

甘肃岷县漳县 6.6 级地震前后区域地壳形变分析^①

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摘要:利用陆态网 GNSS 连续站及流动站观测数据处理结果, 从坐标时间序列、基线时间序列、速度场、形变场等方面分析岷县漳县地震前后青藏高原东北缘地区 GPS 形变场变化, 得出以下结论: 岷县漳县地震前 GNSS 测站时间序列没有明显变化, 震前异常不突出; 地震引起不同测点不同程度的永久性同震位移, 最大值达到 16 mm; 地震前后基线变化不明显, 未发现明显的前兆异常; 阿拉善及附近的祁连构造带存在顺时针运动的迹象, 即运动方向由东侧的南西向逐渐变到西部的北西向, 运动大小的范围基本保持在 7 mm/a 之内; 区域主压应变优势方向为东北-西南向, 最大主压应变区呈带状分布于研究区域南部。

关键词: 岷县漳县地震; GNSS; 时间序列; 速度场; 应变场

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Regional Crustal Deformation Analysis before and after the Minxian—Zhangxian Earthquake

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Abstract: With the establishment of the Crustal Movement Observation Network of China (CMONOC) and the China Tectonic Environment Monitoring Network (CMTEMN), earthquake coseismic displacement can be obtained through global navigation satellite system (GNSS) data processing and analysis. The calculated results can provide basic research data for further study on seismic dynamics characteristics and determination of future earthquake trends. Using the GNSS data processing results from CMTEMN and CMONOC, together with the coordinate time series from the continuous observation stations, the baseline time series between two stations and the velocity and deformation fields were investigated in this study. In addition, the global positioning system deformation field of the northeastern margin of the Qinghai—Tibet plateau before and after the Minxian—Zhangxian Earthquake was analyzed. The results showed that the coordinate time series of the GNSS stations showed no noticeable change before the Minxian—Zhangxian Earthquake, and there were no prominent anomalies before the earthquake. The earthquake caused different levels of permanent co-seismic displacement of various stations, the maximum of which was as much as 16 mm This GSMX station, which is near the epicenter in the Lintan-Dangchang fault, exhibited a noticeable coseismic displacement. The GSWD station had no coseismic displacement. Similarly, the GSLX station, which was far from the epicenter, also experienced no displacement. The strain change of the three stations proved that the east-west strain was primarily line-

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ar, and there was no noticeable imminent anomaly before the earthquake removal of the coseismic step. The north-south strain exhibited a cycle and a half phenomenon, which was related to a corresponding year cycle in a single point, so this was not an obvious imminent anomaly prior to the earthquake. In addition to the obvious linear change, the north-east shear strain showed specific cycles, but no obvious anomalies before the quake, and these were restored to their original displacement after the quake. The GNSS baseline length change was based on the unity of the reference frame, so it was unaffected by the reference benchmark, therefore, it would objectively reflect the dynamic changes of the relative motion between two stations. Therefore, the GNSS baseline time series analysis was used to extract the crust movement microdynamic information as one of the direct routes. In this study, three stations close to the epicenter formed a triangular mesh, crossing the epicenter and the Lintan—Dangchang fault zone. Using the GSWD station as a reference, the statistical baseline series of the GSMX and GSLX stations were analyzed, and the results showed that there was no significant change of the baseline before and after the earthquake and no obvious anomalies; In addition, the long baseline time series across the Lintan—Dangchang fault was calculated employing six stations on either side of the seismogenic tectonic, forming five baselines. The results were same with the short baseline, before the earthquake, the baseline did not exhibit an obvious precursory change phenomenon, and the baseline change caused by the earthquake was not obvious in totality. There were signs of a clockwise motion near the Alashan and Qilian structural belt, where the direction of movement was south west on the east side and north west on the west side. The magnitude of the movement was within 7, which may explain why the push movement to the north in the western region was greater in the eastern area. In addition, due to the extrusion of the Ordos block in the east of the research area, the direction of movement of the edge of the block at the southeastern end in this region was to the southwest and its velocity was approximately 5 mm/a, The movement of the block was diminished in the western portion. The primary direction of the principal compressive strain from 2011 to 2013 was from the SE to NW, the region of maximum strain exhibited zonal distribution and was located in the southern part of the research area.

Key words: the Minxian—Zhangxian Earthquake; GNSS(global navigation satellite system); time series analysis; velocity field; strain field

0 引言

2013年7月22日甘肃岷县漳县交界(E 104.2°, N 34.5°)发生了 M_s 6.6地震。地震所处的青藏高原东北缘是印度与欧亚两大板块碰撞作用由近南北方向向北东、东方向转换的重要场所,是物质东流的汇聚之处^[1-2]。青藏高原东北缘大型构造边界地带以地震活动和构造运动之强烈和减灾意义之重要而倍受关注^[3]。很多学者利用GNSS资料分析了青藏高原东北缘的构造变化^[4-9]。岷县漳县地震后,王双绪等^[10]利用震区所在的青藏块体东北缘地区的区域水准、GPS、流动重力和跨断层短测线等地形变监测资料,结合地质构造、动力环境和已往的研究成果,分析了不同类型资料反映的震前区域性地壳变形背景、断层形变异常特征和可能的机理。李

桂荣等^[11]分析了震中附近“陆态网络”基准站GPS数据,发现大多数基准站位移三分量时间序列曲线出现突变性异常。

本文利用陆态网GNSS连续站和流动站观测资料,利用GAMIT及QOCA软件计算时间序列、速度场,并依据多核函数等新方法^[12-16]提取其应变场信息,进而分析岷县漳县地震前后青藏高原东北缘地区地壳形变。

1 GNSS数据处理

首先,收集陆态网2010年至2014年年积日346日连续站观测数据,2011、2013年陆态网流动观测数据,结合中国周边77个IGS站的相应数据,统一利用GAMIT/GLOBK软件进行GNSS解算,得

到测站坐标及卫星轨道的周日松弛解。解算策略如下:截止卫星高度角为 15° ;基线处理模式为 RELAX(松弛解);卫星钟差模型为精密星历误差的钟差参数;接收机钟差改正模型为伪距计算出的钟差;电离层延迟模型为 LC-HELP;对流层模型为 Saastamoinen 模型;光压模型为 BERNE;固体潮改正为 IERS03;测站坐标约束为 $0.010\text{ m}, 0.010\text{ m}, 0.010\text{ m}$;对流层参数设置为 13。然后利用 QOCA 软件对上述多个周日松弛解结果进行融合,选取分布于全球的 47 个 GPS 测站作为框架点,经过平差计算得到 ITRF2005 框架下的速度场。最后通过基准变换将观测结果转换为区域无旋转下的速度场。在解算过程中为减小 2011 年 3 月 11 日日本 9.0 级地震影响,首先利用 GPS 连续观测数据计算得到该地震引起的远场同震位移,然后利用该结果对速度求解过程中的同震影响进行扣除。在此基础之上,利用多核函数法得到该区域的应变场信息。

2 坐标时间序列分析

在震中附近有三个 GNSS 连续观测站,其中一个位于震中西南约 18 km 处的 GSMX(甘肃岷县)站,另一个是位于震中东北约 68 km 处的 GSLX(甘肃陇西)站,此外还有一个位于震中东南约 132 km 处的 GSWD(甘肃武都)站,见图 1。

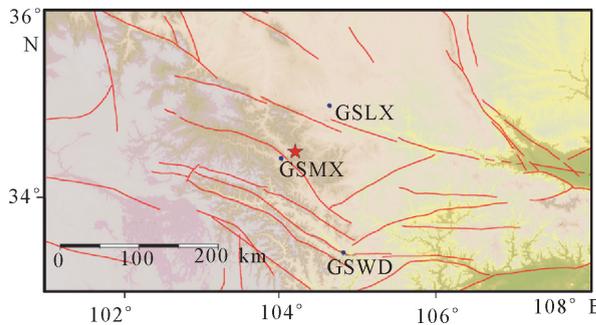


图 1 点位分布图(圆点表示连续站,五角表示地震震中)

Fig.1 Distribution of the stations (dot indicates continuous station, pentagon indicates earthquake's epicentre)

本文分析这三个测站在 N、E、U 三个方向上的坐标时间序列(图 2)。可以看出,从长趋势来看,三个测站在 E 方向上的线性较好,变化稳定,在 N 方向上的变化具有一定的周期性,而在 U 方向上则有明显的年周期特征;从短趋势来看,只有距震中最近 GSMX 站出现了 16 mm 左右的永久同震位移,而且仅在水平方向上;其余两个测站不仅在震前没有出现明显的异常变化,在震时也没有出现同震位

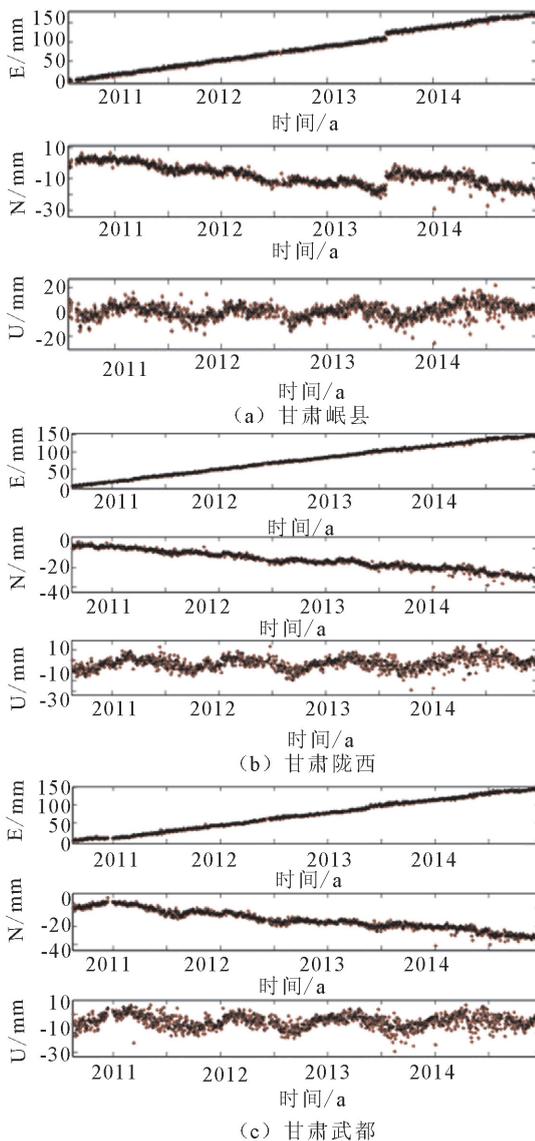


图 2 三个测站时间序列变化

Fig.2 Time series variation of three stations

移。说明该次地震的同震位移不仅量级较小,而且集中在较小的空间范围之内。因此从单个测站的坐标时间序列中很难发现震前的异常情况。

岷县漳县地震后,国内外多家机构给出了地震的震源机制解结果(表 1),显示地震主要以逆冲为主,兼具左旋走滑性质。郑文俊^[17-18],许冲^[19]等的文章也证实了该结论与调查结果基本一致,同时证实地震破裂的走向与临潭—宕昌断裂的走向一致。结合震中周边连续站的同震位移可以看出,离震中较近,在临潭—宕昌断裂上的 GSMX 站有较明显的同震位移,与地震破裂方面相反的 GSWD 没有同震位移,同样,距离较远的 GSLX 站也没有明显的同震位移,这与地震沿临潭—宕昌断裂走向破裂的结论相一致。

表 1 地震震源机制解结果

Table 1 Focal mechanism solutions of the earthquake

机构	节理面 1			节理面 2			震源深度/km	矩震级 M_w
	走向/(°)	倾角/(°)	滑动角/(°)	走向/(°)	倾角/(°)	滑动角/(°)		
USGS ⁽¹⁾	177	60	108	324	34	62	15	5.9
IGPCEA ⁽²⁾	180	47	120	320	51	62	20	6.1
IGCEA ⁽³⁾	188.4	58.8	142	301.3	57.3	38.0	6	6.47

注:(1)USGS NEIC(<http://www.isc.ac.uk/iscbulletin/search/catalogue>)

(2) 中国地震局地球物理研究所(IGPCEA, http://www.cea_igp.ac.cn/tpwx/267408.sthtml)

(3) 中国地震局地质研究所(IGCEA, http://www.eq_igl.ac.cn/admin/upload/files/20130722Dingxi.Pdf)

利用 GSMX、GSLX、GSWD 这三个站的时间序列,计算由这三个测站围成的区域应变变化(图 3)。可以看出,东西向应变主要表现出明显的线性,除去同震引起的阶跃,在震前未发现明显的临震异常;南北向应变具有明显的年周期与半年周期现象,这与单点时间序列在北方向上存在年周期相对应,在震前也几乎看不到临震异常;从北东向剪切来看,除了存在明显的线性变化外,还存在着一定的周期变化,在震前没有出现明显异常,震后也恢复了原来的变化。

3 基线时间序列分析

由于基于统一参考框架的 GNSS 基线长度变化基本不受参考基准的影响,能够较客观地直接反映两

站之间的相对运动的动态变化,所以 GNSS 基线时间序列分析是提取地壳运动微动态信息较直接的途径之一^[20]。本文中距离震中较近的三个测站组成了一个包含震中在内的三角网,并且该网跨越了临潭—宕昌断裂带。以 GSWD 站为参考,统计了 GSMX、GSLX 两个测站与其分别形成的基线,试图从基线长度的变化来分析震前是否有明显的异常(图 4)。

从图 4 可以看出,两条基线长度的变化具有明显的周期性,呈现出夏天变长,冬天变短的季节更替;但在地震前没有出现明显的异常,即从基线长度的变化看不出明显的前兆信息;地震后也没有出现明显的异常变化,可见岷县漳县地震并没有引起断层的明显活动。

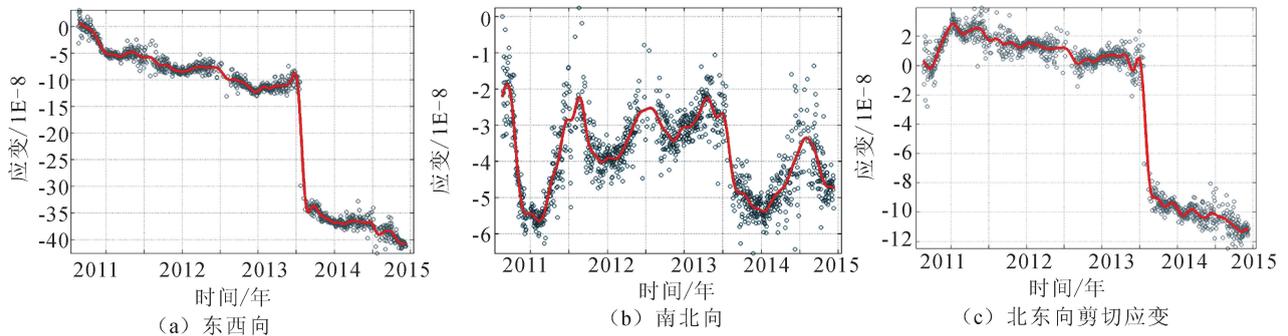


图 3 应变时间序列

Fig.3 Strain time series

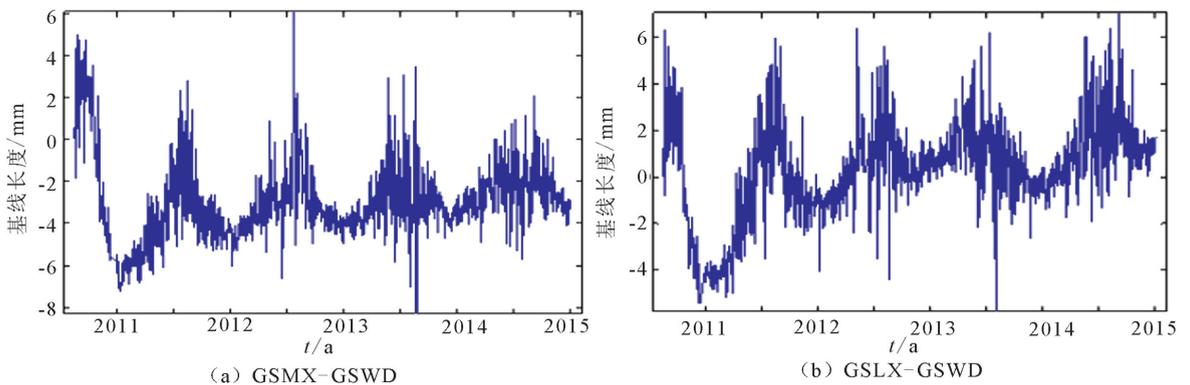
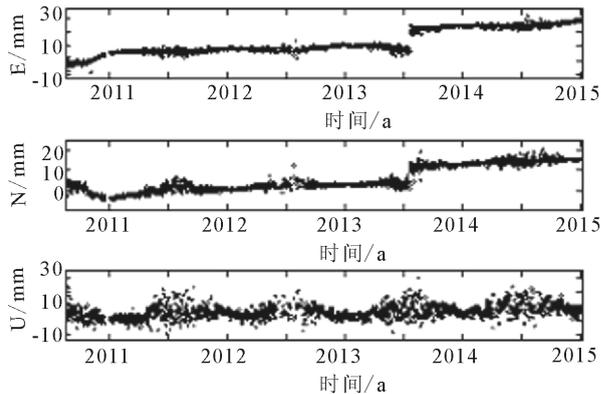


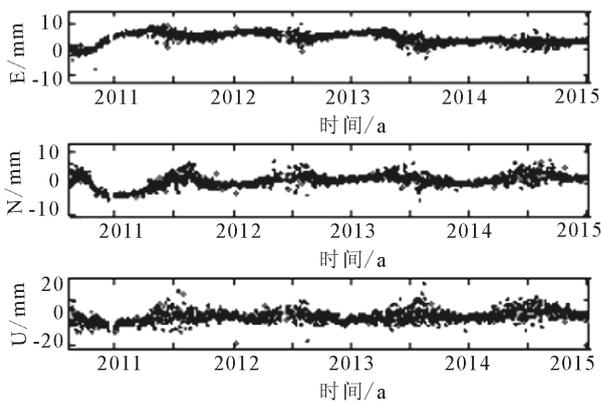
图 4 基线时间序列变化

Fig.4 Time series variation of baseline

另外,本文以 GSWD 站为参考,统计 GSMX、GSLX 两个测站相对于 GSWD 站的两条基线在 N、E、U 三个方向上的变化,从测站相对位置变化的角度分析震前震后的变化(图 5)。



(a) GSMX—GSWD



(b) GSLX—GSWD

图 5 GSMX、GSLX 相对于 GSWD 坐标在 N、E、U 方向上的变化

Fig. 5 Coordinate change of GSMX、GSLX relative to GSWD in N、E、U directions

由图 5 可以看出,GSMX 站相对于 GSWD 站这条基线在三方向上的变化不突出,比较明显的是地震引起的同震导致 E、N 方向上的抬升,在震前及震后没有明显的异常;而 GSLX—GSWD 站则没有明显的变化,符合变化周期运动。这个结果也验证了上面基线长度没有发生明显变化这一结果,说明地震前后该地区断层没有出现明显的异常活动。

此外,本文计算了跨越临潭—宕昌断裂带的长基线时间序列,选择发震构造两侧的若干台站进行分析,一共计算了 5 条基线(图 6)。

其中,GSLX(甘肃陇西)—GSMA(甘肃玛曲),GSLX(甘肃陇西)—GSMX(甘肃岷县),GSDX(甘肃定西)—GSMA(甘肃玛曲)三条基线是成稳定的挤压状态,GSLX(甘肃陇西)—SCSP(四川松潘),

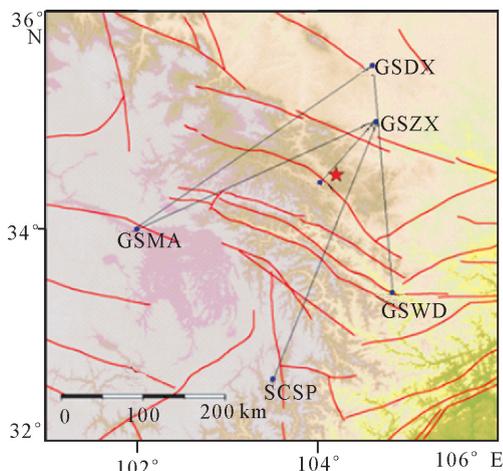


图 6 长基线分布图

Fig. 6 Distribution of long baseline

GSDX(甘肃定西)—GSWD(甘肃武都)成稳定的拉张状态,具体如图 7 所示。GSLX—GSMX 由于 GSMX 站的同震位移引起了阶跃;GSLX—SCSP 基线在震后的变化是由于 SCSP 测站时间序列的变化;结合其它基线变化情况可以看出在震前基线没有明显的前兆变化,地震引起的基线变化整体来看并不明显。

4 速度场及应变场分析

本文收集了 2011、2013 年两期陆态网流动观测数据,结合两年的连续站观测数据进行解算。在 GAMIT 得到单日松弛解的基础之上,利用 QOCA 软件计算去除了 3 月 11 日本大震影响的 2011—2013 年速度场,并利用多核函数法计算应变场信息(图 8)。

图 8(a)为青藏高原东北缘相对于区域整体无旋转基准的区域水平运动结果。从图中可以看出,该区北部(阿拉善及附近的祁连构造带)存在顺时针运动的迹象,即运动方向由东侧的 SW 向逐渐变到 S 部的北西向,运动大小的范围基本保持在 7 mm/a 之内,这可能说明了研究区西部向北的推挤较东部更大。另外,该区东部由于受到鄂尔多斯块体的挤压,东南部西端由北北东向运动随着向东南地域的纵深其方向也有序的变化,到该区的东南端其优势运动方向已指向西南;运动大小也发生了变化,东端约 5 mm/a,向西逐渐变小。这与 2009—2011 年的水平运动场相比^[20],东北方向出现了一些明显的变化,但距离地震较远的地方发生只在量值上发生了较小变化,这可能与岷县漳县地震的发生背景有关。研究区西南地域的运动形态呈扇形展布,这种展布

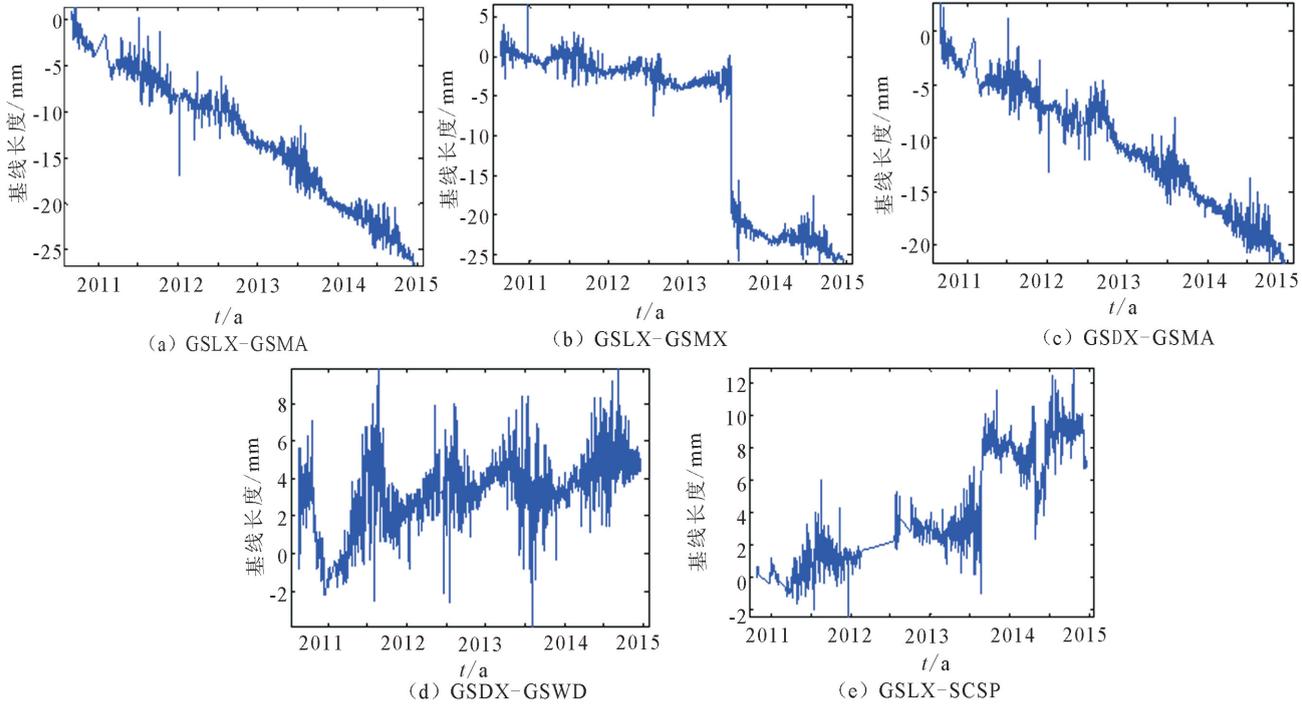


图7 长基线时间序列图

Fig.7 Time series of long baseline

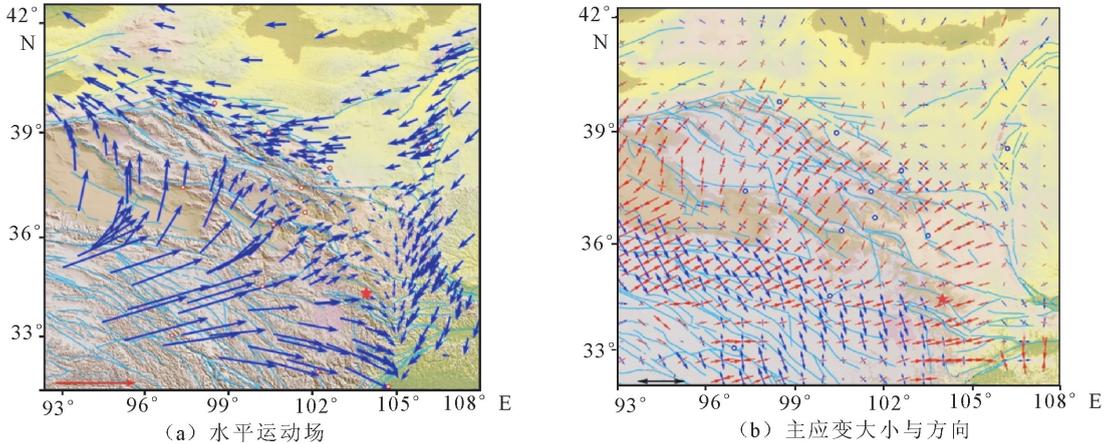


图8 青藏高原东北缘地区2011—2013年水平运动场及主应变大小与方向

Fig.8 Horizontal movement field, principal strain and its orientation in northeastern margin of the Qinghai-Tibetan plateau from 2011 to 2013

与物质逐渐向西北和东南两方向的运移是相辅相成的,而且西南端运动较大,可能与玉树地震的震后调整有关。

图8(b)为以应变张量形式展现主应变方向和大小空间分布状态。该图表明区域主压应变优势方向为东北—西南向,在空间上虽有变化,但有序性较好。从宏观上看,自西向东主压应变的方向为西部的东北—西南向变到东部的近东西向,与早期的结果发生了一些变化^[21-22]。虽然主应变方向上有一定的继承性,但大小发生了一些明显的变化,这与玉

树地震的发生有一定的关系。就整体数值大小而言,南部的巴彦喀拉块体形变最大,随着向北的延伸而逐渐减弱,跨过祁连构造带则接近于零,说明研究区的形变具有明显的分区特征。

5 结论

岷县漳县地震前 GNSS 单站时间序列没有明显变化,震前异常不突出;地震引起不同测点不同程度的永久性同震位移,最大值达到 16 mm;地震前后基线变化不明显,未发现明显的前兆异常;青藏高

原东北缘地区 2011—2013 年水平运动清晰有序,相对于 2009—2011 年的变化较小,地震并未引起运动场的明显变化,区域主压应变优势方向为东北—西南向,最大主压应变区呈带状分布于研究区域南部。GNSS 测站的坐标变化情况还不能为地震提供明显的前兆信息,但从运动场的信息可以看出地震还是引起了运动场的一些变化,有待进一步研究。

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