Journal of Asian Earth Sciences 110 (2015) 85–100

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

The structural and tectonic relationships of the major fault systems of the Tan-Lu fault zone, with a focus on the segments within the North China region

Jiaodong Zhang [a,b], Tianyao Hao [a], Shuwen Dong [b], Xuanhua Chen [b], Jianjun Cui [b,*], Xiaoyong Yang [c], Chengzhai Liu [d], Tiejun Li [a], Ya Xu [a], Song Huang [a], Fenglou Re [d]

[a] Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, 19 Beitucheng Western Road, Beijing 100029, China
[b] Chinese Academy of Geological Sciences, 26 Baiwanzhuang Road, Beijing 100037, China
[c] School of Earth and Space Sciences, University of Science and Technology of China, 96 Jinzhai Road, Hefei 230026, China
[d] The Shengli Oil Company, 1 Jinan Road, Dongying 257100, China

ARTICLE INFO

Article history:
Received 14 April 2013
Received in revised form 5 November 2014
Accepted 6 November 2014
Available online 30 January 2015

Keywords:
Tan-Lu fault zone
Fault systems
Tectonic relationships
Meso-Cenozoic
Space–time framework

ABSTRACT

The Jiashan-Lujiang, Yishu and Bohai segments have been the most tectonically active parts of the Tan-Lu fault system since the Mesozoic. Any analysis of faulting processes in the Tan-Lu system is highly dependent on the relationships among the three segments. Here we divide the Tan-Lu system into three styles of faulting; strike-slip faulting, regional extensional faulting and listric normal faulting on the basis of EMAP data, seismic profiles and geological evidence. We suggest that: (1) the strike-slip faults, which formed in the Late Jurassic, include mainly the Jiashan-Lujiang fault, the deep parts of the Chihe-Taihu Fault and the Guhe-Sanbing fault; these three faults have had the most dramatic effect on the Jiashan-Lujiang segment. The strike-slip style of faulting produced a huge positive-flower structure that extends between the deep section of the Chihe-Taihu fault and the Guhe-Sanbing fault, and overlaps with the position of the Zhangbaling ductile shear zone; (2) the regional extensional style of faulting, whose characteristics are reflected best in the Yishu fault zone, is composed of the Changyi-Dadian, Anqiu-Quxian, Yishui-Yangtou and Tangwu-Gegou faults, all of which were active during the Early Cretaceous. These extension-dominated faults extend southwards to the Jiashan and Hefei Basins and die out in front of the Dabie Mountains; to the north, the faults penetrate the deeper parts of the Weibei depression where they controlled Cretaceous deposition in "graben-horst-graben" structures; (3) the listric normal faults, which were initiated in the Paleogene, generally occur around the Bohai Bay Basin, and include a series of NE-trending faults in the Weibei depression, such as the Tandong and Tanxi faults. These listric faults differ from the regional extensional faults in their localized occurrence and association with basin formation. Our study indicates that these three styles of faulting varied not only in timing and mechanical properties but developed at different levels at different locations, resulting in different tectonic relationships and the formation of different geologic features in the different segments of the Tan-Lu master system.

1. Introduction

The Tan-Lu fault zone is a giant Meso-Cenozoic tectonic mobile belt in eastern China, which is generally thought to begin near Lujiang, Anhui Province in the south, cross the eastern part of the North China Craton, and extend along the Yilan-Yitong fault and the Dunhua-Mizhi fault to the Far East region of Russia (Shi et al., 2012). The portion of the fault zone within the North China Craton has been the focus of many investigations ever since its discovery in the 1950s (Xu, 1964; Xu et al., 1987; Xu and Ma, 1992; BNSA, 1987; Gilder et al., 1999; Grimmer et al., 2002; Lin et al., 2005). It is of great importance because of its distinct faulting behavior, its significant control on the distribution of sedimentary and volcanic rocks, its extensive earthquake activity, and its abundance of associated mineral resources (Xu, 1964; Xu et al., 1987; Xu and Ma, 1992; BNSA, 1987; Gilder et al., 1999; Grimmer et al., 2002; Lin et al., 2005; Yan et al., 2010). This fault system is also of interest because it is closely related to questions regarding convergence of the Mesozoic East Asian Plate, breakup of the North China Craton and subduction of the West Pacific Plate (Dong et al., 2007; Sun et al., 2007; Zhu et al., 2011; You and Zhao, 2011; Zhang

* Corresponding author.
E-mail address: cagscjj@126.com (J. Cui).

http://dx.doi.org/10.1016/j.jseaes.2014.11.011
1367-9120/

et al., 2011; Chen et al., 2012). Research over the past few years has greatly increased our knowledge of the Tan-Lu system, particularly its fracturing geometry, rock mechanics, nature and distance of displacement, dynamic background and relationship to hydrocarbon accumulation and seismic activity (Xu et al., 1982, 2009; Zhai and Cong, 1996; Chen, 2005; Yang et al., 2007, 2008, 2009; Zhang et al., 2012a–c). On the basis of structural features, this fault system is generally divided into three segments - the Jiashan-Lujiang, Yishu and Bohai segments. Studies have shown that, despite all being located in the North China Craton, the three segments vary dramatically in their faulting behavior and active duration (Xu, 1964; Xu et al., 1987; Xu and Ma, 1992; BNSA, 1987; Wang et al., 2000). These studies have also documented the amount and nature of strike-slip movement on the Jiashan-Lujiang segment, the Meso-Cenozoic extension of the Yishu segment, and the Cenozoic faulting of the Bohai segment. Although some consensus has been reached on the evolution of these fault segments (Chen, 1988, 2005; Li et al., 2006, 2012; Teng et al., 2006; Zhu et al., 2006; Pierre et al., 2007), it is still unclear how they are linked structurally, and a number of gaps in our knowledge still exist: (1) Most geologists think that intense faulting took place on the Tan-Lu system in the Mesozoic, but there is still little evidence in the Bohai segment to support this conclusion. Did extensional faulting really occur in the Bohai segment in the Mesozoic? If it did, what is the tectonic relationship between Mesozoic extension and Cenozoic rifting? (2) Although a number of different views regarding the timing and scale of faulting on these segments have been put forward, most workers now agree that strike-slip movement occurred on the Jiashan-Lujiang segment during the Mesozoic while regional extension took place on the Yishu fault belt. However, no location has been found where evidence of both movements is preserved. If both movements occurred simultaneously, where is the transition zone between them? In order to investigate these questions in greater detail, we initiated the present study to combine EMAP data. seismic reflection profiling and surface geological studies, along with gravity and magnetic surveys to investigate the deep structure of these faults. This paper is intended to provide a reference frame for more detailed research of the Tan-Lu fault zone and to propose a new perspective for various controversies that have persisted for many years.

2. Overview of the geological structure

The Tan-Lu fault zone is an important Meso-Cenozoic magmatic, metallogenic and active seismic belt in eastern China (Wei et al., 1993; Wang et al., 2000). On the basis of seismic activity, nature of faulting and tectonic framework this portion of the system can be divided into three segments (Fig. 1), namely the Jiashan-Lujiang segment (also called the Suwan segment or the southern segment), the Yishu segment (the Shandong segment or Jiashan-Weifang segment) and the Bohai segment (Weifang-Shenyang segment or Weifang-Yingkou segment) (Xu et al., 1982; Liu and Tao, 2000; Zhang et al., 2003, 2007). Some geologists regard the Yishu segment and the Bohai segment to be the middle segment of the Tan-Lu system and consider the middle and southern segments as the south-central segment (Zhu et al., 2006; Zhang et al., 2007).

2.1. Jiashan-Lujiang segment

This segment, which is 15–30 km wide, extends 180 km from Jiashan County, Anhui Province on the north to Lujiang County on the south. It is bounded by the Hefei basin on the west and by the Suwan fold belt of the Yangtze Craton on the east. Historically, this segment is the key area for study of strike-slip faulting on the Tan-Lu system; it is commonly accepted that this segment includes both the Chihe-Taihu and Jiashan-Lujiang faults (Fig. 1). In the Zhangbaling area, a large NNE-trending ductile shear zone is located within the Kanji (Ar_2K), Feidong (Pt_1F) and Zhangbaling ($Pt_{2\text{-}3}Z$) Groups (ABGMR, 1987). This NNE-striking fault belt clearly affected deposition in Hefei Basin, which is known for its thousands of meters of Meso-Cenozoic sedimentary rocks that include the Lower Jurassic Fanghushan Group, Middle Jurassic Yuantongshan Group, Upper Jurassic Zhougongshan Group, Lower Cretaceous Xinzhuang Group, Upper Cretaceous Zhangqiao and Qiuzhuang Groups and Paleogene Dingyuan Group.

2.2. Yishu fault belt

This fault belt, which is 220 km long and 20–30 km wide, stretches from the Meso-Cenozoic Jiashan basin, Anhui Province on the south (Jie et al., 1992) to Weifang, Shandong Province on the north. Geographically, this region is characterized by hilly and mountainous landforms, is bounded by the Sulu orocline and Jiaolai basin on the east and the Luxi and Xushu oroclines on the west. This site has always been significant for research on Mesozoic regional extensional activity in the system (Wei et al., 1993; Wang et al., 2000). It includes four roughly parallel major faults: the Changyi-Dadian, Anqiu-Juxian, Yishui-Tangtou and Tangyu-Gegou faults constitute a typical structure characterized as “a horst sandwiched between two grabens”, in which the grabens were later filled with Tertiary pyroclastic and sedimentary rocks.

2.3. Bohai segment

The Bohai segment extends from Shenyang, Liaoning Province on the north to Weifang, Shandong Province on the south, and marks an area of intense Cenozoic tectonism. The present geology in this region mainly reflects Cenozoic activity, which produced a series of both large and small, listric normal faults with variable strikes. The southern part of this segment strikes generally NNE but at the Beijing-Penglai fault it bends eastward to form the margin of the Liaodong (eastern Liaoning) depression, causing a series of alternating uplifts and depressions in this area, including the Weibei depression, Weibei uplift, Laizhou Bay depression, Laibei uplift, Bodong uplift, Liaodong depression and Liaodong uplift. The eastern Ludong uplift is composed mainly of Pre-Cenozoic strata, whereas the western part (the Jiyang depression) contains rocks ranging in age from Archean all the way to the Neogene (Zhang, 2004; Zhang et al., 2009).

3. Data sources

Abundant new data and information were obtained between 1991 and 2007, during which the authors undertook, or participated in, a number of integrated geophysical and geological projects conducted by the Shengli Oil Company that involved most of the segments of the Tan-Lu fault zone in North China.

3.1. Two-dimensional seismic data

Seismic data acquisition was undertaken by the Shengli Geophysical Company (Table 1). Data processing was performed with the large SP2 parallel computer and OMEGA seismic data processing system developed in the United States. Depth migration was done based on the Kirchhoff wave equation after conventional processing in the time domain with a step of 4 m. The migration aperture was 1500 CMPs and the interval velocity increment was 10 m/s.

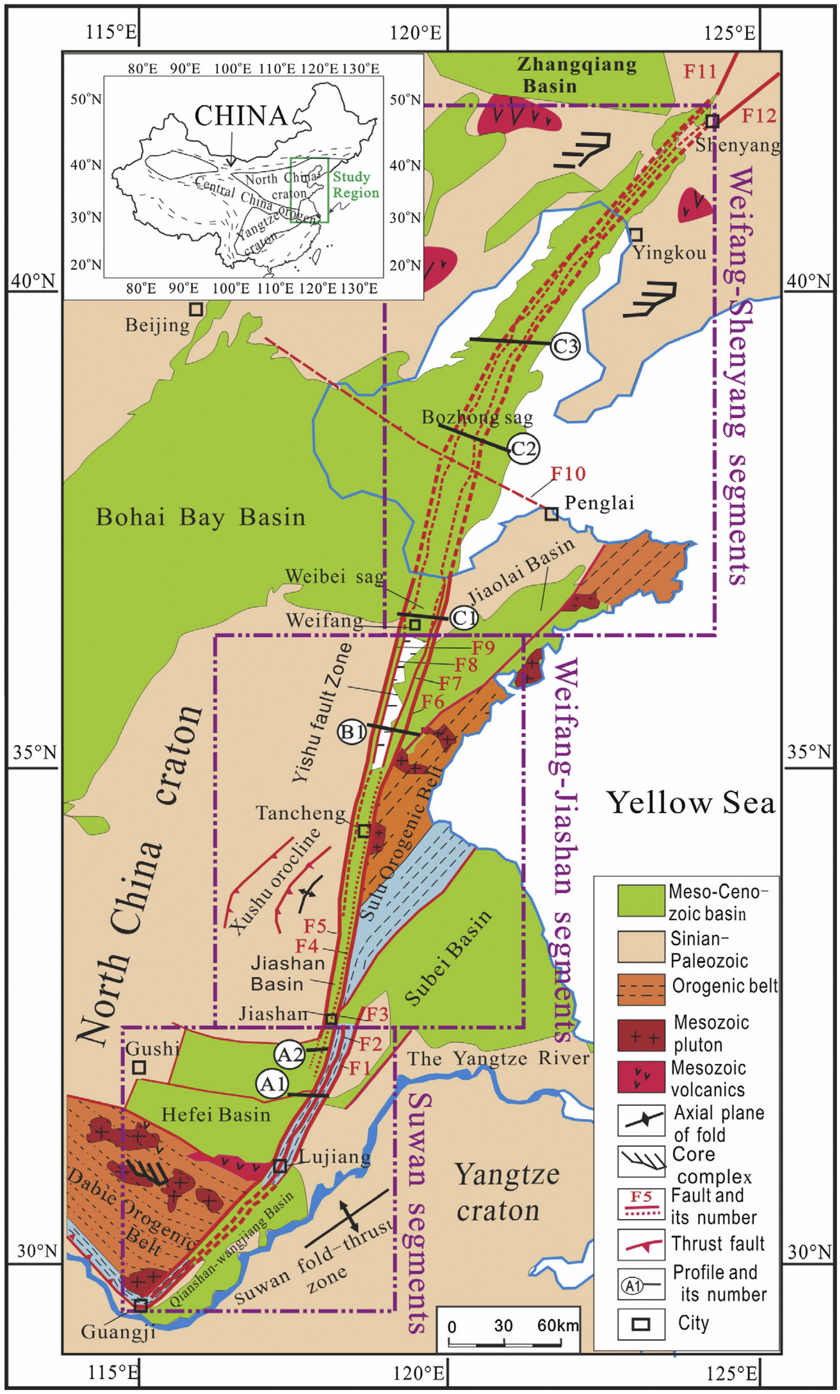

Fig. 1. Map showing the geological structure of the North China segments of the Tan-Lu fault zone and adjacent areas (Xu et al., 1982; Zhu et al., 2006; Zhang et al., 2007; Qi and Yang, 2010). F1 – Guhe-Sanbing fault; F2 – Jiashan-Lujiang fault; F3 – Chihe-Taihu fault; F4 – Shimenshan fault; F5 – Wuhe-Hefei fault; F6 – Changyi-Dadian fault; F7 – Anqiu-Juxian fault; F8 – Yishui-Tangtou fault; F9 – Tangyu-Gegou fault; F10 – Beijing-Penglai fault; F11 – Yilan-Yitong fault; F12 – Dunhua-Mizhi fault.

3.2. EMAP data

EMAP refers to electromagnetic array profiling, which is a data sampling and processing technique applied basically to eliminate static interference produced in magnetotelluric (MT) sounding. Theoretically, this technique is designed to remove static effects of shallow, horizontal electrical inhomogeneity and local topographic relief using low-pass filtering of high-density data. Field data were gathered with a V5-2000 instrument (Canadian Phoenix Geophysics Ltd.). The physical point spacing was 250 m and the electrodes were arranged in a cross with a spacing of 100 m. The sampling pattern was 1:8:3 and sampling frequency was no less than 36 stations. Data were processed by conventional methods, such as data editing, smoothing, static shift correction, polarization pattern recognition and one-dimensional inversion, followed by 2-dimensional continuous inversion. Multiple iterations were performed using the EMAP software developed by the School of Geophysics and Oil Resources Development, Yangtze University to yield a 2-dimensional electrical profile.

Table 1
Seismic data acquisition parameters.

Type	Parameters
Recording	
Recording system	GDAPS-4
Observation system	6000-50-0-50-6000
Sample rate	2 ms
Number of trace	240
Recording length	6 s or 8 s
Head amplifier gain	24 dB
Receivers	
Geophone type	SN4-10
Base distance combination	40 m
Trace spacing	50 m
Source	
Source type	Explosives
Shooting charge	8 kg
Depth of shooting hole	12 m
Shot point interval	200 m
CMP'S	
Coverage	30 folds
CMP spacing	25 m

3.3. Aeromagnetic survey in the Hefei area

A 1:100,000 aeromagnetic survey was carried out with an aerial measurement system equipped with an HC-90K helium optically pumped magnetometer, AADC-II automatic aeromagnetic digital compensator, DS-III data acquisition system, GR-33 graph recorder, GG-24 two-star constellation satellite navigation and positioning system, BG3.0 and ALT-50 radio altimeters, and 1241 barometric altimeter, DDS-1 magnetic diurnal recording system and HC-90D land-based optically pumped magnetometer. Data processing was accomplished on PCs with the AGSDPS and OASIS programs for data input, checking, conversion, general corrections, normal field and diurnal corrections, and leveling of magnetic fields. The total precision for the data processing was 1.10 nT.

3.4. Gravity survey in the Weifang area

This 1:100,000 survey was carried out with a G/D LaCoste 190 Gravimeter and Trimble 4700 GPS receiver. The Beijing Geodetic Coordinate System 1954 was used for the coordinates of the gravity points, and elevation data were taken from the 1985 national height datum. Data processing was performed with the FUGRO-LCT combined gravity-magnetic-seismic interpretation system developed in the United States. Filtering of gravity fields, upward continuation and calculation of the regional gravity fields and residual gravity field were completed following a series of corrections, including earth tide correction, zero-drift correction, normal field reduction, Bouguer reduction, correction for water depth and height of the tripod and terrain correction. The precision for the gravity survey is $\pm 0.043 \times 10^{-5}$ m/s^2.

4. Fault systems

A fault system is a combination of faults of different modes of occurrence, classes, behaviors and different sequences. Most systems have a major fault and several secondary associated faults, whose strikes and dips differ from those of the major fault. Our new gravity, aeromagnetic, magnetotelluric and seismic data reflection allow us to reach some preliminary conclusions about the geometric and kinematic features of the major faults in all three of the studied segments in the Tan-Lu system (Li et al., 2006, 2012). On the basis of our newly obtained MT and artificial seismic data, we discuss the structure and active period of each major fault. However, this fault system has a very complicated history owing to intensive deformation over a large area and a large span of time, which seriously hinders our understanding of the genetic relationships among the major faults.

4.1. Jiashan-Lujiang segment

This segment comprises the main part of the Tan-Lu fault system and has been the focus of many studies of strike-slip movement. However, little consensus have been reached so far regarding the geological and structural evidence for strike-slip faulting and the time at which it occurred (ABGMR, 1987; Xu and Zhu, 1994; Wan et al., 1996; Wang et al., 2000; Zhu et al., 2001, 2006; Tang et al., 2003).

The seismic and MT profiles along line A1 (Fig. 2) indicate great differences in geophysical features along the Jiashan-Lujiang segment. High electrical resistivity is observed in the Jiashan-Lujiang segment, whereas low resistivity occurs at both ends (Fig. 2B). Previous results (Zhang et al., 2012a) show that this segment is divided into three parts by the Chihe-Taihu and Guhe-Sanbing faults: F1, F2 and F3. Between F1 and F3 there is the 20-km-wide Zhangbaling uplift, which is characterized by distinctive electrical properties and seismic reflection features. This fault has relatively weak seismic reflections with poor continuity, making it difficult to trace below the surface. The rocks are characterized by chaotic seismic reflections (Fig. 2A) and high electrical resistivity (Fig. 2B) which is suggestive of Proterozoic strata. Geophysical features of the Daqiao depression on the western side of the Zhangbaling uplift are comparable with those of typical North China-type strata within the Hefei basin (Chen, 2005), but are different from those of the Tan-Lu fault system. The Middle-Lower Jurassic Yuantongshan and Fanghushan Formations, in particular, have distinctive seismic reflections with good continuity. The clear reflection patterns terminate abruptly adjacent to the Tan-Lu fault area (Fig. 2A) and the overall electrical resistivity is low (Fig. 2B). On the eastern side of the Zhangbaling uplift is the North Suwan fold belt, marked by low electrical resistivity. The upper low-resistivity layer is Mesozoic in age, whereas the high-resistivity layer in the middle is pre-Paleozoic, and the lower medium-resistivity layer reflects the basement of the Suwan fold belt (Fig. 2B).

Several large faults have been identified in this area on the basis of continuity of seismic reflection wave groups and gradient variations of electrical resistivity (Figs. 2 and 3). For example, according to previous surface geologic work (e.g. ABGMR, 1987; Chen, 2005), F1, F2, F3, F4 and F5 correspond to the Guhe-Sanbing Jiashan-Lujiang, Chihe-Taihu, Shimenshan and Wuhe-Hefei faults, respectively (Fig. 1). Because a great deal of work has already been completed on these faults (e.g., ABGMR, 1987; Wan et al., 1996; Wang et al., 2000), we do not discuss them in further detail here. Using the deep section of the Chihu-Taihu fault as the dividing point, the characteristics of the fault on opposite sides differ significantly.

The major faults on the east side of the point mainly include the Chihe-Taihu deep fault (F3a), Jiashan-Lujiang fault and Guhe-Sanbing fault. The combination of all of the faults demonstrate a positive-flower structure on the basis of the stimulation test (cf., Harding (1985). These authors state that the pressure distribution on deep strike-slip faults produces a cone structure in cross section, and the cone-shaped basement segments finally converge into a bifurcated fracture zone. The characteristics described above are consistent with what happened in the eastern part of the Tan-Lu fault system. The morphology of the positive-flower structure is so well-developed that it is easily recognized. On the basis of the evidence presented above, we think that the positive-flower structure is highly convincing and is the most direct evidence of strike-slip activity along this segment of Tan-Lu fault system, where F2 is

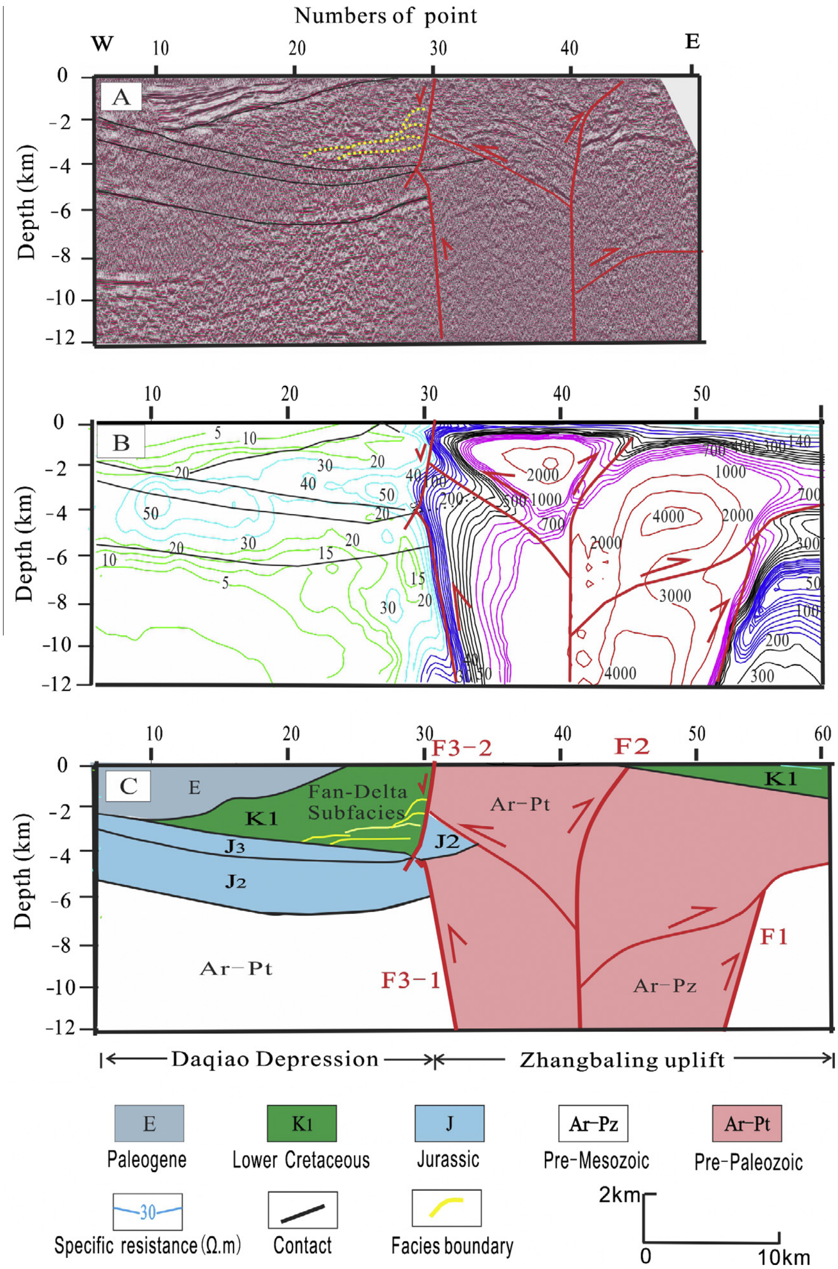

Fig. 2. Geological–geophysical profiles in the Jiashan-Lujiang fault segment. (A) Reflection seismic profile. (B) EMAP profile. (C) Illustration of the deep geological structure. F3-1 is the deep part and F3-2 is the shallow part of the Jiashan-Lujiang fault. Patterns and symbols are the same as for Fig. 1.

the main fault, and F1, F3 and other faults are associated faults. In detail, the major fault (F2) is characterized by having a vertical plane that presumably extends 28 km into the basement on the basis of the fault angles. In addition, it shows an apparent linear trend based on geomorphologic, gravitational, aeromagnetic and outcrop data which precludes the possibility that the Chihe-Taihu fault is the major fault. Taken together the available evidence strongly indicates that the various structures were formed by strike-slip processes, and we assign the name 'strike-slip faulting system' to this segment.

The western major fault mainly includes the shallow section of Chihe-Taihu fault (F3b), the Wuhe-Hefei fault and the Shimenshan fault. Seismic data show that the shallow sections of the Chihe-Taihu and Shimenshan faults are both syn-depositional features (Figs. 2 and 3). Among these major faults, the shallow section of the Chihe-Taihu fault is the largest, and it cuts through the Jurassic stratigraphic sequence to an incision depth of approximately 12 km producing 'graben to half-graben structures' (Figs. 2 and 3). With the aid of surface geological data (ABGMR, 1987), this fault is considered to have formed in an extensional regime, and is named the 'regional extensional fault system'.

The Tan-Lu fault system may have experienced several stages of strike-slip activity during its geological evolution (Wan, 2004; Zhu et al., 2001, 2006), and this article only involves those stages that are related to the formation of the positive-flower structure. Interpretation of seismic profile reveals that pre-Mesozoic rocks have been thrust over the Middle Jurassic Yuantongshan Group (Fig. 2C) along F3a, cutting through Jurassic stratigraphy, which implies that the strike-slip fault occurred after deposition of the Jurassic sequence.

From surface geology and well data in the Hefei Basin (Chen, 2005), it appears that a series of facies zones were formed causing

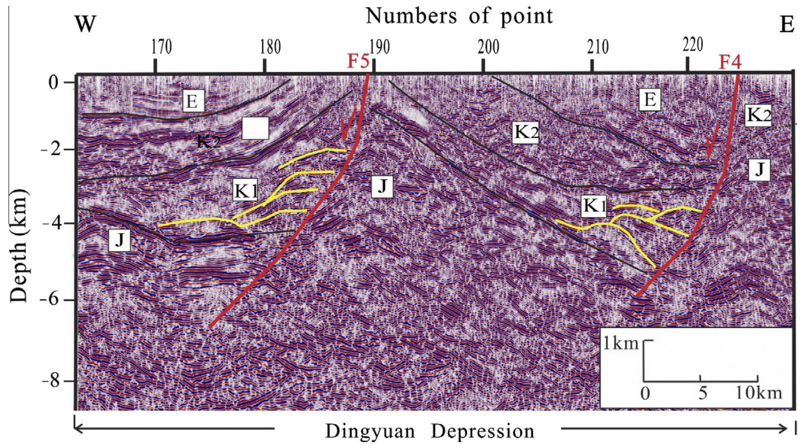

Fig. 3. Reflection seismic profile of the Jiashan-Lujiang fault segment. Patterns and symbols are the same as for Fig. 2.

lateral variations in the Upper Jurassic lithology. From the inner basin to the fault zone, the lithology varies from purple and red mudstone or sandstone in the basin to alluvial fan deposits of sandstone and conglomerate at the basin margin to pyroclastic and volcanic rocks in the fault zone. It is worth noting that the facies transitions are gradual, reflecting continuous deposition of Upper Jurassic sequence. This intact depositional sequence shows that there was no later, large-scale, strike-slip activity in the area.

Support for this view comes from the seismic reflection profile, which shows that the best signals come from the Middle and Lower Jurassic sequences and no serious variations are observed in the features of these rocks. There are no obvious facies changes in this sequence adjacent to the Tan-Lu fault system, which shows that this fault had little, if any, control on deposition of the Middle and Lower Jurassic sediments. On the other hand, seismic evidence reveals facies changes within the Upper Jurassic Zhougongshan Group in the vicinity of the Tan-Lu fault system, showing that the Zhangbaling uplift preceded deposition of the Zhougongshan Group and controlled the process.

From the data outline above, we suggest that the positive-flower structure related to strike-slip movement started to develop in the Middle Jurassic (150 Ma) and continued until the end of the Jurassic. We note that this proposed strike-slip movement started earlier than that indicated by isotope dating (Zhu et al., 2001), hence we speculate that the isotopic dates mark the cessation, rather than the initiation of strike-slip movement. Because we focus on the duration of the strike-slip movement, there is no conflict between our results and those of other authors. Many workers hae shown that the Yanshan orogeny, which began in the Middle Late Jurassic, had a significant impact on the North China Craton (Wan, 2004; Wang, 1996; Dong et al., 2007), and established the regional dynamic background under which large scale shear strike-slip movements later occurred.

Many different proposal have been put forward regarding initiation of extensional activity on this segment of the Tan-Lu Fault, but as pointed out above, we are mostly interested in the duration of this activity. Seismic profiles reveal that the shallow section of the Chihe-Taihu Fault, Wuhe-Hefei Fault and Shimenshan Fault mainly controlled the Lower Cretaceous deposition (Figs. 2 and 3). Our interpretation of the seismic profiles shows that the shallow section of Chihe-Taihu fault flattens upward to the east. The sedimentary facies east of the fault change progressively westward from alluvial fan to lacustrine, shore and alluvial plain depositions (Fig. 2); the Xinzhuang Group is composed of a suite of dark brown muddy sandstone, siltstone and grey mudstone; the dark mudstone facies thickens to more than 400 m to the east (Chen, 2005). These data indicate that the shallow section of the Chihe-Taihu fault controlled formation of the Daqiao depression as it became progressively deeper. We believe that the extensional movement on this fault segment began in the early Cretaceous because previous workers have documented an extensional stress field in the Eastern China Craton at this time (Li, 2000; Zhang et al., 2003; Li et al., 2007).

4.2. Yishu Segment

Some of the earliest research on the Tan-Lu fault system was carried out on this segment and it is now generally accepted as a regional extensional feature (Xu et al., 1982, 1987; Wang et al., 2000; Yan et al., 2010). Unlike earlier regional MT profiling carried out in this area with a point spacing of mostly 2 km or more, we obtained high-density data with a point spacing of 250 m, which allowed us to delineate smaller and deeper structures that could be used for correlations across the fault and in adjacent areas.

The gradient of electrical resistivity of line B1 inversed from MT data (Fig. 4B) shows that the electrical features vary significantly, with a remarkable decrease in resistivity from west to east. These data, combined with studies of the surface geology (Wang et al., 2000), the profile can be divided into three parts according to the electrical characteristics. The western part is composed of the Luxi uplift, which is characterized by high resistivity indicating the presence of Pre-Mesozoic rocks. The eastern part is the Jiaolai basin, which contains mostly Mesozoic strata and is marked by generally low resistivity. The middle part is the Yishu fault belt, which shows alternating zones of high and low resistivity; this belt can be further divided into the Sucun rift, Gongdanshan horst and Juxian rift (Fig. 4C).

On the basis of the inversed electrical resistivity gradient (Fig. 4B), the Yishu fault belt can be divided into four, large normal faults: F6, F7, F8 and F9 (Fig. 4), which are thought to correspond to the Changyi-Dadian, Anqiu-Juxian, Yishui-Tangtou and Tangyu-Gegou faults, respectively (Wei et al., 1993; Wang et al., 2000) (Fig. 4). Considerable information on these faults is already available (BNSA, 1987; SBGMR, 1991; Zhang et al., 2003; Yan et al., 2010), however, in this paper, we are less concerned with the details of each fault than with the relationships among them. The resistivity profile shows that these are all steeply dipping normal faults that extend into the lower crust. All of the faults have 'graben-half-graben' structures on the cross-sections (Fig. 4C), and are called included in the regional extensional faulting system. Owing to the fact that all these syn-sedimentary strata are Lower Cretaceous in age and according to other references (Fig. 4A), we suggest that the regional extensional fault system was active primarily in the early stage of late Mesozoic (Zhang et al., 2009).

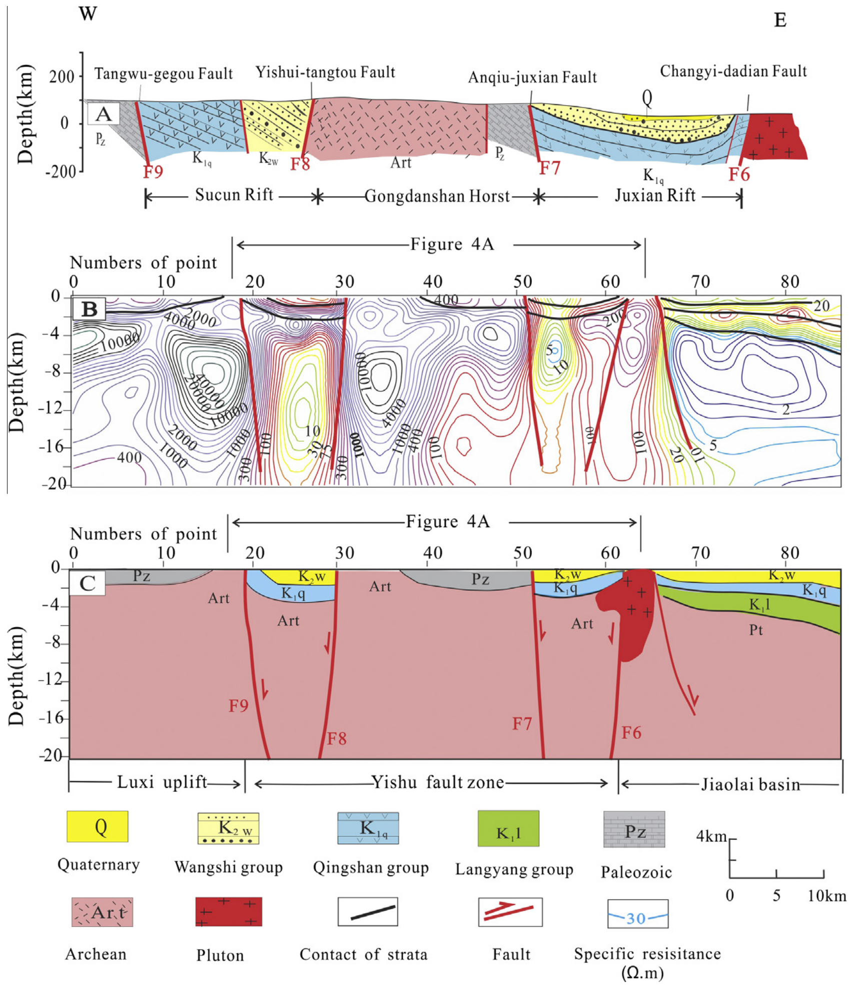

Fig. 4. Geological–geophysical profiles of the Yishu fault belt. (A) Surface geological section (Wang et al., 2000). (B) MT profile. (C) Illustration of the deep geological structure. Patterns and symbols are the same as for Figs. 1 and 2.

4.3. Bohai segment

This segment is the focus of Cenozoic activity on the Tan-Lu fault system. The basic geological and structural framework of this segment has been established based on data obtained from deep hydrocarbon exploration in the Bohai Bay basin (Tian et al., 1992; Wu et al., 2006; Qi and Yang, 2010; Li et al., 2012). Evidence of earlier Mesozoic faulting is difficult to discern because it has been nearly obliterated by the intense Cenozoic faulting. In this paper, our aim is to demonstrate the deep structure of this fault and to reconstruct the nature of the Cenozoic faulting by combining geological interpretations with the new reflection seismic profiles and high-density resistivity data.

The electrical profile along Line BH-1 (Fig. 5B) shows a pattern of alternating zones of high and low resistivity and distinct variations in intensity. On the basis of borehole data obtained during oil exploration (Li et al., 2003; Zhang et al., 2009), this segment of the fault system can be divided into three parts. The Weibei dome within the Luxi uplift lies in the west and it is characterized by alternating zones of medium and low resistivity, which reflect the presence of Mesozoic and Cenozoic strata and crystalline basement, respectively. The Ludong uplift lies in the east, where it shows consistently high electrical resistivity indicative of Pre-Mesozoic strata and magmatic rocks. The middle part, situated in the Weibei depression on the eastern side of the Bohai Bay basin, shows low resistivity reflecting the presence of Cenozoic and Mesozoic strata.

By analyzing the electrical resistivity gradient and the relationships among the blocks (Fig. 5A and B), four large normal faults (F6, F9, Fa, Fb) and some small faults were identified (Fig. 5). The labels Fa and Fb correspond to the Tandong and Tanxi faults, respectively (Li et al., 2003; Wu et al., 2006). These are Paleogene listric normal faults that extend to the middle crust, and they are similar to other Cenozoic faults in the region (Li et al., 2012). All of the Cenozoic listric normal faults are located in the upper crust regardless of variations in strike, scale and mode of occurrence. Abundant research has been conducted on these faults (Wu et al., 2006; Zhang et al., 2009), so they are not discussed further here.

Among these normal faults, F6 and F9 were first discovered during this study. The resistivity profiles show that they extend deep into the crust and that they are marginal faults to a graben termed the Weibei depression (Fig. 5). Two smaller faults, Fa and Fb, lie within the graben and do not extend as deeply as the margin faults. All four faults, however, controlled the Mesozoic sedimentation and thus are thought to have formed in the Early Cretaceous (Zhang, 2004; Zhang et al., 2009). Since the formation age and mode of occurrence of these normal faults differ significantly from others in the area, they are termed the 'regional extensional fault system' in this paper.

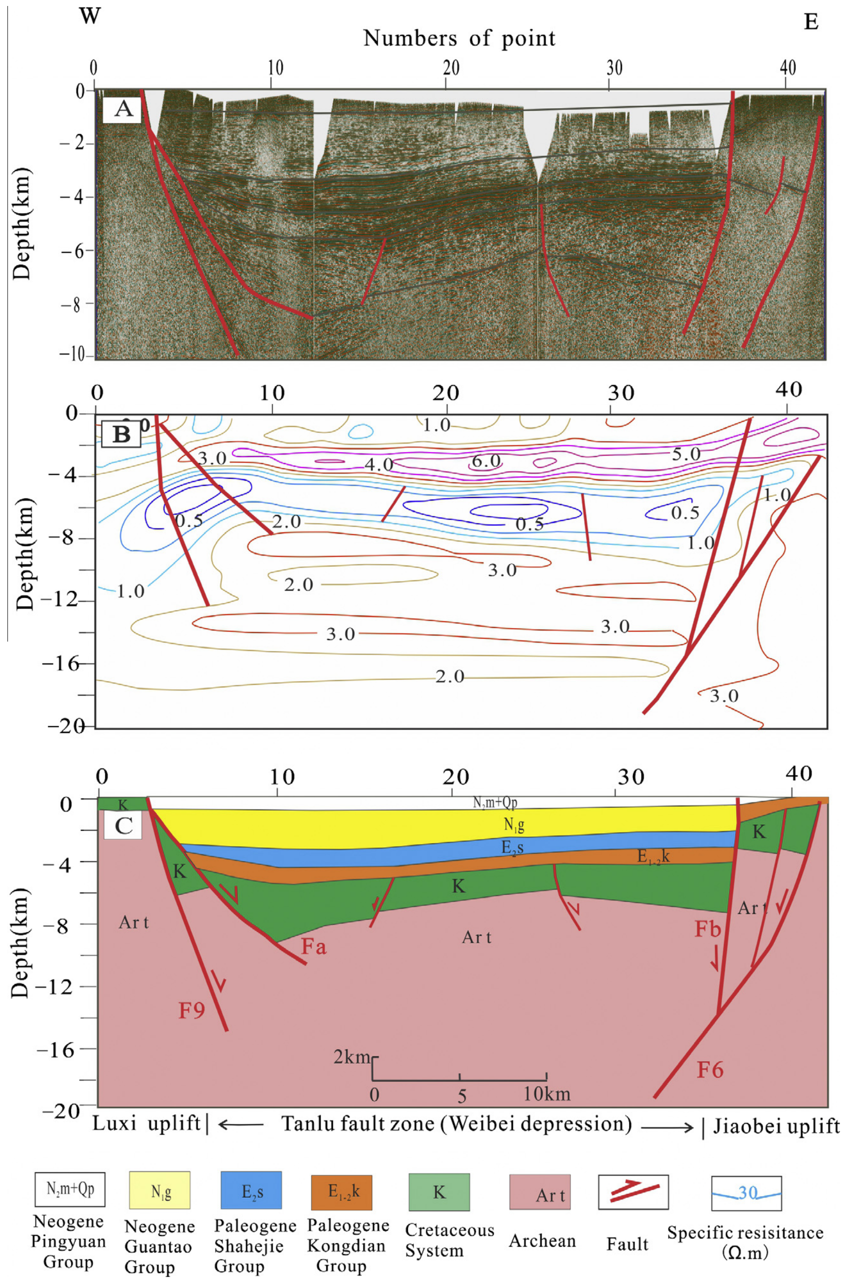

Fig. 5. Geological–geophysical profiles of the Bohai Bay fault segment. (A) Reflection seismic profile. (B) Profile of the gradient of electrical resistivity. (C) Illustration of the deep geological structure. Patterns and symbols are the same as for Figs. 1 and 2.

5. Tectonic relationships

A fault system is defined as a regional feature formed within a certain period of time and within the same geological stress field. Faults in neighboring areas, though formed in the same period, may have different features because of different geological structures and different stress regimes. Nevertheless, these faults should have a certain spatial continuity (Zhang, 1984). Past research on the Tan-Lu fault zone has focused mainly on individual segments with little attention being paid to the structural relationships between these segments. Because different segments of the fault zone have different faulting characteristics, researchers have yet to develop a comprehensive understanding of the overall structural evolution of the Tan-Lu system. This is due, in part, to the difficulty in integrating the many different local observations, commonly focused on different aspects of the system. Thus, we have tried to identify the structural relationships among all of the segments so as to accurately understand the evolution of the entire system.

5.1. Link between the Bohai segment and the Yishu fault belt

Previously, the Tandong and Tanxi faults in the Weibei depression were typically linked to the Yishu segment (Li et al., 2003). In this paper, however, we suggest that the Tandong and Tanxi faults are basically related, but are separated from the Yishu segment. This interpretation is based on different strike directions, mechanical properties, active periods, depth of penetration and nature of the associated strata. This new interpretation opens a window for re-evaluating the relationship between the Bohai Bay segment and the Yishu segment.

Historically, the Tandong and Tanxi faults have been analyzed by many geologists (e.g. Li et al., 2003), and here we merely reiterate that they are listric normal faults that were formed in the Cenozoic and die out in the middle crust. Although the two faults and the Yishu segment are similar in strike direction, they are significantly different in other features. However, the two newly discovered deep faults in the Weibei depression (F6 and F9) are similar in many respects to faults that constitute the Yishu segment. They are all normal faults initiated in the early stage of the late Mesozoic that are characterized by steep dips, long extents, relatively persistent NNE-trending structural lines (Figs. 4 and 5), and graben or half-graben structures. On the basis of these similarities, we consider them to be part of one larger-scale fault system. In addition, the gravity anomalies (Fig. 6) show linear trends along both boundaries of the Weibei depression, and extend southwestward to connect with the Yishu segment, which is another strong line of evidence to support the hypothesis above. On the basis of these observation and data from oil exploration studies (Zhang et al., 2009), we suggest that the deep faults within the Weibei depression and the Yishu segment belong to one larger extensional fault system.

If the Tandong and Tanxi faults are not part of the Yishu fault segment, where do they fit into the system? As described in this paper, they are most similar to faults in the Bohai Bay basin, although they do have different stretching directions (Chen et al., 2005; Li et al., 2012). Specifically, they are listric normal faults of Cenozoic in age with small lateral extents that disappear in the middle crust (Fig. 5). The seismic reflection profile (Fig. 7A and D) shows that the Weibei depression is an early Cenozoic half-graben, faulted on the north. The depositional facies zone which is primarily controlled by the Weibei fault (Fig. 7E) is oriented E–W, rather than parallel to the Tandong and Tanxi faults, implying that the main stress field was elongated in this direction at the time of faulting. We therefore infer that the Tandong and Tanxi faults were developed under the same stress field as the NE-trending basement fault that produced the N–S extension. A relationship between these faults and those of the Bohai Bay basin is supported by the fact that this is the area with the most intense Cenozoic activity on the Tan-Lu fault system (Zhang et al., 2009; Qi and Yang, 2010). In addition, the MT profile across this area shows that the deepest subsidence of the Bohai Bay basin does not overlap with the Tan-Lu fault zone (Fig. 7A and B). Thus, we think it is likely that the Bohai Bay segment was formed in response to the basement fault system related to a regional extensional framework in the Bohai Bay basin.

5.2. Link between the Yishu fault belt and the Jiashan-Lujiang segment

In previously published structural maps of the Tan-Lu fault system, the Yishu and Jiashan-Lujiang segments are directly connected. However, as described above, they belong to different fault systems because of their differences in mechanical properties, active periods and spatial positions. Or study of the proposed link between the two faults aims to provide a new framework under which researchers are able to reconsider the controversial "theory of rifting" and "theory of strike-slip faulting". Our high-precision magnetic survey (Fig. 8) shows that the Jiashan-Lujiang segment has obvious banded anomalies and five magnetic lineaments (F1, F2, F3, F4, F5), which correspond to five previously defined faults: the Guhe-Sanbing, Jiashan-Lujiang, Chihe-Taihu, Shimenshan and Wuhe-Hefei faults, respectively (ABGMR, 1987).

Very few studies have been conducted on Mesozoic extension on the Jiashan-Lujiang fault, but our new findings, i.e. the extensional fault system on the western side of the Chihe-Taihu fault,

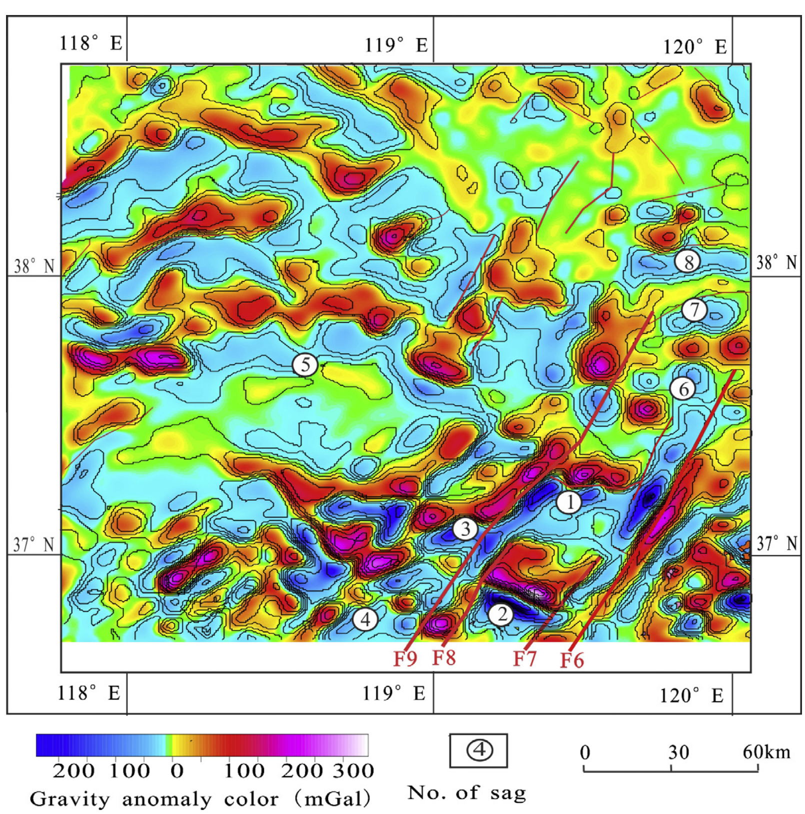

Fig. 6. Map showing gravity anomalies in the eastern part of the Jiyang sag in the Bohai Bay basin (upward continuation to 10 km). 1 – Weibei depression; 2 – Weifang depression; 3 – Houzhen depression; 4 – Changle depression; 5 – Dongying depression; 6 – Qingdongdong depression; 7 – Laizhou Bay depression; 8 – Huanghekou depression. Patterns and symbols are the same as for 1.

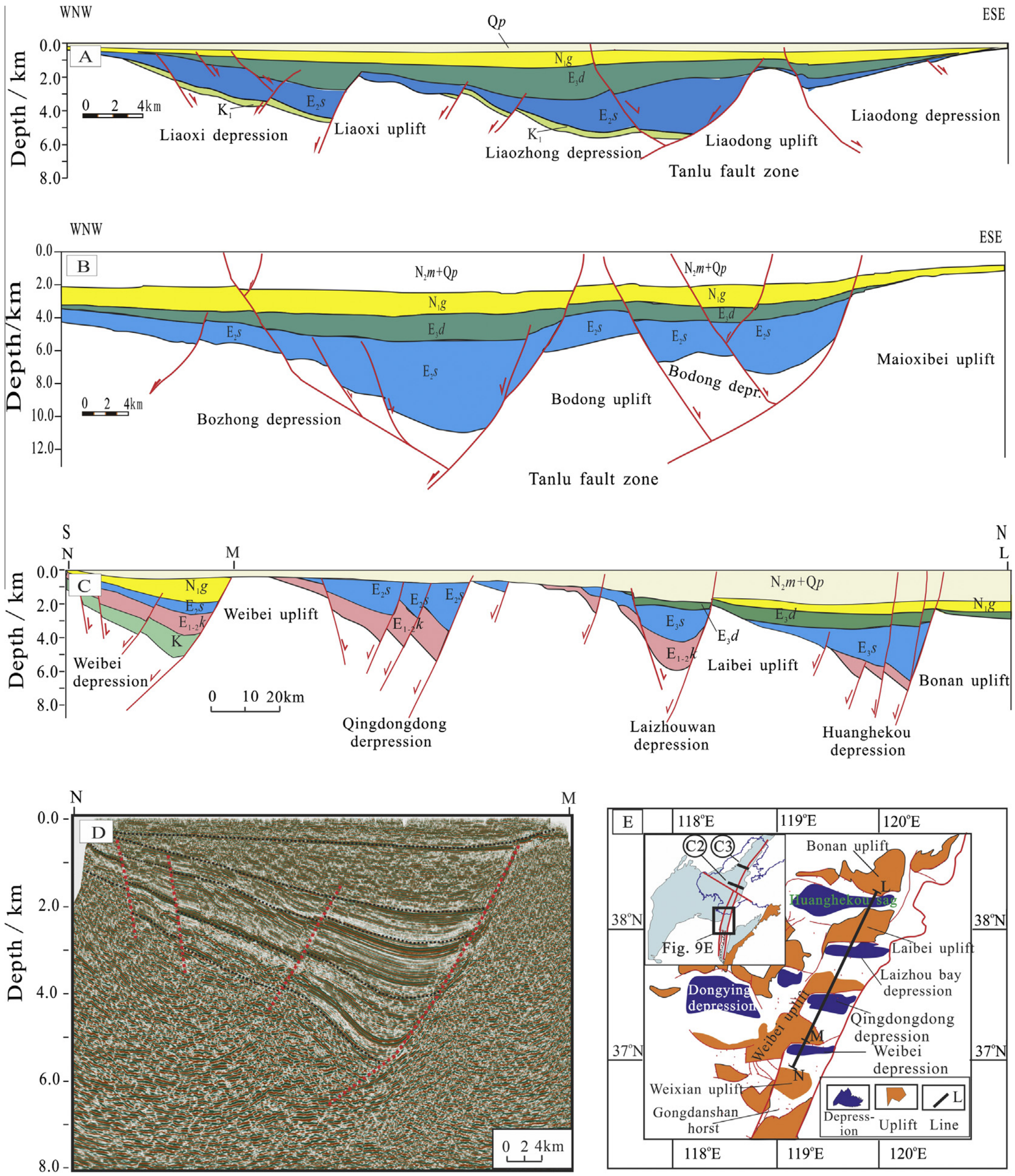

Fig. 7. Cross-sections showing the sedimentary characteristics of the eastern area of the Bohai Bay basin. (A) Illustration of the deep geological structure in the Liaohe sag (Zhang et al., 2009; Qi and Yang, 2010). (B) Illustration of the deep geological structure in the Bozhong depression (Zhang et al., 2009; Qi and Yang, 2010). (C) Illustration of the deep geological structure in the eastern Jiyang sag. (D) N–S seismic reflection profile in the Weibei depression. (E) Fracture map of the eastern Jiyang sag. Patterns and symbols are the same as for Fig. 1.

could help to clarify the structural framework of this fault segment. This extensional fault system is similar to all the faults of the Yishu segment; they are steep, NE-trending, normal faults with graben or half-graben structures that formed during the early stage of the late Mesozoic (Figs. 2–4). We believe that they all belong to the same fault system. Aeromagnetic anomalies associated with the Hefei basin and adjacent regions (Fig. 8) show that the Jiashan-Lujiang extensional fault system lies in the Daqiao depression with a NE-SW-elongated negative anomaly, extending southward to the foreland of the Dabie Mountains and passing northward through the Jiashan basin to connect with the Yishu segment. We designate this area, which includes the Weibei depression, Yishu fault belt, Jiashan basin and Daqiao sag, as a zone of extensional tectonics.

Previous studies of the Jiashan-Lujiang segment have focused on its strike-slip movement (Xu et al., 1987; Zhu et al., 2006). Aeromagnetic survey data (Fig. 8) and surface geology (ABGMR, 1987) show that the Jiashan-Lujiang fault system is part of the Zhangbaling ductile shear zone and has a NESW-trending, positive magnetic anomaly, which extends northward along the low-temperature and high-pressure metamorphic belt of the Sulu orogen and southward to link up with the low-temperature and high-pressure metamorphic belt of the Dabie orogeny (Wang et al., 2000). On the basis of previous work by Wang et al. (2000) and Zhang et al. (2012a), we propose that the Jiashan-Lujiang strike-slip fault system was developed in a compressional stress field along the colliding margin of two converging plates - the Yangtze and North China Cratons (Dong et al., 2007). We designate this as an area of strike-slip activity. This fault system is not spatially related to the extensional system on the west side, but is laterally juxtaposed with it.

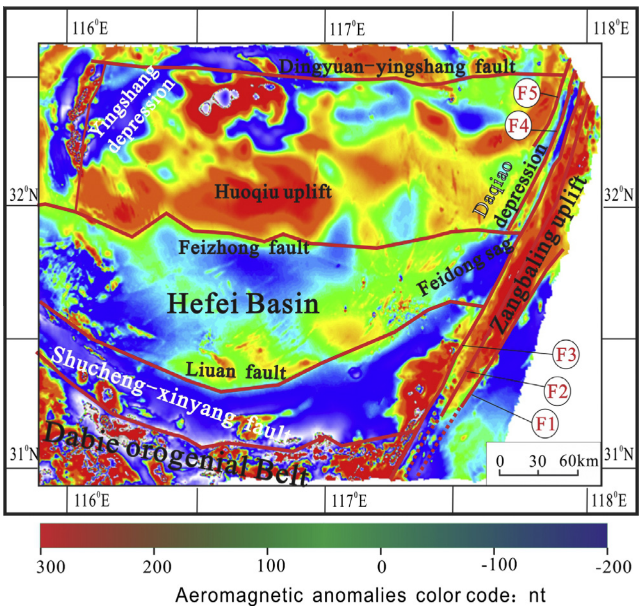

Fig. 8. Aeromagnetic map of the Hefei basin and the southern segment of the Tan-Lu fault zone. Patterns and symbols are the same as for Fig. 1.

6. Space–time framework

Geological structures that are formed at the same period and in the same regional setting are products of a particular tectonic regime, implying an intrinsic relationship between the two (Zhang, 1984). Previous research on the Tan-Lu system has focused on the vertical evolution of the faults in different geological periods, whereas our work, based on exciting new stratigraphic data (Table 1) (ABGMR, 1987; HBGMR, 1989; LBGMR, 1989; SBGMR, 1991), emphasizes the development of geological features associated with the fault zone that formed in adjacent regions during the same time period. The goal of this work was to develop a better understanding of the regional dynamics of the system as a whole.

6.1. Period of strike-slip movement – the late stage of the early Cenozoic

Amalgamation of the North China and the Yangtze Cratons occurred after the Indo-Sinian event (Hao et al., 2004; Ernst et al., 2007), and the East Asian plate further converged during the early Mesozoic (Dong et al., 2007). At this time the eastern Chinese continent was subjected to WNW compression that generated a sinistral NNE-shear stress, leading to large-scale intraplate sliding between the Yangtze and North China cratons, displacing the low-temperature, high-pressure Sulu metamorphic belt (Wang et al., 2000). Influenced by a ancient stable continental nucleus in the Huoqiu area, NNE-directed shearing occurred in the less consolidated Zhangbaling area and translation took place on the Jiashan-Lujiang fault between the North China and Yangtze cratons, thus displacing the Middle and Lower Cretaceous strata to form the Zhangbaling ductile shear zone (ABGMR, 1987; Hu and Zhang, 2007; Zhang et al., 2012a). Owing to a compressional shear stress, the Hefei basin on the western side of the Zhangbaling ductile zone developed as a flexural basin (Chen, 2005) with a circular belt of sedimentary facies (Fig. 9A). The seismic profile reveals alluvial plain facies, shallow lacustrine facies and moderately deep lacustrine facies successively from the center outward. A series of NW–SE-trending nappes and thrust faults (Fig. 9B) developed in the Yangtze Craton on the eastern side of the Zhangbaling ductile zone, generating the Suwan thrust-fold belt (Mei et al., 2008). On the western side of the Yishu segment, a set of SE–NW-trending nappes and thrust faults developed around the Xuzhou area in Jiangsu Province and the Suzhou area in Anhui Province (Fig. 9C), leading to formation of the Xusu oroclinal structure (Shen et al., 1995). These nappes and thrust faults all converged within the Tan-Lu fault zone at relatively low angles to form a positive-flower structure on the surface and that this structure, as well as the ductile shear zone in the Zhangbaling uplift, is closely related to strike-slip movement hidden at depth.

Previous data suggest that during this period other regions in the eastern part of the North China Craton also underwent intense compression (Fig. 9), as indicated by thrusting and folding in the Jurassic (ABGMR, 1987; HBGMR, 1989; LBGMR, 1989; SBGMR, 1991; Mei et al., 2008). For example, the Chuanbanchong section in Jinzhai County of Anhui Province (Fig. 9D) clearly shows that the pre-Mesozoic Foziling Group is thrust over Early-Middle Jurassic strata (Chen, 2005). In the Yanshan area, the Jurassic strata were deformed into large- to medium-scale, tight, NE- to NNE-striking folds and cut by thrust faults (Fig. 9B) (Wang et al., 2001). These features suggest that the Yanshan orogeny affected the North China region extensively, as is indicated by the dominant WNW- to ESE-directed stress field that existed in this region. The extensive, compressional-shear, strike-slip movement on the Tan-Lu fault during this period clearly reflects a regional dynamic framework.

There has been much controversy among geologists regarding the amount of offset on the various faults. Different offsets were proposed by different workers (Xu and Ma, 1992; Tang et al., 2003). To accurately determine the offset on a given fault, correlations of recognizable geological features with the same structure are required. In this study, we selected specific geological and structural features in the Upper Jurassic and younger strata or magmatic rocks. In order to use the geological features developed before the Mesozoic as markers, it is necessary to prove that no offset occurred before the Mesozoic strike-slip movement. Therefore, we suggest that the Middle and Lower Jurassic strata to be the most reliable markers because they were deposited after the active period of deformation on the Tan-Lu fault system when the North China and the Yangtze blocks were amalgamated after the Indosinian (Fig. 2C). In restricting our discussion in this way, we can take into account preceding cumulative effects, the forms of block margins and the diversity of interplate stratigraphy.

Comprehensive investigation of Mesozoic strata on the eastern side of the Tan-Lu fault zone (ABGMR, 1987) revealed that there are no Middle or Lower Jurassic strata that can be correlated with the Hefei basin (It is unlikely that those strata were completely removed by erosion). On the basis of this observation, we conclude that the strike-slip offset on the Tan-Lu fault system was about 180 km, much smaller than that proposed by earlier workers (>550 km) (e.g., Xu et al., 1987). We also conclude that most strike-slip movement on the Tan-Lu fault system took place on the Jiashan-Lujiang segment. Some strike-slip movement may also have occurred on the Yishu segment, but if so, it was small. Considering that the strong regional compressive stress field and strike-slip movement changed direction in Jiashan during this period of time, some offset may have taken place in the area to the north of Jiashan Town. For instance, the offset of the fault on the northern margin of the North China Craton and small-scale ductile shearing in the western Liaoning area (LBGMR, 1989) suggest that some strike-slip faulting might have occurred on the North China segments of the Tan-Lu fault zone.

In recent years, it has been shown that most of the widespread Mesozoic volcanic rocks in eastern China formed in the Early Cretaceous (Chen, 2005; Zhang et al., 2009). In addition, the Linglong gneissic granite in Zhaoyuan, Shandong Province, which

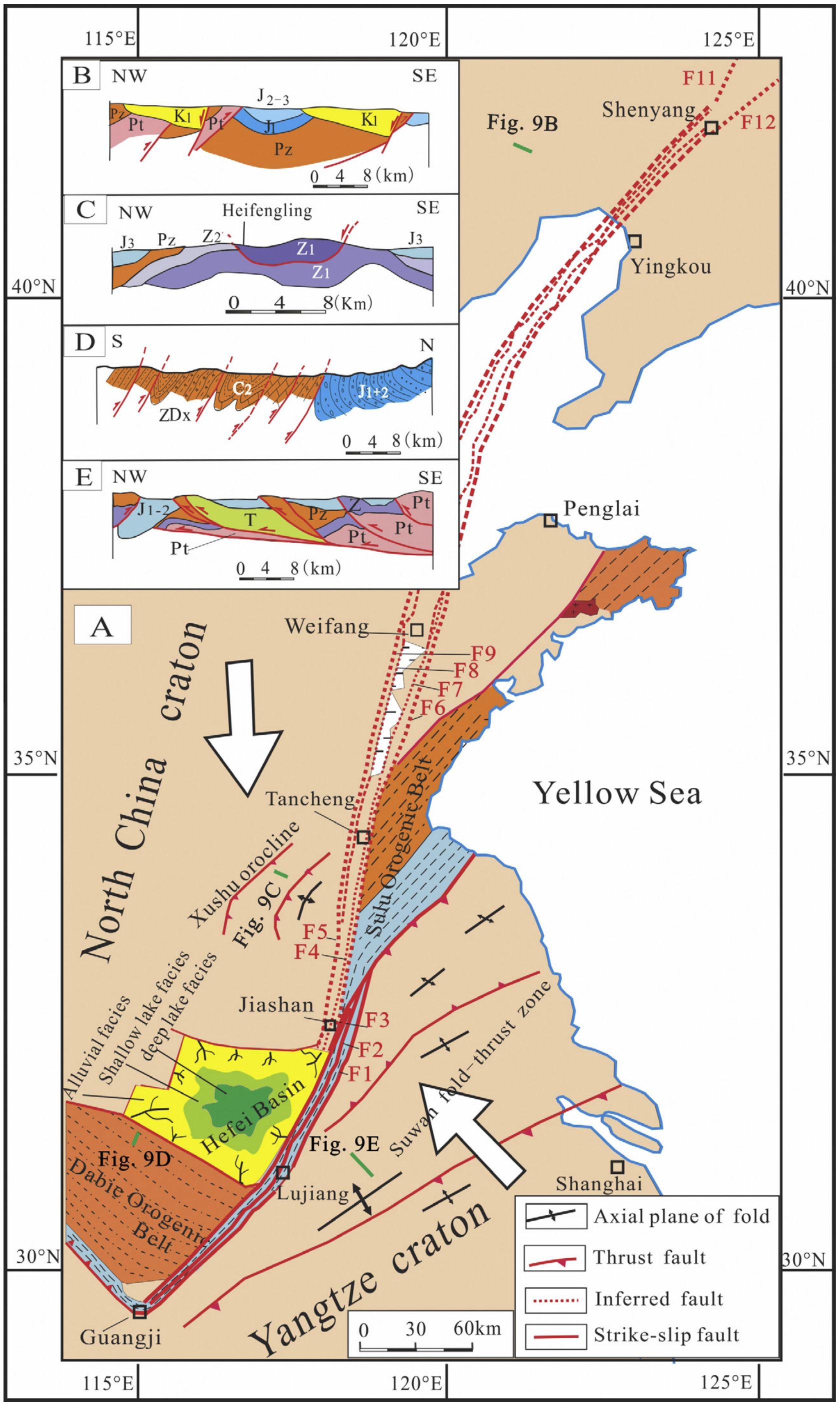

Fig. 9. Map and structure sections of part of the Tan-Lu fault zone. (A) Map showing the geological structure of North China segments of the Tan-Lu fault zone and adjacent areas in the late stage of the early Mesozoic (Zhang et al., 2007, 2009, 2012a; Qi and Yang, 2010). (B) Structural section in the Yanshan area (Wang et al., 2001). (C) Structural section in Suzhou County, Anhui Province (Shen et al., 1995). (D) Chuanbanchong structural section in Jinzhai County, Anhui Province (Chen, 2005). (E) Structural section in the middle and lower reaches of the Yangtze River (Mei et al., 2008). Patterns and symbols are the same as for Fig. 1.

is considered to be Late Jurassic in age (SBGMR, 1991; Song et al., 2009), has been attributed to metasomatism and anatexis of basement rocks that were thickened and partially melted due to strong regional compression.

6.2. Period of extensional activity-the early stage of the late Mesozoic

In the late Mesozoic, as the upper mantle became warmer, subduction of the Paleo-Pacific plate caused mantle upwelling, lithospheric thinning and significant breakup of the North China craton (Zhu et al., 2011). This produced a regional extensional stress field in eastern China, oriented SE–NW, leading to formation of many rift basins in the eastern part of the North China Craton (Li et al., 2007). Some early Cretaceous rift basins, such as the Jiaolai and Huangkou basins, collected extremely thick sedimentary sequences at this time (Zhang et al., 2009; Song et al., 2009). Contemporaneously, segments of the Tan-Lu fault zone in North China also experienced extension (Fig. 10), leading

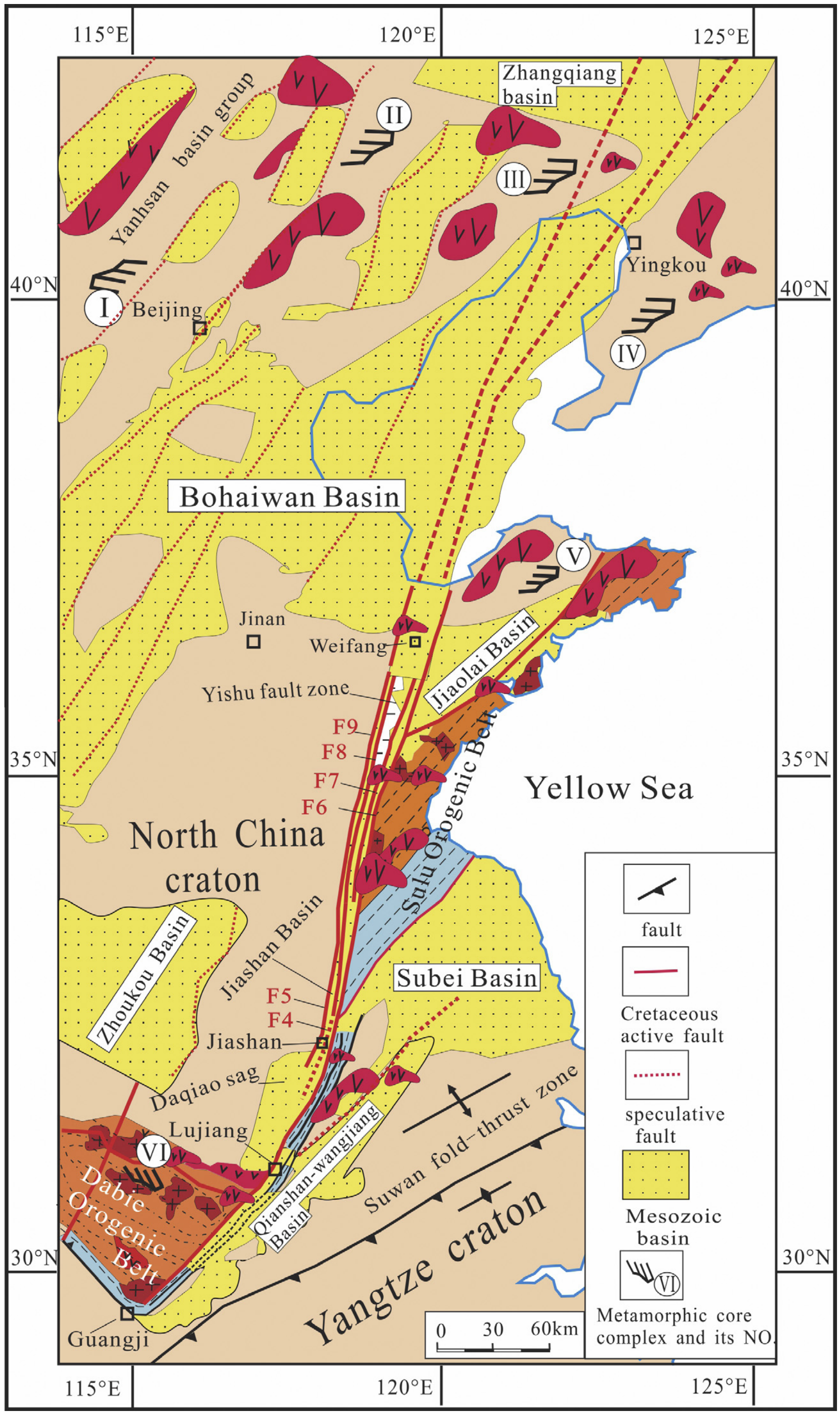

Fig. 10. Map showing the geological structure of the North China segments of the Tan-Lu fault zone and adjacent areas in the early stage of the late Mesozoic (Zhang et al., 2007, 2009, 2012a; Qi and Yang, 2010). I – Hohhot metamorphic core complexes; II – Chifeng Mountain metamorphic core complexes; III and IV – metamorphic core complexes in western and southern Liaoning Province; V – Yunmengshan metamorphic core complexes; VI – the Dabie Mountain metamorphic core complexes. Patterns and symbols are the same as for Fig. 1.

to NE-stretching rift belts, such as the Jiashan basin and Yishu fault belt (Zhang et al., 2003). A suite of Early Cretaceous fluvial and lacustrine sediments, especially sandy conglomerates was deposited in these features. These basins extend southward to the eastern side of the Hefei basin to form the Daqiao rift basin and northward to the Bohai Bay basin. Widespread development of Early Cretaceous sedimentary strata is indicative of large-scale extension of the eastern Chinese continent.

Intense magmatism, regarded as a normal response to lithospheric extension, was widespread in eastern China during the Cretaceous (Fig. 10). Widely distributed volcanic and intrusive rocks are common in the Yanshan structural belt, north Huaiyang structural belt and Jiaodong area (Du and Zhang, 1999; Dai et al., 2003), where they are associated with huge quantities of metallic ore deposits (Du et al., 2003). The major period of magmatism occurred in the interval between about 145–100 Ma, but the focus of volcanic activity in northern China occurred in the Early Cretaceous. The magmatic rocks are mainly lavas, with lesser amounts of pyroclastic and subvolcanic rocks, most of which are calc-alkaline or high-K calc-alkaline in composition (ABGMR,

1987; HBGMR, 1989; LBGMR, 1989; SBGMR, 1991; Gao et al., 2008; Song et al., 2009).

Along with extensional faulting and magmatism, metamorphic core complexes formed extensively in the eastern part of the North China Craton at that time, particularly in areas around Hohhot, Yunmengshan, Chifeng, western and southern Liaoning Province, eastern Shandong Province, and the Dabie Mountains (Liu et al., 2006), again indicating the presence of widespread extension in the region.

6.3. Period of faulting – the Paleogene

In the Paleogene, formation of a trench-arc-basin system in the Western Pacific, plate subduction and development of mantle plumes resulted in lithospheric rifting in eastern China. The relevant regional stress field extended basically in a N–S direction, resulting in the formation of the Bohai Bay (Zhang et al., 2009; Qi and Yang, 2010), southern North China and Hefei basins (Fig. 11). In particular, the Bohai Bay basin is a large area of deposition with significant subsidence, caused by a number of approximately E–W-trending Paleogene, listric normal faults. Generally, individual faults extend for only small distances, strike in various directions and disappear in the middle crust (Tian et al., 1992; Zhang, 2004; Li et al., 2012). Numerous listric faults, both large and small, developed at this time in the Bohai Bay segment of the Tan-Lu fault system (Fig. 7B). They have variable strike directions but generally extend NE–SW and mark the most active regions of Cenozoic tectonism in the entire Tan-Lu fault system. However, our deep structural profiles show that the most tectonically active part of the Bohai Bay basin was not within the Tan-Lu fault zone (Fig. 7A and B), but rather was focused within the basin itself, and was related to the extensional activity that produced this feature.

Abundant Paleogene mafic to silicic magmatism produced thick volcanic sequences in the Bohai Bay basin, particularly on the

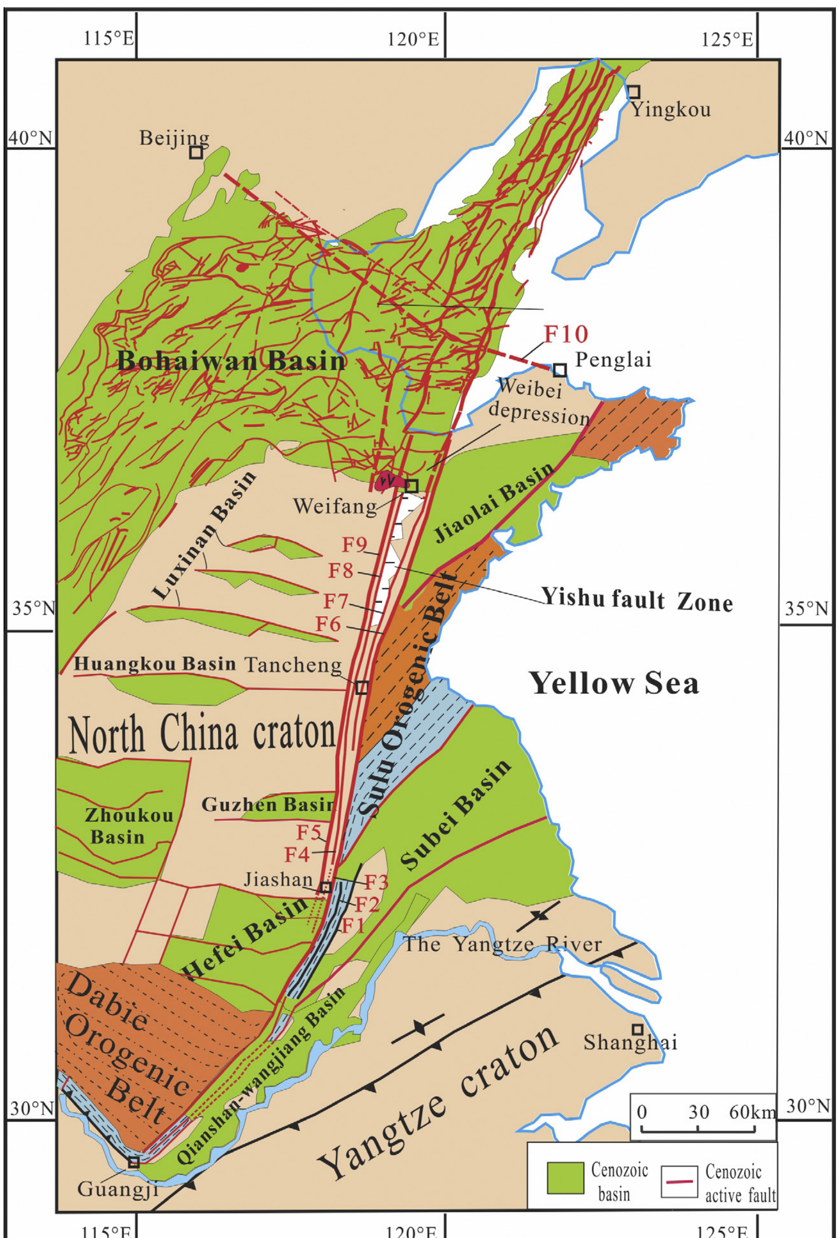

Fig. 11. Map showing the geological structure of the North China segments of the Tan-Lu fault zone and adjacent areas in the Paleogene (Zhang et al., 2007, 2009, 2012a; Qi and Yang, 2010).

eastern side of the Tan-Lu fault zone. For example, up to 1600 m of Paleogene alkali basalt are present in the Weibei depression (Li et al., 2003; Zhang, 2004), and many studies have documented other extensive Paleogene magmatism in this continental rift environment which reflects the prevailing extensional domain at that time (Li et al., 2003; Zhang, 2004; Dong et al., 2010).

7. Conclusions

This study used high precision EMAP data, artificial seismic profiles, magnetic surveys and surface geology to investigate the Weibei depression of the Bohai Bay basin and the Daqiao depression of the Hefei basin. We identified three distinct segments of the Tan-Lu fault zone in this region, namely the Jiashan-Lujiang, Bohai and the Yishu faults and analyzed the structural relationships among them and their space–time distribution. To conclude:

(1) The Jiashan-Lujiang segment is composed of several faults. On the eastern side of Chihe-Taihu fault, there is the Jiashan-Lujiang fault, the deep section of Chihe-Taihu fault and Guhe-Sanbing fault, as well as some buried faults. These faults are characterized by giant positive-flower structures and are classified as strike-slip features in this paper. Most the movement on these faults took place in the Late Jurassic. On the west there lies the Shimenshan and Hefei-Wuhe fault, as well as the shallow section of the Chihe-Taihu fault, all of which are associated with half-grabens, indicating extension in the Early Cretaceous.

(2) The Yishu segment is characterized by alternating zones of high and low resistivity on the electrical profile. Some faults discovered there, such as the Changyi-Dadian, Anqiu-Juxian, Yishui-Tangtou and Tangyu-Gego, are normal faults. All of them are steeply dipping, form graben or half-graben structures and are referred to here as the 'extensional fault system', which was active in the Early Cretaceous.

(3) The Bohai Bay segment consists of two fault systems, one deep and the other shallow. The shallow system is composed of Paleogene listric normal faults that flatten downward and disappear in the middle crust. This group of faults is here termed the 'Cenozoic normal fault systems. The deep faulting system shows graben structures in cross-sections that controlled deposition of the Early Cretaceous sediments. These deep faults are grouped with the 'extensional fault system' in this paper.

(4) Newly discovered fault systems are similar to the faults of the Jiashan-Weifang segment of the Tan-Lu system. They may belong to the same fault system, extending across the Weibei and Daqiao depressions, the Yishu segment and the Jiashan basin. These faults die out southward in the foreland of the Dabie Mountains, whereas they probably extend northward to the Bohai Bay basin; they are inferred to have formed by regional extension in eastern China in the late Mesozoic.

(5) The Jiashan-Lujiang strike-slip fault system lies primarily between the Chihe-Taihu and Guhe-Sanbing faults, overlapping with the Zhangbaling ductile shear zone. This strike-slip fault system is thought to have formed by the lateral movement between the Yangtze and North China Cratons. There is a spatial displacement between this fault system and the extensional fault system on the west, showing a lateral superposition relationship.

In summary, in the Cenozoic and Mesozoic, the Tan-Lu fault system developed several sub-fault systems and internal structures, with different features in different locations. The present integrated geological–geophysical–geochemical anomaly belts of the Tan-Lu fault zone are considered to be the combined result of strike-slip, extensional and rifting movements in the study area. The arguments as to whether this fault zone is characterized by 'rifting' or 'translation' arose in the past because previous workers only focused on specific parts of the system and ignored the overall tectonic framework of the Tan-Lu fault zone. Previously, it seemed that most parts of the Tan-Lu system were dominantly related to rifting because evidence of strike-slip faulting and extensional faulting in the Bohai Bay segment was obscured by strong, late-stage geological reworking. The concept of fault systems and their space–time distribution proposed in this paper may provide a guide for academic discussion on how to understand and unify contradictory evidence from different parts of the system. Hopefully, our approach can help constrain the mechanisms that caused the breakup and thinning of the lithosphere in the eastern part of the North China Craton.

Acknowledgements

This study was supported by the National Project for Deep Exploration Technology and Experimentation (Sinoprobe-08) and the National Natural Science Foundation of China (Grant Nos. 41072080, 90814008 and 90814011). While conducting this study, we benefited greatly from our participation in the exploration for oil and gas in the Hefei basin in the late 1990s, supported by the Shengli Oil Company. Revisions proposed by Prof. Paul T. Robinson improved the manuscript. We would like to express our sincere gratitude for the highly valuable work carried out by our colleagues. Two anonymous reviewers are thanked for providing constructive suggestions and comments.

References

ABGMR (Anhui Bureau of Geology and Mineral Resources), 1987. Regional Geology of Anhui Province. Geological Publishing House, Beijing, pp. 236–347 (in Chinese).

BNSA (Bureau of the National Seismological Administration), 1987. The Tan-Lu Fault Belt. Seismological Press, Beijing, pp. 10–125 (in Chinese).

Chen, P.J., 1988. Timing and framework of huge displacement of the Tan-Lu fault. Chin. Sci. Bull. 33, 289–293 (in Chinese).

Chen, J.P., 2005. Tectonic Evolution and Oil–Gas Exploration During the Mesozoic and Cenozoic in the Hefei Basin. Geological Publishing House, Beijing, p. 121–247 (in Chinese).

Chen, H., Yang, S.F., Jia, C.Z., Sun, H.B., Cheng, X.G., 2005. Origin of Cenozoic "reverse faults in northeastern China – an example from the Rongxintun fault in the Liaohe basin, China. J. Asian Earth Sci. 25, 167–172.

Chen, X.H., George, G., Yin, A., Li, L., Jiang, R.B., 2012. Paleozoic and Mesozoic basement magmatisms of Eastern Qaidam Basin, Northern Qinghai-Tibet Plateau: LA-ICP-MS zircon U–Pb geochronology and its geological significance. Acta Geol. Sin. (English Edition) 86, 350–369.

Dai, S.Q., Deng, J.F., Wu, Z.X., Zhao, H.L., Chen, J.F., Du, J.G., 2003. Evidence of magmatic petrology for the Yanshanian orogeny in the Dabie orogen. Geol. China 30, 159–164 (in Chinese with English abstract).

Dong, S.W., Zhang, Y.Q., Long, C.X., Yang, Z.Y., Ji, Q., Wang, T., Hu, J.M., Chen, X.H., 2007. Jurassic tectonic revolution in China and new interpretation of the Yanshan movement. Acta Geol. Sin. 81, 1449–1461 (in Chinese).

Dong, Y.X., Xiao, L., Zhou, H.M., Du, J.X., Zhang, N., Xiang, H., Wang, C.Z., Zhao, Z.H., Huang, H.X., 2010. of the Nanpu Sag in the Bohai Bay Basin, Eastern China: Geochemistry, petrogenesis, and implications for tectonic setting. J. Asian Earth Sci. 39, 173–191.

Du, J.G., Zhang, P., 1999. Mesozoic volcanic rocks in northern part of the Dabie orogenic belt. Geosciences 13, 57–65 (in Chinese with English abstract).

Du, S.J., Li, H.X., Zhang, Q.L., Du, J.M., Xie, G.A., 2003. Relationship between ore-control structures and gold deposits in the Linglong goldfield, Zhaoyuan, Shandong Province. Geol. J. China Univ. 9, 420–426 (in Chinese with English abstract).

Ernst, W.G., Tsujimori, T., Zhang, R.Y., Liou, J.G., 2007. Permo-Triassic collision, subduction-zone-metamorphism, and tectonic exhumation along the East Asian continental margin. Ann. Rev. Earth Planetary Sci. 35, 73–110.

Gao, S., Roberta, L.R., Xu, W.L., Yuan, H.L., Liu, Y.S., Richard, J.W., Igor, S.P., Liu, X.M., Huang, H., Wang, X.R., Yang, J., 2008. Recycling deep cratonic lithosphere and generation of intraplate magmatism in the North China Craton. Earth Planet. Sci. Lett. 270, 41–53.

Gilder, S.A., Leloup, P.H., Courtillot, V., Chen, Y., Coe, R., Zhao, X., Wang, W., Halim, N., Cogne, J.P., Zhu, R., 1999. Tectonic evolution of the Tancheng-Lujiang (Tan-

Lu) fault via middle Triassic to early Cenozoic paleomagnetic data. J. Geophys. Res. 104, 15365–15390.
Grimmer, J.C., Jonckheere, R., Enkelmann, E., Ratschbacher, L., Hacker, B.R., Blythe, A.E., Wagner, G.A., Wu, Q., Liu, S., Dong, S., 2002. Cretaceous-Cenozoic history of the southern Tan-Lu fault zone: apatite fission-track and structural constraints from the Dabie Shan (eastern China). Tectonophysics 359, 225–253.
Hao, T.Y., Su, M., Liu, J.H., Yan, X.W., Choi, S., Yao, C.L., Liu, S.H., Dai, M.G., Xu, Y., 2004. Deep structure and boundary belt position between Sino-Korean and Yangtze blocks in the Yellow Sea. Earth Sci. Front. 11, 51–61 (in Chinese with English abstract).
Harding, T.P., 1985. Seismic characteristics and identification of negative flower structures, positive flower structure and positive structural inversion. Am. Assoc. Pet. Geol. Bull. 63, 1016–1058.
HBGMR (Hebei Bureau of Geology and Mineral Resources), 1989. Regional Geology of Hebei Province, Beijing, Bianjun. Geological Publishing House, Beijing (p. 36–255, in Chinese).
Hu, B., Zhang, Y.Q., 2007. Discovery of a basement strike-slip ductile shear zone on the eastern margin of the Zhangbaling uplift, Anhui, China, and its tectonic significance. Geol. Bullet. China 26, 256–265 (in Chinese).
Jie, L., Zhu, R.X., Chen, R.G., Wu, S.H., Zhang, Q., Luo, Y.C., Zheng, Y.F., Yao, X.G., Xu, K.D., 1992. Petroleum Geology of China (Jiangsu, Zhejiang and Anhui Provinces). Petroleum Industry Press, Beijing, pp. 398–409 (in Chinese with English abstract).
LBGMR (Liaoning Bureau of Geology and Mineral Resources), 1989. Regional Geology of Liaoning Province. Geological Publishing House, Beijing, pp. 36–255 (in Chinese).
Li, X.H., 2000. Cretaceous magmatism and lithospheric extension in southeast China. J. Asian Earth Sci. 18, 293–305.
Li, X.Q., Wang, Z.H., Cheng, Y.Y., Qiu, D.Z., 2003. Pull Apart basin Analysis and its Oil–Gas. Petroleum University Press, Dongying, China, p. 112–135 (in Chinese).
Li, Y.P., Wu, S.G., Han, W.G., Zhang, Y.Q., 2006. A study on geophysical features of deep structures of the Hefei basin and the southern Tan-Lu fault zone. Chinese J. Geophys. – Chinese Ed. 49, 115–122 (in Chinese).
Li, Z., Li, Y., Zheng, J.P., Han, D., 2007. Late Mesozoic tectonic transition of the eastern North China Craton. Evidence from basin-fill records. Geol. Soc. 80, 239–265.
Li, S.Z., Zhao, G.C., Dai, L.M., Zhou, L.H., Liu, X., Suo, Y.H., Santosh, M., 2012. Cenozoic faulting of the Bohai Bay Basin and its bearing on the destruction of the eastern North China Craton. J. Asian Earth Sci. 47, 80–93.
Lin, W., Faure, M., Wang, Q., Monié, P., Panis, D., 2005. Triassic polyphase deformation in the Feidong-Zhangbaling massif (Eastern China) and its place in the collision between the North China and south China blocks. J. Asian Earth Sci. 25, 121–136.
Liu, D.L., Tao, S.Z., 2000. A study on structure assembles in Tan-Lu fracture zone and near areas. Geotectonica et Metallogenia 24, 314–320 (in Chinese with English abstract).
Liu, J.L., Guan, H.M., Ji, M., Hu, L., 2006. Late Mesozoic metamorphic core complexes: new constraints on lithosphere thinning in North China. Prog. Natural Sci. 16, 633–638.
Mei, L.F., Dai, S.W., Shen, C.B., Tang, J.G., 2008. Formation and disintegration of Mesozoic Cenozoic intra-continental ramp zone in Middle and Lower Yangtze region. Geol. Sci. Technol. Inform. 27, 1–7 (in Chinese with English abstract).
Pierre, V., Hou, M.J., Wang, Y.M., Mercier, J.L., 2007. The kinematics of the Tan-Lu Fault zone during the Mesozoic-Palaeocene and its relations with the North China-South China block collision (Anhui Province, China). Bulletin de la Société géologie France 178, 353–365.
Qi, J.F., Yang, Q., 2010. Cenozoic structural deformation and dynamic processes of the Bohai Bay basin province, China. Mar. Pet. Geol. 27, 757–771.
SBGMR (Shandong Bureau of Geology and Mineral Resources), 1991. Regional Geology of Shandong Province. Geological Publishing House, Beijing, p. 52–146 (in Chinese).
Shen, X.Z., Xiu, Z., Xue, A.M., Liu, L., Lin, Y., 1995. The relationship between tectonics and natural gas in the southern North China basin. Publishing House of China University of Science and Technology, Hefei, pp. 66–135 (in Chinese).
Shi, W.Z., Cartwright, J., Zhao, Z.K., Chen, H.H., Jiang, T., Miao, H.B., Wang, X.L., 2012. Structural and sedimentary characteristics of the Liangjia-Wangchang strike-slip region, Yitong Basin, China. J. Asian Earth Sci. 50, 150–163.
Song, M.C., Xu, J.X., Wang, P.C. and others, 2009. Tectonic Pattern and Tectonic Evolution of Shandong Province. Geological Publishing House, Beijing, p. 8–215 (in Chinese).
Sun, W.D., Ding, X., Hu, Y.H., Li, X.H., 2007. The golden transformation of the Cretaceous plate subduction in the west Pacific. Earth Planet. Sci. Lett. 262 (3–4), 533–542.
Tang, J.F., Li, H.K., Lou, Q., 2003. Progress in the study of the southern segment of the Tan-Lu Fault and a discussion of the nature of the fault. Geol. Bullet. China 22, 426–436 (in Chinese with English abstract).
Teng, J.W., Yan, Y.F., Wang, G.J., Xiong, X., 2006. Structure of Earth's crust and upper mantle, inland subduction and its coupling effects on the Dabie orogenic belt and the Tancheng-Lujiang fault zone. Chinese J. Geophys. – Chinese Ed. 49, 449–457 (in Chinese with English abstract).
Tian, Z.Y., Han, P., Xu, K.D., 1992. The Mesozoic–Cenozoic East China rift system. Tectonophysics 208, 341–363.
Wan, T.F., 2004. An Outline in Tectonics of China. Geological Publishing House, Beijing, pp. 118–250 (in Chinese).
Wan, T.F., Zhu, H., Zhao, L., Lin, J.P., Cheng, J., Chen, J., 1996. Formation and evolution of Tancheng-Lujiang fault zone – a review. Geosciences 10, 159–168 (in Chinese with English abstract).
Wang, Y., 1996. Evolutional Processes and Dynamics of the Orogenic Belts and Basins in North China Since the Mesozoic. Geological Publishing House, Beijing, p. 15–67 (in Chinese).
Wang, X.F., Li, Z.J., Chen, B.L., Chen, X.H., Dong, S.W., Zhang, Q., Wu, H.L., Xing, L.S., Zhang, H., Dong, F.X., Wu, H.M., Huo, G.H., Lin, C.Y., Bai, J.Q., Liu, X.C., 2000. On the Tan-Lu Fault Zone. Geological Publishing House, Beijing, pp. 15–119, 218–348 (in Chinese).
Wang, G.H., Zhang, C.H., Wang, G.S., Wu, Z.W., 2001. Tectonic framework of western Liaoning Province and its evolution during the Mesozoic. Geoscience 15, 1–7 (in Chinese).
Wei, G.X., Diao, S.Z., Zhou, C.Y., 1993. The Seismic Active Research Along Tan-Lu Fault Belt. Seismological Press, Beijing, p. 1–89 (in Chinese).
Wu, S.G., Yu, Z.H., Zou, D.B., Zhang, H.Y., 2006. Structural features and Cenozoic evolution of the Tan-Lu fault zone in the Laizhou bay, Bohai Sea. Mar. Geol. Quatern. Geol. 26, 101–110 (in Chinese).
Xu, J.W., 1964. The shifting movements of the Tancheng-Lujiang fault belt. Geol. Eastern China 5, 18–31 (in Chinese with English abstract).
Xu, J.W., Ma, G.F., 1992. Studies on the Tan-Lu fault belt in the recent ten years. Geol. Rev. 38, 316–324 (in Chinese with English abstract).
Xu, J.W., Zhu, G., 1994. Tectonic models of the Tan-Lu fault zone, eastern China. Int. Geol. Rev. 36, 771–784.
Xu, Z.Q., Zhang, Q.D., Zhao, M., 1982. The main characteristics of the paleorift in the middle section of the Tancheng-Lujiang fracture zone. Bullet. Chinese Acad. Geol. Sci. 4, 17–44.
Xu, J.W., Zhu, G., Tong, W.X., Cui, K.R., Liu, Q., 1987. Formation and evolution of the Tancheng-Lujiang wrench fault system. A major shear system to the northwest of the Pacific Ocean. Tectonophysics 134, 273–310.
Xu, Z.Q., Yang, W.C., Ji, S.C., Zhang, Z.M., Yang, J.S., Wang, Q., Tang, Z.M., 2009. Deep root of a continent–continent collision belt: evidence from the Chinese Continental Scientific Drilling (CCSD) deep borehole in the Sulu ultrahigh-pressure (HP-UHP) metamorphic terrane, China. Tectonophysics 475, 204–219.
Yan, X., Zhang, H.F., Fan, W.M., Ying, J.F., Zhang, J., Zhao, X.M., Su, B.X., 2010. Evolution of lithospheric mantle beneath the Tan-Lu fault zone, eastern North China Craton: evidence from petrology and geochemistry of peridotite xenoliths. Lithos 117, 229–246.
Yang, X.Y., Liu, D.L., Feng, M., Yu, Q.N., Wang, K.R., 2007. Rock deformation, component migration and 18O/16O variation during mylonitization, southern Tan-Lu fault belt. Acta Geol. Sinica 76, 297–311 (in Chinese).
Yang, X.Y., Liu, D.L., Chen, Y.J., Dai, J.X., 2008. Calculation of the CO2 degassing during contact metamorphism and its geological significance. The model and an example in Shuanshan Area from the South Tan–Lu fault belt. Acta Geol. Sinica 82, 562–576 (in Chinese).
Yang, J.S., Li, T.F., Chen, S.Z., Wu, C.L., Robinson, P.T., Liu, D.Y., Joseph, L.W., 2009. Genesis of garnet peridotites in the Sulu UHP belt: examples from the Chinese Continental Scientific Drilling Project-main hole, PP1 and PP3 drillholes. Tectonophysics 475, 359–382.
You, T., Zhao, D.P., 2011. Destruction mechanism of the North China Craton: insight from P and S wave mantle tomography. J. Asian Earth Sci. 42, 1132–1145.
Zhai, M.G., Cong, B.L., 1996. Petrotectonics of Sulu-Dabie metamorphic belt, central and east China. Science in China Series D – Earth Sciences 39, 319–328.
Zhang, W.Y., 1984. Introduction of Fault Block Tectonics. Petroleum Industry Press, Beijing, pp. 23–131.
Zhang, S.W., 2004. The application of an integrated approach in exploration of lacustrine turbidites in Jiyang Sub-basin, Bohai Bay Basin, China. J. Petrol. Sci. Eng. 41, 67–77 (in Chinese).
Zhang, Y.Q., Dong, S.W., Shi, W., 2003. Cretaceous deformation history of the middle Tan-Lu fault zone in Shandong Province, eastern China. Tectonophysics 363, 243–258.
Zhang, P., Wang, L.S., Zhong, K., Ding, Z.Y., 2007. Research on the segmentation of Tancheng-Lujiang fault zone. Geol. Rev. 53, 586–591 (in Chinese).
Zhang, S.W., Sui, F.G., Lin, H.X., Liu, H., Zhang, S.P., Li, J.Y., 2009. Petroleum geology and perspective evaluation on the pre-Paleogene system in the Bohai Bay basin. Geological Publishing House, Beijing, pp. 46–218 (in Chinese).
Zhang, Y.M., Zhang, X.X., Gu, L., Liu, S.Y., Dong, K., Li, B.H., Li, P.R., 2011. Fluid inclusion and H–O isotope evidence for immiscibility during mineralization of the Yinan Au–Cu–Fe deposit, Shandong, China. J. Asian Earth Sci. 42, 83–96.
Zhang, J.D., Yang, X.Y., Sun, W.D., Wang, G.J., Yang, C.C., Liu, C.Z., Liu, D.L., 2012a. New data on the evolution of the Tan–Lu fault belt: constraints from geological geophysical surveys in the southern segment. Int. Geol. Rev. 54, 1562–1578.
Zhang, J.D., Yang, X.Y., Liu, C.Z., Zhang, L.L., Li, B., Xu, Y., Huang, S., Hu, W.J., 2012b. The fine deep structure of the northern margin of the Dabie Orogenic Belt from gravity-magnetic-electrical-seismic combination survey. Chinese J. Geophys. 55, 2292–2306 (in Chinese).
Zhang, J.D., Chen, X.D., Li, Q.L., Liu, C.Z., Li, B., Li, J., Liu, G., Ren, F.L., 2012c. Mesozoic "Red Beds" and their evolution in the Hefei Basin. Acta Geol. Sinica 86, 1060–1070.
Zhu, G., Song, C.Z., Wang, D.X., Liu, G.S., Xu, J.W., 2001. Studies on $^{40}Ar/^{39}$ thermochronology of strike-slip time of the Tan-Lu fault zone and their tectonic implications. Sci. China Series D – Earth Sci. 44, 1002–1009.
Zhu, G., Xu, Y.D., Liu, G.S., Wang, Y.S., Xie, C.L., 2006. Structural and deformational characteristics of strike-slipping along the middle-southern sector of the Tan-Lu fault zone. Chinese J. Geol. 41, 226–241 (in Chinese).
Zhu, R.X., Chen, L., Wu, F.Y., Liu, J.L., 2011. Timing, scale and mechanism of the destruction of the North China Craton. Sci. China (Series D) 54, 789–797.