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Remote Sensing Interpretation and Extraction of Structural Information about Active Faults at Hangzhou, China, and Their Surroundings

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ABSTRACT: It is important to explore active faults in urban areas and their surroundings for earthquake disaster mitigation. Satellite remote sensing techniques can play an important role in such active fault exploration. It can not only reveal the pattern of active faults and active tectonics on a macroscopic scale, but also monitor the occurrence, development and rules of temporal-spatial evolution of active faults. In this paper, we use the Hangzhou area as an example to introduce methods of extracting detailed active fault information when covered by thick unconsolidated Quaternary sediment, using image enhancement and image fusion etc. to improve the definition and precision of satellite images and presenting a three-dimensional (3D) image to illustrate tectono-geomorphic features along the relevant faults. We have also collected aeromagnetic anomaly data, shallow seismic exploration data and dating data, and carried out field surveys to validate the characteristics of active faults based on remote sensing images. The results revealed about the faults showed a high consistency with traditional geological knowledge, and demonstrate that it is feasible to explore active faults in a weakly active tectonic area by using satellite remote sensing techniques and contribute to large engineering projects and research on neotectonics.
KEY WORDS: remote sensing, active faults exploration, Quaternary, image fusion, Hangzhou, Neotectonics.

INTRODUCTION

Active faults give a significant representation of modern tectonic movements reflecting very recent crustal deformation and plate motions (Ding, 1989). Remote sensing images not only express the pattern of active faults and active tectonics on a macroscopic scale but also provide direct information about fault activity, offering profuse information for analyzing the active states of faults and seismogenic tectonics, and

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permitting correlation with seismicity (Yao et al., 2008). Because satellite images are now multi-source, multi-layered, multi-spectral, multi-temporal and high-resolution (Fu et al., 2005) they can reduce mistakes in the interpretation of landforms, climate and obtained by traditional geological methods. They also provide essential timely information for the exploration of active faults (Ding et al., 2003). Remote sensing techniques are now being widely used in the discovery, investigation and research the active faults (Liu et al., 2006).

In this study we have recorded geological and geomorphological features of active faults along a significant fault zone in the Hangzhou area by using tectono-geomorphic analyses of high-resolution satellite images to extract active tectonic information, e.g., lateral displacements of streams resulting from active strike-slip faulting (Sieh and Jahns, 1984; Wallace, 1968). We have used aeromagnetic anomaly data, thermoluminescence (TL) dating and field surveys to validate our results and understand the relationships between the geological and geomorphological features and large-scale seismic activity.

REGIONAL GEOLOGY

Hangzhou is a city with over 2 200 years of history that was one of the earliest Chinese coastal cities to open to the outside world. It lies at the junction of the South China Plate and the Yangtze Plate, where a passive continental margin developed in Palaeozoic times and evolved into an active continental margin in the Mesozoic (Ye, 2001). On a smaller scale, the area can be roughly divided into a Changshan-Zhuji uplift belt and Hangjiahu Plain subsidence zone with their boundary near Wenyan Town (Ma et al., 2011), controlled by NE trending Jinning movements. In the Late Devonian, the Xiaoshan-Qiuchuan fault zone and the Majin-Wuzhen fault zone controlled the deposition of the Qiantang Sea Basin together. Folding associated with the active margin has controlled the tectonic framework since the Indosinian movements and given rise to near surface geological structures such as strong NE trending faults, folds and volcanic structures. These active faults delineated deposition and magmatic activity of the Hangzhou area and gave rise to different geological and geomorphological features in different periods. In the Late Jurassic, the tectonic movement created thrust-nappes with strong extrusion characteristics. In the Early Cretaceous, the Hangzhou area began to extend and form Yanshanian fault basins.

Faults striking NE, NW and EW in the Hangzhou area appear to reflect early sinistral compression and shearing followed by later tension shearing (Fig. 1). This episodic tectonic evolution makes the identification of the stratigraphical and structural boundaries difficult and this gets even worse when conducting remote sensing interpretation because most of the active faults in the Hangzhou area have been covered by unconsolidated Quaternary sediments (Zheng et al., 2002). A combination of multi-sourced data and evidence is needed to understand the tectono-geomorphological evolution of the Hangzhou area.

METHODS FOR EXTRACTING REMOTE SENSING INFORMATION ABOUT ACTIVE FAULTS

Active faults can form obvious geomorphological evidence such as dislocated ridges, fault scarps, fault facets, river offsets and so on and may have hydrogeological and compositional differences on either side causing contrasts between normal and abnormal surface properties (Zhang et al., 2004). By such means we can recognize and analyze active faults better using remote sensing techniques. A selection of methods is as follows.

Selecting Data

Data selection is very important and different satellite images must be used in different areas because of regional geology background and vegetation (Zhang et al., 2004). Hangzhou is located in an area where vegetation, river systems and thick Quaternary unconsolidated sediments are widespread and variable, so we should pay close attention to the methods of recognizing concealed active faults. We should be most concerned with both spatial resolution and spectrum resolution (Fu et al., 2004). Satellite remote sensing data obtained by the US Landsat Enhanced Thematic Mapper (ETM+) has 8 bands and medium-scale geometric resolution. ETM+ multispectral and panchromatic (Pan) images have ground

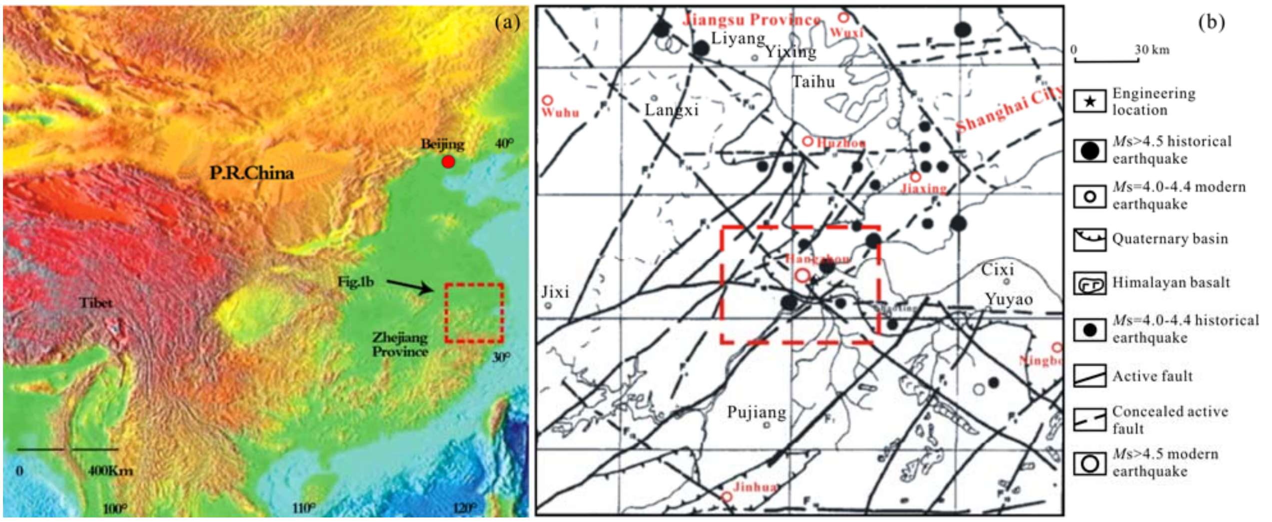

Figure 1. (a) The topographical map of China (Wang, 2003); (b) structural and geological map of the northern part of Zhejiang Province, the Hangzhou area lies in the red box.

resolutions of 30 and 15 m, respectively, and can be used not only to discern macroscopic characteristics of active faults such as geometric structure, geomorphic characteristics, spatial distribution and contact relationships of fault zones, but analyzing abnormal information correlated with movement characteristics of active faults, but also abnormal hydrogeological information, concealed information and secondary characteristic information. At present the economy of the Hangzhou area is developing very fast and natural landscape features are being rapidly destroyed by human beings. ETM+ images that accumulated over several decades are therefore precious. In addition, we have studied radar satellite images that have the ability for all-weather work and penetrate the surface to obtain more information in addition to multispectral data to validate and supplement our conclusions.

Band Combination

Band combination is important for extracting information about active faults. Different band combinations demonstrate different effects in different areas (Fu and Awata, 2007). The principle of choosing the best band combination usually has two requirements: (1) the chosen band combination must have maximal information; (2) the chosen band combination must most readily distinguish different categories of features' boundaries. At present, the common method of choosing band combinations is to compute information contents of different band combinations, information correlations of different band combinations and joint entropy of different band combinations. Variance (standard deviation) reflects the general dispersed degree of image grayscale values and is the simplest measurement for judging the amount of information in remote sensing images. Generally speaking, for primitive image data with the same quantification rank, the larger the variance (standard deviation) is, the more information it contains (Kusky and Ramadan, 2002).

We chose a part of the image to compute the correlation of each band combination and analyze the correlation coefficient (Table 1). The results showed that Band 1 has the most abundant information content, with Band 5 and Band 4 equal second. Because different bands of the same feature have distinctive correlations, we need not only the maximal variance (standard deviation), but also the minimal correlation when selecting the best RGB band combination. Band 1, Band 2 and Band 3 belong to the visible spectrum and have high correlations, so only one of the three bands was selected. Band 5 and Band 7 belong to the middle infrared spectrum and their reflecting information is very similar. Near-infrared Band 4 and the thermal-infrared Band 6 are special spectra and the correlation coefficient between the two and other bands is very small. Although Band 6 is especially sensitive to temperature, its spatial resolution is low (only 60 m), so it is not suitable for extracting structural information of active faults. In summary, according to geological tectonic characteristics of active faults of the Hangzhou area, we adopted optimal 741 band combination false color composites as the best plan. This band combination has information from the mid-infrared, near-infrared and visible spectrum, and has extremely abundant image color information, geological information and environmental information from the Earth's surface. It also has high image clarity and little interferential information and can reflect the differences of lithology, structure, thickness, water-bearing and tone in the areas covered by unconsolidated Quaternary sediments. Therefore it is especially suitable for interpreting active faults of the Hangzhou area where the geological situation is complex, surface denudation is intense, surface exposures are lacking because of artificial destruction, and the vegetation and river systems are widely developed.

Table 1 Correlation coefficients for each band and statistics of the spectral information

	TM1	TM2	TM3	TM4	TM5	TM6	TM7	Standard deviation
TM1	1	0.965	0.914	0.580	0.432	0.220	0.416	34.96
TM2		1	0.978	0.772	0.624	0.194	0.641	20.12
TM3			1	0.810	0.598	0.151	0.622	26.18
TM4				1	0.710	0.332	0.658	29.71
TM5					1	0.668	0.978	32.85
TM6						1	0.685	18.24
TM7							1	25.63

Concealed Abnormal Information Treatments

Abnormal spectrum information in remote sensing images may reveal concealed abnormal information closely related to the faults' activity. Active faults can cause certain substances to gather exceptionally at the surface and affect growing vegetation, leading to anomalies in the electromagnetic spectrum reflected from the surface. Active faults can also cause unusual behavior of river systems, for example, stream displacement, stream dispersion and stream convergence. Moreover, linear arrays of strata, rock masses, loose deposits and vegetation can influence interpreting concealed Quaternary active faults. We should not only distinguish such interpreted evidence accurately, but also use special image treatments before extracting weak abnormal information (Zhang et al., 2004). The usual methods are as follows: (1) Spectrum Information Enhancement, for example, color composites, linear strength, image fusion, and principal component transformation. (2) Spatial domain processing, for example, edge enhancement, Hoffman transform, filtering etc.. (3) Fractal geometry processing, for example, image texture analysis based on fractal geometry, multiple fractal analysis etc.. (4) Ratio processing, different bands have correlated substance characteristics and non-correlated substance characteristics respectively. We can achieve the goal of extracting weak abnormal information by highlighting these non-correlated substance characteristics by ratio processing. Usually, the smaller the correlation is, the better the ratio effect. (5) Wavelet transformation, which can analyze both macroscopic and microscopic image characteristics that play an important role in extracting weak abnormal information about concealed active faults. In the Hangzhou area, linear strength, image fusion, edge enhancement, texture analysis and wavelet transformation are all used to interpret active faults.

No matter which means and methods are adopted, the final goal is to stress prominently useful information (for example, active fault information) and separate abnormal information (for example, concealed information and weak abnormal information). It is very helpful and convenient for the geologists and seismologists to analyze, to interpret and extract the information about active faults in order to study and appraise their activity and harmfulness.

Evidence for Active Faults

The active faults of the Hangzhou area are mainly old faults which have been active since the Quaternary times. They are further divided into two kinds of types: (1) active faults exposed in mountainous areas; (2) active faults concealed in the Quaternary plain and basin (Sieh and Jahns, 1984). According to the remote sensing images and field survey, the interpretation evidence of active faults of the Hangzhou area may be summarized as follows.

(1) Clear and continuous lineaments.

(2) Different boundaries of terrains, landforms and strata, or large scaled linear abnormal tone belts.

(3) Dislocation and displacement of mountains, ridges and valleys (Fu et al., 2004).

(4) Aligned arrangements of alluvial fans and vegetation (Walker, 2006).

(5) Special types of river systems, for example a straight reach of a river or a meandering course. Inflexion points of a river indicate changes of direction; this kind of phenomenon is usually considered as typical evidence of neotectonic uplift.

(6) Characteristics visible in Cenozoic basins, for example, obviously displaced and sinuous rivers, boundaries of abnormal tone and geometric characteristics.

(7) Small scale discontinuous linear images cut by different landforms.

RESULTS AND DISCUSSION

Hangzhou is the political, economic and cultural center of Zhejiang Province (Wang, 2003). Under the influence of many tectonic movements, episodic folds and faults have developed in the Hangzhou area and its surroundings. By means of tectono-geomorphological interpretation of remote sensing images as well as traditional geological analysis and field surveys, we conclude that three groups of faults developed in the Hangzhou area. The Xiaoshan- Qiuchuan fault zone and the Majin-Wuzhen fault zone trend NE. The Xiaofeng-Sanmenwan fault zone and the Qiancun-Guali fault zone trend NW and the Changhua-Putuo fault zone trends E-W (Fig. 2).

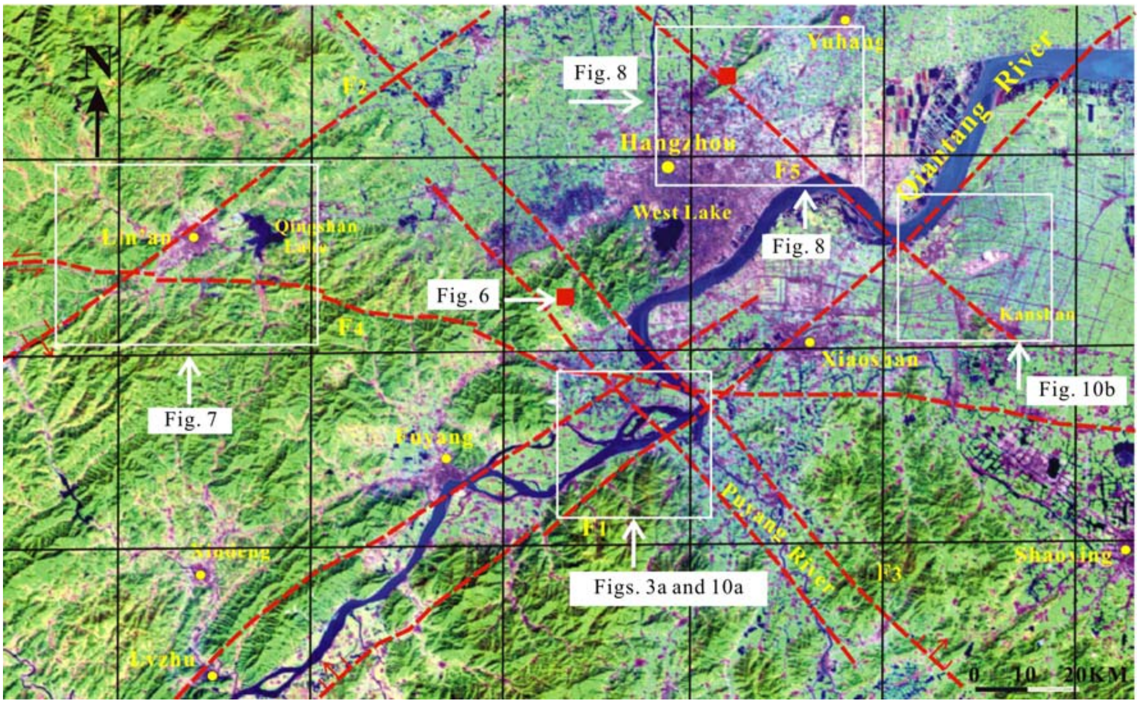

Figure 2. Structural interpretation results of the Hangzhou area and its surroundings; red lines are the faults and red solid rectangular areas are quarry profiles.

The Xiaoshan-Qiuchuan fault zone (F1) is composed of a group of parallel NE-trending faults with a width of 5–7 km, the section that passes through the Hangzhou area is about 42 km long and mostly concealed beneath the Hangjiahu Plain (Zhang et al., 2008a). Obvious images generated from the overlay of the remote sensing (ETM+) data and digital elevation model (DEM) data provide a useful tool for mapping topographic features along the Xiaoshan-Qiuchuan fault zone. Geomorphologically, it constitutes a long narrow ridge, valley and dale. Meanwhile, obviously different tone and texture characteristics can be seen on both sides of the ruptures, which show that the faults have not been cut and eroded for a comparatively long time. The three-dimensional (3D) perspective ETM+ image shows that Jurassic volcanic rocks, green to darkish green in the satellite images, have been cut by the Xiaoshan-Qiuchuan fault zone (Fig. 3a). At the same time, besides perpendicular movements, the fault also has a strongstrike-slip component, which has made the Qiantang River obviously sinuous. Near the Fuchun Reservoir, the fault controls the deposition and development of Quaternary diluvian fans. Moreover, we can also see the clear demarcation line of completely different relief unit and large scale linear abnormal tone belt (Fig. 3b). According to the features introduced above, we conclude that the Xiaoshan-Qiuchuan fault zone has been likely to be active since Late Pleistocene.

The Majin-Wuzhen fault zone (F2) passes through the northwestern Hangzhou area and most of them are covered by Quaternary unconsolidated sediments, only having some fragmentary outcrops at Machetou Village (Zhang et al., 2007). Due to the progradation of the Qiantang River, the Holocene deposition is the thickest in the south and may reach a thickness of more than 60 m; it turns thinner northward and only about 30 m thick somewhere (Ye, 2001). From the satellite images we can see that the vegetation is distributed on both sides of the fault (Fig. 4a) and aligned in a certain direction. The fault develops in the basin covered by thick marine strata composed of Holocene grey silt-mud loam and clay, and makes the valley, ridge and streams nearby obviously sinuous and displaced. We carried out field survey to validate our geologic and geomorphic interpretation of the satellite images and found a fragmentary outcrop at Machetou Village (Fig. 4b). The outcrop shows that the fault cuts the Cambrian shale and the Upper Pliocene loess. We sent the samples of fault gouge obtained from the sampling points to the Institute of Geology of China Earthquake Administration and the electron spin resonance (ESR) dating is about $(117.9\pm11.5)\times10^4$ a B.P., which shows that the active age of this fault is mid Pleistocene. The Institute of Earthquake Engineering of Zhejiang Province has done a lot of work on the Majin-Wuzhen fault zone and concluded that this fault may have been active in the Mid-Quaternary or the Late Quaternary (Yao et al., 2008).

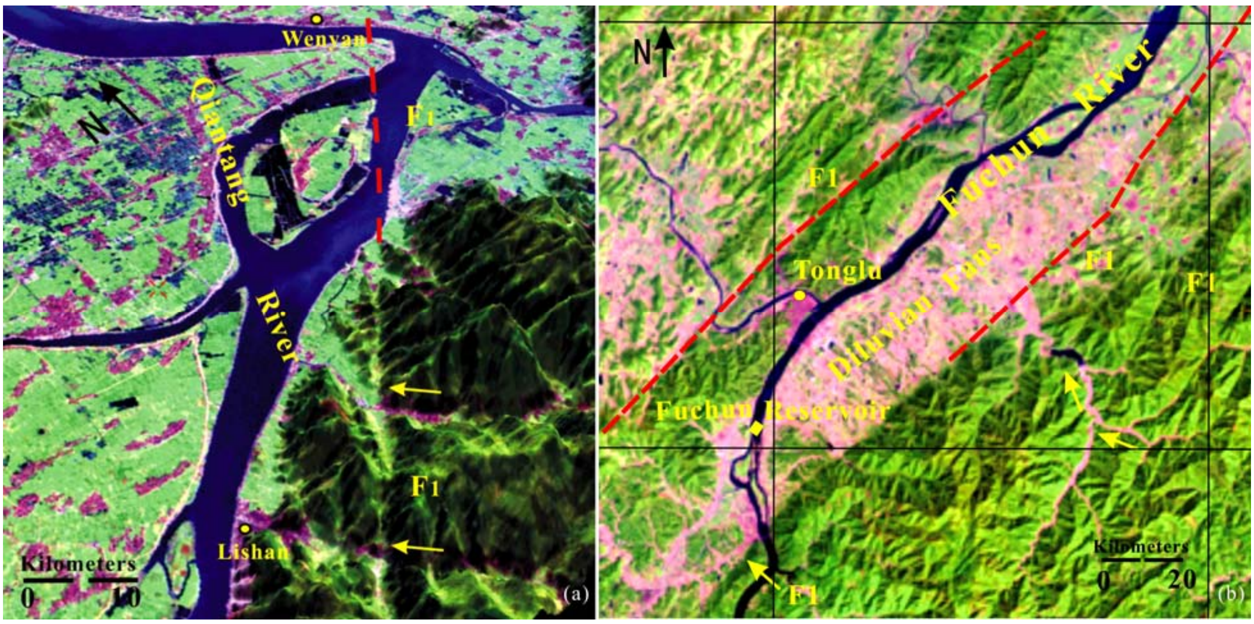

Figure 3. (a) 3D image of the long narrow ridge and sinuous river; (b) diluvial fans at the fault and the demarcation line of different relief units; red lines, fault; and yellow arrows point to significant features.

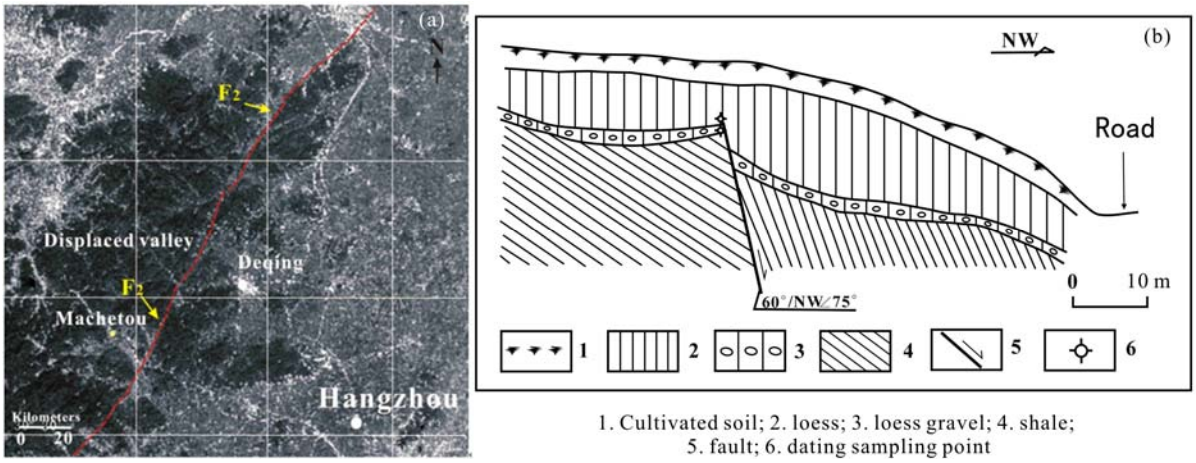

Figure 4. (a) The sinuous fault line valley, red lines, fault; yellow arrows point to significant features; (b) profile at Machetou quarry, the fault cuts Cambrian shale and Upper Pliocene loess.

The Xiaofeng-Sanmenwan fault zone (F3) is about 100 km wide and passes across the Hangzhou area from NW to SE (Fig. 5a). From remote sensing images we can recognize a variety of fault-bounded structures, such as systematically deflected rivers, shutter ridges and straight dales showing that this fault has been eroded for a comparatively long time and sinistral compression shearing occurred in the overlying strata (Zhang et al., 2008b). The most common features of active faults are successive offsetting, bending or termination of a series of laterally continuous reflectors (Wang et al., 2006). This fault diverts the main northeastern stem of the Qiantang River into a right-angled bend and controls the course of the Puyang River, a tributary of the Qiantang River. Geometry and tectono-geomorphological features suggest that the formation and evolution of the Qiantang River was controlled by cumulative movements of the Xiaofeng-Sanmenwan fault zone (Fig. 2). The displacements of rivers and other structures due to the Xiaofeng-Sanmenwan fault zone show that the structural characteristics appear to be transpression and thrusting with dextral slip during an earlier stage and sinistral slip later under different conditions. The fault shows high consistency with aeromagnetic anomaly data (Fig. 5b). Through field survey, we found a clear fragmentary outcrop at Longwu quarry. This fault cuts Ordovician limestone and the upper part was covered by unconsolidated Quaternary sediments. Optical stimulated luminescene (OSL) dating is about $(24.9\pm2.6)\times10^3$ a B.P. (Fig. 6), which further proves that this fault was active in the late Pleistocene. This fault controlled contemporary earthquakes in the Hangzhou area such as the 1998 Shengxian Earthquake of *M*s 4.5 magnitude about 100 km away from the Xiaofeng-Sanmenwan fault zone and might cause future damage to Hangzhou.

The Changhua-Putuo fault zone (F4) passes across the northern part of Zhejiang Province, and is composed of several discontinuous parallel faults with a width of about 3–7 km (Fig. 7a). It is the dividing line between the northern depressed basins and southern uplifted mountains of the Hangzhou area. Based on geomorphological evidence we can observe a group of discontinuous linear systems extending to the east, and the characteristics of discontinuous valley and dale, fault scarps and fault facets show that this fault has been cut and eroded for a comparatively long time (Zhang et al., 2008c). This fault makes displaces, tilts and distorts mountain ridges, gullies, roads, stream banks, edges of alluvial fans and terraces. It causes depression and uplift of strata, repetitions and flaws, sudden changes of rock types and crush zones. These characteristics are displayed in remote sensing images mainly as differences of tone and grayscale and form massive patches (Fig. 7b). According to the geological and tectono-geomorphological features we can conclude that this fault may have been active in the Mid-Quaternary or Late Quaternary. In addition, many earthquakes of 2.3 magnitude and above have occurred near the Changhua-Putuo fault zone in modern history (Table 2) and along this fault we can see a large temperature anomaly zone from west to east. Near the fault, there are some hot wells at Tuankou town whose temperature remains constant about 26 ℃ all the year (Xie, 1992).

The Qiancun-Guali fault zone (F5) passes through the northeast part of the Hangzhou area with a length of about 35 km and most of it is covered by unconsolidated Quaternary sediments to a depth of about 80–120 m, there are only two separate clear fragmentary outcrops at Banshan Village and Kanshan Village (Zhang et al., 2007). From the remote sensing images we can observe that this fault causes obvious

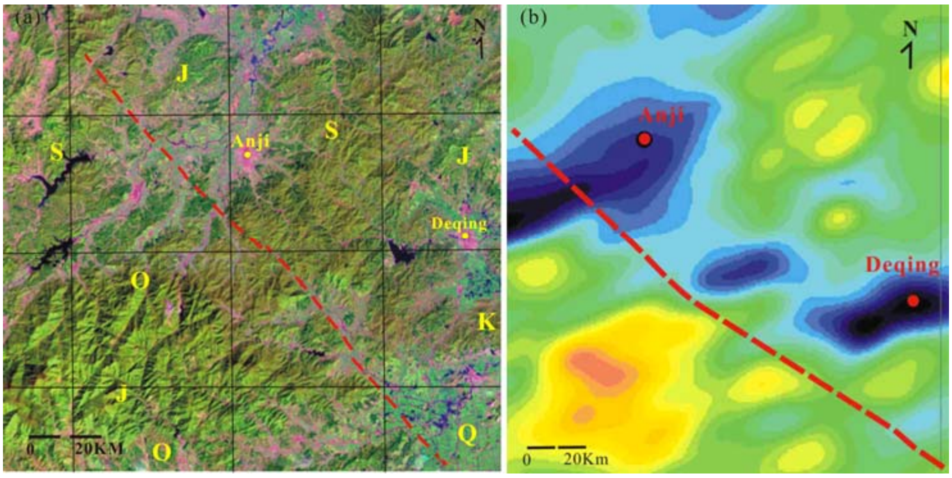

Figure 5. (a) The deflected river, shutter ridge and straight dale cut by the Xiaofeng-Sanmenwan fault; (b) the aeromagnetic anomaly image shows the distribution of the fault; red lines are the fault.

Figure 6. Profile of Longwu quarry. Red triangles are sampling points for OSL dating.

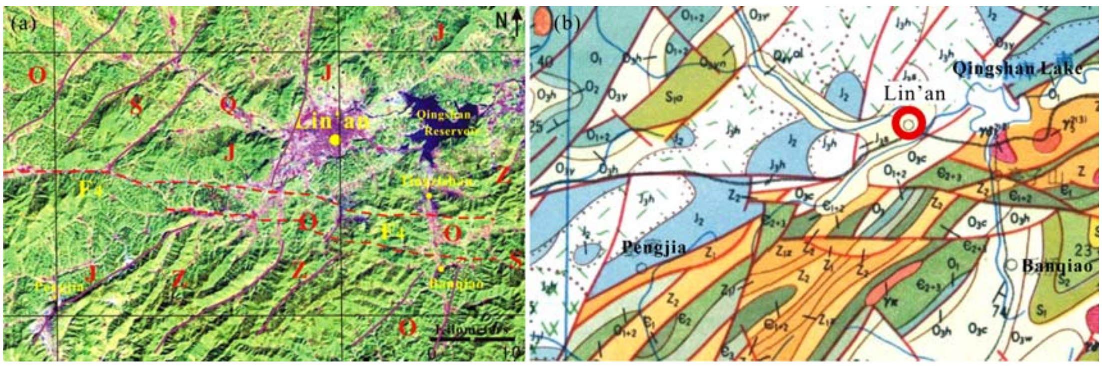

Figure 7. (a) The tectonic map of the Changhua-Putuo fault zone in the Lin'an area; (b) the displaced mountainous ridge, gully and stream bank displayed in the remote sensing image.

sinuosity of the main stream of the Qiantang River (Fig. 8a), which shows that the fault controlled the distribution and development of the Qiantang Sea Basin. The fault is obviously controlling the topography, physiognomy and water systems, which provides convincing evidence of neotectonic movements in the Qiantang Sea Basin. We carried out a field survey at Banshan Village and saw that the fault clearly cut Devonian sandstone and mudstone with the characteristics of a normal fault and strike-slip fault and extends to Quaternary deposits in the upper part of the profile (Fig. 8b). The Xi'an Branch of the China Coal Research Institute has carried out shallow seismic exploration across the Qiancun-Guali fault zone, discovering obvious dislocation of the bedrock and lower boundary of the Quaternary (Fig. 9). The Institute of Earthquake Engineering of Zhejiang Province studied the activity of the Qiancun-Guali fault zone at Jiubao village and in nearby boreholes. The results show that the age of activity may be Late Quaternary (Ye, 2001).

In order to extract and analyze further active structural information and enhance the precision of geological interpretation and definition of different ground objects, we carried out image fusion of ETM+ image and Radarsat-1 image (Fig. 10a). This method makes use not only of high spectrum resolution and profuse color information, but also the high geometrical resolution of the radar image and its characteristics of all-weather work and penetration of the surface (Zhang et al., 2007). At the same time, we have carried out superimposition analysis of remote sensing images and digital elevation model (DEM) data to obtain three-dimensional (3D) dynamic simulation images and observe the faults from different angles and different viewpoints (Fig. 10b). On the basis of all the means and methods introduced above, we extracted and analyzed information about each of the main active faults separately and have drawn a structural interpretation chart of the Hangzhou area and its surroundings.

Table 2 Earthquake catalogue of the Changhua area

No.	Time of earthquakes occurrence	Epicenter location			Magnitude (*M*s)
		Latitude (°)	Longitude (°)	Place name	
1	1739-05-01	30.1N	119.3E	Changhua	3.5
2	1743-10-11	30.2N	119.2E	Changhua	3.0
3	1915-02-15	30.2N	119.2E	Changhua	3.0
4	1976-03-21	30.1N	118.6E	Baiguo	2.4
5	1976-09-15	30.1N	118.6E	Baiguo	3.2
6	1983-03-15	30.1N	119.3E	Changhua	2.3

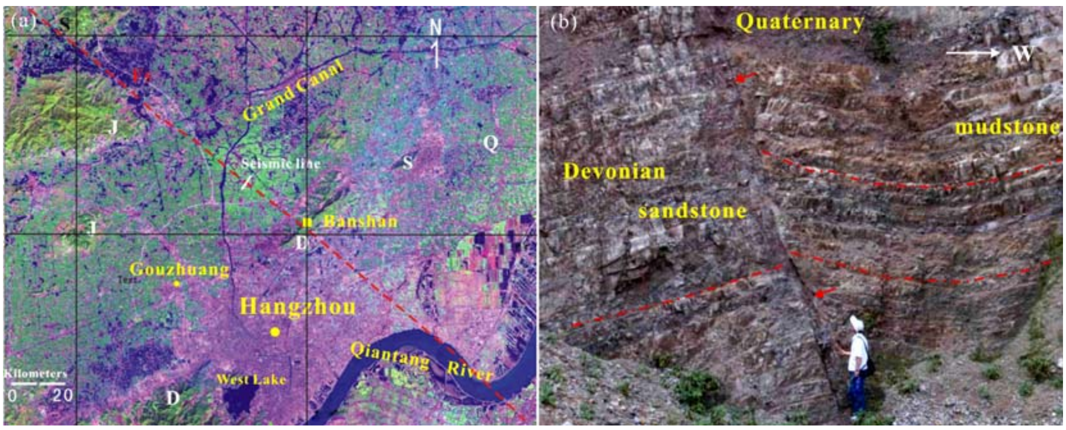

Figure 8. (a) A bend in the Qiantang River made by the fault; the red line is the fault and white line is the seismic exploration section; (b) the fault cutting Devonian sandstone and mudstone, red line shows fault breccia.

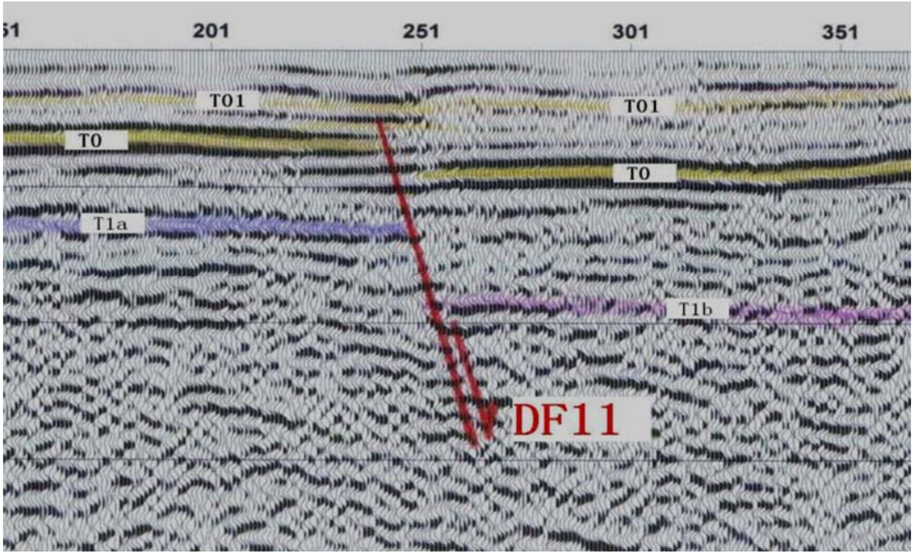

Figure 9. Fracture surface of the fault displayed in a shallow artificial seismic exploration profile; T0 is bedrock and the fault cuts the lower boundary of the Quaternary (T01). The fault dips northeast.

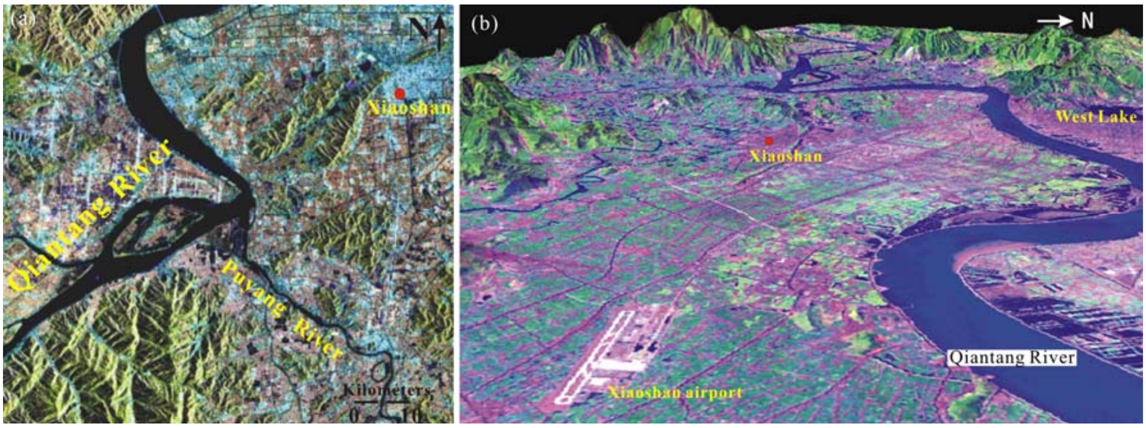

Figure 10. (a) Image fusion of ETM+ and Radarsat images; (b) superimposition analysis of RS images and DEM.

CONCLUSIONS

This paper discusses the theory and technical approach of active fault exploration using remote sensing techniques in an area where there are concealed active faults covered by unconsolidated Quaternary sediments. The results are as fo1lows: (1) ETM+ images provide the best data for interpreting active faults in urban areas. (2) We reviewed the theory of interpreting active faults and identified five active faults in the Hangzhou area by extracting concealed information, weak abnormal information and secondary characteristic information. (3) We adopted several kinds of digital image processing methods to identify the characteristics of these features and improve the extraction of high quality image information about active faults. (4) The activity of the major faults in the Hangzhou area is not strong and the five identified faults have all been inactive since the Holocene. The Xiaoshan- Qiuchuan fault zone and the Xiaofeng-Sanmenwan fault zone may have been active since the Late Pleistocene. (5) In terms of seismotectonic settings, the Hangzhou area has a potential of earthquake occurrence and "Taiwan dynamic antenna" has a weak impact on the region.

Satellite remote sensing technique is very useful in active fault exploration. It can make full use of the advantage of a large amount of data, broad scope, macroscopically dynamic monitoring of the Earth's surface activity and effectively overcome insufficiencies in traditional fault survey techniques. However, active fault exploration and seismic risk assessment in urban areas requires a complex systems engineering and involves numerous subtopics of various fields. Remote sensing techniques should be further used and promoted in active fault exploration and become an effective supplement to conventional exploration methods, such as geophysical methods, geochemical methods and so on. We believe that with the enhancement of high satellite spatial and spectral resolution, the improvement of image processing technique and the abundance of interpretation features, remote sensing techniques will play a more important role in the urban active faults exploration.

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