD P R, BURTMAN V S. 1994. Paleomagnetic evidence for Cenozoic block rotations in the Tadjik depression (Central Asia)[J]. Journal of Geophysical Research, 99(B8): 15141-15160.

THOMAS J C, COBBOLD P R, WRIGHT A, GAPAIS D. 1996. Cenozoic tectonics of the Tadzhik depression, Central

万方数据

Asia[A]//YIN A, HARRISON T M eds. The Tectonic Evolution of Asia. New York: Cambridge University Press: 191-207.

THOMPSON J A, BURBANK D W, LI Tao, CHEN Jie, BOOKHAGEN B. 2015. Late Miocene northward propagation of the northeast Pamir thrust system, northwest China[J]. Tectonics, 34(3): 510-534.

TONG Xiao-xia, MA Wu-ming, SUN Xing-le. 2017. Characteristic and environmental significance of strontium isotope in glacial meltwater of the Tashkurgan area in Pamirs, Xinjiang[J]. Environmental Chemistry, 36(4): 830-838(in Chinese with English abstract).

TRIFONOV V G. 1978. Late Quaternary tectonic movements of western and Central Asia[J]. Geological Society of America Bulletin, 89(7): 1059-1072.

VALLI F, LELOUP P H, PAQUETTE J L, ARNAUD N, LI Hai-bing, TAPPONNIER P, LACASSIN R, GUILLOT S, LIU Dun-yi, DELOULE E, XU Zhi-qin, MAHEO G. 2008. New U-Th /Pb constraints on timing of shearing and long-term slip-rate on the Karakorum fault[J]. Tectonics, 27(5): TC5007.

VAN DER VOO R, SPAKMAN W, BIJWAARD H. 1999. Tethyan subducted slabs under India[J]. Earth and Planetary Science Letters, 171(1): 7-20.

VAN HINSBERGEN D J, KAPP P, DUPONT-NIVET G, LIPPERT P C, DECELLES P G, TORSVIK T H. 2011. Restoration of Cenozoic deformation in Asia and the size of Greater India[J]. Tectonics, 30(5): TC5003.

WANG Chun-yang, CHEN Han-lin, CHEN Xiao-gan, LI Kang. 2013. Evaluating the role of syn-thrusting sedimentation and interaction with frictional detachment in the structural evolution of the SW Tarim basin, NW China: Insights from analogue modeling[J]. Tectonophysics, 608: 642-652.

WANG Chun-yang, CHENG Xiao-gan, CHEN Han-lin, DING Wei-wei, LIN Xiu-bin, WU Lei, LI Kang, SHI Jun, LI Yong. 2016a. The effect of foreland palaeo-uplift on deformation mechanism in the Wupoer fold-and-thrust belt, NE Pamir: Constraints from analogue modelling[J]. Journal of Geodynamics, 100: 115-129.

WANG Cong, CHENG Xiao-gan, CHEN Han-lin, LI Kang, FAN Xiao-gen, WANG Chun-yang. 2016b. From folding to transpressional faulting: the Cenozoic Fusha structural belt in front of the Western Kunlun Orogen, northwestern Tibetan Plateau[J]. International Journal of Earth Sciences, 105(5): 1621-1636.

WANG Guo-can, CAO Kai, ZHANG Ke-xin, WANG An, LIU Chao, MENG Yan-ning, XU Ya-dong. 2011. Spatio-temporal framework of tectonic uplift stages of the Tibetan Plateau in Cenozoic[J]. Science China Earth Sciences, 54(1): 29-44.

WANG Shi-feng, WANG Chao, PHILLIPS R J, MURPHY M A, FANG X M, YUE Y H. 2012. Displacement along the Karakoram fault, NW Himalaya, estimated from LA-ICP-MS U-Pb dating of offset geologic markers[J]. Earth and Planetary Science Letters, 337-338: 156-163.

WRIGHT T J, PARSONS B, ENGLAND P C, FIELDING E J. 2004. InSAR observations of low slip rates on the major faults of Western Tibet[J]. Science, 305(5681): 236-239.

XIAN Li-ju. 2017. Study on climate change impact on runoff of typical watershed in Tajikistan[D]. Urumqi: Xinjiang Agricultural University: 14(in Chinese with English abstract).

XIAO An-cheng, YANG Shu-feng, CHEN Han-lin, JIA Cheng-zao, WEI Guo-qi. 2000. Structural characteristics of thrust system in the front of the west Kunlun mountains[J]. Earth Science Frontiers, 7(S2): 128-136(in Chinese with English abstract).

XU Zhi-qin, LI Hai-bing, TANG Zhe-min, QI Xue-xiang, LI Hua-qi, CAI Zhi-hui. 2011. The transformation of the terrain structures of the Tibet Plateau through large-scale strike-slip faults[J]. Acta Petrologica Sinica, 27(11): 3157-3170(in Chinese with English abstract).

YAO Tan-dong, THOMPSON L, YANG Wei, YU Wu-sheng, GAO Yang, GUO Xue-jun, YANG Xiao-xin, DUAN Ke-qin, ZHAO Hua-biao, XU Bai-qing. 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings[J]. Nature Climate Change, 2(9): 663-667.

YIN An, ROBINSON A, MANNING C E. 2001. Oroclinal bending and slab-break-off causing coeval east-west extension and east-west contraction in the Pamir-Nanga Parbat syntaxsis in the past 10 m.y[R]. American Geophysical Union: F1124.

YIN An, RUMELHART P E, BUTLER R, COWGILL E, HARRISON T M, FOSTER D A, INGERSOLL R V, ZHANG Qing, ZHOU Xian-Qiang, WANG Xiao-feng, HANSON A, RAZA A. 2012. Tectonic history of the Altyn Tagh fault system in northern Tibet inferred from Cenozoic sedimentation[J]. Geological Society of America Bulletin, 114(10): 1257-1295.

ZAI Nu-er. 2010. Analysis of the characteristics of surface water resources in the Gez River[J]. Jilin Water Resources, (8): 14-15, 27(in Chinese with English abstract).

ZENG Lei, YANG Tai-bao, TIAN Hong-zhen. 2013. Response of glacier variations in the eastern Pamirs plateau to climate change, during the last 40 years[J]. Journal of Arid Land Resources and Environment, 27(5): 144-150(in Chinese with English abstract).

ZHOU Yu-chao. 1999. River Hydrology and Water Resources in Xinjiang[M]. Urumqi: Xinjiang Science, Technology and Public Health Press(in Chinese with English abstract).

ZUBOVICH A V, WANG X Q, SCHERBA Y G, SCHELOCHKOV G G, REILINGER R, REIGBER C, MOSIENKO O I, MOLNAR P, MICHAJLJOW W, MAKAROV V I, LI Jie, KUZIKOV S I, HERRING T A, HAMBURGER M W, HAGER B H, DANG Ya-min, BRAGIN V D, BEISENBAEV R T. 2010. GPS velocity field for the Tien Shan and surrounding regions[J]. Tectonics, 29: TC6014.

ZUBOVICH A, SCHONE T, METZGER S, MOSIENKO O, MUKHAMEDIEV S, SHARSHEBAEV A, ZECH C. 2016. Tectonic interaction between the Pamir and Tien Shan observed by GPS[J]. Tectonics, 35(2): 283-292.

万方数据