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专题：纪念汶川地震十周年 评 述

2008年汶川地震与龙门山断裂带的深浅部变形及启示

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摘要 概述了2008年汶川8.0级地震后近10年有关龙门山断裂带的深浅部变形研究结果, 通过较为系统的综合对比分析, 归纳得出的基本共识为: 龙门山断裂带的深部构造形态和速度结构均十分复杂, 2008年汶川8.0级地震是由多次子事件构成的十分复杂破裂过程, 其主要滑动量在深浅部都有展布. 综合分析认为: 龙门山断裂带中北段的深浅滑动速率存在明显差异, 孕震深处的滑动速率约为浅部的2~3倍, 以重复地震分析给出的深部滑动速率估算的汶川地震复发间隔约为500~4500 a. 针对探测程度十分有限的大陆内部断裂带, 应充分发挥重复地震的原位探测优势, 集成地震学、大地测量学和地质地貌学的各自优势进行深浅部构造变形的有效探测分析, 对断裂闭锁段和深浅构造变形差异显著地区的强震危险性尤应重视.

关键词 汶川地震, 龙门山断裂带, 深部变形, 重复地震, 强震危险性, 复发间隔

断层闭锁段通常被认为是应变积累并可能发生强震的危险区[1,2], 而地震复发周期则被作为强震危险性判断的重要依据[1,3]. 地震复发概念可追溯到1911年Reid提出的弹性回跳理论, 认为地震复发是应变能积累和释放过程的轮回. 基于弹性回跳理论提出的地震复发模型(严格周期模型、时间可预报模型和滑动可预报模型)[4]及考虑地震并非严格的原地周期性发生的准周期模型[5], 在强震危险性分析研究中得到了广泛的应用[6~8].

针对强震复发间隔长达数百上千年的问题, Geller和Mueller[9]早在1980年就研究了加利福尼亚的卡拉维拉斯断层和圣安地列斯断层上小震的复发现象. 近年来, 研究者在板块边缘的活动断裂带和俯冲带等不同的构造单元(如文献[10~14])及板内大陆地区, 如中国[15~17]和韩国[18], 相继发现了发生在同一断层位置且波形具有高度相似性和破裂面积相互重叠的小地震(即重复地震或重复微震), 并认为属于孕育或发生过强震的大凹凸体周缘处于弱耦合状态的小凹凸体在区域构造加载作用下所发生的重复破裂[19]. 数值模拟、理论分析和岩石实验等研究[20,21]证实了这种重复地震发生的机理, 即重复地震的孕育发生过程实际上反映了其破裂区周围断层蠕滑区域的应变积累和滑动过程, 可以用以研究断层深部的滑动速率[11], 从而提供了一种直接探测断裂带深部变形活动的新途径.

断层滑动速率是地震危险性分析及其中地震复发周期估算的一个很重要的参数[7,22]. 滑动速率作为衡量断层(断裂)活动性的一个非常重要参数[7], 其给

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出的是断裂在一定时段内的平均位移量, 代表着断裂的相对变形程度. 滑动速率的结果主要来源于地质学、地貌学、大地测量学和地震学等分析研究, 不同的学科方法各有其优势与局限性. 对于2008年5月12日发生的汶川8.0级地震, 其出乎意料发生在位于青藏高原东缘的龙门山断裂带, 对龙门山断裂带强震危险性低估的重要原因之一是其低滑动速率[8,23,24]. 在汶川大地震突发后近十年来, 多学科的研究结果为深入认识汶川地震的破裂过程和孕震构造特征及地震的成因机制等提供了相当丰富的约束信息, 为进一步分析汶川地震的深部构造变形特征提供了可能. 本文通过对发生汶川地震的龙门山断裂带深浅部变形研究结果的对比分析, 就断裂变形探测途径及深浅变形差异与强震活动的关联性问题进行了研讨.

1 龙门山断裂带的变形特征

先后发生2008年5月12日汶川8.0级地震和2013年4月20日芦山7.0级地震的龙门山断裂带, 是青藏高原和华南地块边界的推覆构造带, 主要由汶川-茂县断裂、映秀-北川断裂和灌县-江油断裂3条主干断裂组成(图1), 具有十分复杂的地质结构和演化历史[27~29]. 龙门山断裂带周边包括古生代变质地体、以彭灌杂岩体和宝兴杂岩体为代表的前寒武纪变质杂

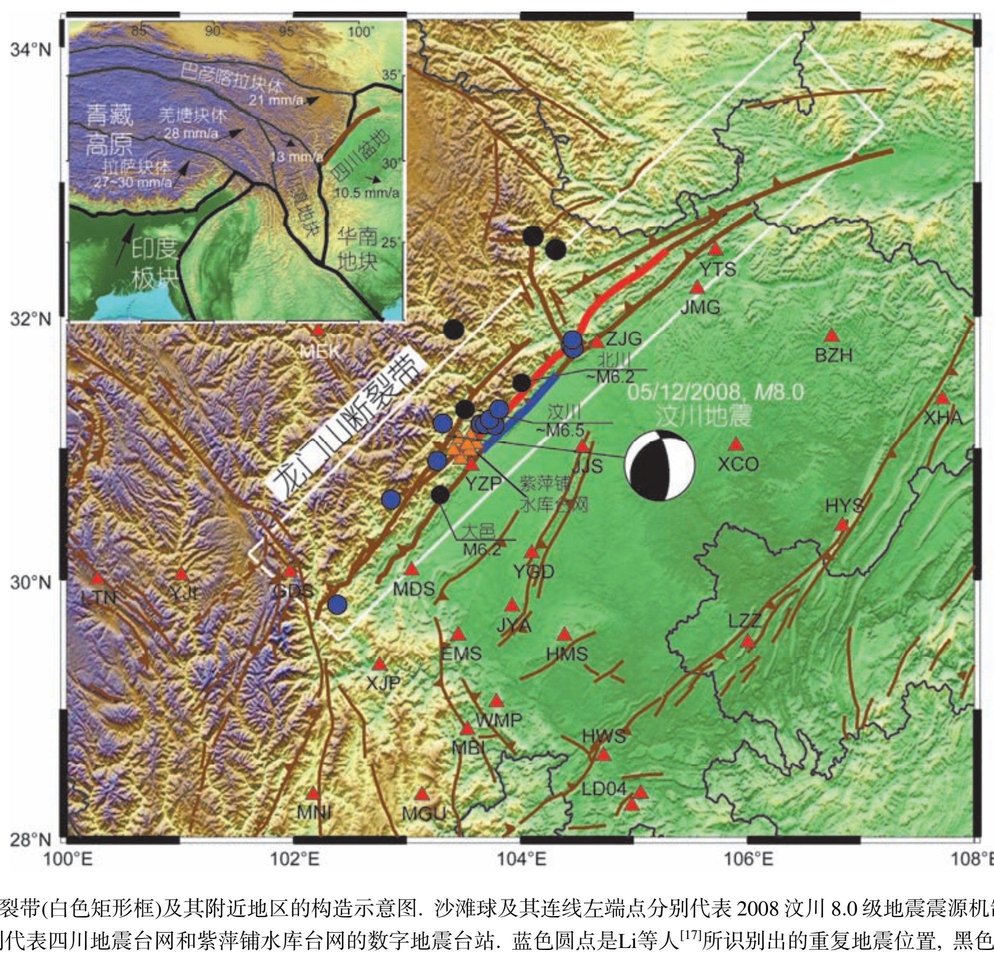

图1 龙门山断裂带(白色矩形框)及其附近地区的构造示意图. 沙滩球及其连线左端点分别代表2008汶川8.0级地震震源机制及其震中. 红色和橙色三角分别代表四川地震台网和紫萍铺水库台网的数字地震台站. 蓝色圆点是Li等人[17]所识别出的重复地震位置, 黑色圆点代表 6 级以上的历史地震. 棕色线段代表断裂, 红色和蓝色线段为据Xu等人[25]给出的汶川地震同震地表破裂段. 左上插图表示印度板块和青藏高原及其次级块体, 数字表示相对于稳定西伯利亚克拉通的地表运动速度[26]

Figure 1 Simplified tectonic map around the Longmenshan fault zone. The beach ball indicates the focal mechanism of the 2008 *M*8.0 Wenchuan earthquake with its epicenter in the end point of the black line. The Sichuan regional seismic network and the local seismic network of the Zipingpu reservoir are shown by red and orange triangles, respectively. Blue circles are locations of the recognized repeating earthquakes given by Li et al.[17]. Black circles indicate historic earthquakes. Surface ruptures[25] associated with the 2008 Wenchuan earthquake along the Beichuan and Pengguan faults are marked by thick red and blue lines, respectively. Insert map in the upper left corner shows surface velocities[26] of different blocks within the Tibetan Plateau relative to the stable Siberian craton

岩、三叠系含煤系地层和侏罗系前陆盆地，其深部结构的非均匀性十分显著[30~33]，并有着十分复杂的深部构造分布[23,34~38]. 对如此复杂的龙门山断裂带，这里仅从断裂滑动速率和汶川地震同震形变角度来概述断裂带的深浅部变形特征.

1.1　断裂滑动速率

汶川地震前的构造地质和地貌等研究表明：龙门山推覆构造带有切割晚更新世地层的地质剖面和断错构造地貌迹象，映秀-北川断裂、灌县-江油断裂和汶川-茂县断裂的垂直(逆冲)滑动速率和右旋滑动速率都≤1 mm/a[25,39,40]，Densmore博士和Ellis教授与中国学者连续7年对龙门山的科学考察合作研究[41~43]得到的逆冲滑动速率<1.1 mm/a和走滑滑动速率<1.46 mm/a. 尽管Densmore等人[41]提到走滑滑动速率要较逆冲滑动速率高出几倍(1~10 mm/a)，但也指出其约束不好. 从汶川地震之后发表的相关文章[24,43,44]可见，龙门山断裂带的走滑滑动速率应不超过3 mm/a.

汶川地震前的GPS观测表明：横跨整个龙门山断裂带的滑动速率不超过2~3 mm/a[45~48]，稍早些年的GPS结果将龙门山断裂带的地壳缩短速率约束到0~5 mm/a[49]、1~5 mm/a[50]、5~11 mm/a[51]、约为7 mm/a[52]、4±2.5 mm/a[26](同时还存在7.5±2 mm/a的左旋走滑速率)、4.0±2.0 mm/a[53]. 但Wang等人[51]将所观测到的较高缩短速率解释为青藏高原顺时针旋转的结果，张培震等人[26]对存在的较大左旋走滑速率归结为青藏高原顺时针旋转在龙门山断裂带以西的高原东边界形成了宽达300 km的左旋剪切带所造成. 汶川地震后，杜方等人[54]利用可获得的两期Ⅰ等水准复测资料(1975和1997年、1987和1997年)计算得到的垂直形变速率数据，反映出映秀-北川断裂和灌县-江油断裂之间的隆升速率仅为0.6 mm/a，后山汶川-茂汶断裂上盘及其以西高原的隆升速率可达2~3 mm/a. 尽管数千年尺度的地震地质研究和10年尺度的大地形变测量研究的结果稍有差异，但相较周边的鲜水河断裂、安宁河断裂、昆仑断裂、小江断裂而言，都认为龙门山断裂带滑动速率较低[8,23,24,43,44,46,47,49,50].

汶川8.0级地震发生后的地震学研究结果则有所不同，赵祎喆等人[55]使用《中国地震月报目录》内1977/01/01~2008/01/01时段内记录完整的M_L2.5以上地震，通过计算累积Benioff应变和震级-频度关系中的a值空间分布，对比分析表明龙门山断裂带的深部形变与其近邻的鲜水河、安宁河、则木河等3个断裂相比并不低. 而Li等人[17]在汶川地震后，利用汶川地震前(2000年5月~2008年4月)数字地震台网记录的波形资料，基于识别出的重复地震估算得到龙门山断裂带深部4~18 km范围的滑动速率为3.5~9.6 mm/a，深部滑动速率约为GPS和地质等浅表观测得出的滑动速率值的2~3倍(图2). 陈棋福等人[60]构建的简单黏弹性有限元模拟结果表明：龙门山断裂带深处的滑动速率比浅表的滑动速率大，龙门山断裂带5~19 km深度是高应力聚集成核区. 对比同样基于重复地震估算得到的鲜水河断裂带南段[61]3.6~18.7 km深度的滑动速率(3.0~10.2 mm/a)和小江断裂带[62]3.0~12.3 km深度的滑动速率(1.6~10.1 mm/a)，同样表现出龙门山断裂带的深部变形速率与其近邻的鲜水河和小江断裂带基本相当.

Li等人[63]通过分析2008年5月12日汶川主震后到2009年7月31日为止，四川地震台网、紫坪铺水库台网和川西流动台阵记录到的52889次余震事件波形和连续波形资料，得到由34个地震组成的破裂面积相互重叠的12组重复地震用于震后波速变化分析，结果表明汶川主震破裂区的西南段和东北段震后波速变化存在明显差异，位于西南段起始破裂区震后波速恢复(增加)约0.1%~0.3%，而位于东北段的北川破裂区波速没有明显的变化，展现了这2个破裂段震后所经历的不同愈合(恢复)过程.

1.2　2008年汶川地震的同震变形

关于2008年汶川地震的同震变形，有许多现场地质地貌调查及地震学和大地测量反演研究结果. 汶川地震形成了迄今为止最为复杂、破裂长度最大且同时兼有逆冲和右旋走滑分量的同震地表破裂带，野外考察测量和遥感影像解译结果[25,64~73]表明：汶川地震同时使2条NE走向近平行的叠瓦状逆断层(映秀-北川断裂和灌县-安县断裂)发生破裂，并产生1条NW走向长约6~8 km的小鱼洞破裂带. 由于观测地点、测量方法和参考标志及对同一现象的认知程度不同，加上地表破裂带规模大、结构复杂和野外考察时间短等因素，不同作者给出的地表同震破裂带长度和最大同震位移的考察结果具有一定的差异[74,75]，对沿映秀-北川地表破裂带长度有研究表明超过300 km，也有小于200 km，最大同震垂直和右旋位移则分别

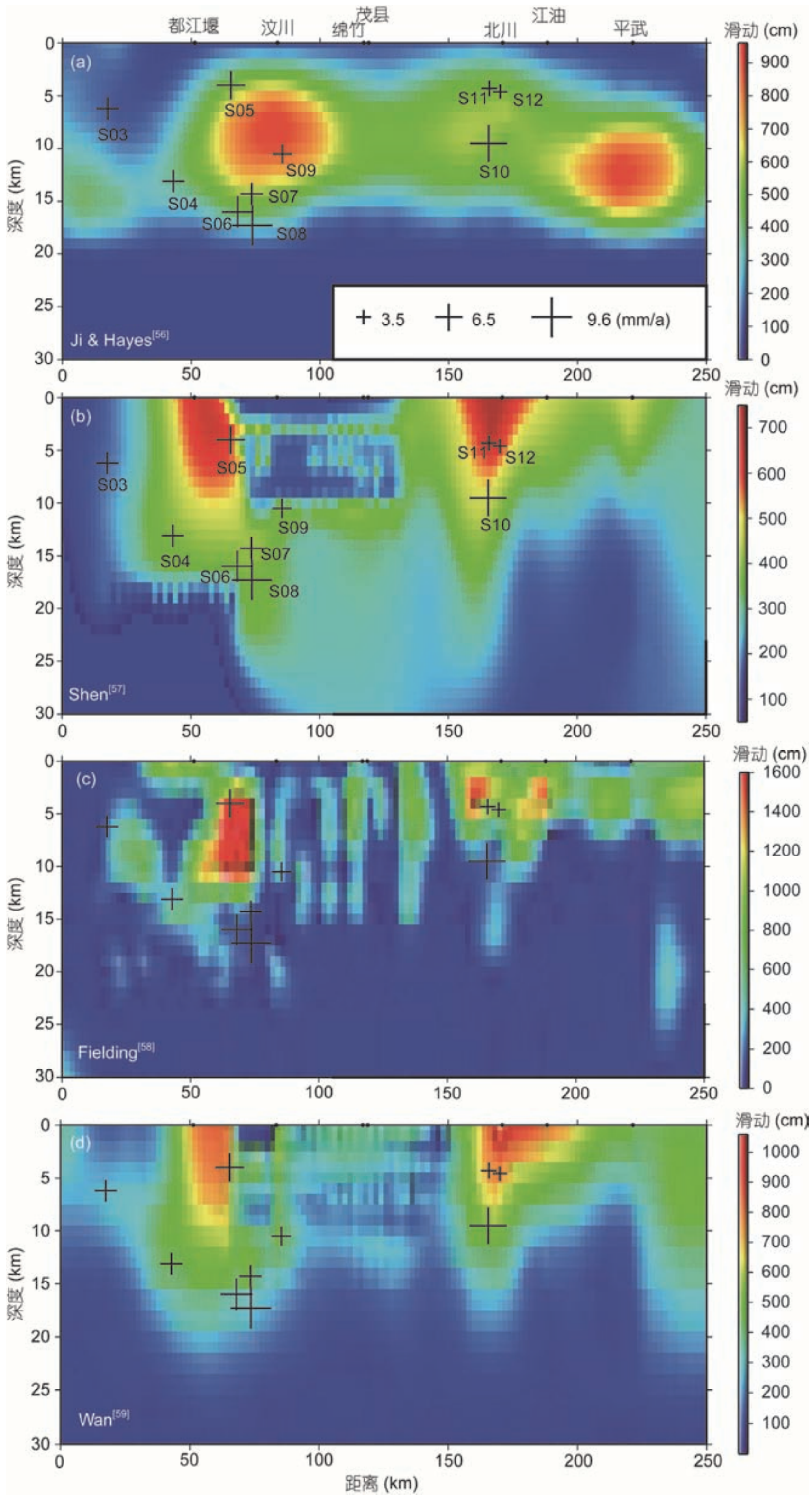

图 2 汶川同震滑动分布[56~59]与利用重复地震估算所得的滑动速率[17]的对比图. 各图右边色标表示相应滑动量的大小, 图中十字大小与重复微震估算的滑动速率大小成正比

Figure 2 The estimated slip rates from repeating microearthquakes[17] are shown together with different published distributions of coseismic slips[56–59]. The color scale of slip amplitude is given on the right side of the map. The size of crosses is proportional to the slip rates

介于5.0~11 m和4.8~12 m; 沿灌县-江油断裂的地表破裂带长度介于60~90 km之间, 最大同震垂直位移为2.5~4 m. 另有研究[72]认为龙门山推覆构造带北段青川断裂上有约50 km长的同震地表破裂存在, 最大同震垂直位移约0.3 m, 且映秀-北川地震地表破裂带南段存在着4.2 m的最大同震左旋位移, 而Feng等人[76]对InSAR资料精细处理则认为青川断裂在汶川地震时并未发生同震破裂. 此外, 对最大滑移量出露位置的认识也有所不同, 分别认为位于虹口乡深溪沟[64,66,72]、北川县擂鼓镇[70]或北川县曲山镇沙坝村[68].

汶川地震后10年来, 许多学者分别或联合利用远场的宽频带地震波形数据、近场的GPS和InSAR等大地测量数据及近场强地面运动波形等资料, 采用多种方法来约束反演汶川地震的同震滑动分布图像[56,77~95]. 这些结果展示出总体一致但具体细节有所差异的特征, 较为一致的认为: 汶川地震是由多次子事件构成的十分复杂破裂过程, 映秀-北川断裂的破裂较灌县-江油断裂剧烈, 2个主要滑动量的集中区分别位于汶川-映秀和北川一带下方; 但在主破裂的长度(260~315 km)、破裂持续时间(90~125 s)、破裂速度(初始破裂速度为1.7 km/s及后期出现超剪切破裂)、最大滑动量(5~15.5 m)和滑动深度分布等方面还存在不可忽视的差异. 基于远场宽频带地震波形记录, 反演得到的主要滑动深度分布差异显著, 如大滑动展布在震源深度上下而未到达地表[56,87,92]、震源深度以下至近地表[77,78,80]、震源深度至近地表[79,93]; 而基于大地测量数据反演得到的主要滑动分布深度相对比地震反演的结果为浅(图2和3), 主要分布在10 km深度之上至地表[57,59,84,85,89,91], 但也给出了15~22 km深处有较大滑动量的结果[90,91]; Fielding等人[58]利用远场地震数据和近场GPS与InSAR同震位移数据的联合反演表明: 远震数据有利于改善断层深部滑动的分辨精度, 显著滑动主要分布在震源深度上下而未到达地表(图2(d)). Hartzell等人[94]利用远场地震数据、近场GPS同震位移和强震记录, 开展的单独和联合反演研究则表明: 静态偏移的大地测量数据对于确定浅部的滑动分布是有价值的, 但对深部断层滑动不敏感, 且无法区分滑动时间; 30°~90°范围的远震资料可以有效辨识深部和浅部的滑动, 但涉及多个断层面时则不能区分不同的滑动情形; 而近场强震记录则易于确定破裂方向, 但易于因不准确的格林函数而误导滑动分布的反演. Hartzell等人[94]联合使用3种数据集反演的汶川地震破裂分布展示出至少在21 km深处仍存在显著的滑动(图3).

温扬茂等人[96]觉察到大多数的大地测量数据反

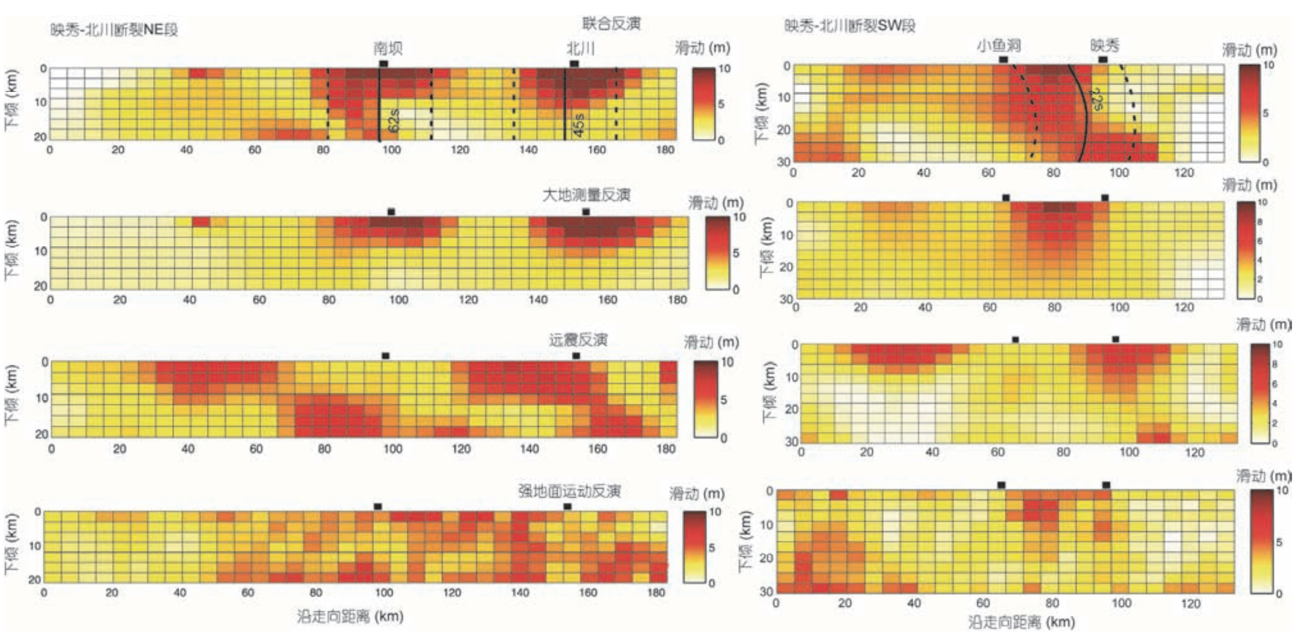

图 3 Hartzell等人[94]给出的映秀-北川断裂反演结果, 从上至下为联合反演、大地测量、远震和强地面运动结果

Figure 3 Slip distributions for two segments of the southwestern and northeastern Beichuan fault based on geodetic, teleseismic and strong-motion data, respectively and joint inversion given by Hartzell et al.[94]

演研究[57,58,84,89,91]中所采用的ALOS/PALSAR雷达数据或多或少包含了较为明显的电离层扰动影响，获取到的InSAR地表形变场中包含有同震、震后及余震等多种形变成分，且在反演同震滑动分布模型均假设只有同震形变信息存在而忽略了震后形变等的影响．故温扬茂等人[96]通过分析覆盖汶川地震震中区域的ALOS/PALSAR像对的方位向偏移量来选择无明显电离层扰动影响的像对进行干涉处理，在获取了高精度、连续的InSAR地表形变场的基础上，结合高精度GPS同震形变数据，采用同震、黏弹性松弛震后形变联合反演模型同时确定了汶川地震的同震滑动分布和龙门山地区的流变结构参数，结果表明汶川地震是一个断层破裂非常复杂的地震事件，其中北川段、岳家山段、虹口段和汉旺段的滑动以逆冲为主，而青川段以右旋走滑为主；同震滑动分布存在着4个高滑动区，滑动主要发生在10 km深度以上的区域，最大10.7 m的滑动量位于虹口段的东北端；在虹口段中部的12 km深度位置存在着一个滑动量达6 m的深部滑动区，认为这部分的滑动可能与远场(>100 km)20 cm以上的同震地表形变相关．

强震破裂尺度和断层错动方式及其造成的位移分布等强震破裂过程信息，是应急救灾决策、断层活动特征及未来强余震发展趋势判断的科学依据，是了解发震构造环境和地震机理及科学减灾的重要基础．随着大地测量技术和反演方法的发展，由于GPS、InSAR和重力及海啸等观测数据与地震体波和面波及强地面震动数据在观测频带的互补性[97]，已越来越多地用于单独或联合约束来反演强震的破裂过程．前述2008年汶川地震及2011年日本东北近海*M*w9.0地震的众多滑动分布估计，大多方法都基于格网式分布的断层几何结构模型上构建适用于特定约束数据的格林函数来反演滑动模型，这是典型的基于简化地球模型和断层几何结构、有限频带观测信号和观测几何内在局限性及对破裂过程的运动学强制约束的不适定问题[98]．使用远震和/或区域地震记录、静态变形的时变大地测量观测等各种不同的组合数据集，有助于克服单一数据反演的局限性而得到更精细的震源破裂过程认识，但必须有效分离大地测量观测数据中所包含的同震和震后变形信号及数据中可能存在的电离层扰动影响，还须考虑不同数据集分辨率的不同和相对权重设置对联合反演带来的复杂性和不确定影响．采用灵敏度互补的不同数据集进行联合反演，以及考虑三维地形和速度不均匀性与复杂起伏变形的断层几何结构模型，可以得到更为精细的汶川地震破裂滑动分布，但也使评估复杂的推断断层与复杂模型参数化间的关联性难度增大．

1.3 震后滑移(震后余滑)

为了了解汶川地震地表破裂带的震后变形特征，何宏林等人[99]对映秀-北川主破裂带上人为破坏较轻的19个断层崖或断层挠曲崖进行反复测量，结果显示5个观测点(26%)没有发生变化，位于主破裂带南西端部的1个观测点(6%)在震后继续抬升(抬升了12.8%)，13个观测点(68%)的断层崖或断层挠曲崖的高度(垂直同震位移)震后降低回落，平均降低了9.7%；尽管这种变化中存在着上冲断层盘虚假抬升后压实回落的影响，但认为主要是沿汶川地震破裂带发生的震后滑移造成的，而且这种震后滑移可能仅发生在较浅的近地表的上地壳中．Shao等人[100]利用汶川地震后14天的GPS观测数据为约束反演的震后变形图像，可见断裂带存在深浅部明显的震后滑移现象，虹口段15~25 km深处的震后滑移量最为显著，并认为震后14天的变形以近场无震滑移和远场黏弹性松弛为主导形成．Huang等人[101]利用长达2年的InSAR和GPS测量数据来调查2008年汶川地震的震后位移场变化，发现不能用简单的单一机制来解释震后位移场，认为可以用青藏高原的的黏弹性下地壳松弛来解释青藏东部的远场位移测量结果，而映秀-北川断裂南部的近场位移(20 km深度之上几个>20 cm和25~40 km深度<10 cm的位移)则可以用震后滑移来解释，浅部的震后滑移与同震滑动分布反相关且靠近Li等人[17]识别出的重复地震处．Jiang等人[102]采用震后一年的GPS观测数据，基于Wang等人[91]和Shen等人[57]的断层几何结构分别构建了相应的FM1和FM2模型来反演同震滑动和震后滑移分布，2个断层模型反演得到的同震滑动分布在高滑动区、滑动峰值和滑动方向上高度一致，同震滑动主要集中在15 km深度以上，滑动幅度超过7 m的高滑动集中区有3~4个，与前人的大地测量反演结果[57,85,90,91]相似，进而认为同震滑动对断层几何结构不敏感，但震后变形对断层几何结构甚为敏感，与Huang等人[101]一致的得到远场震后变形主要由黏弹性松弛引起的结论，认为FM1模型较FM2模型在GPS的近场、中场和远场

的观测和模型预测的一致性方面表现出色，不论是否考虑黏弹性影响；2个模型都显示出深浅部存在较明显的震后滑移，至少有一个高滑移集中区位于映秀-北川断层浅部.

1.4 断层闭锁和复发周期

断层闭锁是应变积累并发生高震级地震的必要条件，而以最近 1 次地震的离逝时间除以平均复发周期(也称复发间隔)得到的地震离逝率接近或大于 1 的活动断层段，则是识别未来可能发生地震危险区的时间紧迫性指标[1]. 汶川地震前龙门山断裂带的较低滑动速率实际反映出其断裂带中段的映秀-北川断裂和灌县-江油断裂处于闭锁状态[1,23,24,43,44,54,66,68,75]. 赵静等人[103]基于单元块体内部点的运动为块体旋转与块体边界由于断层闭锁产生的滑动亏损而引起的地表弹性变形之和的Defnode负位错反演程序，利用1999~2007年的4期GPS水平速度场数据为约束，沿龙门山断裂走向方向设定9个单元节点(节点间距为50~55 km)，深度方向构建6排节点的深度从地表起依次为0.1，6，12，16，21和24 km，每2排节点之间的断层倾角从地表至深部依次为55°，55°，20°，7°和7°进行反演，估算了龙门山断裂在汶川地震前的闭锁程度和滑动亏损分布，结果表明龙门山断裂中北段闭锁深度为21 km，闭锁程度达0.99左右，垂直断层方向的滑动亏损速率约为2.2 mm/a，平行断层走向的右旋滑动亏损速率约为4~6 mm/a. 陈长云和贺建明[104]同样利用1999~2007年GPS数据反演得到巴颜喀拉块体东部及邻区活动块体边界断裂带的长期滑动速率，基于一维弹性位错模型反演给出的龙门山断裂带闭锁深度约为13.6±3.9 km；而李煜航等人[105]使用线性球面块体模型理论，对青藏高原东缘中南部建立的三维块体几何模型，也使用1999~2007年GPS数据反演得到的龙门山断层最优闭锁深度则为10~15 km.

汶川地震前的有限研究认为：龙门山断裂带3条主干断裂的单条断裂上的强震复发间隔至少在2000~3000 a左右[106]或地震复发周期为数千年到万年尺度[39]. 汶川地震后，利用地质或GPS的滑动速率与汶川地震同震位移或滑动矩率对比，估算出在龙门山断裂带或映秀-北川断裂发生类似强震的复发周期分别为约1000 a[72,78,86]、1310~3932 a[107]、2000 a以上[67]、2000~6000 a[8]、约2500 a[44]、约3000 a[24]、3000~6000 a[68,108]、2000~10000 a[109]和4000 a[57]. 谢富仁等人[110]利用地质资料、地震学和大地测量学资料，采用3种方法分别计算综合判定的龙门山断裂带的大震复发间隔：7.0级地震的500 a左右，7.5级地震的1000 a左右，8.0级地震的3000 a左右. 较为详细的古地震研究[111,112]则表明：发生汶川地震的北川-映秀断裂和灌县-江油断裂北川以南段2008年前最近1次地表破裂型(古)地震发生在距今3300~2300 a之间，更早的1次发生在距今5920~5730 a之间，平均复发间隔约为3000 a. Ren和Zhang[113]基于GPS和InSAR数据约束的地震矩率法估算的复发间隔为3900±400 a. 祝爱玉等人[114]对川滇地区的三维黏弹性有限元模拟计算得到整个龙门山断裂带的8级地震复发间隔为2000~10000 a. Liu等人[115]通过对龙门山断裂带岩石圈的三维有限元黏弹性动力学模拟，估算的发生类似汶川地震的强震复发周期为4200~6500 a. Thompson等人[116]则基于Gan等人[47]给出的龙门山断裂带周围的GPS观测约束(不包括鲜水河断裂带和昆仑山断裂带)，通过准静态弹性边界元来统一模拟研究区域的震间大地形变变化，得出龙门山断裂带存在9 mm/a的滑动亏损率，并推断汶川地震的强震复发周期为600 a.

上述地震复发周期的变动范围很大，其主要原因在于断层的长期滑动习性定量参数(滑动速率、单次同震位移量、古地震发生时代、地震复发模型、区域应变加载速率)测定存在着较大的不确定性[1,6,112,117]，以及深部断层面的几何结构特征(凹凸体或障碍体位置和大小)及构建的模型参数差异致使应力-应变强度的不确定性等因素(如[115,116]). 依据不确定性较大的滑动速率和同震位移量，基于刚体均匀变形假设来估算的平均地震复发周期不可避免地具有较大的误差.

反演得到的同震破裂滑动量集中区常被解释为断层的凹凸体(asperities)[25,86,89~92,118]或障碍体(barriers)[57,59,94,95]，就凹凸体的结果来说就明显有2个、3个[90]、4个[89,118]或13个[91]的不同认识.

2 断裂深浅部变形的探测途径及有效性

活动断裂是地震的发震构造，对活动断裂变形特征的研究，是认识和理解地震过程与有效进行地震灾害防御的重要基础. 活动断裂研究涉及构造地质学、地貌与第四纪地质学、地震学和大地测量学等

多个学科，其主要研究方法可以归纳为地质学方法、地貌学方法、大地测量学方法和地震学方法[119].

活动断裂往往保留有较好的地质地貌证据，因此可以从构造地貌、现代沉积和年代学方面来认识其不同的变形特征[120]. 由于断裂活动的直接结果是断错地质体，而地质体的断错也是比较容易获得的参数，所以用地质学方法研究断裂活动的最大优势是可以观测到几百年~万年尺度甚至前新生代的断错现象，可以为研究不同时间尺度的断裂活动历史提供可靠的基础资料，但其困难在于断错地质体年代的准确测定和逼近断裂发生断错的真实年代[119]. 地貌是地球表层的剥蚀过程与地球内部动力过程相互作用的结果，可以作为标准层去研究断裂的活动性，其优势在于断裂断错地貌面的现象往往比较清楚且容易测定其年代，但地貌面的形成年代、废弃年代和剥蚀年代及断裂断错年代非常复杂，其后期存在的剥蚀、沉积、变形作用等改造致使恢复地貌面变形前的原始形态具有各种不确定性[119]. 地质地貌考察和古地震研究因仅在有限的探槽或考察点进行，对显著的地震(如2013年芦山7.0级地震[121]和2010年海地7.0级地震[122])等没有地表破裂出现的现象必然难以识别而遗漏，何况对2008年汶川地震发生的新鲜地表破裂特征及滑移量，都出现前述明显不同的现场考察结果与认识情况. 故地质地貌研究给出的活动断裂构造浅部变形的定量描述结果(如滑动速率)，不可避免地存在着一定的不确定性. Dolan和Haravitch[123]通过包括中国2001年昆仑山口西*M*w7.9地震在内的6个*M*w≥7.1走滑地震的地表位移与大地测量反演得到的深部滑动量对比，分析表明基于地表破裂估算的地质滑动速率会低估发震深度处的断层实际滑动速率.

现代空间大地测量技术(特别是GPS和InSAR)的对地观测数据的高时空分辨率，对监测研究断裂位错滑动引起的断裂周围形变变化具有独特的优势[124]. 以GPS等大地测量数据为约束，主要基于刚性块体运动模型和弹性介质空间断裂位错模型[48]，对地表变形进行模拟分析计算的主要断裂滑动速率，给出结果不可避免地受到断层模型的不确定性和断层闭锁深度及GPS观测点位分布有限的影响[48,125]. Evans[125]新近对美国加州已发表的33个大地测量结果给出的滑动速率，分析发现对复杂断裂的结果偏差可以达到5~10 mm/a. 当然我们必须认识到，因GPS观测到的滑动速率只是断裂的现今速率，故只有断裂的滑动速率在相当长的时间内保持不变时，GPS观测到的现今滑动速率才会与活动断裂得到的长期平均滑动速率一致.

中国大陆的现今构造变形既有刚性地块的运动又有非刚性的连续变形[126]，主要依据刚性块体运动和弹性位错的连续变形理论，模拟反演限制了大地测量推断断裂深部变形信息的精度，如前述利用大地测量资料反演给出的2008年汶川地震同震滑移的10 km以下深度结果及断层闭锁深度就存在明显差异. Barbot等人[127]对非均匀和各向异性的弹性半空间旋转位错引起的变形，分析展示出假定横向均匀模型的同震变形反演可能低估孕震深处的滑动量达20%. 即使对研究程度较高的板缘大地震，Lay[128]揭示出2010年智利*M*w8.8级地震的15 m以上破裂区与GPS资料震前估计的闭锁区存在相当程度的差异. Smith-Konter等人[129]对比分析美国San Andreas断裂带的GPS反演和地震精定位的结果，发现多数断层段给出的GPS闭锁深度与地震活动性展示的孕震深度相差不大(在2 km之内)，但在Imperial，Coyote Creek和Borrego断层段则差异明显，GPS的结果偏浅了7~10 km.

地震活动是断裂活动的最直接体现，精定位的震源深度客观反映了断裂深部发生地震滑动变形的起始位置，断裂深部发生的慢滑动和重复地震等对揭示断裂深部行为具有重要的指示意义[2]. 在同一构造部位重复发生并具有高度相似波形的重复地震可作为天然的“地下蠕变计(subsurface creepmeter)”[130]，慢地震(慢滑动)因其对应力扰动的敏感性可被视作为“应力计(stress meter)”来反映慢地震发生区附近强闭锁区的应力累积状态[131]，具有地震地质和大地测量等浅表观测难得的“原位(*in situ*)观测”优势[60]，为探测断裂深部变形信息提供了有效的途径. Thomas等人[132]新近发展了利用持续重复发生的慢滑动事件(低频地震)作为“深部蠕变计(deep creepmeter)”，来估算美国加州San Andreas断裂的平均滑动速率. Nadeau和McEvilly[11]利用San Andreas断裂带Parkfield地区的重复地震，获取的断层滑动速率展示了浅部与大地测量和蠕变仪观测的结果相当，而深部滑动速率增大的深浅滑动差异分布图像，而重复微震不发育的区域(即断层闭锁区)在2004年发生了6.0级地震. Igarashi等人[19]和Li等人[17]通过重复地震分析，

分别得到日本俯冲带和龙门山断裂带深浅部(图2)滑动速率差异明显的图像，而在显著滑动亏损区分别发生了超出预估强度的2011年日本东北近海*M*w9.0地震和2008年汶川8.0级地震．2011年日本东北近海*M*w9.0地震的发生[19]以及2008年汶川8.0级地震[17]和1984年Morgan Hill 6.2级地震[133]等同震破裂区周缘发育的重复地震等事例，还展示了利用重复地震空间分布勾画强震潜在闭锁区的可能性．美国加州1989年*M*w6.9 Loma Prieta地震[130]、日本东北近海2011年*M*w9.0 Tohoku-oki地震[134]、智利西北部海域2014年*M*w8.2 Iquique地震[135]等事例，重复地震序列记录都展示出震前在不同时间尺度(长期、短期)出现了深部滑动速率的加速变化．我们仔细分析龙门山断裂带中北段检测到的10组重复地震序列，可见虹口-汶川附近14~16 km深部的S06和S07二组重复地震序列与北川附近4.3~9.5 km处的3组重复地震序列，在2006年前后开始出现不同程度的滑动短期加速变化迹象(图4)，与赵祎喆等人[55]观察到2006/01/01至汶川地震发震时刻前微震活动的类似于指数上升的明显变化趋势较为相符．

利用微小的重复地震和慢滑动事件作为深部蠕变计，探测断裂深部变形虽有着原位观测的优势，但不可避免地受限于地震台网分布和台间距及其可检测到重复地震或慢滑动事件的能力局限，尤其是中国大陆至今仍未有确切观测到慢滑动事件的证据．而所检测到的重复地震序列是否在观测时段内完整且无遗漏，对于客观估算断裂深部的滑动速率是十分重要的．此外，为能够更好地与地质和大地测量的结果进行对比分析，尝试获取微小的重复地震震源机制解，结合重复地震的破裂节面解或可能确定的破裂方向，来约束所估算滑动速率的滑动方向是十分必要的．

尽管过去20多年识别活断层的能力取得了显著进展，但大陆内部包括2008汶川地震的出乎意料的发生等事例说明我们对陆内断层的认知还很有限[136]．强震的复发间隔远超出几十年来现代观测仪器记录的地震时长，且我国华北的古地震活动展现的非线性活动特征[137]，可能存在与澳大利亚和美国中东部的断裂带类似魔鬼阶梯函数(Devil’s staircase functions)的活动间隔[3]，故我们必须充分发挥地质地貌、大地测量学和地震学等多学科的综合优势，就强震相关的断裂深浅部变形信息进行有效探测分析，

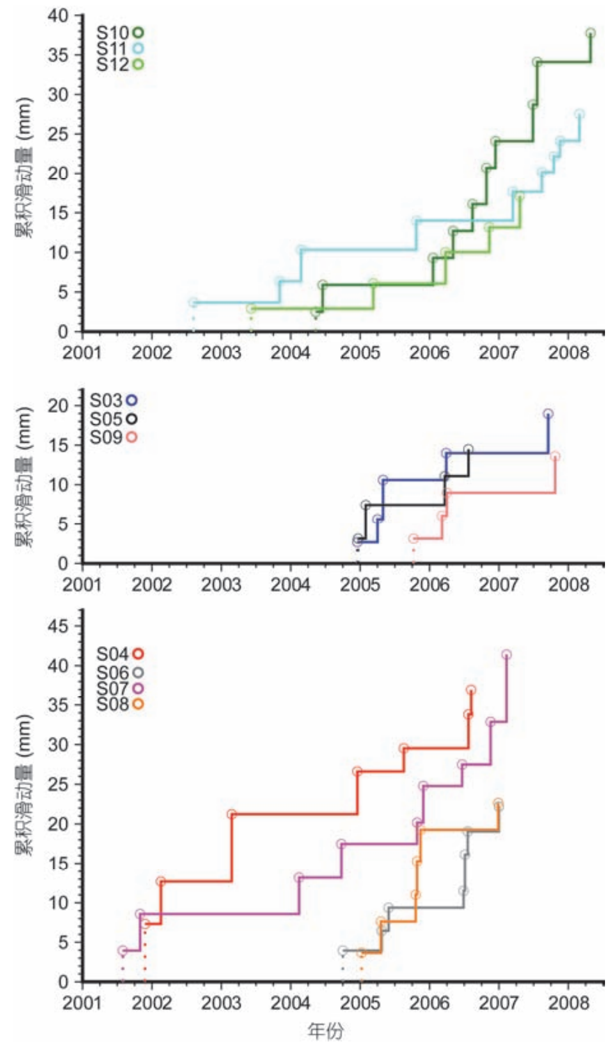

图 4　龙门山断裂带中北段检测到 10 组重复地震序列的时间-滑动量累积图

Figure 4　Cumulative slip calculated from the 10 repeating earthquake sequences in LMSFZ

对断裂闭锁段和深浅构造变形差异显著地区的强震危险性尤应加以重视．

3　结论

对发生2008年汶川8.0级地震的龙门山断裂带多学科的研究结果，通过较为系统的对比分析，可以归纳出以下几点基本认识：

(1) 龙门山断裂带的深部几何形态十分复杂，深部速度结构极不均匀；

(2) 2008年汶川8.0级地震是由多次子事件构成的十分复杂破裂过程，其破裂长度为300 km左右，在深浅部都有大滑动量展布，并主要聚集在汶川-映秀

和北川一带下方;

(3) 地质地貌、大地测量和地震学研究给出的龙门山断裂带中北段的深浅滑动速率存在明显差异, 浅部的滑动速率较为一致, 由重复地震获取的10~17 km孕震深处的滑动速率约为浅部的2~3倍;

(4) 不同研究结果给出的龙门山断裂带发生类似汶川强震的复发周期变化甚大(600~10000 a). 若以重复地震分析给出的滑动速率(3.5~9.6 mm/a)和汶川地震最大同震位移(5.0~15.5 m)为约束, 则发生类似汶川地震的复发间隔约为500~4500 a, 较地质学或大地测量学单独或综合估算的约1000~10000 a为短, 主要原因在于重复地震分析估算的深部滑动速率较地质学和大地测量学估算的大.

2008年汶川8.0级地震后近十年来, 关于龙门山断裂带深浅构造变形研究取得了丰富的成果, 加深了我们对汶川地震发震构造环境及发震机理探索与认识. 对比俯冲带发生的2011年日本东北近海Mw9.0 Tohoku-oki地震的研究(参见Lay[98]的最新综述及所引文献), 有关2008汶川地震及龙门山断裂深浅构造变形研究还存在不少值得深入研究的问题, 至少在资料开放程度和多学科综合研究, 尤其是震后滑移的动力学研究、震前闭锁和震间蠕滑与强震滑动分布间的关联性等方面还有待加强. 人们对大陆内部深部构造变形探测的程度还十分有限, 未来应充分发挥重复地震和慢滑动事件探测断裂深部变形的原位观测优势, 集成地震学、大地测量学和地质地貌学等多学科的综合优势进行有效探测分析, 对断裂闭锁段和深浅构造变形差异显著地区的强震危险性尤应加以重视.

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Summary for “2008 年汶川地震与龙门山断裂带的深浅部变形及启示”

Deep deformation of the Longmenshan fault zone related to the 2008 Wenchuan earthquake

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This paper reviews studies of the past ten year related to the crustal deformation of the Longmenshan fault zone (LMSFZ) which was struck by the *M*8.0 Wenchuan earthquake on May 12, 2008. The tectonics of the LMSFZ located at the eastern margin of the Tibetan Plateau is complex, with complicated fault geometry and a heterogeneous velocity structure. The Wenchuan earthquake rupture extended for about 300 km along the middle and northern segments of the LMSFZ, with a very complicated rupture process involving multiple sub-events. The Wenchuan slip distribution is characterized by two major slip patches near Hongkou/Yingxiu and Beichuan with peak slip of 5.0–15.5 m and extended from near the surface to below 20 km depth.

Prior to the Wenchuan earthquake, the LMSFZ had been seismically quiet for several centuries and there were no hints that suggested that such an *M*8.0 earthquake might strike the area. The long-term geological investigations and short-term geodetic measurements before the Wenchuan earthquake generally agree that the horizontal slip rate along the LMSFZ is no more than 3 mm per year. The low slip rate observed at the surface around the LMSFZ may not reveal the real state of accumulated strain at depth where the devastating Wenchuan earthquake nucleated. Rates of aseismic slip at depth derived from seismological investigation of repeating microearthquakes were found to be approximately twice as large as the interseismic rates inferred from surface GPS and geological data. Most of the clusters of repeating microearthquakes are located at the edge of locked areas where large coseismic slips were observed during the Wenchuan earthquake, suggesting a close relationship between microearthquakes and impending large earthquakes. A two-dimensional viscoelastic finite-element model produces a depth-related slip rate pattern around the LMSFZ that is consistent with that revealed by the seismological observation of repeating earthquakes. The measured *in situ* deep slip rates increase with depth and vary from 3.5 to 9.6 mm/a over a depth range of 4–18 km. The seismological observations of deep slip rates and microseismicity in the three decades before the Wenchuan earthquake reveal that the LMSFZ is indeed not as “quiet” as traditionally assumed in comparison with its neighboring fault systems. Considering the deep slip rates (3.5−9.6 mm/a) from the repeating microearthquakes and coseismic peak offsets of 5.0–15.5 m, the recurrence interval of Wenchuan-like events is estimated to be about 500−4500 years. The estimated recurrence interval based on the deep slip rates is much smaller than those estimates using the same coseismic displacements divided by GPS-derived or geological slip rates.

Slip rate increases with depth were also recognized in the Parkfield section of the San Andreas fault zone and in the northeastern Japan subduction zone before the ruptures of the 2004 *M*w6.0 Parkfield earthquake and the 2011 *M*w9.0 Tohoku-oki earthquake, respectively. Accelerated slip is thought to have preceded a number of recent large subduction zone earthquakes and the 2008 Wenchuan earthquake, and repeating earthquakes may document short-term precursory slip at depth. Alternatively, the rapid slip rates indicated by the repeating microearthquakes may represent transiently accelerated slip preceding the Wenchuan mainshock. We suggest that slip rates at seismogenic depths are of critical importance in seismic hazard analysis. Repeating earthquakes can be regarded as “deep creepmeters” that measure the *in-situ* deep slip rate on otherwise aseismically slipping faults. For less well defined and widespread faults within the continents, it is essential to reveal a fault’s or region’s seismic history over different time scale. Combining a better understanding of earthquake diversity with modern technology is the key to effective and comprehensive hazard mitigation practices. The potential earthquake hazard of locked faults with unusually high inferred deep slow slip rates should be paid more attention.

The 2008 Wenchuan earthquake is the best-studied continental earthquake to date with a large number of scientific publications enabled by the vast collected data sets. The research community efforts have provided first-order information about this unexpected event regarding its coseismic slip distribution and fault geometry. However, there are many remaining questions about the basic nature of this earthquake to be further constrained with multiple data sets, including the relationship of its rupture with prior coupling and interseismic creep, the varying dynamical rupture processes with depth, the frequency dependence of seismic radiation across the fault zone, and the role of multiple postseismic deformation processes.

Wenchuan earthquake, Longmenshan fault zone, deep deformation, repeating earthquakes, seismic hazard, recurrence interval

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