青藏高原向东挤出与向北扩展——高原隆升深部过程之探讨

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摘要 青藏高原下方的软弱物质在印度-欧亚大陆的汇聚挤压作用下, 从增厚、抬升的高原中部向东部逃逸挤出。本文基于一条宽频地震密集台站剖面观测给出的青藏高原-秦岭构造转换带地壳和上地幔顶部结构断面, 结合前人的地质和地球物理学研究成果, 探讨了青藏高原物质向东的挤出, 揭示秦岭作为一个可能的通道, 将如何协调青藏高原物质的挤出, 进而探讨上述地球动力学过程如何影响高原东缘的隆升和扩展, 并对比了青藏高原东缘和北缘的地壳变形增厚机制以及地幔岩石圈行为模式之差异。研究结果揭示了, 受区域大型断裂带控制的中下地壳软弱物质挤出和由软流圈地幔流触发的岩石圈底部拆沉导致的重力均衡, 可能同时在青藏高原东缘下方发生, 断裂和块体控制的壳内软弱物质挤出可能是青藏高原东缘边界带上大地震发生的一个重要深部孕震机制。上述两个机制的共同作用导致了青藏高原东缘与秦岭以及四川盆地构造转换带区域的高原隆升和扩展。青藏高原东缘物质挤出的深部过程与处于青藏高原北缘的青藏高原-阿拉善构造转换带区域的高原向北扩展之深部机制存在差异, 而造成高原北缘与东缘差异隆升模式的根本动力学原因, 可能是从青藏高原中东部(青藏高原内部)到高原北缘岩石圈性质的横向变化。

关键词 青藏高原东缘与北缘, 高原隆升, 深部过程, 岩石圈拆沉, 地壳流

20世纪60年代以来实施的一系列深部地球物理探测揭示了青藏高原的地壳增厚具有低P波速度、低电阻率和高热流值的特点, 且发现了其中下地壳的低剪切波速度^[1]。确实, 大量的地球物理学观测发现了青藏高原中东部下方中下地壳中广泛存在着大片的高导低速($V_s < 3.3$ km/s)区域^[2~8], 这些观测指示了这些区域的中下地壳中的物质在物理属性上是软弱的并可能发生互相连通的塑性流动。为此地质学家提出了下地壳管道流(lower crustal channel flow)模型

来解释青藏高原东部的地形变化, 并获得了较好的效果^[9,10]。这个模型预测青藏高原中部地壳被增厚抬升后, 深部地壳软弱物质向东逃逸流出, 在刚性四川盆地的阻挡下, 被分成两支分别流向四川盆地的东南和东北。近年来, 较多的地球物理调查发现了东南支的下地壳流以管道(channel)的形式向川滇地块和印支地块挤出^[2,6,11]; 而另一支向东北的流动可能以秦岭作为一个挤出的通道^[9,10], 但对其观测程度相对不足。

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地震学观测指出青藏高原中北部相对较热较软的地幔物质在印度和欧亚大陆汇聚的挤压和剪切作用下^[12]也可能以地幔流(mantle flow)的形式发生向东的挤出^[13,14],而这一地幔流也可能绕过刚性四川盆地向东流动,其中秦岭可作为一个地幔物质挤出的通道.地震层析成像和各向异性观测显示地幔流发生的深度应在软流圈^[15~18],其中,Zhang等人^[18]观测到了从青藏高原东缘至秦岭造山带下方125~200 km深度上的一个连通的低速带,认为它可能指示了青藏高原下方软流圈地幔流向东流出的一个通道.但是,一些其他的学者通过远震SKS波分裂和地表变形数据的联合分析指出,青藏高原内部(即,中东部青藏高原)的软弱岩石圈被挤压增厚,在重力的驱动下向东部坍塌^[19~21],他们观测到的这种地震各向异性模式实际上代表了一种青藏高原岩石圈挤出(而不是软流圈)的方案.

中国地质科学院地质研究所岩石圈研究中心于2015年6月完成布设一条从青藏高原东缘松潘甘孜地块至秦岭造山带的宽频地震密集台站剖面(图1),总共30个台站,平均台间距~15 km,连续观测一年时间.此剖面提供出一条切过青藏高原-秦岭构造转换带的地壳和上地幔顶部的速度结构断面,在比以往更高的分辨率上揭示了沿此断面从青藏高原到秦岭的地壳和上地幔顶部结构和物质流变属性的过渡特

征.本文基于此条剖面台站的地震接收函数与面波(包括环境噪声)的联合反演结果,并综合前人研究成果,特别是Liu等人^[6]实施的川西流动地震台阵在青藏高原东缘的观测进行细致对比,来探讨青藏高原下方软弱物质向东的挤出,揭示其在何深度上可能发生向位于相对刚性的四川盆地与鄂尔多斯盆地之间的秦岭造山带(作为一个可能的物质流出通道)下方的流动,进而探讨上述地球动力学过程如何影响青藏高原东缘的隆升和扩展.同时,对青藏高原东缘和北缘的地壳变形增厚机制以及地幔岩石圈行为模式进行对比,来探讨青藏高原物质向东挤出与向北扩展的深部过程的差异.

1 地震接收函数与面波频散联合反演图像

用于联合反演的原始数据集如图2(a)和(b)所示,分别为剖面 TT' 台站收集得到的地震接收函数和每个台站位置的群速度和相速度频散数据,利用上述两种类型的地震数据联合反演能够大大地减少反演的不确定性^[22,23](详细的数据处理见Ye等人^[24]),联合反演结果如图3(a)所示.这里作为比较,将Liu等人^[6]实施的川西流动地震台阵观测切出的一条跨青藏高原-四川盆地构造转换带的地壳和上地幔顶部Vs结构断面 LL' 与我们的剖面 TT' 结果画在一起(统一比例尺下,图3(b)).跨青藏高原东缘的上述两条联合反演剖

图 1 宽频地震密集台站(黑色三角)剖面 TT' (浅蓝色实线)和前人川西流动地震台阵观测剖面 LL' (红色实线,取自Liu等人^[6])叠合于地形图(a)和95 km深度剪切波速度分布图(取自Bao等人^[4])(b).黑色实线表示主要断裂带:F1,海原断裂;F2,西秦岭断裂;F3,昆仑断裂;F4,龙门山断裂;F5,六盘山断裂;F6,灵宝-鲁山-舞阳断裂

Figure 1 Our broadband seismic station (black triangles) profile TT' (light-blue solid line) and an observational profile LL' (red solid line) sliced from the Western Sichuan Mobile Seismic Array Observations conducted by previous researchers (from Liu et al.^[6]), superimposed on topographic map (a) and shear-wave velocity map at 95 km depth (from Bao et al.^[4]) (b). Black solid lines indicate major faults: F1, Haiyuan fault; F2, West Qinling fault; F3, Kunlun fault; F4, Longmenshan fault; F5, Liupanshan fault; F6, Lingbao-Lushan-Wuyang fault

图2 联合反演原始数据集. (a) 沿剖面 TT' 的地震接收函数总共 1681 条; (b) 面波频散数据(10~70 s)提取自Bao等人^[4]的环境噪声和地震面波成像结果, 这里展示的是Rayleigh面波频散反演得到的相应 V_s 剖面

Figure 2 Original datasets used for joint inversion include 1681 seismic receiver functions (a) and surface wave dispersion data (10–70 s) extracted from ambient noise and earthquake surface wave tomography results of Bao et al.^[4] (shown here is the corresponding V_s profile inverted from Rayleigh wave dispersion curves) (b)

面图像显示出最明显的特征是青藏高原与其东部相邻的秦岭块体/四川盆地之间截然不同的结构, 地壳结构和上地幔顶部结构从青藏高原到秦岭/四川盆地皆出现明显的突变, 其突变的边界与地表地形显示的高原与秦岭/四川盆地的边界基本对应一致(图3, 在剖面 TT' 的纬度上, 处于 $104.5^{\circ}\sim 105^{\circ}\text{E}$, 而在剖面 LL' , 此边界基本与龙门山断裂带一致). 我们发现, 青藏高原的康定和松潘甘孜地块下方的中下地壳被一个显著的低速带(LVZ)所占据, 其剪切波速度 $V_s < 3.4 \text{ km/s}$, 在剖面 TT' 位置, 这一壳内低速带呈锥形向东逐渐变薄并且基本终止在青藏高原与秦岭的边界上, 而剖面 LL' 显示, 该壳内低速带受块体的控制并也有向东逐渐减弱的趋势(图3). 上述两条剖面图像还观测到在青藏高原东缘下方Moho界面以下存在一个显著的上地幔顶部低速带($V_s < 4.2 \text{ km/s}$), 前人在松潘甘孜地块东部开展的S波接收函数观测显示在约70~100 km深度上出现一个明显的负震相^[25~28], 与上述联合反演观测结果一致. 而相邻的秦岭/四川盆地地块下方具有完全不同的地壳和上地幔结构特征,

其下地壳剪切波速 V_s 约为 $3.6\sim 4.0 \text{ km/s}$, 而它们的上地幔顶部总体呈现一个正常的剪切波速, 整体来看, 相对于西部的青藏高原, 秦岭/四川盆地的地壳和上地幔顶部具有明显较高的速度(图3). 值得注意的是, 秦岭地块的上地幔顶部西侧靠近青藏高原部分(剖面 TT' , 约 $105^{\circ}\sim 106^{\circ}\text{E}$)相对于其东侧部分, 显示了相对较低的剪切波速($V_s < 4.4 \text{ km/s}$)(图3(a)), 可能指示了在西部青藏高原低速(较热)地幔物质的作用下, 与其接触的秦岭岩石圈地幔发生了一定程度的岩石圈活化(lithospheric reworking)(图4).

2 青藏高原物质向东挤出和高原隆升模式探讨

我们对剖面 TT' 联合反演图像的解释如图4所示. 青藏高原与秦岭地块之间截然不同的地壳和上地幔顶部结构说明当今的秦岭地壳尚未像高原北缘的祁连山一样被卷入青藏高原的地壳变形. 剖面 TT' 和 LL' 所观测到的青藏高原东部康定地块和松潘甘孜地块下方中下地壳中发育的向东部秦岭/四川盆地延伸并

图 3 剖面 TT' 联合反演得到的剪切波速度结构断面图像(a)和前人川西流动地震台阵联合反演观测剖面 LL' 剪切波速度结构断面图像(统一比例尺下, 修改自Liu等人^[6])(b), 剖面位置见图 1. (a)和(b)中的红色圆点分别表示 2017 九寨沟 $M_s7.0$ 级地震和 2008 汶川 $M_s8.0$ 级地震

Figure 3 V_s cross-section image along profile TT' from joint inversion (a) and V_s cross-section image along profile LL' (under a unified scale with TT') from joint inversion conducted by previous researchers using seismic data of the Western Sichuan Mobile Seismic Array Observations (modified from Liu et al.^[6]) (b). Locations of profiles TT' and LL' are shown in Figure 1. Red filled circles in (a) and (b) indicate the 2017 Jiuzhaigou $M_s7.0$ earthquake and the 2008 Wenchuan $M_s8.0$ earthquake, respectively

逐渐减弱的壳内低速带似乎展现了青藏高原的壳内软弱物质向东部挤出的行为特征, 这一结构特征与下地壳管道流模型模拟的地壳结构相似^[10]. 基于剖面 TT' 和 LL' 的联合反演观测图像, 康定地块和松潘甘孜地块下方低黏度的中下地壳低速物质的挤出可能是造成青藏高原-秦岭和青藏高原-四川盆地这两个

高原东缘构造边界带上地表隆升的一个非常重要的驱动力. 但是, 我们也发现壳内低速带的分布和产状明显受块体的控制和断裂带的截切(图3和4). 剖面 LL' 显示鲜水河断裂带明显控制了青藏高原东部壳内低速带的分布, 其西侧的康定地块和东侧的松潘甘孜地块壳内低速带无论在强度和规模上都存在很大

图4 青藏高原-秦岭构造转换带地壳和上地幔顶部速度结构图像的地球动力学解释. 红色圆点表示2017九寨沟 $M_s7.0$ 级地震; $\times$ 号指示接收函数 $H-\kappa$ 扫描得到的地壳厚度; 顶部灰色实线表示延剖面 TT' 的地形线; 浅蓝色实线为延剖面 TT' 的简单布格重力异常变化(重力数据来自International Center for Global Earth Models (<http://icgem.gfz-potsdam.de/ICGEM/>)); 黑色三角表示地震台站

Figure 4 Geodynamic interpretation for the crustal and uppermost mantle velocity structure across the Tibet-Qinling transition zone. Red filled circle indicates the 2017 Jiuzhaigou $M_s7.0$ earthquake; markers $\times$ indicate the crustal thicknesses obtained from $H-\kappa$ grid-searching of receiver functions; gray solid line on the top shows the topography along profile TT' ; light blue solid line shows the Simple Bouguer gravity anomaly (SBA) along profile TT' (the gravity data are from International Center for Global Earth Models (<http://icgem.gfz-potsdam.de/ICGEM/>)); black filled triangles denote the seismic stations

差别, 分布深度也不一致^[6](图3(b)); 而剖面 TT' 显示邻近秦岭的松潘甘孜地块下方中下地壳低速带上表面产状被断裂带截切(图3(a)和4), 说明此区在昆仑断裂带的左旋走滑体制下发育的一系列NW-SE或N-S走向次级断裂(如, 塔藏断裂和岷江断裂^[29,30])的走滑和逆冲作用, 也可能促使了这一边界带上的地形抬升. 事实上, Liu等人^[30]通过一条高密度(500 m点距)短周期地震台站剖面观测发现若尔盖盆地东部和岷山下方存在地壳规模的逆冲推覆构造, 在挤压应力作用下造成上地壳向东的仰冲以及地壳缩短, 吸收了塔藏断裂和昆仑断裂的走滑, 造成了青藏高原东缘的抬升. 张乐天等人^[31]利用大地电磁测深剖面发现了松潘甘孜地块东部的若尔盖盆地下方的中下地壳存在大规模显著的高导区域(电阻率普遍不超过10 Ωm), 且其分布受大型走滑断裂带的控制; 松潘甘孜东部的重磁异常也显示出与此区大型断裂带相关的分布模式特征^[29]. 总结上述讨论, 我们推测, 伴随区域大型断裂带的走滑和逆冲作用所控制的壳内低速

(低黏度)物质的挤出, 导致了青藏高原-秦岭和青藏高原-四川盆地构造转换带上的高原隆升和扩展(图4). 另外, 剖面 TT' 经过九寨沟地区, 2017年九寨沟 $M_s7.0$ 级地震震源位置投影至我们的速度结构图像, 刚好位于锥形壳内低速带上表面被断裂带截切位置附近(图3(a)和4), 剖面 LL' 经过2008年汶川 $M_s8.0$ 级地震震中区域, 汶川地震震源位置投影与壳内低速带与龙门山断裂带交切部位对应(图3(b)), 说明上述区域大型断裂带与壳内低速物质挤出的共同作用机制可能也是青藏高原东缘边界带上大地震发生的一个重要深部孕震机制^[6,32,33].

除了壳内低速带的挤出作用, 这里所观测到的最东缘松潘甘孜地块下方紧邻秦岭地块的上地幔顶部低速带可能是影响高原隆升的另一个不可或缺的重要因素, 它可能在均衡作用下对这一边界带上的地表抬升做出贡献. 从沿剖面 TT' 的简单布格重力异常曲线变化可看出, 重力异常低值区与我们的地震学观测图像显示的上地幔顶部低速带位置具有很好

的对应性(图4). 剖面 TT' 和 LL' 所观测到的上地幔顶部低速带与前人利用S波接收函数在龙门山附近的松潘甘孜区域下方所观测到的异常浅的岩石圈-软流圈界面LAB(<100 km)^[25,27]具有一致性. 结合前人在青藏高原东缘的地震层析成像和接收函数观测研究成果^[25,27,34], 我们认为这里所观测到的上地幔顶部低速带是由从青藏高原北部和东部挤出逃逸而来的较热的软流圈地幔流触发了岩石圈底部的拆沉或热侵蚀作用而造成的结果(图4). 前人对藏北地区(羌塘和松潘甘孜地块)大面积出露的新生代含钾火山岩(图5)所做的地质和地球物理观测指出了此区经历了强烈的岩浆活动, 推测可能与软流圈地幔流的上涌和流动对藏北高原岩石圈底部的破坏作用相关^[35~39]. 地震层析成像观测^[4,12,16,40]也发现了大面积的一条地幔低速带存在于上地幔顶部深度, 并从青藏高原中北部连续延伸到高原的东部地区(图5), 这一现象可能也指示了上述青藏高原下方的软流圈地幔流(可能包括青藏高原本身较热、较软的岩石圈地幔)在印度-欧亚大陆的板块汇聚挤压下向东的逃逸挤出, 前人对青藏高原中北部和东部地区开展的SKS波各向异性观测和分析同样也支持这一软流圈地幔流挤出的动力学模型^[41]. Mo等人^[42,43]对青藏高原新生代钾质火山活动时空迁移规律的研究为上述地球动力学模型提

供了很好的地表岩石学和地球化学证据的约束, 他们的研究发现印度-亚洲大陆碰撞以来青藏高原火山岩的时空分布显示了一种醒目的、分三阶段(65~40 Ma, 45~6 Ma, 6 Ma~近代)从高原腹地向周缘迁移的趋势特征, 他们将其解释为上述印亚板块汇聚诱发的软流圈地幔流向周缘区域流动的地表响应, 其中高原东北部西秦岭礼县-宕昌地区出露的含有地幔包体的钾质基性火山岩(时代为23~7 Ma)可能指示了青藏高原下方流向秦岭的地幔流通道(图5)与中国东部亏损地幔的相互作用^[43]. 向东流动的软流圈地幔流与周缘刚性块体(如高原东部的四川盆地和秦岭地块)发生碰撞, 致使地幔流发生局部扰动, 从而触发和加速了青藏高原-四川盆地和青藏高原-秦岭边界下方的岩石圈地幔拆沉和热侵蚀过程, 形成了这些边界带下方较薄的岩石圈和上地幔顶部低速带(图4和6(b)). Bao等人^[44]利用面波成像在毗邻北美克拉通的加拿大Cordillera高原也观测到了相似的现象, 他们的观测结果显示沿着北美克拉通大陆岩石圈边缘发生的软流圈物质扰动上涌触发了加拿大西部Cordillera高原整个岩石圈地幔的拆沉, 从而使得软流圈直接处于Cordillera高原的地壳之下. 剖面 TT' 的地震学图像(图4)和前人三维地震台阵观测图像^[45,46]都显示秦岭地块下方除了其西部岩石圈地幔在青藏

图5 青藏高原及其邻区新生代火山岩的时空分布叠合于95 km深度剪切波速度分布图(据Bao等人^[4]和Mo等人^[42]修改)

Figure 5 Shear-wave velocity map at 95 km depth of the Tibetan Plateau and its adjacent area, overlain by spatial and temporal distribution of the Cenozoic volcanisms (compiled from Bao et al.^[4] and Mo et al.^[42])

高原较热的地幔物质侵蚀下发生了一定程度的岩石圈活化, 总体保持了一个刚性的岩石圈(图1(b)和4), 所以青藏高原黏塑性性地幔物质向秦岭挤出的通道只可能发生在秦岭岩石圈之下的深度(至少100 km以下深度的软流圈)。

3 与青藏高原北缘的比较

总结我们近年来在高原东缘和北缘地区开展的地球物理探测成果, 并紧密结合前人资料成果, 我们对青藏高原东缘和北缘的地壳变形增厚机制以及地幔岩石圈行为模式进行对比, 力求揭示这两个边界区域在高原隆升和扩展模式的深部机制上的差异(图6)。在青藏高原北缘的祁连造山带, 近年来开展的地球物理学观测发现其上地壳底部也存在一个壳内低速带, 并且被解释为与地壳内的部分熔融或流体有关^[5,28,46,47], 这个低速带可能成为祁连造山带下方地壳中的一个物理软弱层^[46], 虽然这一中下地壳低速带表现出显著的地壳各向异性^[48], 但它的厚度(约10~15 km)和规模远不及青藏高原内部块体(如松潘甘孜地块), 并且具有较高的剪切波速度(3.3~3.5 km/s)^[49,50], 因而可能有更高的黏度^[5,46], 所以这里我们认为它不能被视为地壳流存在于祁连造山带下方的明确证据, 它在机制上更可能作为一个壳内滑脱层使上地壳变形与下伏地壳和岩石圈产生解耦^[51~54]。前人于20世纪90年代对格尔木-额济纳旗地学断面开展的综合地球物理调查(包括深地震反射剖面探测、深地震测深、大地电磁探测、重磁测量、热流测量等)提供的地壳和上地幔深部信息指示了青藏高原北缘也正在发生大陆岩石圈的汇聚碰撞作用^[55~57], 在不同经度区域上穿越祁连山的深反射地震剖面^[51,52,57,58]揭示了地壳逆冲构造越过了海原断裂和北祁连山前断裂, 向北扩展, 并在河西走廊盆地发现了隐伏的青藏高原北边界逆冲断裂NBT(north border thrust)^[55~57], 这似乎说明在壳内滑脱构造的控制下, 高原正通过上地壳逆冲作用向北扩展。对于更深部的地幔岩石圈的变形行为, 近年来大规模实施的宽频地震流动台阵(如中国地震局组织实施的“喜马拉雅”项目二期), 大大提升了对青藏高原北缘地区岩石圈深部结构的观测程度^[49,59~64]。但由于不同观测方法、台站分辨率以及结合地球物理观测资料与区域地质构造演化的理解等方面的差异, 关于青藏高原北缘的岩石圈深部结构及变形机制, 尚未形成统一的地球动力

学认识^[1]。如Li等人^[49]利用“喜马拉雅”二期数据开展的面波成像研究, 他们观测到了阿拉善地块与祁连造山带的岩石圈剪切波速度的差异, 认为华北板块西缘的阿拉善地块并没有俯冲到祁连山下方。我们仔细观察青藏高原北缘的面波成像(包括与体波接收函数的联合反演)结果^[4,49,64], 可以发现虽然祁连造山带的地壳和上地幔顶部(~90 km以上)相对于其两侧块体具有更低的剪切波速度, 指示了新生代活化的祁连造山带具有较软弱的地壳和上地幔顶部岩石圈, 在两侧更具刚性块体(南部柴达木盆地和北部阿拉善地块)的挤压下发生了缩短变形; 但在90~100 km以下的岩石圈下部, 剪切波低速区域基本沿着北祁连缝合带出现(图5), 而整个祁连造山带的岩石圈下部基本表现为剪切波高速特征, 与北部阿拉善地块保持一致, 这种高速特征可能指示了青藏高原北缘下方伏着一个稳定的欧亚岩石圈, 也可能与小尺度的欧亚大陆岩石圈俯冲有关^[1,65], 而观测到的沿北祁连缝合带的剪切波低速异常可能与后期缝合带活化后的走滑剪切作用有关。近期科研人员在高原北缘祁连山地区也开展了一系列穿过高原边界的宽频地震密集台站剖面观测, 这种针对性的重点观测获得了切过高原北缘边界的较高分辨率的地壳和上地幔结构断面^[28,66,67], 观测结果指示了祁连造山带在南北两侧刚性块体(柴达木盆地和北部阿拉善地块)的挤压下^[66], 作为亚洲板块一部分的华北板块岩石圈地幔有可能部分俯冲楔入到了祁连山之下^[26,28,65,67~70]。Guo等人^[69]同样利用“喜马拉雅”二期数据开展的多尺度地震层析成像观测到了相似的现象。事实上, 构造地质学家通过构造平衡剖面恢复指出了华北板块岩石圈地幔俯冲楔入祁连山下的模型能够合理地解释青藏高原北缘新生代发生的大规模地表缩短应变^[71,72], 地幔的楔入促使了高原在一系列走滑逆冲断裂带(如, 海原断裂带、天景山断裂带、北边界逆冲断裂带)的控制下以地壳逆冲(主要以上地壳在壳内滑脱层之上的逆冲扩展)的形式向外扩张和生长(图6(a))。而在青藏高原东缘地区, 我们的剖面TT'所观测到的青藏高原-秦岭构造转换带区域的高原隆升机制与前人^[6,25,27]在青藏高原-四川盆地构造转换带的龙门山区域观测到的现象(剖面LL')具有相似性(图3和4), 即, 受区域大型走滑逆冲断裂带控制的中下地壳软弱物质挤出和由软流圈地幔流触发的岩石圈底部拆沉导致的重力均衡, 共同作用于青藏高原东缘的高原隆升和扩

图6 青藏高原北缘(a)与东缘(b)高原隆升与扩展深部机制的比较

Figure 6 Comparison between the northern (a) and eastern (b) margins of the Tibetan Plateau for the deep mechanisms of the plateau uplift and expansion

展(图6(b)). 显然, 以上论述的青藏高原北缘的隆升与扩展机制与青藏高原东缘存在明显差异. 造成青藏高原北缘与东缘差异隆升模式的根本动力学原因可能是从青藏高原中东部(青藏高原内部)到高原北缘岩石圈性质的横向变化. Ye等人^[65]开展对青藏高原东北部的地震各向异性体制研究, 并结合前人研究成果指出, 在宏观上以昆仑-西秦岭一线为界, 青藏高原北缘的柴达木和祁连地块(以及北邻的阿拉善地块)下方下伏着一个相对较冷/刚性的亚洲岩石圈, 而青藏高原中东部的松潘甘孜和羌塘地块下方下伏着一个相对较热/软弱的青藏高原岩石圈, 正是这种岩石圈性质的差异造成了高原北缘和东缘岩石圈变形方式的差异.

4 结论

综上所述, 基于我们的地震学观测图像, 紧密结合前人的地质和地球物理学研究成果, 我们认为, 伴随区域大型断裂带的走滑和逆冲作用所控制的中下

地壳流有可能在青藏高原东缘下方发生, 并且可能是青藏高原东缘边界带上大地震发生的一个重要深部孕震机制, 但并没有大规模挤出越过青藏高原-秦岭边界带进入秦岭的下地壳. 同时, 青藏高原下方的软流圈地幔流在印度-欧亚大陆的板块汇聚挤压下可能发生向东的逃逸挤出, 并向秦岭下方流动, 触发和加速了青藏高原-秦岭/四川盆地边界带下方的岩石圈地幔底部的拆沉和热侵蚀作用. 青藏高原东缘地区的高原隆升机制受上述两个机制的共同作用, 即, 受区域大型走滑逆冲断裂带控制的中下地壳软弱物质挤出和由软流圈地幔流触发的岩石圈底部拆沉导致的重力均衡, 共同作用于青藏高原东缘(包括青藏高原-秦岭/四川盆地构造转换带区域)的高原隆升和扩展; 上述机制与处于青藏高原北缘的青藏高原-阿拉善构造转换带区域的高原向北扩展之深部机制存在差异, 而造成高原北缘与东缘差异隆升模式的根本动力学原因可能是从青藏高原中东部(青藏高原内部)到高原北缘岩石圈性质的横向变化.

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Summary for “青藏高原向东挤出与向北扩展——高原隆升深部过程之探讨”

Eastward extrusion and northward expansion of the Tibetan Plateau—Discussions for the deep processes of the plateau uplift

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The weak materials beneath the Tibetan Plateau have been escaping and extruding eastward from beneath the thickened and elevated central plateau driven by continuous convergence between India and Eurasia. This paper presents a detailed shear wave velocity cross-section image of crustal and uppermost mantle structure across the Tibet-Qinling transition zone that was generated from a dense linear seismic array. Based on our inverted seismic image together with previous geological and geophysical studies, we discussed about the material extrusion of the Tibetan Plateau, unveiling the depth extent in which the Qinling belt (which could serve as a flow channel) may accommodate the extrusion of the ductile material beneath the Tibetan Plateau, and suggested that how these dynamic processes might accommodate plateau uplift and expansion in the eastern margin of the Tibetan Plateau; furthermore, we compared the mechanisms of crustal deformation/thickening and the behavior patterns of lithospheric mantle between the eastern and northern margins of the Tibetan Plateau. Integrating our seismic image with previous observations, we can obtain the following findings: (1) A vigorous low velocity zone (LVZ) ($V_s < 3.4$ km/s) resides in the middle to lower crust beneath the eastern margin of the Tibetan Plateau and presents an extrusive behavior extending and weakening easterly toward the Qinling belt and Sichuan basin; the distribution patterns of the intracrustal LVZ are obviously controlled by the blocks and the major faults; large earthquakes tend to occur in the intersection zones between the intracrustal LVZ and the regional major faults. (2) A prominent uppermost mantle LVZ ($V_s < 4.2$ km/s) resides beneath the Tibet-Qinling/Sichuan boundary area, contrasting to the high-velocity upper mantle to the east beneath the Qinling block and Sichuan basin. A synthetic analysis based on these findings and previous geological/geophysical observations leads to the corresponding conclusions: (1) Middle to lower crustal flow accompanied by regional fault-related strike-slip/thrusts may be occurring beneath the eastern margin of the Tibetan Plateau, and may be a significant deep seismogenic mechanism of the large earthquakes occurrence in the eastern margin of the plateau, but it has not vastly extruded farther beyond the Tibet-Qinling boundary into the lower crust of the Qinling belt. (2) The hot asthenospheric mantle material beneath the Tibetan Plateau may escape eastward driven by convergence/squeezing between India-Eurasia continents and flow to the Qinling belt, accelerating the delamination or thermal erosion of the base of the lithosphere beneath the Tibet-Qinling/Sichuan boundary area. Combination of the preceding two mechanisms, i.e., the extrusion of ductile middle to lower crustal materials accompanied by regional fault-related strike-slip/thrusts and isostatic buoyancy resulting from lithospheric detachment (triggered by asthenospheric flow), may have jointly engendered the plateau uplift and expansion in the Tibet-Qinling and Tibet-Sichuan transition zones. In contrast, uplift of the Qilian Shan in the northern margin of the Tibetan Plateau significantly depends upon upper crustal shortening processes above a weak midcrustal decollement, which is subject to the North China plate underthrusting beneath the plateau. Obviously, the deep process of material extrusion in the eastern margin of the Tibet Plateau is distinguishable from the deep mechanism responsible for the northward expansion within the Tibet-Alxa transition zone in the northern margin of the plateau. The fundamental geodynamic mechanism leading to the mode discrepancy of plateau uplift between the eastern and northern margins of the Tibetan Plateau may be attributed to the lateral variation of the nature of the lithospheres from central and eastern Tibet (interior part of the plateau) to the northern margin of the plateau. A relatively hot/weak Tibetan lithosphere underlies the Songpan-Ganzi and Qiangtang blocks in the central and eastern Tibet, while a relatively cold/rigid Asian lithosphere underlies the Qaidam and Qilian blocks (as well as the northern bordering Alxa block) in the northern margin of the Tibetan Plateau, with the boundary extending along the Kunlun-West Qinling range on a large-scale view.

eastern and northern margins of the Tibetan Plateau, plateau uplift, deep process, lithospheric detachment, crustal flow

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