Remote sensing analysis of northewest-striking fault in Wenchuan earthquake zone

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Abstract: By interpreting remote sensing image of Wenchuan earthquake region from Beijing-1 Microsatellite Sensors data, there are a series of NW trending faults which ruptured the belt of Longmen shan faults at a length of 90—110 km, and this phenomenon has been confirmed partly in field. We suggest that Longmen shan faults may show a NS trending faults, the same as Anninghe-Xiaojiang faults before Himalayan orogeny. India began colliding with Eurasia over 50 million years ago, this plate collision makes Tibetan plateau uplift rapidly and elevate the highest mountains in the world and thus attributed the area of the high plateau to eastward-moving along large-scale slip-striking faults, and the mechanically strong lithosphere of the Sichuan Basin obstructs it eastward in Longmen Shan region, thrust and strike slip faulting occur. These faults gradually translate from NNE to NE to NEE from south to north and form the structural pattern which we saw in remote sensing image of Longmen Shan region. If these faults can be validated in the further study in the future, it will provide new ideas to solve many geologic questions, including the reasonable explanations about seismic mechanism of Wenchuan Ms8.0, rupture segmentation of active deformation zones of Longmen Shan fault zones, the transformation of the coseismic displacement that reverse and right-slip components are of comparable magnitude along the southwestern portion of the rupture, but right-slip dominates the northeastern portion of the rupture.

Key words: Wenchuan earthquake, NW-faults, remote sensing interpretation, segment of active faults

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1 INTRODUCTION

On May 12, 2008, a Ms8.0 earthquake occurred in Wenchuan, Sichuan province, China. The communication and the transportation were totally cut down after the earthquake; the disaster area was isolated from outside world. At that moment, remote sensing technique became the main way to get the information from the disaster area. A map was derived from the Beijing-1 small satellite which provides the first one showing disaster relief. The authors analyzed the geologic structure background of Wenchuan earthquake zone which is mainly formed by faults. The macroanalysis showed that beside the NE-trending Longmen Shan fault zone, there were a group of NW-trending faults which are bigger and more active.

The Wenchuan earthequake occurred at the east edge of Bayan Har block in Qinghai-Tibet Plateau. Because the block moved to the east and was stopped by high-intensity Sichuan block, then it formed the Longmen Shan NE-trending thrust nappe structure with a length of 500 km (Zhang, et al., 2008). Wenchuan earthquake occurred at the south and central segments of fault zone, making two imbricate thrust faults Beichuan–Yingxiu fault and the Guanxian–Jiangyou fault broken at sometimes (Fig. 1). Among them, the surface rupture zone along the Beichuan–Yingxiu fault is about 260 km, and mainly composed by the reverse fault with right-lateral strike-slip. The maximum vertical displacement is about 6—11 m, and the largest right-lateral strike-slip displacement is 5—12 m. The surface fracture along the Guanxian–Jiangyou fault is about 80 km, which is a typical reverse fault. The maximum vertical displacement is 3—4 m. On the west of these two faults, there is a NW-trending Xiaoyudong surface rupture which is the sinistral strike-slip with thrust component, its length is about 6 km. (Xu, et al., 2008; Li, et al., 2008).

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2 THE TEMOTE SENSING SENSING TECHNIQUE AND ANALYSIS

2.1 The characteristics of remote sensing image on fault

Fault zone is a kind of linear structure. The basic picture elements of satellite sensors scanning linear imagery are made up of points and lines. The physical characteristics of remote sensing image are particularly sensitive to the linear bodies on the ground, and the difference is very obvious between highlighted linear objects and nonlinear bodies. The fault has its spectrum response characteristics in remote sensing image, showing as a directional difference in color or hue. In the mass spectrum of information, by scanning the information of fault, many local, small, complex faults in linear distribution are automatically sorted, summarized and synthesized, making the whole scene more like a selected structure outline map and the macroscopical geologic phenomenon is easily to be discovered. Using these information, the specialists could analyze the major fault with the helping of human-computer interaction interpretation.

Beijing-1 small satellite can get a coverage of 600 km wide with multispectral image (green 523—605 nm; red 630—690 nm; near infrared 774—900 nm) with 32 m resolution and the 4 m resolution panchromatic image, by which we can find the "heat" material flow that released or passed by the active fault belt, and all these phenomenon would obviously appear as the linear image character ([2011-04-03] http://zhengwu. beijing. gov.cn/gzdt/bmdt/ t962965. htm; Wei, 1978). The experienced specialists can find out the fault belts directly through the series of linear image marks, linking with the difference of geomorphic features, fault scarp, fault triangular, fracture zone by fault compression, fault depression, fault river, dislocation formation and granite body in the remote sensing image. They would also analyze the position of fault belts, its activity, the extended direction and the incision relation of different faults in different directions base on three-dimensional vision formed by shadow in image.

Drainage pattern is always compatible with the tectonic framework. Water system's distribution, its dislocation, change of its channel, the river elbow-shaped bend and other geological phenomena are significant to identify faults and their size, and analyze their activity features (Wei, 1978; Zhu, 2007; Roberts, et al., 1989).

By analyzing the data of surface characteristics acquired from the remote sensing image, geology, physiognomy, water system, historical geography etc., surveying in field and consulting many materials, one could draw a certain conclusion, which requires a wide range of analyses on satellite images with the varieties of mass information.

2.2 The fault system of Wenchuan earthquake zone

The earthquake's scale and damage degree to the surface are related to the fault system in the earthquake zone. Then it is the basis of earthquake damage investigation. In order to analyze the fault system of Wenchuan earthquake zone, and to get the trend of aftershock under an emergency, instead field investigation, the authors used the remote sensing image at the same time to map and analyze the fault system of Wenchuan earthquake zone, and compile the map of the analysis of remote sensing image of the fault structure system. (Fig. 1).

After interpreting Beijing-1 small satellite image, there were three main groups of faults in Wenchuan earthquake zone, which were along the North East (NE), North West (NW), close to North South (NS), respectively. For each of them, the main fault of the North East (NE) is Longmen Shan fault belt, the main fault of the North West (NW) is Xianshuihe fault belt, and the main fault of the North South (NS) is Anninghe- Xiaojiang fault belt. These three groups constituted the fault system of Wenchuan earthquake zone according to the satellite images, and performed a "Y"-shaped planar structure.

It is speculated that Longmen Shan fault belt and the Anninghe-Xiaojiang fault belt belonged to the same NS-trending fault belt before Himalayan orogeny, and this fault also was the major controlling fault belt in China's north-south seismic belt. Before Himalayan orogeny, the Indian plate moved northward, collided with the Eurasian Plate after 45 Ma, and subdued under the Eurasian plate, resulting in rapid uplift of the Tibetan Plateau. Then material of the plateau moved eastward under gravity, and with the strong resistance of Chengdu block in Longmen Shan, it formed a series of thrust faults (Deng, et al., 1994; Burchfiel, et al., 2008; Tapponnier, et al., 2001; Judith & John, 2009; Molnar & Tapponnier, 1975; Xu, et al., 2006; Molnar & Tapponnier, 1978; Xu, et al., 2007; Burchfiel, 1995). The trend of fault gradually deflected to east on its north part, and from south to north, part by part, turned NNE to NE and NEE, then finally compounded with Qinling belt at north.

Satellite images can also show that the Longmen Shan fault belt is an imbricate thrust system with right-lateral strike-slip. It consists of five main faults, including: Hill-back fracture of Longmen Shan (Luding–Wenchuan–Maoxian–Beichuan), Mid-fracture of Longmen Shan (Luding–Yingxiu–Beichuan–Nanba–Linan Temple–Mianxian), Hill-front fracture of Longmen Shan (Tianquan–Dujiangyan–Han Wang–Anxian–Jiangyou–Guangyuan), Longman Shan hill-front buried fault (Yaan–Dayi–Pengzhou–Mianzhu), and Pingwu–Qingchuan–Mianxian fault. These analysis and interpretations are quite same with the pre-research on Longmen Shan fault belt. (Deng, et al., 1994; Burchfiel, et al., 1995; Lin, 1994; Liu, 1994; Zhang, 2008; Wang, 2008).

After the Wenchuan earthquake, it is generally believed that Wenchuan earthquake occurred on main central Longmen Shan faults (Judith & John, 2009; Zhang, 2008; Wang, 2008). But according the analysis of the satellite images, it is suggested that the earthquake occurred on the crossing of Longmen Shan fault belt with 60 km wide and the northwest-trending fault (F2 fault).

2.3 The north-west faults of Wenchuan earthquake zone

In addition to Xianshui He fault zone, the previous research of geological tectonic of Wenchuan earthquake zone rarely involved the North-West fault belt. After recognizing the marks of the fault in satellite images and interpreting faults in Wenchuan earthquake zone, and also comparing with other data, it is concluded that:

The NW-trending faults in Wenchuan earthquake zone are

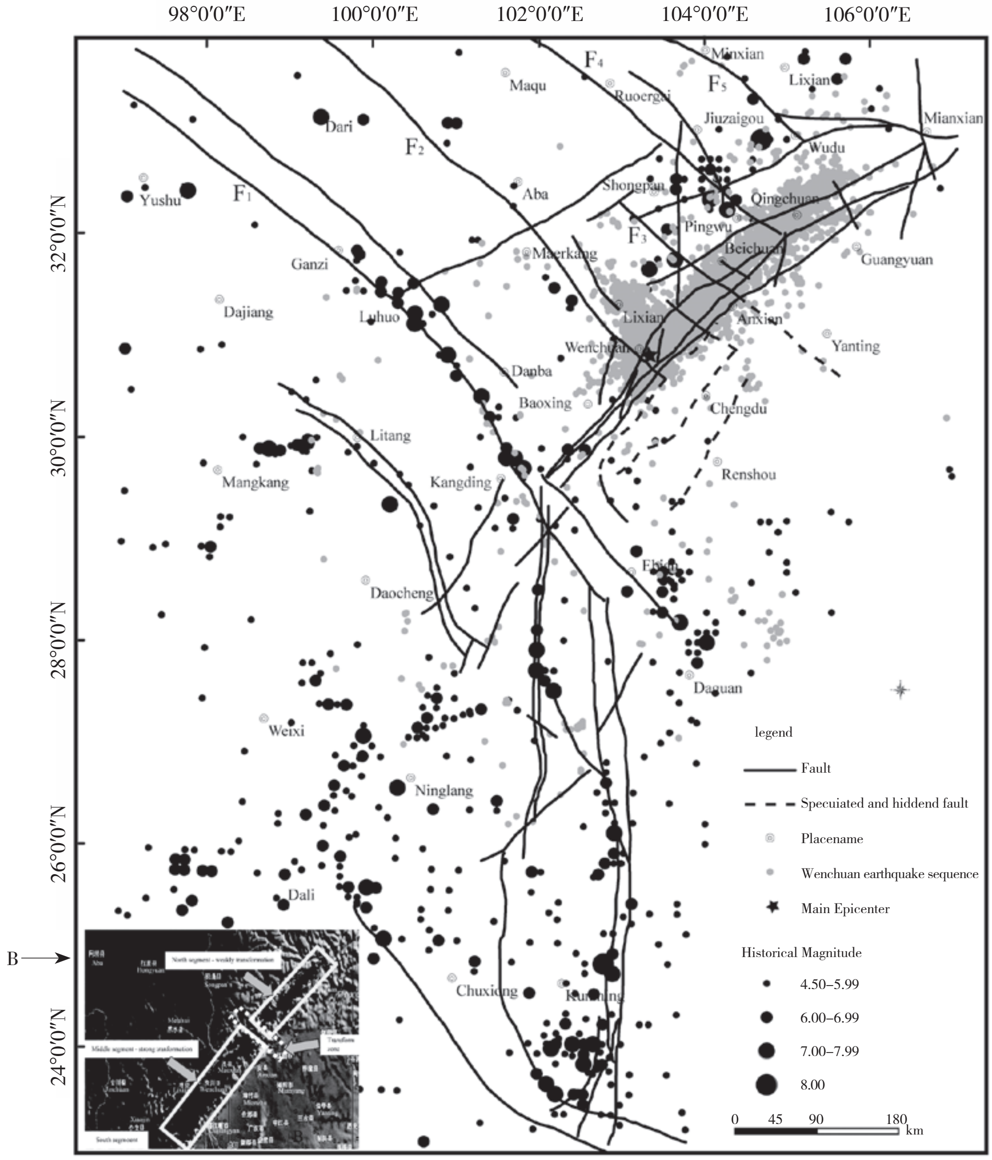


Fig. 1 The interpretation map of faults inWenchuan earthquake zone

clear, large, active, and they are parallel with Xianshui He fault belt, distributed systematically and equally spaced arranged. It is obviously that the fault belt controls the geological structure, modern geomorphology, the water system, and the spatial distribution of intense earthquake of the earthquake zone. It also controls the segment and activity intensity of Longmen Shan fault belt. The Wenchuan Ms8.0 earthquake is not only under the control of Longmen Shan NE fault belt, but also had a close relation with NW-trending fault belt.

The NW-trending faults in Wenchuan earthquake zone control the geomorphologic evolution and the landform unit division, and the ridge was reconstructed. The fault scarp, fault triangles, fault depression and fault river is clear. NW-trending faults cut the stratum, the complex and the granite in Longmen Shan region.

River system is the most sensitive geological factor in reflecting the movement of fault. The NW-trending faults in Wenchuan earthquake zone control deformation and development of river. The flow direction of Minjiang first grades tributary and some modern river channels are the same as the direction of these faults. River valley distributing along the north-west Fault zone is open and flat. According to the relationships between the mainstream and tributaries, it is easily to find out that the NW-trending faults have left-lateral strike-slip characteristics.

Altogether there are five NW-trending faults interpreted in Wechuan earthquake zone (Fig. 1, Table 1, Table 2), which together with the NE-trending faults, forming an X-type crossing conjugate fault system. The scale of NW-trending fault belt of Longmen Shan is much lager than the NW-trending one. It is stated that since Cenozoic deformation and evolution of Wenchuan earthquake zone was controlled not only by the NE-trending faults in the Longmen Shan, but also by the NW-trending faults. Meanwhile, the NW-trending faults cut the faults with other direction.

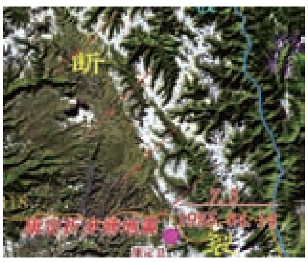
Table 1 Nw-trending faults and historical earthquakes in Wenchuan earthquake zone

Fault number	Direction	Length	Interpretation Symbol
F1	320	> 350	Linear image is clear, straight, distributed along the river valley. 1955 7.5 earthquake in Kangding, 1973 7.9 earthquake in Luhuo.
F2	320	> 350	To transform, control landscape, river channel is clear. 2008 8.0 earthquake in Wenchuan.
F3	330	> 200	To transform, control the direction of ridge, to cut the NW faults. 1933 7.5 earthquake in Diexi. May enter the Sichuan basin in southeast.
F4	330	> 150	To control the direction of ridge. 1937 7.2 earthquake in Songpan-Pingwu.
F5	335	> 120	Clearly transform, control landscape and river channel. 1879 8.0 earthquake in Wudu.

After analyzing the activity and the scale of these 5 faults, it is concluded that they are obviously NW-trending, extend to Chuanxi and connect with the NW-trending faults. By using spatial analysis of Geographic information system(GIS), overlaying all the epicenters of over Ms 7.0 earthquakes in past a hundred years on the NW-trending faults in spatial location, it is found that every large NW-trending fault belt in Wenchuan earthquake zone, without exception, has occurred a strong earthquake over Ms 7.0. Then it is stated that there is a certain relationship between the NW-trending faults with strong earthquakes. In Wenchuan earthquake zone, the crossing of the NW-trending faults and the Longmen Shan faults is the most possible part where earthquake occurs and it has higher probability of strong earthquake than anywhere else.

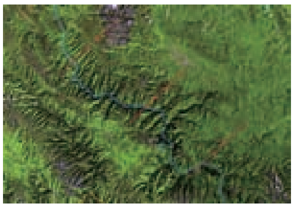
The five NW-trending faults in Wenchuan earthquake zone which lined equally parallel with 90—110 km space control segment and activity intensity of the NE-trending Longmen Shan fault belt. The Longmen Shan faults horizontally "broken" part by part in the long process of squeeze. Horizontal "break points" are, from south to north, Luding, Yingxiu, Beichuan, Qingchuan, and Wudu. Every time when the fault belt "break", there was a NW-trending left-lateral strike-slip formed in each "breakpoint". Xianshuihe fault belt is the earliest and the most active NW-trending fault belt, which was formed in deflection processing of faults turning NS-trending to NE-trending.

Table 2 Interpretation map and analysis of character about NW-trend faults of Wenchuan earthquake

Name of fault	Distribution of faults in image	Character point of fault	Characteristic map of fault interpretation	The characteristics description about fault interpretation
F1		1		Faults triangular is clear and geomorphology shows obvious differences on both sides of fault
		2		River valley distributes along the fault and Luhuo earthquake occurs in the faults
		3		The mountain occurs deformation , controlled by structure, height difference of the mountain on both sides of fault, the 1955 Kangding-Zheduo earthquake occurs on the fault

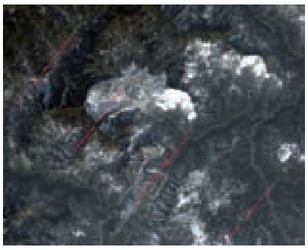
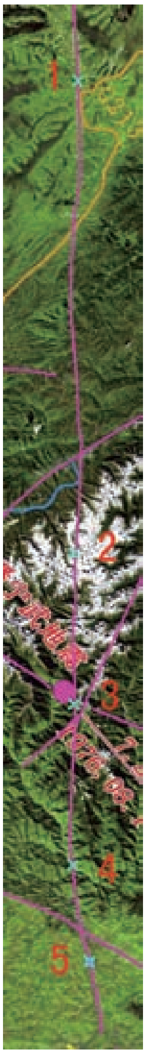
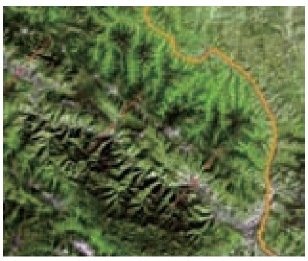
to be continued

continue

Name of fault	Distribution of faults in image	Character point of fault	Characteristic map of fault interpretation	The characteristics description about fault interpretation
F2		1		Fault triangular is clear and geomorphology shows obvious difference
		2, 3		Fault crosses the north-east entend mountain and forms the pass in the mountain. The extend of the mountain shows obvious change
		4, 5		The fault crossing the north-east trend ridge and formed the north west pass, height difference of the mountain on both sides of fault
		6		Faults extending along a series of NE-trend hill made by broken hard rock, geomorphology showing obvious asymmetry on both sides of fault
		7		The fault cutting the north east water system and extending along the northwest trend ditch with head to head
F3		1		The mountain and its water system controlled by faults have significantly change
		2, 3		Along the fault occurred Diexi earthquake in 1933; Consecutive elbow-shaped bend showed in Minjiang

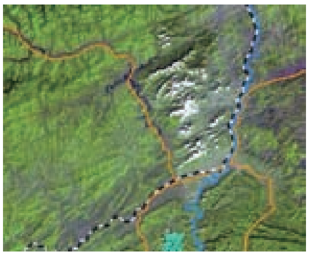
to be continued

continue

Name of fault	Distribution of faults in image	Character point of fault	Characteristic map of fault interpretation	The characteristics description about fault interpretation
F3		4, 5		Water system shows right angle or elbow-like change, differences of landform are significant, rock obvious dislocated
F4		1		Fault developed along the river valley, geomorphological features have obviously differences on both sides of faults, trend of geological bodies is different, the water system controlled by the faults occurs the elbow-like bending
		2		There has a pass in the ridge along the fault
		3		Fault crosses the mountain and changes the trend of mountain. Especially distribution of a 7.2 earthquake in 1976
		4, 5		River channel distributes along fault and the microrelief has a significant difference both side of fault. These phenomena have obvious shown in the geological map
F5		1		Faults cut the mountain, formed the fault river

to be continued

continue

Name of fault	Distribution of faults in image	Character point of fault	Characteristic map of fault interpretation	The characteristics description about fault interpretation
F5		2		Cross-section of faults cut hillside and have obviously reflect in the microrelief, and form fault river
		3		Faults cut through the rock and development along the rive valley

3 VERIFICATION ON FIELD

It is found that some parts of the surface rupture zone make deflection on the direction of the rupture in the site inspection. The sizes of these rupture zone are smaller than the NE-trending ones, generally because they are transition faults of NE-trend faults without attention (Xu, et al., 2008; Yang, et al., 2008). Fig. 1 B is the map of “Wenchuan earthquake rupture segmentation and aftershock distribution (to 5.21)” made by Active faults and earthquake disaster investigation group in Chinese Academy of Geological Sciences. In this figure, the transition zone is handled in this way. However, according to the analysis of geomorphology and the old structure, the scale of these rupture zones is much larger than the surface rupture zone and much more significant to analyze the activity of Longmen Shan fault zone.

After the earthquake, when doing the field survey to testify the result of the analysis of remote sensing interpretation, it is found that there is a NW-trending fault in Beichuan (Fig. 2). The trend of fault is about NW330°, and extends more than 3 km. In addition, there is a very large fault triangular in the mountain of Shiyan Cun, and there is a fractured zone wider than 100m in the mountain paralleling to triangular. The fault rock is clearly zonation from the triangular to the mountain. The fault rocks near the triangular are cataclastic, while the rocks far away from the triangular crushed less and the diameters increase obviously (Fig. 2(c)). Some large cemented calcareous breccia blocks rolled down to the farmland in front of the mountain due the earthquake, and there is a big fractured zone proved that the scale of this fracture is much larger than the fracture surface rupture, and the surface rupture zone may be just a local display of the fracture which affected by the earthquake. The location of this fracture after field survey and the southern extension of the NW-trending F2 fault northern part by interpreting from remote sensing image is the same.

Fig. 2 The surface rupture zone and fault triangular in northwest Shiyan village Shigu town (toward east)

Another NW-trending fault is Xiaoyudong surface rupture zone (Fig. 3), which is researched by many experts in the science surveies after the Wenchuan earthquake. Xu Xiwei ect. believed that Wenchuan Ms8.0 earthquake produced a N(35°±5°)W-trending secondary surface rupture, which located between the echelon transfer zone of two secondary surface rupture zone between Hongkou and Longmen shan town–Qingping and the western part of Wanghan-Bailu rupture zone, as the two secondary surface rupture zone. This secondary surface rupture is about 6 km long, and nearly perpendicular to the two main earthquake rupture zones, and the character of the movement is sinistral strike-slip with chief thrust component (Xu ,et al., 2008). From a geomorphological point of view, there is

Fig. 3 The surface rupture zone and geomorphological map in north west Xiaoyudong (toward southeast)

Jianjiang valley developing along the fault, so it is supposed that this fault is over 10 km long from Zhongba Cun to Tongjichang east. This fault corresponds to the north of F3 NW-trending fault interpreted the remote sensing image.

In the scientific survey after the Wenchuan earthquake, it is also found that there is a sand blasting up to 6 m high in a 2 km long river valley in NW-trending of Yanting Xian in the southeastern part of NW-trending An Xian F3 fault belt (Fig. 4). In Zhangqu River terrace, the southern extension of NW-trending Xianshui River fault zone, found the latest fault (Fig. 5).

In addition, Li Yong and Deng Bing from the Institute of Sedimentary Geology, Chengdu University of Technology stated in their article "The explanation to 'The geothermal and the combustible gas appeared in Qingchuan earthquake relic' ", that "the geothermal and the combustible gas appeared in Donghekou earthquake relic of Qingzhu River Qingchuan county Sichuan Province are respectively along the NW-trending or NE-trending. It is shown that they are the Wenchuan earthquake tectonic products (Fig. 6), and controlled by the underground fracture or cracks." [1] It is indicated that there is a NW-trending fault in this area, and its location is basically the same with the NW-trending F4 fault interpreted from the remote sensing imagery.

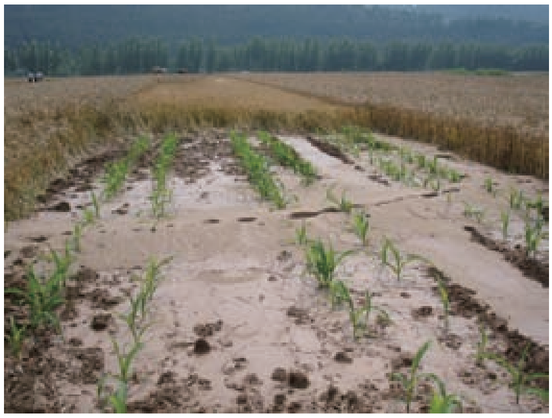


Fig. 4 Phenomenon of blasting sand and water (Line shows NW trend and extension up to 2 km)

Fig. 5 The fault along Zhangqu river terraces in NW-trending Xianshuihe fault

Fig. 6 Gas appearance point in Shibangou Linear distribution along Qingzhu river[1]

[1] [2010-04-03] http://www.eqsc. gov.cn/manage/html/ff808181126-bebda01126bec4dd00001/_content/09_03/05/1236267847432.html

4 THE TECTONIC SIGNIFICANCE OF NW-TRENDING FAULTS

Since the Wenchuan earthquake, there are lots of geological researches on this earthquake. It is very rare that only one earthquake comes up to so many results in a very short time. However, their works mainly focused on the reflection and summary to past work, and the study also focused on the narrow earthquake zone. Basing on the past experience of remote seismic response, it is stated that interpretation of satellite remote sensing image will help to explore the causative structure and mechanism of earthquake. After the earthquake, according to the multi-source remote sensing data, the experts could interpret the structural framework in the earthquake to meet emergency needs, and it could also provide another perspective to investigate the fault framework in the earthquake (Wei, et al., 2008; Wang, 2003). If these interpretations are confirmed, it will provide l reasonable explanations to the unsolved questions. Such as segmented signs of fault activity, the mechanism and the location of earthquake occurrence, the explanation about reasons of the transition that coseismic activities earthquakes change from thrust to thrust- strike-slip to slip in fault and so on.

(1)The NW-trending faults of Wenchuan earthquake zone provides an explicit structure signs for the segment of the activity fault in Longmen Shan. Since the Wenchuan earthquake, it is demonstrated that it could be divided into three sections according to the surface rupture zone and seismic activity (Chen ,et al., 2007), including south of the epicenter of Wenchuan earthquake namely the Yingxiu as the southern segment, Yingxiu to Beichuan as the middle segment, the north part of Beichuan as the northern segment. However, the study on the evidence of segment structure is rare; there is no corresponding and supportive sign of structure. We presents that the evidence of segment of structure of Longmen Shan faults is NW-trending fault belt. E.g., the F2 fault is the northern border of the southern part of the Longmen Shan fault belt. The short fault of northern F2 fault is the NW-trending of Xiaoyudong fault belt, and F2 and F3 faults control the surface rupture zone of the front mountain. The small fault in the north of F3 fault corresponds to the NW-trending surface rupture zone of Leigu, and it is also the structure boundary of the middle and northern segment of Longmen Shan.

(2) NW-trending fault provides a structure sign for the location of epicenter and mechanism of Wenchuan earthquake. By the use of spatial analysis of GIS technology to compare the interpretation of faults and historical earthquakes, it is clear that in Wenchuan earthquake zone most strong historical earthquakes occurred in the vicinity of these faults. In particular, it is worth to point out that, in the Longmen Shan block, the seismogenic faults of historical earthquakes are NE-trending or NS-trending, but to some extent controlled by the NW-trending fault. Specifically, the intersection of seismogenic fault and NW-trending fault is more likely to get a strong earthquake. Ding peoposed the idea of “rupture grid” (Ding, et al., 1979), and stated clearly that over the past decade many strong earthquakes such as Tonghai (Ms7.8), Ganzi (Ms7.9), Simao (Ms6.6), Zhaotong (Ms7.1), Longling (Ms7.6), Songpan (Ms7.2) occurred in the intersection of NE-trending and NW-trending seismic activity zone or near this site (Fig. 7). The discovery of NW-trending faults provides strong evidence to this idea, and furthermore, provides the new explanation to the occurrence mechanism of Wenchuan earthquake and controlling structure.

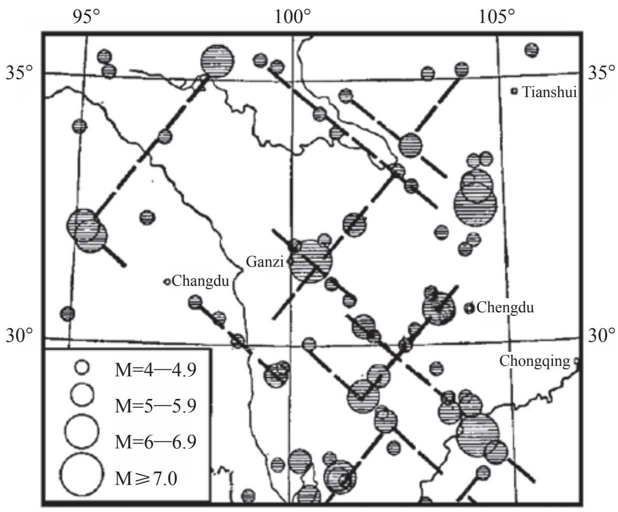


Fig. 7 The rupture grid diagram of M≥4.0 epicenter in the Longmen Shan and adjacent areas (Ding, et al., 1979)

(3) On geological interpretation of coseismic displacement conversion of the fault. In Wenchuan earthquake, the coseismic displacement of Longmen Shan faults transforming from the thrusting-reverse strike-slip-slip characteristic from south to north is known to all (Burchfiel, et al., 2008; Judith & John, 2009; Xu, et al., 2008). However, how this transformation happened is not well explained, at least not in the structure point, and it did not get more convincing evidences. In this paper, it is stated that there are NW-trending faults that provide a new solution to this problem. This is the transformation is achieved by the NW-trending faults. It is a pioneering work for the geological interpretation of fault coseismic displacement conversion, although the evidences acquied from the surface are not so strong and some mechanisms have not been resolved properly.

5 CONCLUSIONS AND DISCUSSION

(1) Based on satellite remote sensing image interpretation, there is a series of NW-trending faults of Wenchuan earthquake zone lined equally parallel from 90 km to 110 km space, and verified by the preliminary field survey. The crossing of the NW faults and the faults of Longmen Shan has higher probability of strong earthquake than anywhere else. Wenchuan Ms8.0 earthquake occurred at the crossing of the NW faults and Longmen Shan faults.

(2) The trend of Longmen Shan fault turns from NNE to NE to NEE part by part. We Speculate that Longmen Shan faults and Anninghe-Xiaojiang fault zone are originally the same NS-trending fault zone. Because the Tibetan Plateau uplifted rapidly and moved to the east, the trend of Longmen Shan faults gradually deflected. The Longmen Shan faults of horizontally “broken” part by part in the long process of squeeze. Horizontal “break points” are, from south to north, Luding, Yingxiu, Beichuan, Qingchuan, and Wudu. Every time when the fault belt “break”, there was a NW-trend left-lateral strike-slip formed in each “breakpoint”.

(3) The discovery of NW-trending faults in Wenchuan earth-

quake zone explains segment signs of the fault activity, the mechanism of earthquake occurrence, the location and transformation of coseismic displacement. It also provides new evidences to these issues.

(4) It is very important to interprete the NW-trending faults in Wenchuan earthquake zone. As the limitation of field survey and the author's acknowledge, there still a long way to go for testing this theory about NE-trending faults in Longmen Shan faults, and many discussions did not go further, and need to dig deeper in the future.

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汶川地震区北西向断裂带遥感分析

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摘　要：利用北京一号小卫星遥感影像判读汶川地震区的断裂构造，发现了一系列100 km左右等间距排列的北西向断裂，结果已部分地得到实地考察验证。龙门山断裂与北西向断裂的交汇部位发生强烈地震的几率较高。这些新发现将对汶川Ms8.0级地震发生机理、龙门山断裂带活动性分段、断裂同震位移自南西向北东、由右旋走滑逆断层向右旋走滑断层转变等重大问题提供了新的合理解释。

关键词：汶川地震，北西向断裂，遥感构造判读，活动断裂分段

中图分类号：TP79　　**文献标志码：**A

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1 引　言

2008年5月12日，中国四川省汶川发生了Ms8.0级地震，使得重灾区的通讯和交通完全中断，几乎与外界隔绝。当时，遥感应用技术成为获得灾情信息的主要途径。地震后，童庆禧院士、迟耀斌总设计师、魏成阶研究员立即组织用存档数据制作了《四川汶川地震背景北京一号小卫星影像图》([2011-04-03]http://zhengwu.beijing.gov.cn/gzdt/bmdt/t962965.htm)，这是震后第一幅供救灾用的遥感影像图。作者在该影像图上，完成了以断裂构造为主的汶川地震区地质构造背景分析。宏观分析结果表明，汶川地震区除了北东向的龙门山断裂带之外，还存在一组规模较大、延伸较长、活动性明显的北西向断裂构造。

汶川地震发生在青藏高原巴颜喀拉块体东缘，由于块体向东运移，受高强度四川块体的阻挡，从而形成了龙门山推覆构造带,构造带NE走向，全长约500 km(张培震　等，2008)。汶川地震发生在构造带中南部，使其中的北川-映秀断裂和灌县-江油断裂两条叠瓦状逆断层同时发生破裂(图1)。其中，沿北川-映秀断裂展布的地表破裂带长约260 km，以兼有右旋走滑分量的逆断层型破裂为主，最大垂直位移6—11 m，最大右旋走滑位移5—12 m；沿灌县-江油断裂连续展布的地表破裂带长约80 km，为典型的纯逆断层型地表破裂，最大垂直位移3—4 m；在上述两条地表破裂带西部还发育着1条NW向带有逆冲垂直分量、左旋走滑性质的小鱼洞地表破裂带，长约6 km(徐锡伟　等，2008a；Li　等，2008)。

2 遥感方法与分析

2.1 断裂构造的遥感影像特征

断裂带是一种线性构造。卫星传感器扫描成像的基本像元是以点、线组合，呈线状排列构成的图形。这一遥感成像的物理特性对地面呈线状体分布的地物反映特别敏感。在遥感影像中突出显示的地面线状

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体与非线性体的区别十分明显。断裂构造在遥感影像中有其自身的波谱响应特征，显示为具有方向性的色彩或色调差异。在海量波谱信息中，有许多局部、细小、复杂的呈线状分布的断裂构造信息，经过扫描成像基本像元的自动分选、概括和归纳，使得整景成像类似一幅经过制图综合取舍的构造纲要图，一些宏观地质现象被突出展现，主要断裂构造非常明显。利用这些物理特性，遥感影像判读专家采用人机交互判读的方式，很容易分析出主要的断裂构造。

北京一号小卫星具有同步获取600 km幅宽的32 m多光谱(绿523—605 nm；红630—690 nm；近红外774—900 nm)影像和4 m全色影像的双遥感器成像能力，能“发现”活动断裂带上向空中释放或传递的“热”物质流，并在影像中表现为显而易见的线性影像标志(魏成阶，1978)。有经验的遥感影像判读专家根据影像上一系列线性影像标志，并结合地貌形态差异、断层陡坎、断层三角面、断层挤压破碎带、断裂谷、断层洼地、断层河、错断的地层和花岗岩体等，可以在影像上直接判读断裂带。并根据其阴影给人眼造成的立体视觉，进行断裂构造的定位及其活动性质、延伸方向和不同方向断裂交接关系的分析。

水系格局总是与构造格局相适应。水系的总体展布及其错位或流向的突变、河流肘状拐弯等地学现象是识别断裂构造及其规模大小，并分析其活动特征的重要判读标志(魏成阶，1978；朱亮璞，2007；罗伯特 等，1989)。

通过卫星影像判读的断裂是综合分析各种影像的平面形状特征和地质、地貌、水系、历史地理等自然和人文现象，并进行野外调查、参考其他资料的基础上而得出的结论。这需要进行多方面的分析研究，从内容丰富的卫星影像信息中找出各种断裂构造的存在的证据。

2.2 汶川地震区的断裂构造体系

地震区的断裂构造体系决定地震发生的规模和对地表的损害程度。研究地震必须研究断裂构造体系，它也是完成地震震害调查的基础。为了分析汶川地震区的断裂构造体系，掌握震后强余震的活动动向，作者在紧急情况下，打破常规，先不去实地调查，而是在室内采用卫星图像，结合已有地质图，对汶川地震区的断裂构造体系进行大区域的宏观分析，快速地编绘了《汶川地震区断裂构造体系卫星影像判读分析图》(图1)。

对北京一号小卫星影像判读发现：汶川地震区有3组主要断裂构造，分别沿着北东(NE)、北西(NW)、近南北(NS)向分布。其中，北东向断裂以龙门山断裂带为主；北西向断裂以鲜水河断裂带为主；近南北向断裂以安宁河-小江断裂带为主。这3组断裂构成了在卫星影像上所看到的汶川地震区断裂构造体系在总体上表现为“Y”字型的平面结构特征。

据卫星影像分析推测：龙门山断裂带在喜马拉雅造山运动前与安宁河-小江断裂带同属一条南北向的断裂带。这条断裂带也是中国南北地震带的重要控制性断裂带。喜马拉雅造山运动前，印度洋板块向北运动，于45Ma前后与欧亚板块碰撞，并俯冲在欧亚板块之下，造成青藏高原的迅速隆起，高原物质在重力作用下，沿大型走滑断裂向东运移，在龙门山地区由于受到成都地块的强大阻力，形成一系列逆冲断裂(邓启东 等，1994；Burchfiel 等，2008；Paul 等，2001；Judith和John，2009；Molnar和Tapponnier，1975；许志琴 等，2006；Molnar和Tapponnier，1978；许志琴 等，2007；Burchfiel 等，1995)。断裂的走向往北有向东偏转的趋势，自南而北逐段由NNE向NE、NEE方向偏转。最北端与东西向的秦岭构造带复合。

卫星影像还可以看出：龙门山断裂带为叠瓦状的逆冲推覆构造，并伴随有右旋走滑特征。它由5条主干断裂组成，包括龙门山后山断裂(泸定－汶川－茂县－北川)、龙门山主中央断裂(泸定－映秀－北川－南坝－林奄寺－勉县)、龙门山山前主边界断裂(天全－都江堰－汉旺－安县－江油－广元)、龙门山山前隐伏断裂(雅安－大邑－彭洲－绵竹)和平武－青川－勉县断裂。这些判读分析结果与前人对龙门山断裂构造带的研究结果基本一致(邓启东 等，1994；Burchfiel等，1995；林茂炳，1994；刘和甫 等，1994；张培震，2008；王二七和孟庆任，2008)。

汶川地震发生后，人们普遍地认为：汶川地震发生在龙门山断裂构造带的主中央断裂上(Judith和 John，2009；张培震，2008；王二七和孟庆任，2008)。卫星影像分析认为：这次汶川Ms8.0级地震发生在全长500 km、宽约60 km的龙门山断裂带和北西向断裂(F_2断裂)的交汇处。

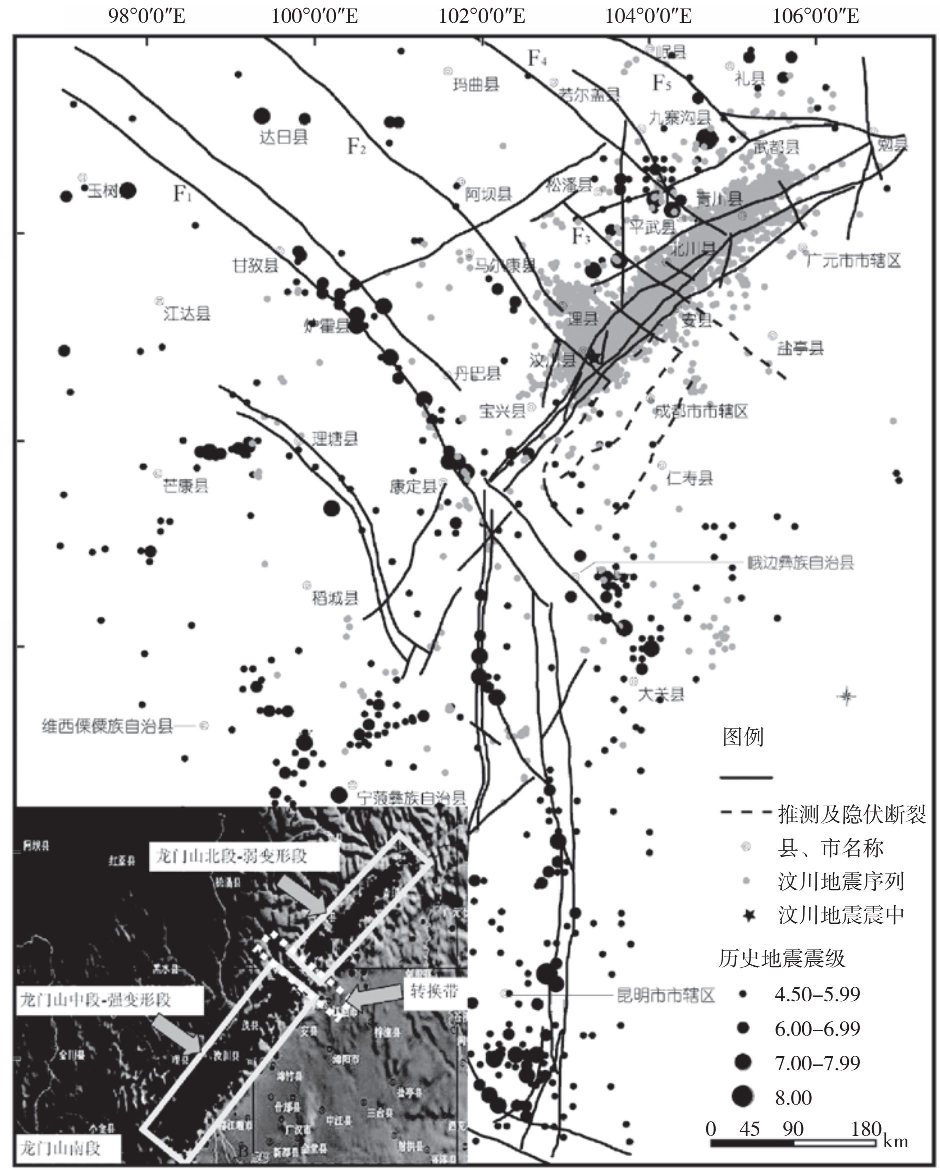


图1 汶川地震区断裂构造体系卫星影像判读分析图

2.3 汶川地震区的北西向断裂构造

除了鲜水河断裂带以外，前人在汶川地震区的地震地质构造研究中，很少涉及北西向断裂带。作者运用在卫星影像中识别断裂构造的标志，对汶川地震区进行断裂构造的人机交互判读，并用其他资料作对比分析，结果表明：

汶川地震区北西向断裂影像形迹清楚，规模较大，平直延伸，活动明显。与鲜水河断裂带平行，而且成系统分布，呈等间距排列，对地震区的地质构造、现代地貌和水系、强烈地震的空间分布起到明显的控制作用。它控制着龙门山断裂带的分段及其活动强度。汶川Ms8.0级地震的发生，除了受北东向的龙门山断裂带控制以外，还与北西向断裂带的关系密切。

汶川地震区的北西向断裂对地貌发育起控制作用。地貌单元分区明显地受北西向断裂控制，山地的山脊被北西向断裂活动改造，断层陡坎、断层三角面、断层洼地以及断层河的地貌形态明显。龙门山地区的地层和杂岩、花岗岩体都显示出被北西向断裂错断的迹象。

河流水系是反映断裂活动最敏感的地学因子。汶川地震区的北西向断裂对河流的发育与形变起着重要的控制作用。岷江的一级支流总体流向和一些现代河

流的河道及其流向与这组断裂方向一致。沿北西向断裂带分布的河谷地貌开阔平直。根据干流与支流的关系可以判断北西向断裂带具有左旋走滑的活动特征。

作者在汶川地震区共判读分析出5条北西向断裂构造(图1、表1和表2)。它与北东向断裂一起，形成一对X型共扼交叉断裂系。北东向的龙门山断裂带的规模明显大于北西向断裂。这说明汶川地震区新生代以来的形变发育不仅受到北东向的龙门山断裂带的明显控制，还受到北西向断裂的影响。北西向断裂还有穿切其他方向断裂的迹象。

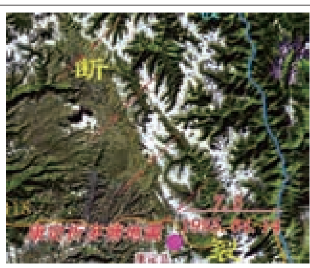
表1　汶川地震区北西向断裂及其与历史地震的关系

断裂编号	走向/(°)	长度/km	判读标志
F1	320	＞350	线性影像清晰，平直，沿河谷分布1955年7.5级康定地震，1973年7.9级炉霍地震
F2	320	＞350	改造、控制地貌、河道明显。2008年8.0级汶川地震
F3	330	＞200	控制改造山脊走向，切割北东向断裂。1933年7.5级叠溪地震。向东南可能进入四川盆地边缘
F4	330	＞150	控制改造山脊走向 1973年7.2级松潘-平武地震
F5	335	＞120	改造、控制地貌、河道明显 1879年8.0级武都地震

作者对这5条北西向断裂构造作了规模和活动性分析。它们呈明显的北西向条带向西北延伸至川西境内，并与川西的北西向断裂相连。作者利用GIS技术的空间分析能力，在汶川地震区，将一百多年来所发生的Ms7.0级以上强烈地震的震中与北西向断裂进行空间位置的复合处理，发现在汶川地震区的每条较大规模的北西向断裂带上都毫无一例外地发生过Ms7.0级以上的强烈地震。这说明北西向断裂构造与强震活动有着密切的关系。在汶川地震区，北西向断裂与龙门山断裂带的交叉是发生强烈地震的有利部位，发生强烈地震的几率较高。

汶川地震区5条北西向断裂构造带呈50—60 km等间距平行排列，控制着北东向的龙门山断裂带的分段及其活动强度。龙门山断裂带在长期被挤压的过程中被逐段的横向“折断”。横向“折断”的“断点”从南向北分别为：泸定、映秀、北川、青川和武都。每“折断”一次，就在这些“断点”附近形成一条以左旋走滑活动为主的北西向断裂。鲜水河断裂带就是近南北向断裂发生向北东向的偏转过程中，形成最早，活动性最强的北西向断裂带。

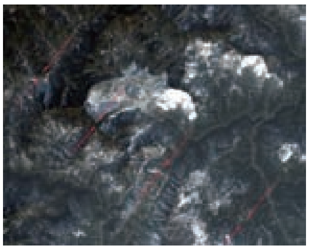
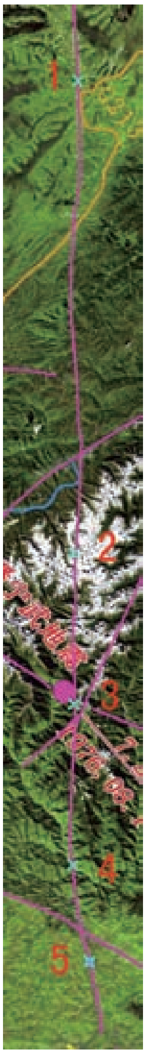
表2　汶川地震北西向断裂遥感解译图谱及其特征分析

断层名	断层图像	解译特征点	断层解译图谱	解译特征描述
F1		1		断层三角面清楚，两侧地貌差异明显
		2		断裂沿河谷分布，历史上炉霍地震发生在该断裂带上
		3		山体受构造控制发生形变，断层两侧高差悬殊，1955年康定折多塘7.5级地震发生在该断裂带上

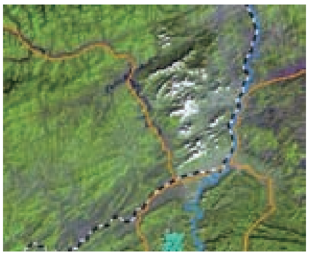
续表

断层名	断层图像	解译特征点	断层解译图谱	解译特征描述
F2		1		断层三角面清楚，两侧地貌差异明显
		2、3		断裂穿过北东走向的山体并在断裂通过处形成地貌哑口，北东向的山体走向发生巨大改变
		4、5		断裂横穿所以北东向的山脊，在山脊上形成北西地貌哑口，高差明显
		6		一系列沿着北西向展布的小山头组成，小山头由坚硬的岩层所组成的破碎带，沿着断裂两侧地貌明显不对称
		7		断层沿着北西向对头沟发育，切割北东向水系
F3		1		山体及其水系受断裂控制发生明显改变
		2、3		沿着该条断裂带，发生1933年叠溪地震；岷江发生连续肘状拐弯

续表

断层名	断层图像	解译特征点	断层解译图谱	解译特征描述
F3		4、5		水系受其断裂控制发生直角或者肘状改变，两侧地貌差异明显，特别是岩体明显被错断
F4		1		断层沿河谷发育，断层两侧地貌特征差异，地质体走向明显不同，水系受断层控制发生肘状弯曲
		2		沿断裂延伸方向在山脊上出现斜切山脊的地貌哑口
		3		断层沿着山体穿过，改变山体走向，特别是有1976年的7.2级地震分布
		4、5		河道沿断裂展布，断层两侧微地貌差异明显，地质图上有反映
F5		1		山体被错断，形成断层河

续表

断层名	断层图像	解译特征点	断层解译图谱	解译特征描述
F5		2		断裂沿着山坡横切形成微地貌反映明显，断裂穿切地质体后形成断层河
		3		断层切穿岩体，沿着河谷发育

3　实地调查验证

人们在地震现场考察时，发现在地表破裂带的一些部位发生了破裂方向的偏转。这些破裂带的规模比北东向破裂带小，一般都认为它们是北东向断裂的转折断层而未受到重视(徐锡伟 等，2008；杨军杰 等，2008)。如图1左下角插图是中国地质科学院活动断裂与地质灾害考察组所做的《汶川地震破裂分段性及余震分布(至5.21)》的结果图。图中的转换带就是这样处理的。但是，从地貌以及老构造上分析，这些破裂带的规模可能远比地表看到的破裂带的规模要大得多。它们对龙门山断裂带的活动性分段具有重要意义。

在震后对遥感判读分析结果进行野外调查验证过程中，在北川县擂鼓镇石岩村附近发现北西向的断裂(图2)。断裂走向NW330°左右，断裂延伸大于3 km。此外，在石岩村后山可见规模很大的断裂三角面，在平行三角面的后山发现断裂破碎带，宽度大于100 m，断层岩自三角面向山后呈明显的分带性。靠近三角面的断层岩，呈碎裂状。而远离三角面的断层岩破碎程度较小，直径明显增大(图2(c))。有些被钙质胶结甚好的大角砾岩块，由于地震作用而被滚落到山前的耕地里。如此大的破碎带证明这一断裂的规模远比地表破裂显示的规模要大得多。而地表破裂带可能只是这一断裂受地震影响的一个局部显示。野外调查的这一断裂与判读结果的F_2断裂北侧的北西向断裂的南延部分位置一致。

图2　擂鼓镇石岩村北西向地表破裂带及断裂三角面(镜向东)

另一条北西断裂就是小鱼洞地表破裂带(图3)。在汶川地震后的科学考察中，这条破裂带人们有大量的研究。徐锡伟等人(2008)认为：汶川Ms8.0地震产生的一条走向N(35° ± 5°)W的次级地表破裂，位于北川-映秀破裂带的虹口与龙门山镇-清平两条次级地表破裂带的斜列阶区附近至南部汉旺-白鹿破裂带西端之间，长约6 km，近于垂直上述2条地震主破裂带，运动性质为左旋走滑兼逆冲分量(徐锡伟 等，

图3 小鱼洞北西向地表破裂及地貌图(镜向南东)

2008b)。从地貌上看，沿断裂发育的湔江河谷，推测断裂可能自中坝村附近延伸到通济场以东，全长应大于10 km。此断裂与遥感判读的F_3断裂北侧北西向断裂相对应。

在汶川地震后的科学考察中，还发现在北西向安县断裂带(F_3)的东南段的盐亭县出现沿NW向延伸长达2 km的河道喷砂冒水高达6 m的震害现象(图4)。在北西向鲜水河断裂带的南延的张曲河流阶地上发现了最新断层(图5)。

此外，成都理工大学沉积地质研究院李勇、邓斌在“对《青川地震遗址出现地热和可燃气》的说明”中所做的成因分析，提到：“四川省青川县青竹河东河口地震遗址区出露的地热和可燃气体分别沿北西向或东西向展布，表明他们的出露受到地下断裂或裂隙的控制，是汶川地震的构造作用的产物(图6)。”[1]这说明在该地区存在着北西向断裂，其位置与遥感判读的F_4北西向断裂基本一致。

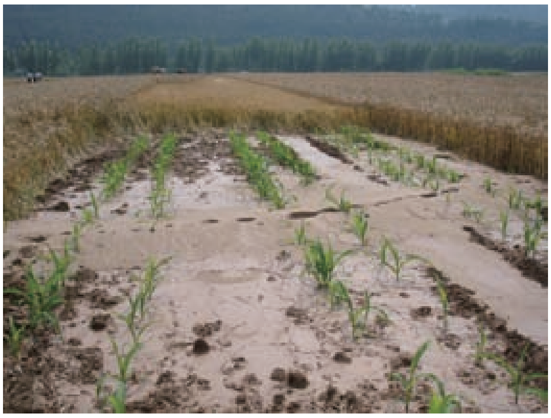


图4 盐亭喷砂冒水高6 m,NW向延伸长达2 km

图5 北西向鲜水河断裂带张曲河流阶地断层

图6 石板沟天然气出露点，沿青竹河线状分布[1]

[1] [2010-04-03] http://www.eqsc.gov.cn/manage/ html/ff808181126bebda01126bec4dd00001/_content/09_03/05/1236267847432.html

4 北西向断裂的构造意义

自汶川地震以来，地质工作者进行了大量的研究。一次地震所产出的成果之快、之多实属罕见。但是，他们的工作主要还是集中在对以往工作的总结和反思中，研究范围也主要集中在震区狭窄的范围内。作者根据以往地震遥感应急经验，认为卫星遥感影像判读对发震构造和发震机理的研究大有裨益。地震后，在第一时间内根据多源遥感资料，判读出地震区断裂构造格架，满足应急需求，可以给广大地震地质工作者提供地震区构造格架的支持和另一种思考问题的视角(魏成阶 等，2008；王晓青 等，2003)。这些判读结果如果得到进一步的证实，将会对很多悬而未解的问题提供合理的解释。如断裂活动性分段构造标志、地震发生的机理和发生的位置、断裂同震活动性质由逆冲–逆走滑–走滑的转变机制的解释等。下面就这些问题作简单的探讨。

(1)汶川地震区的北西向断裂为龙门山断裂带活动分段提供了较为明确的构造标志。自汶川地震以来，对龙门山断裂带的分段研究，较一致的结果认为：按地表破裂带及地震活动性可将它分为3段(陈国光 等，2007)：汶川地震震中即映秀以南为南段，映秀至北川为中段，北川以北为北段。但是，对分段的构造依据研究则相对较少，没有给出相对应的、有支撑作用的构造标志。本文提出龙门山断裂带分段的构造依据是北西向断裂带：如F_2断裂带为龙门山断裂带南段的北边界；F_2北侧延伸较短的断裂为小鱼洞北西破裂带所在位置，F_2和F_3对前山地表破裂带起到了控制作用；F_3北侧小断裂与擂鼓北西向地表破裂带相对应，也是龙门山断裂中段与北段的分界构造。

(2)北西向断裂为汶川地震机理和震中位置提供了构造标志。作者利用GIS技术的空间分析能力，将判读出的断裂与历史地震对照，可以明显发现：在汶川地震区，历史上大多数强烈地震均发生在这些断裂的附近。尤其值得指出的是，在龙门山地块中，历史地震发震断裂均为北东或南北向，但是在一定程度上受北西断裂的控制，尤其是发震断裂与北西断裂交汇部位发生几率较高。丁国瑜院士在1979年提出破裂网格的思想(丁国瑜，1979)，并明确提出近十年来发生的通海(7.8级)、甘孜(7.9级)、思茅(6.6级)、昭通(7.1级)、龙陵(7.6级)和松潘(7.2级)等多次强烈地震都发生在北东和北西向地震活动带的交会部位或其附近(图7)，北西向断裂的发现为这一思想提供了良好的佐证。当然也对汶川地震的发生机理和构造控制作用的解释提供了新的论据。

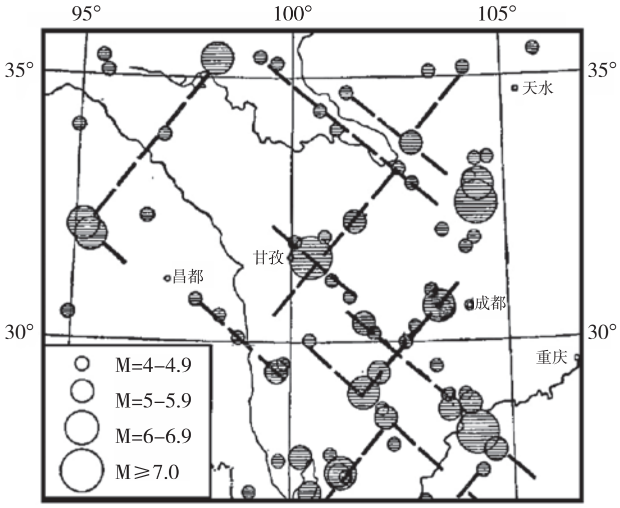


图7 龙门山及邻区M≥4.0震中的破裂网络图
(改编自文献(丁国瑜，1979))

(3)关于断裂同震位移转换的地质解释问题。汶川地震在龙门山断裂带上的同震位移，自南而北，由逆冲–逆走滑–走滑的转变特点是现有研究资料较为统一的认识(Burchfiel 等，2008；Judith和John，2009；徐锡伟 等，2008)。但是，这一转换机制是如何产生的没有得到很好的解释，至少在构造上无法解释这一转换，也没有得出较为信服的证据。而本文提出北西向断裂的存在，为这一问题的解决提供了一条新思路，那就是转换是通过这些北西向断裂来实现的。虽然，目前在地表得到对这种认识的证据还不是很多，一些机理还不可能一下都得到完满的解决，但是作者毕竟为断裂同震位移转换的地质解释做出了开创性的工作。

5 结论与讨论

(1)本文根据卫星遥感影像判读，提出汶川地震区存在一系列50—60 km等间距排列的北西向断裂，并得到了野外调查的初步验证。北西向断裂与龙门山断裂的交叉部位发生强烈地震的几率较高。汶川Ms8.0级地震就发生在北西向断裂带与北东向的龙门山断裂带的交叉部位。

(2)龙门山断裂走向由NNE-NE-NEE向逐段偏

转。推测龙门山断裂带与安宁河——小江断裂带原为同一条南北向的断裂带。由于青藏高原隆升，并向东的运移作用，而使龙门山断裂的走向逐步发生偏转，并被逐段的横向“折断”。横向“折断”的“断点”从南向北分别为：泸定、映秀、北川、青川和武都。每“折断”一次，就在这些“断点”附近形成一条以左旋走滑活动为主的北西向断裂。

(3)汶川地震区北西断裂的发现与现有对龙门山断裂分段、汶川地震发生机理及其位置，和同震位移的转换等现象有较好的符合，也同时为这些问题的解释提供了较好的构造依据。

(4)客观地认识汶川地震区北西向断裂带，在理论和实践上都具有重要意义。受限于野外调查验证的条件和作者的研究领域，对龙门山构造区北西断裂构造的研究还有待于进一步的验证和完善。

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