

龙门山断裂带深部结构与2008年汶川地震发震机理

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摘要 汶川地震后, 为认识发震机理, 在龙门山断裂带及周边地区开展了丰富的地震学和地球物理学等方面的野外观测与研究工作, 获得了有意义研究成果. 近震成像获得的地壳结构显示, 以汶川主震震中为界, 龙门山断裂带南北两侧波速存在明显差别, 以南地区为明显低波速异常, 而以北地区为显著横向不均匀性, 这也许可以解释汶川地震的余震为何向东北方向延伸. 汶川主震发生在高低波速异常的边界, 且其下方存在低波速高泊松比异常. 这一结果表明, 印度-欧亚板块的碰撞挤压在龙门山断裂带附近形成的高温高压导致了部分熔融或流体作用, 降低了断层面的有效正应力, 因而诱发了汶川地震. 远震成像获得的上地幔结构显示, 龙门山断裂带处于松潘-甘孜地块下方的低波速异常向四川盆地下方的高波速异常的过渡区, 且这种结构延伸至200~300 km深度, 而在地幔转换带中的高波速异常与缅甸弧下方的上地幔高波速异常相连接, 说明汶川地震的发生与印度板块深俯冲而形成的“大地幔楔”结构中的低波速异常所代表的热湿物质上涌等动力学过程密切相关. 因此, 本文认为汶川地震不仅与地壳结构密切相关, 而且还受上地幔异常结构的影响. 另外, 汶川地震还可能与下地壳流、地壳缩短和紫坪铺水库触发等动力学过程有关.

关键词 龙门山断裂带, 地震层析成像, 地壳结构, 地幔结构, 汶川地震机理

2008年5月12日在我国四川省汶川县发生 $M_s8.0$ 级大震(图1), 在龙门山断裂带上形成了长约300 km的地震破裂^[5,6], 地震地表破裂长约240 km, 地表实测最大同震垂直位移达 6.5 ± 0.5 m^[7,8], 是自1976年河北唐山 $M_s7.8$ 级地震以来我国遭受最强的破坏性地震, 造成约6万9千余人死亡和1万7千余人下落不明. 更为重要的是, 2013年4月20日在龙门山断裂带上汶川地震震中西南约90 km处发生了四川芦山 $M_s7.0$ 级地震(图1), 造成约192人死亡. 汶川地震的余震和芦山地震的余震分别沿龙门山断裂带向东北和西南方向扩

展^[2,3,9-11](图1), 其两者之间有较少余震发生(图1), 即存在余震空区^[3,12,13]. 汶川地震和芦山地震的形成机理及此空区未来是否会有较大地震发生均是人们备受关注的科学问题. 尽管地震地质学等学科的学者们针对这些问题开展过大量研究工作, 也取得了有意义的研究成果, 对于理解汶川地震和芦山地震发生机理具有重要意义^[8,14-16].

由于篇幅的原因, 本文主要回顾了龙门山断裂带及周边地区的体波成像方面的研究成果, 并结合接收函数研究结果, 以深入认识和理解汶川地震和

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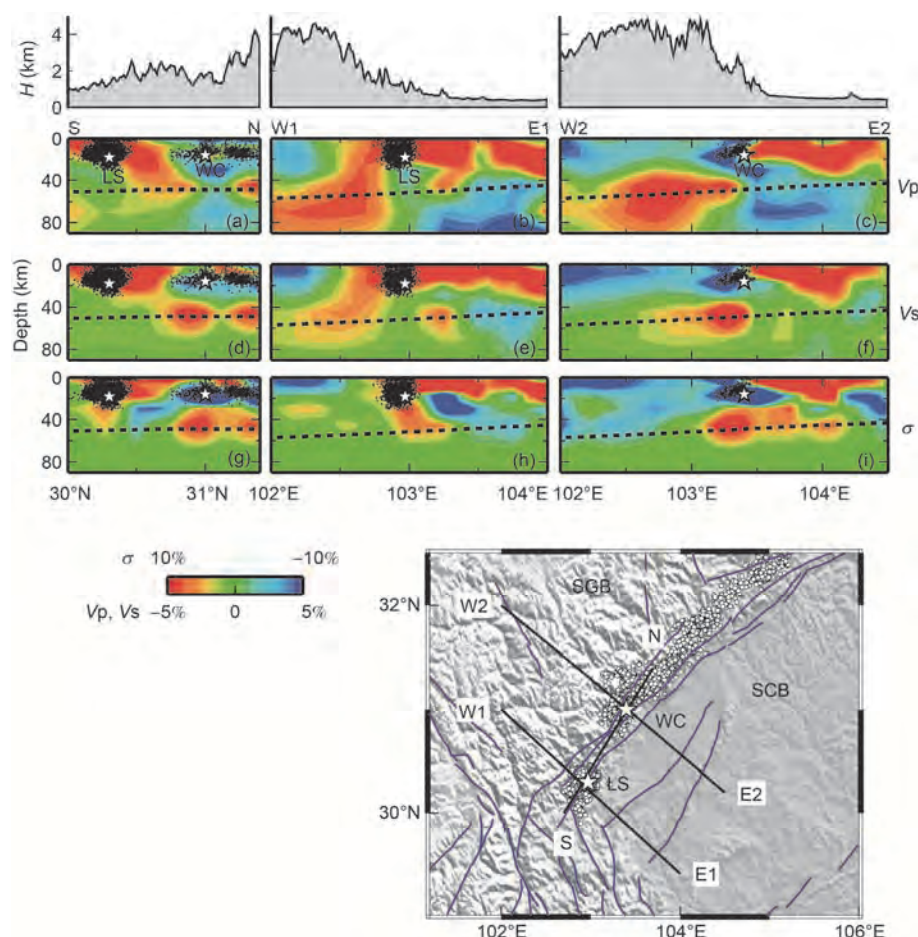


图 1 穿过 2008 年汶川地震(WC, 星号)和 2013 年芦山地震(LS, 星号)震源区的 P 波速度(V_p)、S 波速度(V_s)和泊松比(σ)的纵剖面^[1]. 插图显示出纵剖面位置. (a-c), V_p 速度结构; (d-f), V_s 速度结构; (g-i), 泊松比结构. 红色代表低波速高泊松比异常, 蓝色代表高波速低泊松比异常, 其色标位于图底. SGB 代表松潘-甘孜地块, SCB 代表四川盆地. (a-i) 中黑点和插图中白色圆圈均代表黄媛等人^[2]的汶川地震余震序列和 Lei 等人^[3]的芦山地震余震序列的重定位结果. 虚线代表莫霍面深度. 蓝线代表主要活动断层^[4]的分布

Figure 1 Vertical cross-sections of P-wave velocity (V_p), S-wave velocity (V_s), and Poisson's ratio (σ) tomography along profiles passing through hypocenters of the 2008 Wenchuan earthquake (WC, star) and the 2013 Lushan earthquake (LS, star)^[1]. Locations of the profiles are shown in the map. (a-c), V_p tomography; (d-f), V_s tomography; (g-i), Poisson's ratio (σ) image. Red colors denote low-velocity and high Poisson's ratio anomalies, whereas blue colors mark high-velocity and low Poisson's ratio anomalies, whose scales are shown beside the map. SGB, the Songpan-Ganzi block; SCB, the Sichuan basin. Black dots in (a-i) and white circles in the map denote aftershocks of the 2008 Wenchuan earthquake determined by Huang et al.^[2] and aftershocks of the 2013 Lushan earthquake determined by Lei et al.^[3]. The dashed line in each panel denotes the Moho discontinuity. Blue lines in the map denote major active faults^[4]

芦山地震机理及地震空区未来地震危险性. 根据所用的地震资料和研究区域的大小, 可将体波成像分为三类: 一类是近震成像^[17,18], 一类是远震成像^[19-21], 还有一类是全球成像^[22-24]. 近震成像是指利用研究区内地震台站记录到研究区内地震事件的到时资料开展的成像, 这类成像的震中距范围一般较小, 且射线主要分布于地壳和地幔浅部. 远震成像通常是指利用研究区内的地震台站记录到的远离研究区(一般是指震中距在 $30^\circ \sim 90^\circ$ 之间)的远震事件到时资料开展台站下方上地幔结构的成像. 全球成像

是指利用全球范围内的地震台站记录到任意震中距范围内地震事件的震相到时资料开展整个地球的成像. 由于全球成像结果具有较低的模型空间分辨率, 难以清楚地反映龙门山断裂带的深部结构, 因而全球成像结果在此不做讨论. 龙门山断裂带地区的地震和台站均较为密集, 因此近震成像和远震成像结果中的地壳、上地幔结构具有较好的模型空间分辨率, 可以深入讨论其主要结构特征及汶川地震形成机理等动力学问题.

为减轻地震灾害, 汶川地震和芦山地震发生后,

国内外的学者们围绕龙门山断裂带及其周边地区深部结构开展了大量野外观测与研究,取得了富有创新性的成果.这里,我们主要围绕在龙门山断裂带开展的地壳上地幔波速成像方面的研究成果,深入分析汶川地震区的主要结构特征及其深部动力学过程,为防灾减灾提供重要的基础支撑.

1 地壳结构

龙门山断裂带处于川滇地区,是南北地震带的重要组成部分,其周边地区发生过多次历史强震,如1976年松潘-平武7.2级地震.因此,该区深部结构与动力学研究一直备受关注.相对于中国其他地区而言,龙门山及周边地区中小地震活动较为频繁,地震台站分布也较为密集,因此利用近震成像技术获得研究区的精细地壳结构成为可能,所获得的地壳结构成像结果也较多.汶川地震前,由于地震台站数量与空间分布有限,研究结果仅展示出龙门山断裂带为松潘-甘孜地块与四川盆地之间的过渡带^[25,26].汶川地震后,随着地震台站数量的增多和台网布局的改善,获得了很多有意义的成像结果.雷建设等人^[27]利用2001~2008年期间被四川地区固定与流动地震台站观测到的到时资料,开展了三维P波速度成像工作,结果显示以汶川主震震中为界,龙门山断裂带南北两侧存在明显差别,以南地区为明显低波速异常,而以北地区存在强烈的横向不均匀性(图1),这种结构特征也许可以解释余震为何向东北方向延伸的原因.这种成像结果所揭示的结构特征,得到了吴建平等人^[28]和Wang等人^[29]研究结果的支持.汶川地震主震位于高波速低泊松比异常区,且震源区下方存在明显的低波速高泊松比异常体(图1),该异常结构往西延伸至松潘甘孜地块的中下地壳深度^[1,29,30].这样的结构特征,与刘启元等人^[31]利用川西台阵密集流动地震观测和杨海燕等人^[32]利用四川省部分地震台站资料使用接收函数方法得到的S波速度结构相类似.尽管有研究者认为该结构特征与青藏高原中下地壳的软弱物质向东向上挤压有关^[33],本文认为印度板块与欧亚板块的碰撞挤压在龙门山断裂带形成的高温高压导致了部分熔融或流体作用,降低了断层面的有效正应力,因而诱发了汶川地震^[1].这种流体作用已经被大量的地球物理观测结果所证实,如大地电磁测深^[34~36]、地壳各向异性^[37]和人工地震测深^[38]等.

汶川地震震源区下方存在明显的低波速异常,与我国和全球其他地区大地震震源区的结构特征相类似,如1995年1月17日日本神户(Kobe)7.2级地震^[39]、2001年1月27日印度普杰(Bhuj)7.6级地震^[40]和1976年7月28日我国唐山7.8级地震^[41,42].这种震源区下方存在的低波速异常,可能与过压流体填充裂隙岩石有关.这一解释已经得到广泛证实^[43~46].这种过压流体作用,可能会影响断层的结构与成分的长期演化,会改变断裂带强度和局部应力状态^[47~49].这些影响会使孕震层应力更加集中,导致力学失稳和地震成核作用.另有研究者认为,流体进入断裂带会降低断层面的有效正应力,从而触发地震^[50].地壳中的流体可能有多种不同来源:一种是地壳羟基矿物脱水作用,一种是岩石空隙流体,还有一种是气象水,但也有来自上地幔的流体.来自地幔的流体与地震的发生区域有关,如1995年神户地震的发生可能与菲律宾海洋板块在40~60 km深度处的海洋地壳蛇纹岩脱水作用有关^[39];华北地区的地震发生(如1976年唐山地震)可能与太平洋板块深俯冲至地幔转换带、然后滞留脱水和热湿物质上涌所携带的流体到达地壳有关^[41,42].2008年汶川地震的发生是否与上地幔中的热湿物质上涌等动力学过程相关,这需要高分辨率的上地幔波速结构等研究结果的验证.

2 上地幔结构

对于上地幔速度结构的研究,Pn波很有效,因为它的到时拾取精度高而且在莫霍面下方的上地幔顶部能形成很好的交叉性射线覆盖.由于地震台站分布较密,在龙门山断裂带已开展过很多Pn波成像工作^[51,52].这些结果,均显示出相类似的结构特征,即龙门山断裂带以西的松潘-甘孜地块下方存在明显的低波速异常条带,而以东的四川盆地下方则显示出明显的高波速异常,表明龙门山断裂带位于高低波速异常的过渡带.在龙门山断裂带以西的松潘-甘孜地块下方的低波速异常区具有较强的NE-SW向各向异性分布,而在以东的四川盆地下方的高波速异常区具有较弱的NEE-SWW向各向异性.这些结果可能说明,由于印度板块与欧亚板块的碰撞挤压,东向物质流在龙门山断裂带处由于四川盆地的阻挡,形成东北向和西南向流动的高温高压物质流,对于汶川地震的形成具有重要意义.上地幔顶部的这种物质流,是否与地幔更深处动力学过程有关,需要远震成

像结果揭示的三维上地幔研究结果的验证。

由于远震射线在地壳深度范围内以近乎垂直于地表方向到达地震台站,因而难以在地壳深度形成交叉性覆盖,但在上地幔深度远震射线能够形成较好的交叉性覆盖,因此上地幔成像多使用远震成像技术。郭飏等人^[53]利用川西台阵记录到的远震P波到时资料,揭示出川滇地块、松潘-甘孜地块和四川盆地3个不同块体的构造差异,认为青藏高原东向挤压和地幔上涌的双重作用造成了松潘-甘孜地块隆升,汶川地震震源区应力容易在此集中。Lei和Zhao^[54]利用青藏高原东缘固定地震台站和云南地区流动地震台站观测资料,通过成像反演获得了研究区深至地幔转换带(410~660 km深度)的P波三维速度结构模型。

其结果显示,青藏高原下方的上地幔呈现明显低速异常,四川盆地为明显高波速异常(图2),而在地幔转换带深度向北至昆仑山断裂带、往东至小江断裂带均为明显高波速异常(图3)。这些高波速异常在缅甸弧下方向上延伸,与中深源地震形成的和达-贝尼奥夫地震带(Wadati-Benioff deep seismic zone)相连(图2),说明印度板块在缅甸弧下方深俯冲至地幔转换带、然后在地幔转换带内行进了较长距离、最终形成“大地幔楔(Big Mantle Wedge, BMW)”结构模型(图2)。这样的结构模型与Wang等人^[33]和Li等人^[58]成像结果相类似。地幔转换带中的高波速异常,也得到接收函数结果显示的地幔转换带明显增厚^[56,57]的结果支持(图3)。在“大地幔楔”结构模型中,汶川地震处

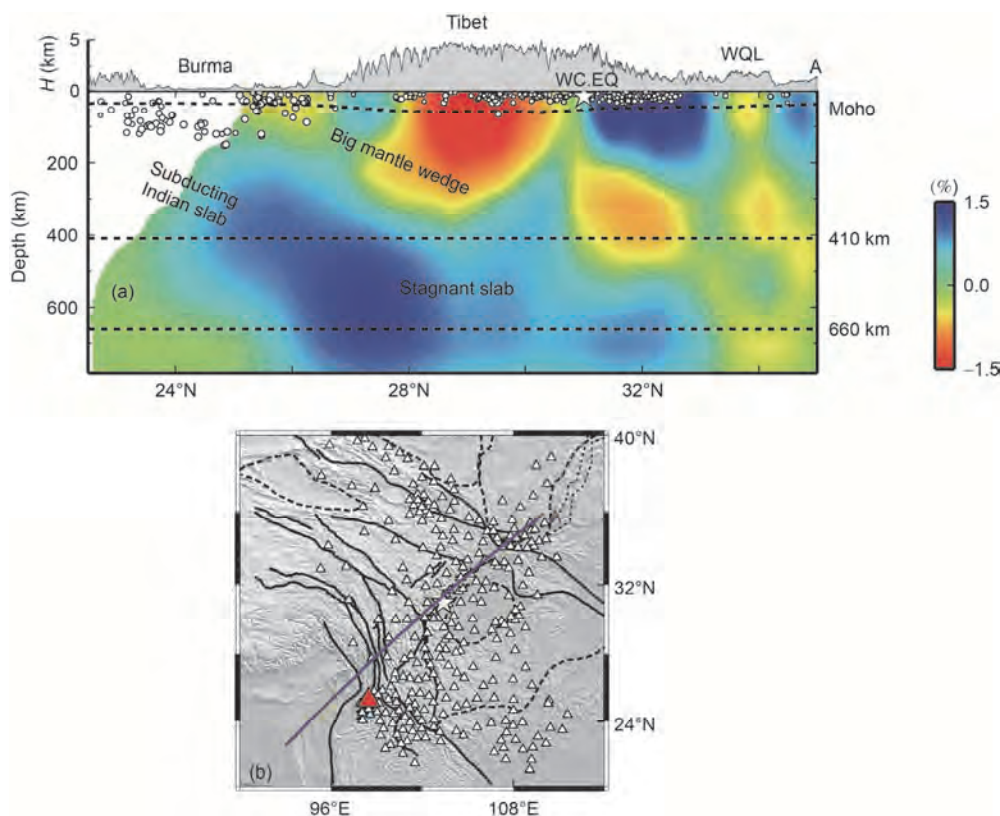


图2 青藏高原东缘远震成像结果^[54]。(a) 沿纵剖面A的远震成像。该结果暗示“大地幔楔(big mantle wedge)”形成于俯冲的印度板块之上。红色代表低速异常,蓝色代表高波速异常,其色标位于图右侧。白色圆点代表距离A剖面35 km范围内的1970~2007年期间国际地震中心的观测报告中选出的4级以上地震^[55]。白色星号(WC.EQ)代表2008年汶川Ms8.0地震震中。WQL,西秦岭。(b) 剖面所在位置。白色三角表示远震成像^[54]时所用到的地震台站。黑色实线代表主要活动断裂带,而黑色虚线代表主要块体边界

Figure 2 Results inferred from teleseismic P-wave tomography beneath eastern Tibet^[54]. (a) Vertical cross-section of teleseismic tomography along the profile A. This result suggests that a big mantle wedge has formed above the subducting Indian plate. Red and blue colors denote low- and high-velocity anomalies, respectively, whose scale is shown on the right. White dots denote earthquakes ($M > 4.0$) within a 35-km width of the profile AB, which are selected from the International Seismological Center bulletins from 1970 to 2007^[55]. The white star (WC.EQ) denotes the 2008 Wenchuan earthquake (M_s 8.0) hypocenter. WQL, western Qinlin. (b) Distribution of the seismic stations (white triangles) used to determine the teleseismic tomography^[54]. The black and solid lines denote major active faults, whereas the black and dashed lines denote the boundaries of major blocks

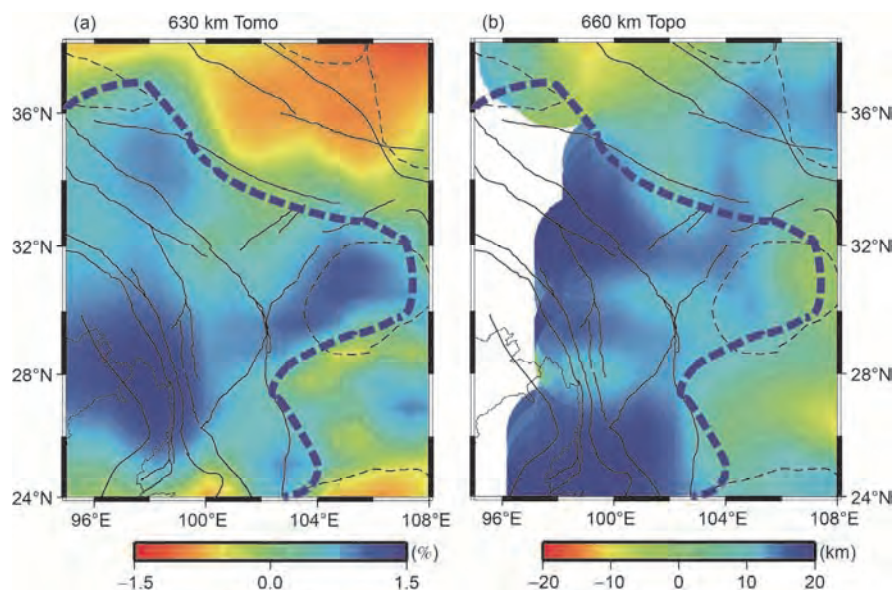


图3 地幔转换带成像结果与接收函数结果的对比。(a) 地幔转换带中 630 km 深度的远震成像结果^[54]。红色代表低波速异常，蓝色代表高波速异常，其色标位于图底。(b) 660 km 间断面埋深的接收函数结果^[56,57]。红色代表 660 km 间断面变浅，蓝色代表 660 km 间断面变深，其色标位于图底。粗虚线代表俯冲印度板块前缘在地幔转换带中可能到达的位置^[54]。黑色实线代表主要活动断裂带，而黑色虚线代表主要块体边界

Figure 3 Comparison between the results inferred from teleseismic tomography and receiver function analysis in the mantle transition zone. (a) P-wave tomography^[54] at 630 km depth in the mantle transition zone. Red and blue colors denote low- and high-velocity anomalies, respectively, whose scale is shown at the bottom. (b) Depth distribution of the 660 km discontinuity from receiver function analyses^[56,57]. Red and blue colors denote shallower and greater depths, respectively, whose scale is shown at the bottom. The thick and dashed line denotes the possible location of the subducted Indian slab front in the mantle transition zone^[54]. The black and solid lines denote major active faults, whereas the black and dashed lines denote the boundaries of major blocks

于松潘-甘孜地块下方的低波速异常向四川盆地下方高波速异常的过渡区，这一结构特征往深延伸至 200~300 km 深度(图2)，说明汶川地震的发生可能与青藏高原东缘的“大地幔楔”结构及动力学过程有关。有关“大地幔楔”结构与动力学模型，最初是为解释我国东部长白山火山的成因及东亚深部动力学过程而提出的。有关细节，请参阅相关文献[21,59~61]。这种地壳强震的发生与上地幔异常结构的相关性，在中国华北^[62]、日本列岛^[46]、北美西部^[63]和全球很多地区^[46,64]也得到发现和证实。

3 余震空区

2008年汶川地震的余震沿龙门山断裂带向东北方向扩展^[2,9]，而2013年芦山地震的余震却向西南方向扩展^[3,10,11]。两者的余震均表现为单侧向扩展，而在两者之间形成了一个长约60 km的余震空缺区。在此空缺区内，未来是否会发生大地震备受关注。使用三维弹性模型和GPS资料，有研究者认为龙门山断裂带未破裂的西南段在汶川地震后50年内具有发生 Mw7.7级地震的可能性^[65]。通过分析地震构造、地震

活动性、地震矩释放“亏空”区以及余震活动规律等资料，陈运泰等人^[12]认为地震空区完全破裂可能会发生 Mw6.8级地震。易桂喜等人^[66]通过龙门山断裂带南段b值分析，认为南段部分地区应力增强，具有发生中-强震的条件。Liu等人^[67]认为芦山地震仅释放了龙门山断裂带南段地震能量的三分之一，在地震空区应力还在增加，未来还有孕育更大地震的可能性。何富君等人^[68]利用在地震空区开展流动地震观测与固定地震台站资料和H-k远震接收函数方法^[69]，揭示出地震空区具有沿龙门山断裂带由西南的高泊松比向东北的明显低泊松比剧烈变化特征，似乎支持该空区有积累能量形成地震的可能性。然而，由于H-k接收函数结果展示的泊松比为整个地壳深度范围内的平均值，因而不能完全反映该地震空区不同深度的介质结构特征。

相对而言，三维层析成像揭示的波速结构特征可较为客观地反映大震的孕育环境。Lei和Zhao^[1]利用近震三维P波和S波成像结果展示出，位于上地壳的该地震空区呈现明显的低波速高泊松比的结构特征，但在20 km以下的深度则呈现低泊松比异常(图1)。这样

的波速和泊松比结构特征,可能表明地震空区20 km深度之上的介质较为软弱,因而很难积累应力形成强震,但在20 km深度之下的地壳有可能会积累能量孕育地震.因此,Lei等人^[3]认为,如果在此地震空区发生强震,则其震源可能在20 km深度之下的中地壳内.Wang等人^[70]将地震空区的流动地震观测与固定地震观测资料相结合,开展了P波和S波成像结果反演,结果均显示地震空区在20 km深度之上呈现明显的低波速高泊松比异常,认为该区的上地壳内发生强震的可能性不大,但在20 km深度之下为低泊松比异常区.因此,本文认为该余震空区如果发生强震,则可能是在20 km深度之下的中地壳内.

4 讨论与结论

通过应用近震和远震层析成像技术对2008年汶川Ms 8.0级地震震源区的地壳、上地幔波速和泊松比结构进行了研究,结果显示汶川地震震源区下方的地壳深度存在低波速高泊松比异常,在上地幔位于由松潘-甘孜地块下方的低波速向四川盆地下方高波速异常的过渡区,而在地幔转换带存在北至昆仑山断裂带、东至小江断裂带的大范围高波速异常.这些结果可能表明,汶川地震的发生可能与印度板块和欧亚板块的碰撞挤压在龙门山断裂带处的下地壳形成高温高压造成部分熔融或流体作用有关.这种流体作用也与印度板块在缅甸弧下方向深处俯冲至地幔转换带、然后向北、向东范围推进并滞留、脱水和热物质上涌等动力学过程密切相关.

本文所述的龙门山断裂带特别是汶川地震震源区下方中下地壳存在低波速高泊松比(图1)和高导结构特征^[1,29,35,36,71,72].也有研究者将该结构特征解释为,由于印度板块北向碰撞俯冲,在青藏高原东缘的下地壳物质向东挤压,在龙门山断裂带处遇到四川盆地阻挡、然后沿盆地边缘向上挤压^[73,74]并造成逆冲发震断层破裂,从而形成汶川大地震^[35,36,72].地震地质学者在龙门山断裂带上的野外调查结果表明,发震断层的最大垂向同震位移达6.5 m^[8],由此提出龙门山断裂带地壳深部存在着叠瓦状结构特征,并且该结构特征是由地壳缩短机制形成^[8,75,76],并造成高原物质向东南挤出^[77,78].这种地壳缩短机制也可导致发震断层破裂形成汶川地震^[8,75].

位于川西地区的紫坪铺水库于2005年9月开始蓄水,在2006年12月蓄水量达到最高海拔875 m,至汶

川地震前(约两年半时间)水位一直处于817 m以上^[79].由于汶川震中距紫坪铺水库最近距离约6 km,因此汶川地震的发生是否与水库蓄水有关一直是很多研究者关心的热点问题^[79~87].通过分析水库地震的特征和力学上的解释,有人认为汶川地震不可能是由水库蓄水造成的^[81],然而Kerr和Stone^[80]则认为紫坪铺水库可能诱发了四川地震.为解决这一争论,很多研究者用数值模拟方式开展了相关研究.Deng等人^[83]通过计算弹性效应和扩散效应讨论了该问题,认为在10和15 km深处库仑应力分别为1和0.1 kPa,这个量级远小于固体潮效应,可以忽略不计,因此紫坪铺水库对汶川地震的影响作用非常有限.Gahalaut和Gahalaut^[84]根据水位变化,计算了水库载荷的Boussinesq解和水的扩散效应,得到在震源处的库仑应力为-0.1 kPa,认为紫坪铺水库对汶川地震没有任何触发效应.与此相反,雷兴林等人^[79]根据紫坪铺水库蓄放水过程,考虑了水库载荷的弹性效应和水的渗透效应,计算得到了在震源深度处库仑应力能够达到0.1 MPa量级,由此认为紫坪铺水库对龙门山断层有明显作用.Ge等人^[82]通过二维模型计算得到在震源深度处的库仑应力最大可达0.05 MPa,结合龙门山地区每年荷载增长率小于0.005 MPa,因此认为紫坪铺水库使得汶川地震提前了10~100年.陶玮等^[86]基于完全耦合孔隙弹性理论,利用二维有限元模型,模拟水库蓄水造成的区域孔隙压力场和应力场的演化过程,结果认为紫坪铺水库蓄水打破了原来的区域孔隙压力平衡,形成了孔隙压力梯度源,向周围地壳传播,进而造成龙门山断裂带库仑应力正值范围不断扩大,由浅入深影响到整个断层,震源区库仑应力呈持续增长趋势,起到了加载作用,有可能触发地震.孙玉军等人^[85]基于三维孔隙弹性理论,根据紫坪铺水库开始蓄水到汶川地震发震时的水位变化情况,计算了整个区域的孔隙压力与库仑应力,结果表明当弹性模量和扩散系数为代表性值时,在汶川地震发震时震源处的库仑应力变化量为+1 kPa,因此他们认为紫坪铺水库使得汶川地震发震断层更加危险.尽管很多研究者认为紫坪铺水库对汶川地震有影响作用,但他们推测出的库仑应力值却存在很大差别,而这些差别均与其模拟过程中所用参数(如模型维数、断层面倾角、震源参数和扩散系数等)的取值密切相关,且不同取值在震源处会获得显著不同的库仑应力值^[87].因此,在将来研究工作中,需

加强震源区微细结构的研究,由此而求出较为可靠的模拟参数深入认识紫坪铺水库对汶川地震的影响作用.

2008年汶川地震之后不到五年时间,沿龙门山断裂带余震最南端约60 km处发生了2013年芦山地震.与汶川地震震源区结构相类似,芦山地震震源区下方的地壳和上地幔也存在低波速高泊松比的异常结构,因此芦山地震的发生可能也和地壳上地幔流体作用降低断层面正应力密切相关,还可能与下地壳流作用和地壳缩短机制等动力学过程有关.然而,关于芦山地震震源区的波速结构,不同的研究结果却存在着明显差别:一些研究结果显示其震源上方存在明显的低波速高泊松比异常,这也许可以解释芦山地震的震级比汶川地震小的原因^[3];而另一些研究结果却显示该地震震源上方为明显的高波速异常,与汶川地震区的波速结构十分类似^[70].这样的

差别,可能与不同研究者所用到时数据和所采用的初始速度模型的不同有一定关系. Lei和Zhao^[1]所用的数据没有包括芦山地震的余震数据,而Wang等人^[70]则使用了这样的余震数据.另外,前者所用的反演初始模型在20 km深度以上的P波速度要比后者高约1.0 km/s. 2008年汶川地震发生后,龙门山断裂带西南段,特别是2013年芦山地震发生后,两者余震之间形成了约60 km余震空区.今后在这一空区是否会有强震发生,目前还存在较大争议.因此,在未来的研究工作中,还需进一步加强芦山地震震源区与汶川-芦山地震空区的密集流动地震观测,从而获取该地区更加精细的三维成像结果.同时,还需进一步加强与其他学科如地质学、地球化学、大地电磁学和数值模拟等研究结果相结合,从而更加深入地认识汶川地震和芦山地震的发生机理以及地震空区的未来发震的危险性.

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Summary for “龙门山断裂带深部结构与 2008 年汶川地震发震机理”

Deep structure of the Longmenshan fault zone and mechanism of the 2008 Wenchuan earthquake

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Since the occurrence of the 2008 Wenchuan earthquake ($M_s8.0$), many researchers have conducted extensive seismological and geophysical observations and investigations and obtained important results about the Longmenshan fault zone. Crustal structure inferred from local tomography shows that seismic velocity exhibits significant changes across the Wenchuan earthquake hypocenter from the south to the north. To the south, obvious low-velocity (low-V) anomalies exist, whereas strong lateral heterogeneities are revealed to the north, which may explain why the aftershocks extend northeastward. The Wenchuan earthquake occurred at the boundary between high-velocity (high-V) and low-V anomalies and a significant low-V zone is revealed below the mainshock hypocenter, suggesting that the nucleation of the Wenchuan earthquake was related to partial melts and/or fluid effects and associated with the reduction of effective normal stress on the fault plane, due to high temperature and high pressure in the Longmenshan fault zone caused by the India-Asia collision. The upper-mantle structure inferred from teleseismic tomography shows that the Longmenshan fault zone is located in the transition zone from low-V anomalies beneath the Songpan-Ganzi block to high-V anomalies beneath the Sichuan basin. This structural feature extends down to 200–300 km depths. High-V anomalies in the mantle transition zone are connected with those in the upper mantle beneath the Burma arc, indicating that the Wenchuan earthquake could be associated with upwelling of hot and wet materials in the big mantle wedge formed by the deep subduction of the Indian plate. These results suggest that the generation of the Wenchuan earthquake was related to structural heterogeneities in not only the crust but also the upper mantle.

In addition, high-poisson's ratio and high-conductivity anomalies are revealed beneath the Wenchuan earthquake source area, which may also reflect lower crustal flow that is compressed and moving eastward. When the eastward flow encountered the strong Sichuan basin block around the Longmenshan fault zone, the flow is further compressed upward along the margin of the Sichuan basin, which could have caused the fault rupture and generated the Wenchuan earthquake. Some geologists found a vertical co-seismic displacement of 6.5 m in the Longmenshan fault zone, suggesting that there exists an imbricate structure due to the crustal shortening. Such a shortening mechanism could rupture the seismogenic fault leading to the large earthquake.

The Zipingpu reservoir is located very close to the Wenchuan earthquake epicenter. It is still debated whether the reservoir triggered the 2008 Wenchuan earthquake or not. Although some simulation results suggest that the Wenchuan earthquake could be triggered by the reservoir, there are large differences in the estimated stress in the hypocentral area due to large uncertainties of the physical parameters adopted in the numerical simulations. Hence, the physical parameters should be determined precisely in future investigations so as to clarify the effect of the reservoir on the seismogenesis.

We also discuss the causal mechanism of the 2013 Lushan earthquake ($M_s7.0$) and future seismic risk in the gap between the aftershock zones of the Wenchuan and Lushan earthquakes.

Longmenshan fault zone, seismic tomography, crustal structure, mantle structure, mechanism of the Wenchuan earthquake

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