Adaptability of ESR dating of fault gouge in aseismic region: A case study on Hangzhou region, China^{*}

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Abstract

ESR dating has been widely used in seismic assessment. In this paper, we collected fault gouge samples systematically for ESR (Electron Spin Resonance) dating, and sediment samples of overlying strata, and offset strata for OSL (Optically Stimulated Luminescence) dating along Xiaoshan-Qiuchuan fault (XQF) trending NE-SW, Xiaofeng-Sanmen fault (XSF) trending NW-SE, and Changhua-Putuo fault (CPF) trending E-W. In the same fault outcrop, the ESR data of fault gouge is greater than the OSL data of the strata offset by fault. Therefore, the ESR data of fault gouge collected in Hangzhou region do not represent the time of weak fault movement in Late Quaternary region, but represent the strong fault movements in Late Cenozoic. The episode of fault movement in Late Cenozoic could be speculated according to the ESR data: 1.00~0.58 Ma, there were strong fault movements along the XSF, XQF and CPF in Hangzhou region; 0.58~0.45 Ma, the fault movements of all faults became weaker and did not zero ESR signals significantly for ESR dating of fault movements; 0.45~0.20 Ma, there were strong fault movements along part of XQF; 0.1~0.01 Ma, there were fault movements along the XSF only, but the fault movements were not strong enough to reset the ESR signal; Since 0.01 Ma, the Hangzhou region tends to be stable. In addition, the XSF might be the division line of fault segmentation of XQF; there were strong fault movements along the southwest segment of XQF during 0.45 Ma to 0.20 Ma; while the fault movements along the northeast segment of XQF mainly occurred during 1.00~0.58 Ma.

Key words: fault gouge; ESR dating; fault activity; Xiaoshan-Qiuchuan fault; Hangzhou region

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Introduction

Since Ikeya (1982) presented that ESR (Electron Spin Resonance) dating of fault gouge could be accepted as an actual time of latest fault movement, the ESR dating has attracted a lot of

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attentions from geologists (CHEN and PENG, 1991; SUN *et al*, 1999; Skinner, 2000; LIN *et al*, 2005; YANG *et al*, 2006). In recent years, geologists began to doubt the reliability of ESR dating in aseismic region (Fukuchi, 2001). The depth of overlying strata, water content and the strength of fault movement controlled the resetting of ESR signal (CHEN and PENG, 1991; Fukuchi, 1993, 2001; LI *et al*, 1999). The ESR data of fault gouge can be accepted as the time of the latest fault movement in intensive seismic area which could be deduced with the OSL (Optically stimulated luminescence) or TL (Thermoluminescence) data of overlying strata, and offset strata (WANG *et al*, 2002; YU *et al*, 2004). However, the adaptability of direct ESR dating of fault gouge in aseismic region is still dubious.

During the study on fault activities in Hangzhou region, the ESR dating method of fault gouge and the OSL dating method of sediments were used to confirm whether the ESR data match the latest fault movement in aseismic region.

1 Geological background

Hangzhou region locates in the east of Lower Yangtze area and mainly consists of NE-SW trending structures. There are three groups of faults in the region: faults trending NE-SW such as Xiaoshan-Qiuchuan fault (XQF), faults trending E-W such as Changhua-Putuo fault (CPF), and faults trending NW-SE such as Xiaofeng-Sanmen fault (XSF). All the faults had several active stages that made the structure more complex (HUO *et al*, 2004). Since Quaternary, the fault movement became weaker than before and made Hangzhou region be a typical aseismic region. There are four moderate history earthquakes ($M \geq 4.0$) in the region: Hangzhou earthquake occurred in 929 ($M5.0$), Fuyang earthquake occurred in 1855 ($M4.75$), Haining earthquake occurred in 1867 ($M4.75$) and Wukang earthquake occurred in 1911 ($M4.0$) (ZHONG and YAO, 2000).

There are several TL data of fault gouge collected from the bedrock of the three faults. The TL data shows that the latest fault movements of the three faults occurred during the late middle Pleistocene to the early stage of late Pleistocene (YE, 2001; DING *et al*, 2003).

2 Sample locations and data analysis

For the XQF, CPF and XSF in Hangzhou region, 26 samples of fault gouge for ESR dating and 8 samples of sediments for OSL dating were systematically collected. The sample locations are showed in Figure 1, the sample environment is listed in Table 1, and the photographs of outcrop for sample collection are given in Figures 2. The samples for ESR dating were collected from unconsolidated, no secondary mineral inside

Figure 1 Sample locations in Hangzhou area
XQF: Xiaoshan-Qiuchuan fault; XSF: Xiaofeng-Sanmenwan fault; CPF: Changhua-Putuo fault

Figure 2 Photographs of fault gouge samples in Lingqiao Town
(a) Artificial outcrop; (b) Sampling position which is labeled with a black triangle

Table 1 Sample information and the data of ESR, OSL and TL

Geographic location	Sample number	Dating method	Fault	Lithology	Fracture width/cm	Sample position in fracture zone	Data/ 10^4 a B P	
Longshan Chemical Plant	LS-23-1	ESR	XQF	B/B	1020	Fault plane	24.10±2.40	
	LS-23-2					Middle of fracture zone	34.40±3.40	
	LS-23-3					End of fracture zone	41.70±4.20	
Wangjiawu	WJW-23-4			B/B	100	Fault plane	43.20±4.00	
Xianghu Farm	XH-23-5			B/B	80	Fault plane	83.50±8.40	
Lingqiao	LQ-3-1			B/B	50~80	Fault plane	29.00±3.00	
Qiushan Quarry,	MQT-7-1			B/B	100	Fault plane	12.80±1.30	
Muqiaotou Town	MQT-7-2			B/B	120	Fault plane	19.50±2.00	
Muqiaotou Town	MQT-8-1			B/B	40	Fault plane	25.90±2.60	
Changhe trench	CH-01			OSL	—	—	Overlying sediments	2.63±0.27
	CH-02	ESR	B/B	<20	Fault plane	87.00±6.70		
Huangdongling trench	HDL-03	OSL	—	—	Overlying sediments	4.09±0.44		
	HDL-05		—	—	Displaced stratum	5.12±0.56		
	HDL-06		ESR	S/S	<10	Fault plane	36.00±2.80	
Luoshan, Lingqiao Town		TL	B/B	—	Intra fault	10.40±0.90		
Dahengshan Quarry, Haining City		TL	B/B	—	Intra fault	7.01±0.60		
Qingshan Quarry Trench, Longwu Town	LW-2-1	ESR	XSF	B/B	100	Fault plane	82.10±8.00	
	LW-2-3			B/B	100	Fault plane	62.50±6.30	
	LW-2-4			B/B	100	Fault plane	79.80±8.00	
	LW-2-5			B/B	100	Fault plane	86.40±8.50	
	LW-5	OSL		—	—	Displaced stratum	2.49±0.26	
	LXLW-01	—		—	Overlying sediments	1.65±0.17		
	Tea File Trench, Longwu Town	LXLW-02		OSL	—	—	Displaced stratum	1.91±0.21
		LXLW-08			—	—	Displaced stratum	2.75±0.28
		LXLW-09			—	—	Overlying sediments	4.20±0.42
Dalingtou Quarry, Liuxia Tow		TL	B/B	—	Intra fault	11.65±0.99		
Linshan	LS-3-1	ESR	CPF	B/B	20	Fault plane	72.30±7.00	
	LS-4-1			B/B	20	Fault plane	93.40±9.00	
Yaojiawu Quarry	YJW-6-1			B/B	200	Fault plane	78.50±7.90	
	YJW-7-1			B/B	20~30	Fault plane	65.70±6.60	
Fengjia Quarry	FJ-8-1			B/B	550	Fault plane	79.70±8.00	
	FJ-9-1			B/B	40	Fault plane	71.60±7.20	
Lingjiaqiao Town	LJQ-11-1			B/B	100	Fault plane	58.90±5.90	
Jingshanling Trench	LXJS-3			OSL	—	—	Overlying sediments	1.97±0.21
	LXJS-1				—	—	Displaced stratum	1.83±0.21
Zhuantang Town				TL	B/B	—	Intra fault	12.79±0.95

Note: B/B: Both the hanging wall and the foot wall consist of bedrock; S/S: Both the hanging wall and the foot wall consist of loose sediment of Quaternary.

fault gouge along the fault plane. The sediment samples were collected from clay and fine sand with some gravel inside. The dating was finished by Institute of Geology, China Earthquake Administration (IGCEA). The ESR data was obtained on E' center in quartz. The OSL data was obtained on simplified multiple aliquot regenerative-dose (MAR) using Post-IR OSL. The data is listed in Table 1.

3 Adaptability of ESR dating

3.1 Comparison between the ESR data and OSL data obtained in Huangdongling trench

Several prospecting trenches were excavated in Hangzhou region in order to study the time of the last fault movement and the characteristic of fault activity. In Huangdongling trench, both the ESR data of fault gouge and the OSL data of sediments were collected. Six faults were exposed in the trench which had several activity episodes (Figure 3). For example, the fault f_a was normal fault in early stage. That fault movements made the weathered bedrock of hanging wall slide down, and covered by Quaternary loose deposit. In contrast, the bedrock and deposits overlying was squeezed later by fault f_a which changed to thrust fault as other faults developed in loose deposit. The fault f_a was the major fault and its activity influenced the other faults. The ESR sample was collected from the grey, nearly consolidated fault gouge from the fault plane. The buried depth of ESR sample was 4 m. The ESR data of fault gouge was $(36.00 \pm 2.8) \times 10^4$ a B P. The fault f_a offsets the formation b , but hasn't extended to the top of that. The OSL data of the sediment which was offset by fault f_a is $(5.12 \pm 0.56) \times 10^4$ a B P, while the OSL data of the sediment overlying is $(4.09 \pm 0.44) \times 10^4$ a B P. Considering the successive deposition of formation b (Figure 3), the latest fault movement of fault f_a was later than $(5.12 \pm 0.56) \times 10^4$ a B P. Therefore, the ESR data of fault gouge is much older than the time of the latest fault movement. There is an offset between the ESR data and the OSL data.

Figure 3 ESR data and OSL data obtained in Huangdongling trench

The difference between the ESR data and OSL data are found in other trenches excavated in Hangzhou region. All the ESR data of fault gouge is greater than the OSL data of strata. The geochronological ages of fault gouge using ESR dating method is older than the time of the latest fault movement which can be limited by OSL data of overlying strata, and offset strata (Figure 4).

3.2 Comparison between seismic region and aseismic region

All the data of the three faults are showed in Figure 4. Most of the ESR data is greater than 0.20 Ma, only two ESR data is about 0.20~0.10 Ma. Most of the OSL data of overlying strata, and offset strata is about 0.05~0.01 Ma, whereas the TL data of fault gouge is about 0.12~0.07 Ma (Figure 4). All the ESR data is much greater than the OSL data and the TL data. Because of the different dating accuracy and age range, it is ineligible to compare the data directly. We use ESR data of fault gouge and TL data of overlying strata, and offset strata in Kunming region which is a typical seismic region to compare the adaptability of direct ESR dating of fault gouge in Hangzhou region which is a typical aseismic region. The TL data of fault gouge collected in Hangzhou region is few and unsystematic collected. Therefore, the TL data of fault gouge is used as supplement.

Figure 4 Result of ESR data, OSL data and TL data in Hangzhou region
TL data of gauge is from the following^{①②}

^① The Engineering Seismology Institute of Zhejiang Province. 2004. The fault activity research of Xiaoshan-Qiuchuan Fault (Fuyang-Yanguan segment), China.

^② The Engineering Seismology Institute of Zhejiang Province. 2001. The report on seismic safety evaluation of the Fourth Bridge engineering sites of Qiantang River, China.

Assuming ESR data of fault gouge, TL data of fault gouge, TL and OSL data of strata have the same stability and reliability, the variance $[D(\Delta T)]$ of different dating methods for the same segment of the same fault was obtained for data fluctuating. The magnitude of the largest history earthquake ($M_{\max}$) depicted in Figure 5 is considered as regional geological background.

$$\Delta T = E(T_{\text{ESR}}) - E(T_{\text{OSL}}) \text{ or } \Delta T = E(T_{\text{ESR}}) - E(T_{\text{TL}}) \quad (1)$$

$$D(\Delta T) = E\{[\Delta T - E(\Delta T)]^2\} \quad (2)$$

The ESR data of fault gouge, the TL and OSL data of sediment are stable in Hangzhou region and Kunming region. However, the offset of data using different dating methods fluctuate in Hangzhou region much more than that in Kunming region. As shown in Figure 5, the variance $[D(\Delta T)]$ of Hangzhou region is much greater than that of Kunming region. The variance is also related to geological background. The variance $[D(\Delta T)]$ has inverse proportion relation with the largest earthquake ($M_{\max}$). It indicates that the resetting of ESR signal has direct correlation with the seismic background. In seismic area, the fault movements are strong enough to reset the accumulated ESR signals completely at the time of fault movement and the ESR data of fault gouge are close to the latest fault movements. In contrast, the ESR data of fault gouge is much older than the OSL or TL data of overlying strata, and offset strata in aseismic region, since the ESR signal cannot be completely reset during the latest fault movement.

Therefore, the difference between the ESR data of fault gouge and OSL data of overlying strata, and offset strata due to the weak fault movement in Late Quaternary. The ESR signals of fault f_a in Huangdongling trench accumulated again since 0.36 Ma and had not been reset because the later fault movements were not strong enough.

For these reasons, the ESR data of fault gouge cannot be accepted as the time of the latest fault movement in Hangzhou region. On one hand, in aseismic region, the fault movements since late Quaternary were too weak to reset the ESR signals. On the other hand, the large offset between the ESR data and the time of latest fault movement represents the geological background of aseismic region.

Figure 5 Variance $[D(\Delta T)]$ of ESR data of fault gouge, OSL or TL data of overlying strata, and offset strata in Hangzhou region and Kunming region

4 Episodes of strong fault movements

Based on the above analysis, the ESR data of fault gouge in Hangzhou region cannot be accepted as the time of the latest fault movement. According to the resetting mechanism of ESR signals, the ESR data represents the episode of strong fault movements in Hangzhou region since Cenozoic (Fukuchi, 2001). The ESR data can be divided into two time zones: 1.00~0.58 Ma and 0.45~0.2 Ma (Figure 4). For the time zone of 1.00~0.58 Ma, there are eleven ESR ages of XQF, CPF and XSF. It probably represents that there were strong fault movements along the three faults

in Hangzhou region and the fault movements reset the ESR signal during 1.00 Ma to 0.58 Ma. From 0.58 Ma to 0.45 Ma, it is a blank time zone of ESR data. The blank zone indicates that the fault movements of the three faults were not strong enough to reset the ESR signals. From 0.45 Ma to 0.20 Ma, part of ESR data of XQF is in this time zone. It indicates that there were strong fault movements along part of XQF and the fault movements reset the accumulated ESR signals. However, there are no ESR data of XSF and CPF in this time zone. It means there was no strong fault movement along the XSF and CPF, or the fault movements were not as strong as XQF. We have not found any ESR data smaller than 0.1 Ma; In contrast, all the OSL data obtained from the trenches are less than 0.1 Ma. Considering that all the trenches locates along the XSF (Figure 1), the fault movements exposed in trenches (Huangdongling trench, Jingshanling trench, Qingshan trench, and Tea Files trench) were influenced by XSF. The OSL data of sediments indicates that there were fault movements along the XSF and its second fractures since 0.1 Ma. However, these fault movements were not strong enough to reset the ESR signals. Neither the ESR data nor OSL data is less than 0.01 Ma. It indicates that the Hangzhou region tends to be stable in Holocene.

Accordingly, the episodes of strong fault movements in Hangzhou region can be deduced as follows: from 1.00 Ma to 0.58 Ma, there were strong fault movements along the XSF, XQF and CPF; from 0.58 Ma to 0.45 Ma, the fault movements were not as strong as before; from 0.45 Ma to 0.20 Ma, there were strong fault movements along part of XQF; from 0.1 Ma to 0.01 Ma, there were several fault movements along XSF; Since 0.01 Ma, the Hangzhou region became an stable region. The episodes deduced from the ESR data are consistent with the neotectonic character of Hangzhou region. In middle Pleistocene, the mountainous area uplifted, and the fault movements occurred along NE-SW trending faults showed much more piecewise than that in early Pleistocene. At the same time, the NW-SE trending faults began to control the subsidence of plain (LI, 2004). The neotectonic character of Hangzhou region matches the episodes of fault movements concluded from the ESR data of fault gouge.

Based on the analysis of ESR data for XQF at the locations of fault gouge samples (Figure 6), The ESR data of fault gouge is subdivided into two parts bordered with XSF. In the southwest of XSF, most of the ESR data of XQF is less than 0.29 Ma which is in the episode of 0.45~0.20 Ma. It indicates that there were strong fault movements occurred along southwest part of XQF. In the northeast of XSF, all the ESR data of XQF are greater than 0.34 Ma, most of ESR data is in the episode of 0.1~0.58 Ma except the ESR data obtained from Longshan chemical plant. It indicates that there were strong fault movements along the northeast segment of XQF in early Pleistocene, but the fault movements became weaker later. The ESR signals began to accumulate at that moment.

Figure 6 Statistical analysis of ESR data of XQF

5 Conclusions

The adaptability of ESR dating of fault gouge in aseismic region is studied based on the analysis of the ESR data of fault gouge and OSL data of sediments for the NE-SW trending,

NW-SE trending and E-W trending faults in Hangzhou region. The fault movements were not strong enough to reset the ESR signals in Late Quaternary. The ESR data cannot be accepted as the latest fault movement but indicates the time of fault movements.

The fault activity of Hangzhou region became weaker gradually since Quaternary. The fault movements in Quaternary could be sorted to five episodes: ① there were strong fault movements along all the three faults; ② the fault movements became much weaker; ③ there were strong fault movements along the XQF with NE-SW trending; ④ there were weak fault movements along the XSF with NW-SE trending; ⑤ the Hangzhou region tended to be stable.

Above all, the adaptability of ESR dating of fault gouge in different geological background should be considered during the seismic risk evaluation. Besides the reset mechanism, special attention should be given to the sample collection and preservation, especially the estimation of moisture content, the influence of expected age for irradiation (LIN *et al.*, 2005), the influence of the later movements (Fukuchi, 2001). Furthermore, the improvement of measurement accuracy, dating material and geological application are urgently expected.

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Reference:

- CHEN Wen-ji and PENG Gui. 1991. Age dating to the young geological system [M]. Beijing: Seismological Press: 132-173 (in Chinese).
- DING Bo-yang, YE Jian-qing, MENG Fan-li, *et al.* 2003. The tectonics around Hangzhou and the fault's influence on construction [J]. *Journal of Zhejiang University of Technology*, **31**(3): 319-323 (in Chinese).
- Fukuchi T. 1993. Vacancy-associated type ESR centers observed in natural silica and their application to geology [J]. *Appl Radiat Isotopes*, **44**: 179-184.
- Fukuchi T. 2001. Assessment of fault activity by ESR dating of fault gouge: An example of the 500 m core samples drilled into the Nojima earthquake fault in Japan [J]. *Quaternary Science Reviews*, **20**: 1 005-1 008.
- HUO En-jie, LIU Chang-sen, ZHANG Zhen-quan, *et al.* 2004. *Study on the Fault and Its Activity in Shanghai Region* [M]. Beijing: Seismological Press: 23-32 (in Chinese).
- Ikeya M, Miki T, Tanaka K. 1982. Dating of a fault by electron spin resonance on intrafault materials [J]. *Science*, **215**: 1 392-1 393.
- LI Li-gang, HUANG Pei-hua, FU Rong-shan, *et al.* 1999. Frictional heating by stick slip and its significance for TL, ESR dating [J]. *Seismology and Geology*, **20**(4): 387-396.
- LI Zhi-hong. 2004. The geomorphic characteristics and evolution of Cenozoic, Northern Zhejiang Province [D][Master Dissertation]. Guangzhou: Department of Earth Science, Sun Yat-sen University: 36-39 (in Chinese).
- LIN Min, JIA Li, DING Yan-qi, *et al.* 2005. Dose determination in ESR dating research [J]. *Seismology and Geology*, **27**(4): 698-705 (in Chinese).
- Skinner R A. 2000. ESR dating: is it still an experimental technique? [J]. *Applied Radiation and Isotopes*, **2**: 1 311-1 316.
- SUN Ying-jie, LU Yan-chou, YIN Gong-ming. 1999. A study on ESR dating for the Dashuichang gouge profile of the Yishu fault zone [J]. *Seismology and Geology*, **21**(4): 346-350 (in Chinese).
- WANG Zhi-cai, CHAO Hong-tai, CUI Zhao-wen, *et al.* 2002. Quaternary activity of the NE-trending faults in Qingdao city and its surrounding area [J]. *Seismology and Geology*, **24** (2): 167-176 (in Chinese).
- YANG Kun-guang, LIANG Xing-zhong, XIE Jian-lei, *et al.* 2006. ESR dating: The principle and application of a method to determine active ages of brittle faults [J]. *Advances in Earth Science*, **21**(4): 430-435 (in Chinese).
- YE Jian-qing. 2001. Urban active faults and city building of Zhejiang Province [J]. *Shanghai Geology*, (4): 31-33.
- YU Wei-xian, XIE Ying-qing, ZHANG Jian-guo, *et al.* 2004. Age studies of major active faults around Kunming Basin [J]. *Journal of Seismological Research*, **27**(4): 357-362 (in Chinese).
- ZHONG Yu-yun and YAO Li-xun. 2000. Numerical simulation of strain field in north Zhejiang and its adjacent area and prediction for seismic hazard zone [J]. *Journal of Seismology*, **20**(3): 9-17.