

# Structural geochemistry of gold mineralization in the Linglong-Jiaojia district, Shandong Province, China

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**Abstract** The Linglong-Jiaojia district is one of the most important regions containing gold deposits in China. These gold deposits can be divided into: a) the pyrite-gold-quartz vein type (Linglong type), which is controlled by brittle-ductile to ductile deformation structures, and b) the alteration-zone type (Jiaojia type), characterized by small veinlets, or the disseminated type recognized in brittle shear zones. Lode gold deposits in the Jiaojia area occur in NE brittle fracture zones, formed in a dominantly simple shear deformation regime, mainly in thrust attitude with a minor sinistral strike slip component. In the Linglong area, the lode gold deposits are located at the intersection of three types of structures: NNE and NE brittle-ductile fault zones and the ENE ductile reverse shear zone in the south of the area. The structural characteristics of these brittle shear zones are consistent with a tectonic NNW-SSE principal stress field orientation. Similar stresses explain the ENE Qixia fold axes, the Potouqing and several other ENE reverse ductile shear zones elsewhere in the region, the Tancheng-Lujiang fault zone and its subsidiaries in the vicinity of the Linglong-Jiaojia district, as well as the southern ENE suture zone north of Qingdao. Therefore these structural systems occurred as part of different major tectonic events under NNW-SSE compression principal stress fields in the area.

Gold deposits are hosted in smaller-scale structures within the brittle fault zones and brittle-ductile shear zones. Although ore bodies and, on a smaller scale, quartz ore veins often seem to be randomly oriented, it is possible to explain their distribution and orientation in terms of the simple shear deformation process under which they were developed. The progressive simple shear failure is characterized by various fracture modes (tension and shear) that intervene in sequence. The tension and shear fractures are influenced by the stress level (depth of burial beneath the paleosurface) in their structural behavior, show variable dilatancy (void openings) and extend on all scales. By making use of these characteristics, a progressive failure analysis can be applied to predicting the shape and extent of ore bodies as well as the styles of mineralization at any given location.

**Key words** shear zone; gold-bearing quartz vein; alteration type; Linglong-Jiaojia area; China

## 1 Introduction

The Linglong-Jiaojia gold mining district is located in the eastern part of Shandong Province (Fig. 1) and it is one of the most important gold camps in China (70 km long and 30 km wide) with an accumulation of more than 900 tons of gold (Zhou Taifu and Lü Guxian, 2000; Qiu et al., 2002). Tens of individual gold deposits and hundreds of showings in the area provide about one fourth of China's total gold reserves and production. The most significant gold deposits discovered in the area are the Linglong mine

(a quartz vein type), the Jiaojia mine (an alteration zone type) and the Jiuqu mine (a transition type) as defined in this study. The Linglong mine has been put into operation since 1007, and over 11.36 metric tons of gold has been produced between 1962 and 1978 (Kong Qingren et al., 1989). Numerous syntheses were done on the basic geology, tectonics, structural environments, ore geochemistry and fluid inclusion features of gold deposits (No. 6 Geological Team, 1976, unpublished; Lu Huanzhang and Fang Genbao, 1988; Lu Huanzhang, 1988; Kong Qingren et al., 1989; Zhu Fenshan, 1989; Lü Guxian and Kong Qingren, 1993; Li Ziping and Yang Mingzhi, 1993; Zhou Taifu

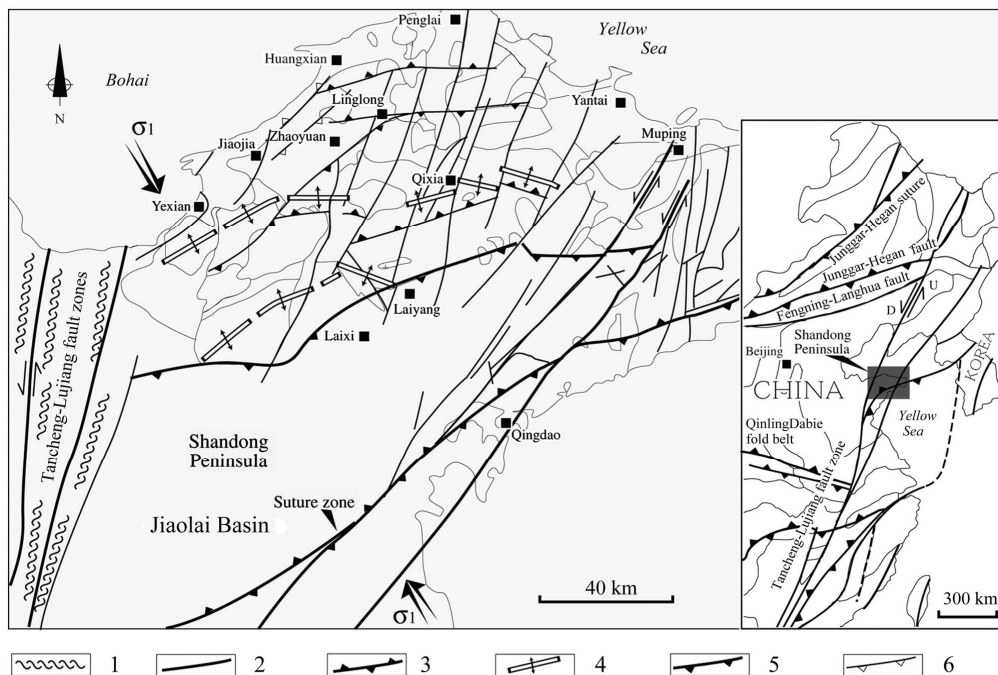


Fig. 1. Structural map of Shandong Province, China (modified from Lü Guxian and Kong, 1993; Yang Mingzhi and Lü Guxian, 1996) with an inset sketch map showing the principal structural divisions of eastern China (after Wang Hongzhen and Mo Xuanxue, 1995). The Tancheng-Lujiang fault zone extends from the Yangtze Valley through Shandong and the NE part of China. During this major tectonic event, several shear zones including Potouqing, Pingdu, Zhaoyuan, Sanshandao, Jiaojia, Huangxian-Yexian, were formed in the eastern part of Shandong (Fig. 2). 1. Ductile shear zone; 2. brittle fault; 3. suture zone; 4. fold axis; 5. ductile reverse fault; 6. brittle thrust shear zone.

and Lü Guxian, 2000; Zhou Taifu et al., 2002; Qiu et al., 2002). Since 1988 studies have been intensified both on the regional geology and on the different gold deposits in this area (Fig. 2) including Linglong, Jiaojia, Hedong, Hexi, Lingnan, Xincheng, Qixia, Muping and Jiuqu.

The East Shandong gold province stretches along the southeastern margin of the North China Craton, dominated by Archean rock units, and has undergone multiple Proterozoic and Phanerozoic orogenies along both northern and southern boundaries. The gold deposits are hosted in Mesozoic Yanshanian granitoids (208–90 Ma) that intruded the Precambrian metamorphic rocks at the Craton margin, attributed either to the collision and suturing of the North China and Yangtze (South China) cratons (Zhou Taifu and Lü Guxian, 2000; Zhou Taifu et al., 2002) or to the distal influence of subduction of the Pacific Ocean plate under the Eurasian continent (Lu Huanzhang et al., 1999; Qiu et al., 2002).

Lü Guxian and Kong Qingren (1993) classified the structural features by defining structural zones and domains with varying deformation intensities and by defining a new tectono-petrofacies concept based on a combination of these structural zones and domains with a certain shape, distribution and genetic relations to geologic and tectonic processes. On this basis they

pointed out that there exist dense ENE regional linear structures in the eastern part, while NE compress-shear structures are recognized predominantly in the western part. Through such an approach they interpreted very schematically the structures and concluded too rapidly that the latter structures controlled the gold mineralization.

The structures in the Linglong-Jiaojia area were mostly indicated as fracture or fault zones, although the presence of a ductile shear zone in the Linglong mine was observed (Wang Jijun and Yu Heyong, 1990; Lü Guxian and Kong Qingren, 1993; Li Ziping and Yang Mingzhi, 1993; Yang Mingzhi and Lü Guxian, 1996 and Lu Huanzhang et al., 1999). It is only recently that lines of evidence were developed for the Potouqing fault as a ductile shear zone (Wang Jijun and Yu Heyong, 1990; Lu Huanzhang et al., 1999) indicated that in the vertical section, the Linglong quartz vein type is located in the upper part whereas the Jiaojia, Xincheng and Sanshandao gold deposits (Fig. 2) (alteration zone type) were formed at deeper levels. According to the interpretation, in order for ore deposits in the Linglong gold mining area to fit in the vertical sequence, the quartz vein type (occurring in the western part of the mining area) must have been deposited at a high level in the sequence while the alteration zone to the transition type, at the Jiuqu mine,

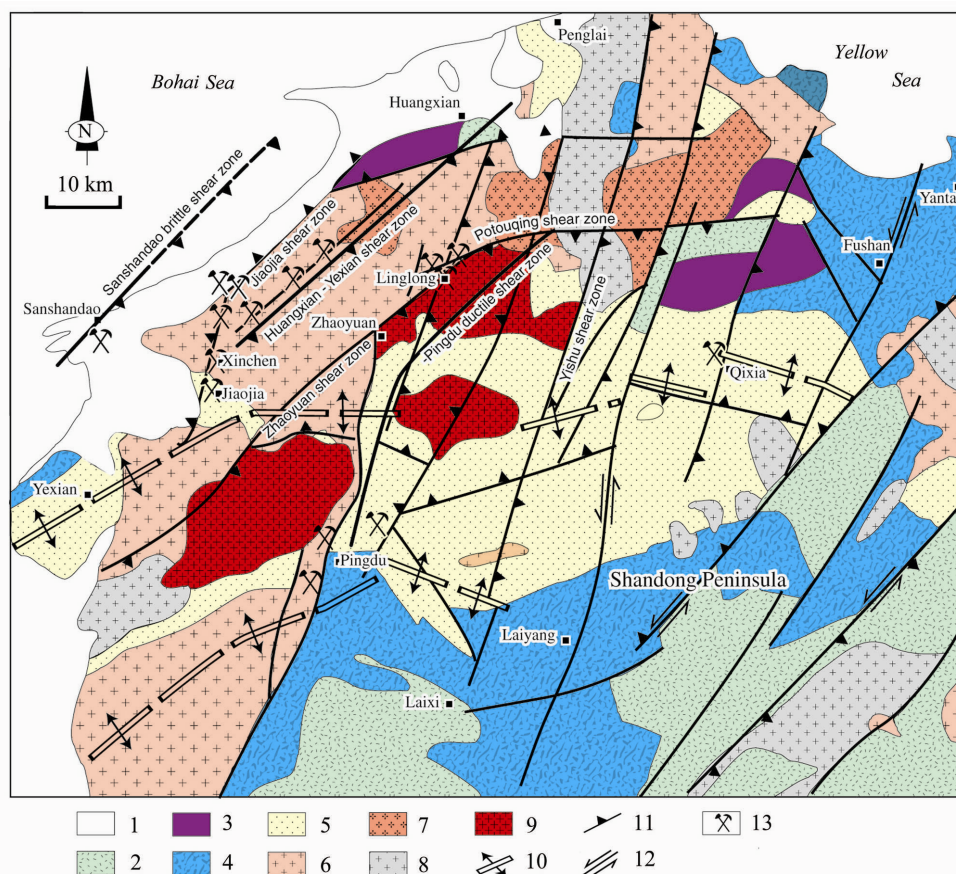


Fig. 2. Geological map of the Jiaojia-Linglong area (compiled data from the No. 6 Geological Team and Linglong mine staff, unpublished). Several shear zones are present in the region and the Linglong, Guojialing and Luanjiahe granites intruded into a Precambrian terrain along a NE direction. Most of the gold deposits occurred in the shear zones within the Linglong granite. 1. Quaternary; Cretaceous volcanic rock; 3. Jurassic rock; 4. Proterozoic rock; 5. Archean Jiaodong Group; 6. Linglong granite; 7. Guojialing granite; 8. Yanshanian granite; 9. Luanjiahe granite; 10. fold axis (anticline); 11. thrust fault; 12. strike-slip fault; 13. gold mine.

observed in the eastern sector of the Linglong gold mining area, occurred at a deeper level which is questionable.

Thus, a better understanding of the deformation style in the Linglong-Jiaojia district is essential to interpret the structural environment of the deposits and the relationship between structures and gold mineralization, so as to guide ore exploration in the region. In this paper, the geologic characteristics of these deposits will be reviewed, as well as the deformation styles of the different shear zones and their relationship with gold mineralization. An attempt is made to integrate the geologic characteristics of these deposits with their structural deformation features into geomechanical models.

## 2 Geological setting

### 2.1 Regional geology

The Jiaodong Peninsula is located along the southeastern margin of the North China Craton and on

the western margin of the Pacific Plate. It is bounded to the west by the NNE-trending Tancheng-Lujiang (Tan-Lu) fault zone which is approximately 3600 km in length and crosses the Shandong Province dividing it into eastern and western geological provinces. Precambrian rocks cover a large part of eastern Shandong Province and the Linglong-Jiaojia gold camp, hosted by the Linglong Mesozoic granite, occurs in this part of the Shandong Province (Figs. 1 and 2). This gold camp is located on the northern flank of the ENE-trending Qixia anticlinorium of eastern Shandong Province. The eastern boundary of the Linglong-Jiaojia gold camp is marked by the Yishu shear zone with the Bohai Sea as its western boundary (Figs. 1 and 2). Mineralization is controlled by several shear zones including the ENE-trending Potouqing and NE-trending Zhaoyuan and Pingdu ductile shear zones, located at the SE margin of the Linglong mine and the NE-trending Jiaojia, Huangxian-Yexian, Zhaoyuan and Sanshandao brittle shear zones and several others in the Jiaojia area. The Linglong gold field occurs on both sides of and along

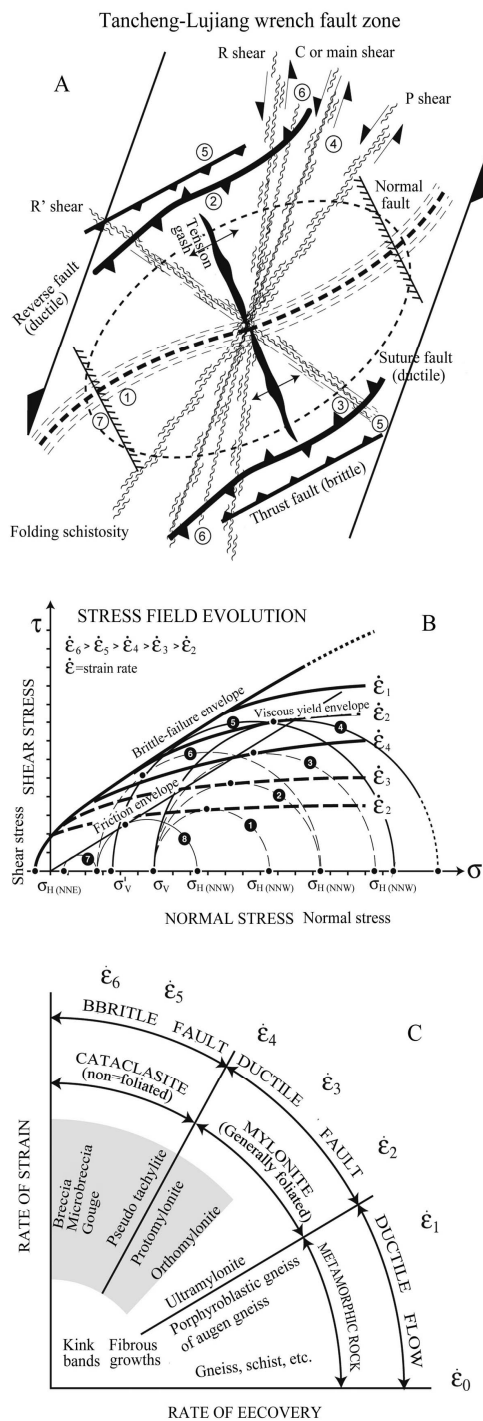


Fig. 3. Geomechanical modeling of the eastern part of Shandong Province. A. Schematic structural modeling of the Tancheng-Lujiang wrench fault zone and surrounding structures; B. stress field evolution in the Mohr-Coulomb stress space with envelopes at various strain rates illustrating both brittle and ductile behaviors of rocks (after Dusseault and Mraz, 1983); C. strain rate vs. rate of recovery of rock with their resulting strain behaviors and structures in the brittle and ductile fields (after Wise et al., 1984). Note: Encircled numbers refer to deformational events described in the text.

the Potouqing shear zone (Fig. 2) and includes the main deposits of the Linglong, Lingnan, Jiuqu, Dakaitou, Shuangding, Dongshan and Dongfeng mines. In the Jiaojia gold field, the main deposits are those of the Jiaojia, Xincheng, Wangershan, Hedong, Hexi, Madong, Sanshandao and Cangshang mines that occur along the Sanshandao-Cangshang, Jiaojia, Huangxian-Yexian and Zhaoyuan brittle thrust oblique slip fracture zones.

Lithologically, in the eastern part of Shandong Province are distributed low to high-grade metamorphic rocks of the Archean to Proterozoic Jiaodong, Jinshan, Fenzhishan and Penglai groups (Table 1 and Fig. 2) described in detail by Zhou Taifu and Lü Guxian (2000). The Jiaodong Group (3.6 km) metamorphic rocks are composed of biotite granulites, amphibolite, biotite gneisses, schist, and marbles, with U-Pb ages ranging from 2940–2670 Ma. The Jiaodong Group is overlain unconformably by the Proterozoic Jinshan (4.1 km) and Fenzhishan (3.1 km) groups of metamorphic mafic igneous rocks, granulites, amphibolite, marble and schist (U-Pb ages of 2480–2030 Ma). The Penglai Group (4.1 km), consisting of slate, phyllite and carbonate rocks, lies unconformably on the previous sequences. Post-Precambrian strata are absent, whereas late Jurassic rocks consist of clastic sediments and the Cretaceous is characterized by volcanic and clastic rocks. Yanshanian granitoid plutons intruded all these units.

## 2.2 Granites

According to their relationship and mineral composition, texture, relation with wall rocks and chronological characteristics, Zhou Taifu and Lü Guxian (2000) identified two groups of Mesozoic granitoids in East Shandong, namely the Middle Yanshanian (160–150/130? Ma) and the Late Yanshanian (117–85 Ma) granitoids. The first group of granitoids is restricted to the north of the suture zone, while the second group occurs on both sides of it. There are three types of Mesozoic granites of the first group of granitoids in the Linglong-Jiaojia district: the gneissic-biotite-granite suite (Linglong), the porphyritic granodiorite suite (Guojialing), the medium- to coarse-grained granite suite (Luanjiahe) and a few other suites (Fig. 2), as described in detail by Zhou Taifu and Lü Guxian (2000), Qu Xiaoming et al. (2000) and Qiu et al. (2002). The contact between the Linglong granite suite and the Jiaodong Group is intrusive and is not clearly defined because of interdigitation and xenoliths of the country rock within the granite. Locally the Linglong granite possesses a distinct gneissosity, generally consistent with the one in the Jiaodong Archean metamorphic rocks, considered as being transitional into both the

relict metamorphic enclaves in the granitoid and the surroundings. The Linglong granite batholith, which hosts most of the ore deposits, is measured at about 3500 km<sup>2</sup> and trends NNE controlled by NE regional fold-fault structures. The Luanjiahe granite intruded the central part of the ENE-trending Qixia anticlinorium and is locally deformed and foliated. The Guojialing porphyritic granodiorite occurs mainly on the northern limb of the Qixia anticlinorium and the east of the Linglong granite suite, with a clear cut relationship to the wall-rocks and rare foliation (Fig. 2).

The ages of the Linglong granite vary between 150.2 Ma and 164.2 Ma and most likely around 150–140 Ma (Zhang Jiasheng, 1992; whole rock and K-feldspar, U-Pb isochron and K-Ar methods; Lu Huanzhang and Li Huaqin, 1996; Rb-Sr method). The ages of the Luanjiahe granodiorite vary between 134.0 Ma and 140.0 Ma (whole rock and K-feldspar, U-Pb isochron and K-Ar methods). The ages of the Guojialing granite range from 124.0 Ma to 126.0 Ma (K-Ar method). Recently, the Linglong, Luanjiahe and Guojialing granites were dated, yielding SHRIMP zircon ages: 153±4 to 163±4; 152±10 to 154±4 and 126±2 to 130±3 Ma, respectively (Guan Kang et al., 1998). There is an extremely large age variation reported in the literature, discussed in detail by Zhou Taifu and Lü Guxian (2000) and Qiu et al. (2002), caused by sampling different materials, using different analytical methods but being mainly attributed to the influence of multiple tectonic movements and magmatism in the area. Briefly, granitoids in the Linglong-Jiaojia district were dated to be three intruding periods: the Linglong granite during the Middle Jurassic (160–140 Ma); the Luanjiahe granodiorite during the Late Jurassic (150–140 Ma) and the latest intrusions of the Guojialing granite during the Early Cretaceous (130–120 Ma), all in the Middle Yanshanian orogeny.

Based on the geological occurrence, structure, texture, contact relationships with the wall rocks (particularly for the Jiaodong Group), REE patterns and isotope geochemistry, the granitic magmatism has been attributed to partial melting and anatexis of the Precambrian Jiaodong metamorphic Group during the Mesozoic Indosinian and Yanshanian orogenies (Lu Huanzhang et al., 1988; Zhu Fenshan, 1989; Kong Qingren et al., 1989). A large number of Mesozoic (Yanshanian dykes) intermediate to mafic dykes: lamprophyre, diabase and diorite, strike NNE to NE and are mostly hosted in the intrusions. Even if the dykes show various rock types and different mineral associations, their REE patterns are quite similar to those of the intrusions in which they were developed. They can be found along or cross-cutting the ore veins and locally form wall rocks of the ore bodies such as

the hanging wall of the vein No. 108 of the Linglong mine (Fig. 4).

So, the Mesozoic is the most important period in the Linglong-Jiaojia area as it includes the deposition of the Late Jurassic sediments, the development and evolution of the continental Tancheng-Lujiang fault zone, the intrusions of the Linglong granites and Cretaceous volcanic rocks and the emplacement of gold mineralization. Gold mineralization probably originated from the Precambrian Jiaodong metamorphic rocks, derived from originally mafic volcanic and sedimentary rocks, but is spatially and temporally related to the granitoid intrusions (particularly the Linglong granite) in the region.

### 2.3 Tectonic and structural settings

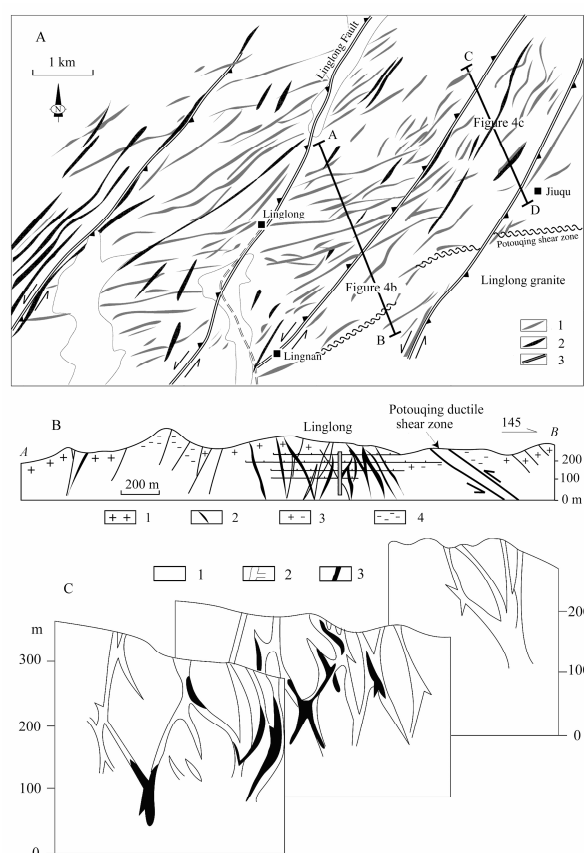


Fig. 4. Schematic geological and structural map of the Linglong gold field (modified from Linglong mine staff, 1994, unpublished). A. Showing the orientation of large gold-bearing quartz veins, different types of dykes, Potouqing shear zone and Linglong faults: 1. Au-quartz vein; 2. dyke; 3. fault. B. Geological cross section of the Linglong gold field showing the anastomosed pattern of X-shaped conjugate brittle-ductile shears: 1. Linglong granite; 2. gold ore body; 3. altered granite; 4. sericite-quartz altered rock. C. Profile map of cross sections through the Jiuqu alteration-type gold deposit (along exploration lines Nos. 90, 96 and 101, after Linglong mine staff, 1994, unpublished) showing the same pattern as in B: 1. Linglong granite; 2. ore body; 3. rich ore.

Tectonically, the East Shandong gold province is located at the SE margin of the North China Craton or along the northern boundary of the suture zone between the North and South China cratons, developed during the Triassic to the Jurassic. The evolution of the orogenic belt is complex, hence leading to controversial models well summarized in Zhou Taifu et al. (2002) and Zhou Taifu and Lü Guxian (2000). The North China Craton was cratonised after the Wutai (ca. 2.3 Ga.) and Luliang (ca. 1.8 Ga.) orogenies, and was first uplifted during the Caledonian Orogeny, when both the Mongolian and the Qaidam-Qinling oceanic plates subducted underneath the North China Craton from the north and south, respectively. The North China Craton was uplifted again during the Hercynian to Indosinian orogenies when the Siberia and South China cratons subducted from the north and the south, respectively. Also, a general consensus exists that the Pacific Ocean Plate subducted obliquely the Eurasia during the Yanshanian orogeny (Early Cretaceous), and provoked magmatism along the convergent margin. These collisions led to the formation of the Banpu-Qixia anticlinorium and associated faults as well as the NNE-striking continental Tancheng-Lujiang transform fault that established the basic tectonic framework of China and structured the metallogenic provinces in eastern China (Kumarapeli et al., 1990; Xu Jiawei et al., 1986; Xu Jiawei, 1993; Zhang Jiasheng, 1992; Yin An and Nie S., 1993; Xu Jiawei and Zhu Guang, 1994; Zhou Taifu et al., 2002).

The Jiaodong Peninsula is broadly divisible into two pre-Jurassic components: the Jiaobei terrain in the north and the Su-Lu terrain in the south. The two terrains are separated by the Wulian-Qingdao-Yantai suture and the Jiaolai (or Laiyang) basin comprising Jurassic and Cretaceous sedimentary rocks (Fig. 1) (Qiu et al., 2002). The Jiaolai Basin looks like a pull-apart basin (Fig. 2 in Qiu et al., 2002) created between the Tancheng-Lujiang fault and a NNE-striking subsidiary fault under NNW-SSE compressional forces. The two terrains experienced deformation and metamorphism as early as in Archean time, but the major structural deformation and magmatic intrusion occurred later during the Mesozoic (Zhou Taifu et al., 2002; Zhou Taifu and Lü Guxian, 2000). The geological history of this region (Table 1) started from 2700–2500 Ma, during which the Precambrian Jiaodong Group (the most abundant in the area) was formed, followed by the Proterozoic Jingshan and Fenzishan groups, all generally striking EW, and they are the predominant rocks mainly developed in the central part of the region. The metamorphic rocks resulted from strong regionally tectonic deformation and moderate-high-grade metamorphism during the Archean Wutai and

**Table 1. Geological chronology of the Linglong-Jiaojia area**

Quaternary	
Mesozoic	
Cretaceous	
Gold mineralization	126–120 Ma
Linglong granite	155–124 Ma
Cretaceous volcanic rock	140–63 Ma
Brittle faulting: thrust and strike-slip	145–95 Ma
Tancheng-Lujiang brittle activity	145–95 Ma
Jurassic	
Linglong granite	165–125 Ma
Late Jurassic sedimentary rock	160–140 Ma
Yanshanian orogeny	208–90 Ma
Triassic	
Tancheng-Lujiang ductile shear belt development	250–208 Ma
Ductile reverse faulting	260–250 Ma
Folding	270–260 Ma
Indosinian orogeny	270–208 Ma
Proterozoic:	
Late	
Jinningian orogeny	1000–800 Ma
Penglai Group	1500–600 Ma
Early	
Fenzishan Group: greenschist	2000–1600 Ma
Lüliangian orogeny	2000–1800 Ma
Jingshan Group: amphibolite facies	2500–2000 Ma
Wutaian orogeny	2500 Ma
Archean	
Jiaodong Group: amphibolite and granulite facies	2700–2500 Ma.
Funginpiian orogeny	2800–2700 Ma
Continental nuclei	3200–2800 Ma

Data compiled from Zhang Jiasheng, 1992; Xu Jiawei, 1993; Wan Tianfeng, 1995; Zhu Guang et al., 1995; Guan Kang et al., 1998; Zhou Taifu et al., 2002; Lu Huanzhang et al., 1999; Qiu et al., 2002, and this study.

Proterozoic Lüliang and Jinning orogenies that developed long tight fold belts, associated faults with accompanying intrusions of granitoids and other igneous rocks of corresponding ages. This was followed by small tectonic movements with low-grade metamorphism, since the younger Penglai Group was slightly metamorphosed.

Tectonic movements during the Indosinian and Yanshanian orogenies (270–85 Ma), caused by the collision between the South China and North China cratons (270–208 Ma) followed by the oblique subduction of the Pacific-Izanagi Ocean plate under Eurasia (208–85 Ma), produced massive magmatism

of numerous acid-to-intermediate rocks and fault-fold belts along the convergent margins, leading to remobilization of the Precambrian rocks and structures. Syntectonic intrusions of the Linglong, Luanjiahe and Guojialing granites (160–130 Ma) were emplaced in the low- to high-grade metamorphic rocks of the Archean to Proterozoic Jiaodong, Jinshan, Fenzhishan and Penglai groups, according to their respective ages (Table 1). They are located mainly in the northern part of eastern Shandong Province (Fig. 2). Late Yanshanian granitoid intrusions (Aishan granite) (~117–85 Ma) occur on both sides of the suture zone, associated with different tectonic events (Kumarapeli et al., 1990; Xu Jiawei, 1993; Yin An and Nie S., 1993; Zhou Taifu and Lü Guxian, 2000; Zhou Taifu et al., 2002).

Shandong Province was submitted to various episodes of structural deformation, regional metamorphism and magmatism that were reactivated and/or developed at the early stages of the Mesozoic tectonic cycles with the EW suture between the North and South China Cratons (Fig. 1) and by the distal oblique subduction of the Pacific plate underneath the eastern margin of the China continent during the Triassic, Jurassic and Early Cretaceous periods that defined a complex regional structural pattern (Xu Jiawei et al., 1986; Xu Jiawei, 1993; Zhou Taifu and Lü Guxian, 2000; Zhou Taifu et al., 2002). The main deformational events in the region are interpreted as pulses in a continuum of deformation rather than several different orogenic phases under NS to NNW-SSE compressional forces that varied in magnitude with time, covering different orogenic phases.

### 2.3.1 D1 events: Regional EW-striking folds

This NS compression was mainly accommodated by the Banpu-Quixia anticlinorium, truncated by the Mesozoic Tancheng-Lujiang fault zone (Fig. 1 in Xu Jiawei et al., 1986) in eastern China. Examples are the Qixia and Laiyang anticlinoria (Fig. 2) in the central-northern part of eastern Shandong Province discussed by Lü Guxian and Kong Qingren (1993). A regional schistosity was developed, constituting the main structural fabric outside specific high strain zones (shear zones) and showing an ENE trend with a subvertical dip.

### 2.3.2 D2 events: EW-trending reverse ductile shear zones

The NS compression developed EW-trending reverse ductile shear zones dipping 45°–65° either N or S, subparallel to the stratigraphic sequence in Shandong Province. Examples of these are the

Potouqing ductile shear zone and others in the northern and southern parts of the region (Fig. 2). These ductile deformation zones are characterized by a strong subvertical mylonitic fabric with downdip stretching lineation that can be interpreted as strain concentration, either within the same type of rock or between rocks of different rheological behaviors. Mostly they follow the regional schistosity but sometimes crosscut it and truncate the fold hinges. Displacement on these faults is either north-over-south or south-over-north, depending on dip attitude, as recorded by the juxtaposition of different structural levels and rock sequences and may present late dextral strike-slip movement. Possibly late NE and SE conjugated faults may have developed crosscutting the previous ones (Table 1).

### 2.3.3 D3 events: EW-trending suture thrust shear zones

This regional NS to NNW-SSE compression, during the Mesozoic Indosinian and Yanshanian orogenies, developed the suture zone between the North and South China cratons and the corresponding EW thrust shear zones (Fig. 1). Other faults and shear zones of various scales were developed and this compression must have remobilized the pre-existing (D2) ENE reverse ductile shear zones, like the Potouqing shear zone (Table 1).

### 2.3.4 D4 events: NNE to NE Tancheng-Lujiang fault zone

The most important structural event that occurred during the Mesozoic Indosinian and Yanshanian orogenies from Late Triassic to Late Cretaceous is the formation of the major Tancheng-Lujiang fault zone and its subsidiaries striking NNE to NE, which cut across eastern China from south to north (Fig. 1). It extends at least from the Yangtze Valley, through Shandong Province, to the northeastern part of China and ends in the Sakhalin Bay in the Sea of Okhotsk, over a distance of more than 3600 km (Fig. 1) (Xu Jiawei et al., 1986; Xu Jiawei, 1993). The Tancheng-Lujiang transform fault is a major ductile to brittle-ductile shear zone striking NNE (18°–25°) to NE (45°) culminating an average of 450 km of sinistral displacement. It is an intensely deformed belt, 40–50 km wide, of very high shear strain (Xu Jiawei et al., 1986). Several minor faults were developed in parallel to this major structure that cut across the region (Fig. 1) through the previous (D1–D3) structures and distorted them. The Late Triassic (around 210 Ma) marked the beginning of the development of the sinistral transcurrent Tancheng-Lujiang fault zone and its peak activities

ceased in the Middle Cretaceous (around 100 Ma) during the Yanshanian orogeny (Xu Jiawei et al. 1986; Zhang Jiasheng, 1992; Xu Jiawei, 1993; Zhu Guang et al., 1995 and Wan Tianfeng, 1995). During that period the granitoids intruded the Linglong-Jiaojia district involving three intruding episodes: the Linglong granite (160–140 Ma); the Luanjiahe granodiorite (150–140 Ma) and the latest intrusions of the Guojialing granite (130–120 Ma), all in the Middle Yanshanian orogeny. It is between the Tancheng-Lujiang fault, one of its subsidiaries and the suture zone fault where the Jiaolai Basin was developed as a pull-apart basin. The continental Tancheng-Lujiang shear zone played an important role in metallogeny in NE China (Zhang Jiasheng, 1992), such as the Jiaodong gold mining camp in Shandong Province, the Jiapigou gold mining district in Jilin Province and the Wulong gold camp in Liaoning Province, all located in the vicinity of this major fault.

### 2.3.5 D5 events: NE- and NW-trending faults

The continuing regional NS to NNW-SSE compression caused the development of NE-trending thrust faults and shear zones on the eastern side of the NNE Tancheng-Lujiang fault zone while on the western side were developed conjugated NNW-trending faults. The NE-trending faults and shear zones bounded the batholith of the Linglong suite and many cut through it. There are a large number of these brittle oblique-slip faults striking 30°–40°NE and dipping around 40°NW or SE across the Shandong Peninsula. Among them are the Sanshandao, Jiaojia, Huangxian-Yexian and Zhaoyuan brittle thrust oblique slip shear zones and the Linglong oblique-slip faults (Figs. 2 and 4).

### 2.3.6 D6 events: NS- to NNE-trending faults

With the weakening of the regional NS to NNW-SSE compression, the progressive uplift of the early structures coupled with erosion and a variable fluid pore pressure, caused variations in stress state and strain rate, inducing a last phase of brittle behavior on the previous brittle, brittle-ductile and ductile faults. New strike and oblique slip faults trending NS to NNE and dipping subvertically to 60°E or W cut through all the rock facies in the area and through all the previous structures (Table 1; Figs. 1 and 2). Progressive thickening of the crust, resulting from previous deformation events, was such that the stress field was reversed into a gravity stress field that induced normal displacements on most of the previously developed faults in the area. During that period the Tancheng-Lujiang fault zone showed

sporadic brittle offsets, then small amounts of dextral shearing and finally normal displacements from Late Cretaceous to Early Cenozoic.

Eastern Shandong Province was continually submitted to various episodes of regional NS to NNW-SSE compression and uplifting according to the previously described deformational phases, except during the D6 deformational events, which produced, at the end, the NNE- to ENE-oriented structures with few of them trending EW on the eastern side of the NNE Tancheng-Lujiang fault zone (Fig. 1) while on the western side were developed conjugated NNW- to WNW-oriented structures with few of them trending EW (Lü Guxian and Kong Qingren, 1993). All these structures have similar tectonic major principal stress ( $\sigma_1$ ) fields essentially oriented in a NS to NNW-SSE direction varying in spatial and chronological intensity, except in the last deformation phase where the major principal stress ( $\sigma_1$ ) field was gravitational. Most of the actual regional planar and linear structures (foliation and cleavages), fold axes and reverse ductile shear zones are ENE-oriented, while most strike- and oblique-slip ductile and brittle faults trend NNE to NE and NNW to NW on the eastern and western sides of the Tancheng-Lujiang fault, respectively (Lü Guxian and Kong Qingren, 1993) and can be related to the various episodes of this regional tectonic stress field at the northern boundary of the suture zone in the Shandong Peninsula (Figs. 1, 2 and 3A).

## 2.4 Geomechanical interpretation

A schematic representation of the different types of structures induced by the different phases of the NS to NNW-SSE tectonic major principal stress ( $\sigma_1$ ) field at various times is shown in Fig. 3A and corresponds to the main deformational events previously described: ① folding and associated schistosity, ② ENE ductile reverse faulting, ③ ENE to EW suture thrust faults, ④ NNE to NE Tancheng-Lujiang oblique ductile faulting system, ⑤ NE brittle faulting under thrust conditions and ⑥ NNE brittle faulting under strike-slip conditions as well as normal displacements on all the previous faults. This representation synthesizes the present structural pattern (Fig. 2) observed in Shandong Province (Lü Guxian and Kong Qingren, 1993). Conditions equivalent to those of simple shear deformation were imposed on the Shandong Peninsula between the Tancheng-Lujiang fault zone and its subsidiaries (Fig. 1), after the third deformational event. The equivalent of a very large shear belt was developed, characterized by the typical fault pattern: R and R' shears, P shears and C shears (Tchalenko, 1970). It was superposed on the structures formed in response to the three first deformational events: folding, reverse ductile faulting and suturing

(Figs. 2 and 3A). The Tancheng-Lujiang main shear zone is the direction C shear, its subsidiaries and the NNE fault system are the R shears while a few NW faults are the conjugate R' shears and the NE fault systems are the P shears developed in sequence. This large simple shear belt induced a distortion and displaced sinistrally fold axes, reverse ductile shear zones and suture zones in response to the three first deformational events (Figs. 1, 2 and 3A). During the last two brittle deformational events, the same fault pattern was reactivated to which were added NE oblique-slip and ENE brittle thrust faults as well as normal displacements on most of these faults.

The previous structural pattern can be interpreted in terms of the evolution of the stress regime active during that period. A possible graphic representation for stress evolution is the Mohr diagram stress space representation (Fig. 3B) in which, as suggested by Dusseault and Mraz (1983), are considered the brittle failure envelope for high strain rate (elastic behavior and brittle failure or faulting) and different viscous yield envelopes for various stress or strain rates ( $\dots\dot{\epsilon}_2, \dots, \dot{\epsilon}_n, \dots$ ). The corresponding types of deformation and structures are illustrated in Fig. 3C. On the basis of this conceptual representation, the mobilization of the tectonic stress field induced a differential stress ( $\sigma_H - \sigma_V$ ) in 2D (or stress deviator in 3D) under a vertical gravitational stress ( $\sigma_V$ ) corresponding to the load of the rock column above the point considered. These stresses may be represented by a Mohr circle in which the radius of the circle is given by  $(\sigma_H - \sigma_V)/2$  and the two coordinates on the abscissa are  $\sigma_V$  and  $\sigma_H$  corresponding to the vertical and horizontal stresses imposed, if these are the principal stresses ( $\sigma_V = \sigma_3$  and  $\sigma_H = \sigma_1$ ) in 2D (Means, 1976). When the Mohr stress circles become tangent to the brittle failure envelope or to the ductile yield envelopes, the critical stress conditions are reached, under which brittle failure (faulting) or ductile deformation (plastic flow or viscous creep) under a prescribed strain rate would occur, respectively.

So, at a given depth for which the vertical stress is  $\sigma_V$ , the tectonic stress field developed a horizontal stress  $\sigma_H^I$ , both being represented by the Mohr stress circle ① tangent to an envelope corresponding to a slow strain rate  $\dot{\epsilon}_2$  (Fig. 3B). This stress circle ① could represent the stress states of the first deformational event, related to folding and schistosity development (Fig. 3A). With overtightening of the folds, the deformation decreased progressively and the horizontal stress increased to a new value ( $\sigma_H^{II}$ ) with increasing differential stress and an increment in the strain rate to a new level ( $\dot{\epsilon}_3$ ). This new stress state is given by the Mohr stress circle ② (Fig. 3B) and represents the development of reverse ductile shear zones, like the Potouqing shear zone and several

others in the area (Fig. 3A) that took advantage of the anisotropy created by folding and schistosity development in the previous deformational events. The third event occurred with the collision between the North and South China cratons and the development of the suture zone in the southern part of Eastern Shandong Peninsula. This deformation event enhanced the horizontal stress to a new value  $\sigma_H^{III}$  and defined a new stress circle ③ tangent to a new ductile yield envelope of higher strain rate  $\dot{\epsilon}_4$  (Fig. 3B). The progressive locking of this new deformation mechanism pushed the horizontal stress to an increased value  $\sigma_H^{IV}$  and defined a new stress circle ④ tangent to a new ductile yield envelope of higher strain rate  $\dot{\epsilon}_5$  (Fig. 3B). This phase of deformation is characterized by the development of the major Tancheng-Lujiang ductile fault zone and its subsidiaries striking NNE to NE according to the model of Tchalenko (1970) and this new system of faults disturbed and displaced the previous events of folding and ductile reverse fault structures (Fig. 3A).

With progressive uplift/erosion and the action of fluid pore pressure, the level considered is also uplifted and characterized by a reduced vertical stress ( $\sigma_V^I$ ). As the induced differential stress ( $\sigma_H^I - \sigma_V^I$ ) is maintained, the horizontal stress would decrease from  $\sigma_H^I$  to a new value  $\sigma_H^V$  so that  $(\sigma_H^I - \sigma_V^I) = (\sigma_H^V - \sigma_V^I)$ . This variation in the stress regime caused by the uplift/erosion phenomenon and the action of fluid pore pressure induced an increase in strain rates and displaced the Mohr stress circle in position ⑤ tangent to the brittle failure envelope (Fig. 3B). The fifth deformational event was responsible for brittle and brittle-ductile faulting, in which brittle fracturing (tension and shearing) and brittle-ductile faulting are superposed on the previous ductile shear zones (reverse and wrench faults) and there were developed new brittle thrust oblique slip faults striking  $30^\circ$ – $40^\circ$ NE and dipping around  $40^\circ$ NW or SE (Fig. 3A).

With the pursuit of progressive uplift/erosion and the action of fluid pore pressure, the vertical stress ( $\sigma_V^I$ ) was reduced to a new value ( $\sigma_V^{II}$ ). The horizontal stress decreased from  $\sigma_H^V$  to a new value  $\sigma_H^{II}$  so that the differential stress became  $(\sigma_H^{II} - \sigma_V^{II})$ . This variation in the stress regime displaced the Mohr stress circle in position ⑥ also tangent to the brittle failure envelope (Fig. 3B). This phase of the last sixth deformational event of brittle faulting developed new oblique slip faults striking NNW to NNE and dipping subvertically to  $60^\circ$ E or W (Fig. 3A). With the progressive thickening of the crust, resulting from the previous deformation events, the stress field was reversed into a gravitational stress field where the major principal stress ( $\sigma_1$ ) became vertical and induced normal displacements on most of the previously developed faults in the area. The horizontal stress decreased from

$\sigma_{\text{H}}^{\text{VI}}$  to a new value  $\sigma_{\text{H}}^{\text{VII}}$  while the vertical stress stayed at the same value  $\sigma_{\text{V}}^{\text{VI}}$  so that the differential stress became  $(\sigma_{\text{V}}^{\text{VI}} - \sigma_{\text{H}}^{\text{VII}})$ . This variation in the stress regime displaced the Mohr stress circle in position ⑦ tangent to the friction envelope (Fig. 3B) in the Rankine plastic active stress state with horizontal and differential stresses much lower than the previous ones for the same vertical stress ( $\sigma_{\text{V}}^{\text{VI}}$ ). After this sixth event of brittle faulting and fracturing, if horizontal compressive stresses  $\sigma_{\text{H}}^{\text{VII}}$  are developed for the same vertical stress ( $\sigma_{\text{V}}^{\text{VI}}$ ), the deformation thereafter is accommodated essentially through displacement on the discontinuities created in the previous phases, mobilizing friction on them accompanied by fracturing, crushing to produce breccias and grinding the rock particles to yield fault gouge. The stress state is given by the Mohr stress circle ⑧ tangent to the friction envelope (Fig. 3B) in the Rankine plastic passive stress state for the same vertical stress ( $\sigma_{\text{V}}^{\text{VI}}$ ) and at a differential stress  $(\sigma_{\text{H}}^{\text{VII}} - \sigma_{\text{V}}^{\text{VI}})$ .

### 3 Shear zones and mineralization

#### 3.1 Northeastern Shandong Peninsula tectonics

Most of the gold deposits in East Shandong are spatially associated with shear zones and faults within the Linglong and Guojialing granitoids or along their contacts or along the contact zones between the granitoids and Archean amphibolites and Proterozoic gneisses and very few are hosted in structures within the Archean metamorphic rocks except in the Qixia and Pingdu areas (Zhou Taifu and Lü Guxian, 2000; Qiu et al., 2002). The ENE ductile shear zones like the Potouqing and the NE subsidiaries of the major Tancheng-Lujiang ductile fault zone systems were remobilized during the brittle to brittle-ductile last deformational events during which brittle fractures and shears were superposed on the previous ductile deformation zones and developed fractured zones that extend across strike. The Potouqing brittle-ductile shear zone system is characterized by interlayered mylonite, protomylonite, breccia and gouge (Fig. 5). These shear zones range generally from 30 km to 80 km in length and the distance between them is about 10–15 km (Fig. 2).

During the same phase of brittle deformation several oblique slip thrust shear zones were developed in the area, trending N30°–45°E like the Sanshandao and Zhaoyuan shear zones dipping 30°–40°SE, the Jiaojia-Xincheng and Huanxian-Yexian shear zones dipping 30°–40°NW (Fig. 2). These latter faults and shear zones formed a pattern of dip-conjugated structures. As established before, during the D6 deformational events the stress field was reversed into a gravitational stress field that induced normal

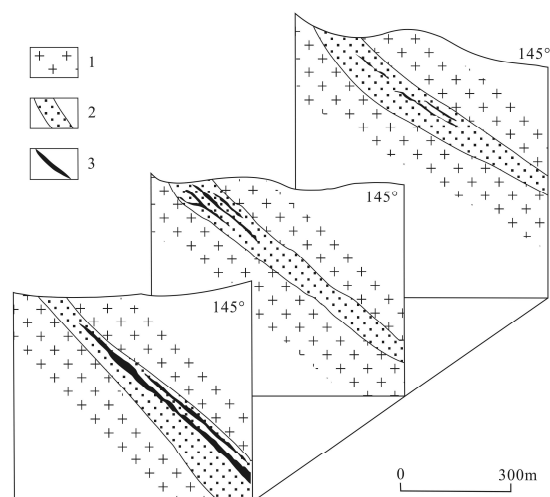


Fig. 5. Cross section through the Potouqing ductile shear zone (compiled data from the No. 6 Geological Team, Lingnan mine staff and this study). The original wallrock is the Linglong granite that became, after ductile deformation, mylonite and protomylonite and after brittle deformation, breccia and fault gouge. Several gold mines (including Lingnan) are located in the Potouqing ductile shear zone. 1. Linglong granite; 2. Potouqing ductile; 3. gold ore body.

displacements on most of the previously developed faults in the area. Several lines of evidence of reverse shear movements followed by normal shear displacements during or after mineralization on most of the developed faults were reported from different gold mines of the Linglong-Jiaojia area (Qiu et al., 2002).

Gold deposits are hosted within parts of these first-order or second-order structures and the gold lodes are parallel to the main fault zones or filled the adjacent structural sites like fault jogs, intersections, splays and flexures as well as tension gashes and en-echelon arrays of quartz veins. The basic features of the larger gold deposits and the styles of gold mineralization in these deposits are well documented in Qiu et al. (2002). They concluded that the variation in style of gold mineralization in the area appears to be related to the degree of deformation within the host structures and is probably also related to the orientation of the resultant host structures to the regional stress field. Commonly developed in gold orebodies that are hosted within the first-order structures is disseminated-style mineralization whereas those hosted in smaller-scale second- or third-order structures are characterized by quartz vein-style mineralization with a transition-style between both types as well exemplified by the Linglong gold camp.

#### 3.2 Mineralized shear zones in the Linglong area

In the Linglong gold field there are two major structural systems: the NE-ENE-trending reverse Potouqing shear zone, 30–40 km long and 100–300 m wide, and the NNE Linglong fault system (Fig. 4A). The Potouqing shear zone is essentially a reverse ductile shear zone as observed underground in the Lingnan mine (Fig. 6A), but on surface, several outcrops show ductile characteristic indicators whereas others show brittle structural features. The shear zone development was firstly characterized by a ductile behavior on which was superposed a brittle deformation phase that extends across strike in developing parallel ENE secondary faults dipping either N or S (Wang Jijun and Yu Heyong, 1990; Qiu et al., 2002). It is localized in the Linglong granite but near the contacts between the Linglong, Luanjiahe and Guojialing granites (Fig. 2). The Potouqing shear zone shows kinematic indicators of ductile deformation under reverse movement: steeply dipping schistosity near the footwall sub-parallel to shear zone boundaries towards the hangingwall in the section (Fig. 6A), mineral lineations in the schistosity plane, tension and shear veins, C-S fabrics, crenellation cleavages, shear bands, more competent minerals deformed in lenses and rotated fragments. Quartz c-axes were studied in the area (Lü Guxian and Kong Qingren, 1993, Tu Guangzhi and Li Chaoyang, 2006), which also sustained the fault characteristics. The shear zone has experienced a mylonitization process in the Linglong granite according to Sibson's classification (1977) in which features indicate that brittle fracturing and faulting were superposed on an earlier ductile deformation phase (Robert and Brown, 1986).

These last brittle to brittle-ductile deformation events gave rise to en-echelon brittle faults and fractures subparallel to the Potouqing shear zone in its vicinity, dipping 60°–80°SE and NW, forming anastomosed patterns, both in section and plan. This shear fracture pattern is cut by the oblique-slip Linglong fault system trending N30°–40°E and dipping 60°–70°E or W, disturbing and displacing slightly the previous ones (Fig. 4A) with which there were also developed NNE en-echelon brittle faults and fractures subparallel to the Linglong fault system. It is in these shear zones and fractures that gold mineralization and dykes are localized in the Linglong area (Fig. 4A, B and C). Also, with the reversing of the stress field into a gravitational stress field, normal displacements were induced on most of the developed faults and fractures in the area. En-echelon shear fractures, extensional quartz veins and different types of dykes feature the western part of the Linglong gold field while in the eastern and southern (near the Potouqing shear zone) parts are developed veinlets and alteration-zone type mineralization consisting of

quartz veinlets and microveins within a pyrite-sericite-native gold alteration-type assemblage (Fig. 6C).

Brittle faulting superposed on the Potouqing ductile shear zone (Fig. 5) as well as the brittle shear fractures intersections in dip and strike (Fig. 4A, B and C) in its northern sector seem to be especially favorable structures for ore deposition and are important target sites for exploration. Most gold-bearing quartz veins strike N40°–80°E (there are more than fifty quartz veins in the Linglong area) with a strike length of one to five thousand meters (Fig. 4A). The brittle shears dip 50°–70° towards SE near the Potouqing shear zone, while away from it, the veins change their dips towards NW (Fig. 4B). The fractures vary in width from several centimeters to tens of meters, with the larger ones in the western part and the smaller ones mostly occurring in the eastern part. The shear fractures show similar brittle-ductile characteristics like the Potouqing shear zone near it and more brittle fault breccia and gouge away from it as detailed by Qiu et al. (2002) (Figs. 5 and 6). The large quartz veins (or vein-type mineralization of the

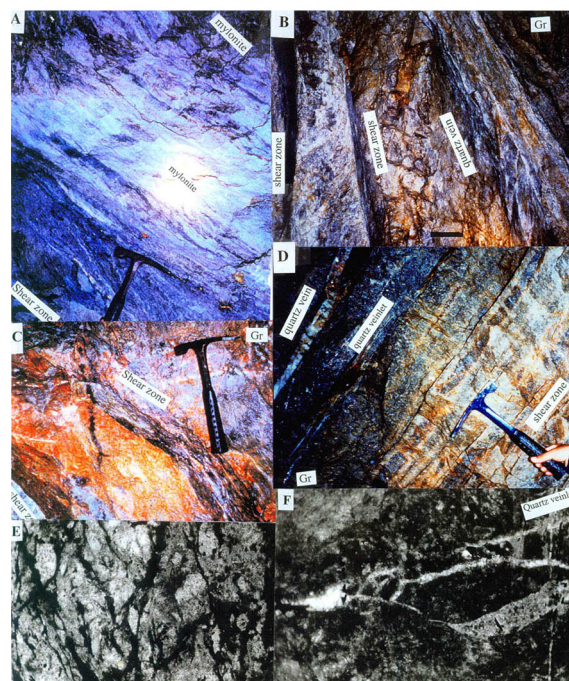


Fig. 6. Shear zone and gold mineralization in the Linglong gold deposits. A. The Potouqing shear zone in the Lingnan mine; B. gold-bearing quartz-sulfide vein filling shear zone structures, Lingnan mine; C. two small shear zones and gold mineralization, Jiuqu mine; D. shear zone-related fractures filled by quartz veinlets, Lingnan mine; E. small quartz veinlet filling a brittle-ductile shear zone, photomicrograph, length of photo: 1.5 mm; F. enlargement of the previous photo showing pyrite and native gold (black) filling the micro-shear structures, length of photograph: 0.01 mm.

Linglong deposit) are located in the western part of the Linglong area while the microveinlets and veinlets with pyrite-sericite-native gold alteration assemblage, known as the alteration-zone type, are located in the southern part (the Lingnan deposit), with the transition type between them in the eastern part (the Jiuqu deposit). Veins, veinlets and microveinlets are subparallel to the main Potouqing shear zone (Fig. 4).

In the vein system, there are several mafic to intermediate dykes, including diorite, lamprophyre and diabase filling structures are mainly of NNE to NE orientation, which seem to cut through and displace slightly the ore veins. The Linglong NNE fault system (four of them in Fig. 4) striking roughly  $N25^{\circ}E$  with steep dips, appears to be part of a post ENE brittle fault system corresponding to the sixth deformational event and put in place during or after the vein system and was accompanied by normal displacements due to reversing of the stress field. Orebodies of the gold-pyrite-quartz vein type occur as lenses arranged in an en-echelon pattern within the faults and brittle-ductile shear zones. The strike length of single ore veins varies from 350 to 5000 meters, with 40 to 400 meters in vertical extension and 0.2–12 meters in width. Vein No. 108, located in the western part of the mine, was exposed for 5000 meters along strike.

Gold occurrences of the alteration-zone type include gold-pyrite-sericite-quartz veinlets and microveinlets as well as gold-pyrite-sericite altered granites. Orebodies of this type occur in the eastern part of the area (the Jiuqu mine) and in the Potouqing shear zone, for example, vein No.10, and ore bodies Nos. 1 and 2 in the Lingnan mine (Fig. 5). The only difference between the quartz veins and the alteration zone is the size of the fractures and faults, which were filled later by the veins and veinlets (Qiu et al. 2002). The ore grade ranges from 5–8 g/t. to more than 30 g/t.

### 3.3 Mineralized shear zones in the Jiaojia area

The Jiaojia gold field consists of the Jiaojia, Xincheng, Hedong, Hexi, Madong, Cangshang-Sanshandao, Wangershan and Jiahe gold deposits, occurring along the Sanshandao, Jiaojia-Xincheng, Huanxian-Yexian and Zhaoyuan brittle thrust fault zones detailed in Qiu et al. (2002) (Figs. 2 and 7). The host rocks in this region include the Precambrian Jiaodong Group metamorphic rocks as well as the Linglong granite, Guojialing granodiorite and dykes which had intruded into the Jiaodong Group. The Sanshandao, Jiaojia - Xincheng, Huanxian-Yexian and Zhaoyuan brittle thrust oblique slip shear zones strike  $N30^{\circ}-40^{\circ}$  and dip  $30^{\circ}-50^{\circ}NW$  or  $SE$ , the width of the fracture zones ranges from 50 to 200 m and extend in

depth to more than 850 m. The gold deposits occur mostly in the thrust fractured zones within the Linglong granite, but some occur at the contact between the Linglong granite (footwall) and the Archean Jiaodong Group (hanging wall). The Jiaojia deposit is 2–4 m thick, more than 1 km in length,

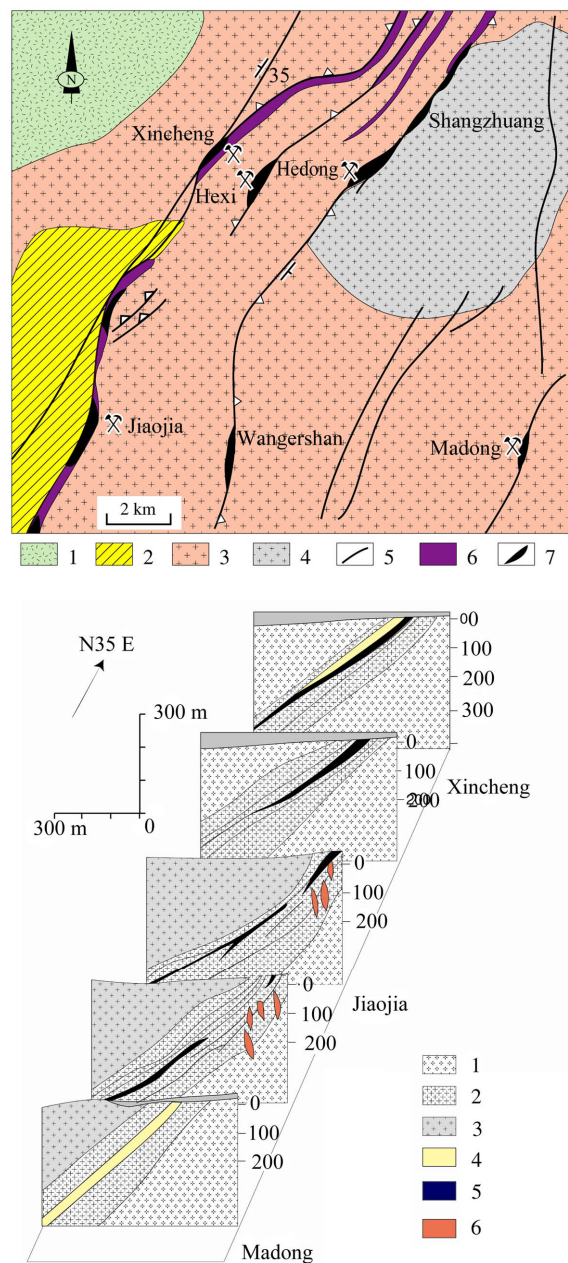


Fig. 7A. Geological and structural map of the Jiaojia gold field (after No. 6 Geological Team, unpublished). 1. Archean metamorphic rock; 2. altered metamorphic rock; 3. Linglong granite; 4. Guojialing granite; 5. fault; 6. alteration type; 7. pyrite-quartz vein. 7B. Geological cross section of the Jiaojia-Xinchen gold field. 1. Linglong granite; 2. sericitized granite; 3. pyritized granite; 4. archean metamorphic rock; 5. alteration type ore body; 6. pyrite-quartz vein (modify from the No. 6 Geological Team).

striking N 10°–35° E and dipping 30°–45°NW, at the same attitude at the Jiaojia shear zone. There are six ore bodies in the Jiaojia mine, including both the alteration zone type (Nos. 1 and 2 orebodies, etc.) and large quartz vein type (No. 3 ore body). All the ore bodies are located near the hangingwall of the shear zone entirely developed in the Linglong granite except for the hangingwall contact itself (Fig. 7A and B).

In the Jiaojia, Xincheng, Hedong and Hexi mines, the rocks hosting the mineralization are cataclasites that can be subdivided according to progressive comminution by the ratio of remnant protolith to crushed matrix as protocataclasite, cataclasite, and ultracataclasite (Sibson, 1977). The cataclasites are typically unlayered and unfoliated, but banding is present in few places in the Jiaojia mine and an anastomosed pattern is well developed (Fig. 8A). The No. 3 ore body in the Jiaojia mine (Fig. 7B) is composed of extensional structures parallel in strike but dipping in an opposite direction to the main shear zone. They are probably large tension gashes, developed during shearing within the phase of normal displacement on the shear zone with the reversing of the stress field into a gravitational stress field during the D6 deformational events. Figures 6 and 8 illustrate different microtectonic features and mineralization characteristics within mineralized structures in different mines located in both Jiaojia and Linglong areas (Figs. 4A and 7A) discussed above. These features provide evidence of the brittle characteristics of the Jiaojia orebodies in which cataclasites were

observed (Fig. 8) as well as other brittle features (Fig. 6) similar to those found (Fig. 6E and F) in the Linglong area, away from the main ductile shear zone.

Quartz veins, in the Linglong-type quartz vein-style gold deposits, appear to fill pre-existing faults, as they are commonly bounded by fault gouge or thin zones of quartz-sericite schist. They may contain fragments of country rock and rarely cut the foliation of the bounding schist or the fault gouge, suggesting that at least some of the hosting faults were formed prior to the quartz veins. Most of the quartz veins, particularly zones of massive sulfides within the quartz veins, have been fractured, brecciated or boudinaged. Veins occur as lenticular discrete bodies bounded by fault gouge and adjacent alteration assemblages, developed in the host granite, include sericitization, silicification, pyritization, carbonatization, K-feldspathization and chloritization. K-feldspathization and sericitization (Qiu et al. 2002) are not only closely related to gold mineralization, but also are used as a reliable exploration guide. The Jiaojia-type disseminated- and stockwork-style deposits occur in the first-order fractured shear zones surrounded by broad alteration halos that show the following alteration zones: a fault gouge zone of around 50 cm thick that consists of gray, white or black clay materials with variable-sized round fragments of granitoids; a quartz-sericite-pyrite zone (2 m thick) is the most intensely altered zone and the altered rocks are essentially cataclastic breccias, formed during late brittle deformation, which may comprise K-feldspar, quartz and sericite within a zone as thick as 50 m, with disseminated pyrite and pyrite-quartz stockworks; and finally an outer reddish alteration zone, several hundred meters in length, characterized by secondary K-feldspar and sericite in clastically deformed granitoids (Qiu et al. 2002).

The age of gold mineralization (Lu Huanzhang and Li Huaqin, 1996; and this study), has been determined on the basis of the sericite in the quartz veins and in the alteration assemblages. The Rb-Sr isochron age of sericite in the No. 108 large quartz vein is  $110.7 \pm 3.6$  Ma, and the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio is  $0.712030 \pm 0.000167$ , suggesting Rb and Sr in the sericite were derived from the crust. The Rb-Sr isochron age of sericite in the alteration zone-type Jiuqu gold mine is  $111.4 \pm 2.8$  Ma, with  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio being  $0.712108 \pm 0.000478$ , indicating the mineralization occurred at the crustal depth and is younger than the Linglong, Guojialing and Luanjiahe granites. A synthesis of other studies on gold mineralization ages by Qiu et al. (2002) shows that the ages vary between 130 Ma and 100 Ma with most of the data concentrated at 120–110 Ma. Gold mineralization in the Shandong Peninsula (126–120 Ma) is about 100 Ma younger than the suture between the North and

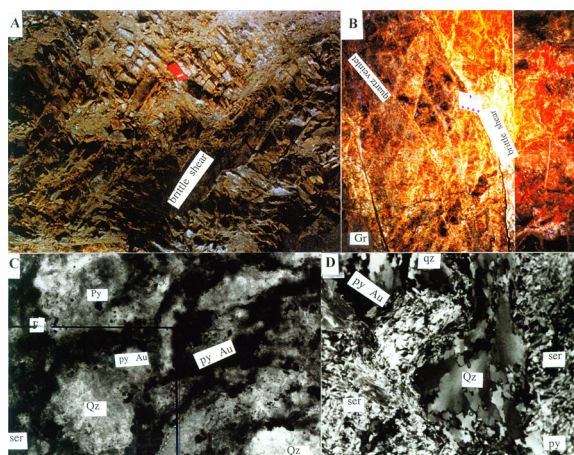


Fig. 8. Shear zone and gold mineralization in an anastomosed pattern of the Jiaojia gold deposit: A. Small brittle shear zone (showing anastomosed pattern) in the Jiaojia mine; B. brittle shear (showing an anastomosed pattern) with gold mineralization in the Hedong mine; C. microstructure of the Jiaojia alteration-type gold mineralization. The original granite has been deformed to cataclastic rocks in the brittle fractures, filled by sulfide and native gold (black); D. deformed features of pyrite, quartz and sericite in the brittle fractures, enlargement of Fig. C, the length of photo: 0.01 mm.

South China cratons (230–200 Ma) but overlaps the subduction of the Pacific plate beneath the Eurasian continental crust during the Yanshanian orogeny. The 126–120 Ma age is also characteristic of basement uplifts along the entire eastern half of the North China Craton.

#### 4 Brittle mineralized shear zone modeling

Even if the Linglong and Jiaojia gold mining districts are within a  $50 \times 50 \text{ km}^2$  area, localized within the same Linglong granite intrusive body, and formed under the same tectonic stress field, their structural features and patterns are distinctly different. This is due to local variations in deformation mechanisms related to heterogeneities on different scales in the rock media as well as the shape of the Linglong granite in relation to the applied stress field. These conditions are responsible for the localization of deformation and failure in the rock media and for the development of different types and patterns of structures. The gold mineralization filled openings developed within the faults and shear zones as well as shear and tension fractures formed during the phases of brittle deformation (D5 and D6 events). These structures were developed under varying magnitude of the NNW-SSE tectonic major principal stress ( $\sigma_1$ ) field with local variations in orientation giving rise to particular structures and fractures. During the last phases of the D6 deformational events, in which the stress field was reversed into a gravitational stress field, normal displacements were induced on most of the previously developed shear zones, faults and fractures.

##### 4.1 Fault pattern in the Linglong-Jiaojia region

A schematic representation of the various brittle and brittle-ductile faults and shear veins of the Linglong-Jiaojia region (Figs. 2, 4A and 7A) in the eastern vicinity of the Tancheng-Lujiang fault zone is illustrated in Fig. 9A. Plotting the various fault systems and shear vein arrays in a stereonet (Fig. 9B) shows that the faults and brittle-ductile shear zones of the whole region seem to be arranged in two superposed orthorhombic patterns in which shear movements are oblique-slip displacements similar to what is described in the model proposed by Reches (1978, 1983) and Reches and Dieterich (1983). The geometry and kinematics of the faults developed under a three-dimensional stress field ( $\sigma_1 > \sigma_2 > \sigma_3$ ) and bulk coaxial non plane strain need at least three or four fault sets in orthorhombic symmetry to satisfy the strain compatibility conditions (Fig. 9C), instead of the two conjugate fault sets usually formed under the Andersonian model (biaxial stress  $\sigma_1 > \sigma_2 = \sigma_3$  and

coaxial plane strain). In this model, the sets of faults are arranged in such a way that the three mirror planes of symmetry coincide with the principal planes of bulk finite strain and the orthorhombically arranged fault sets show six intersection lineations between faults instead of the one intersection lineation in conjugate faults. Such patterns of fault sets were confirmed by several field observations (Oertel, 1965; Reches, 1978; Aydin and Reches, 1982; Krantz, 1988, 1989; and Kirschner and Teyssier, 1994). Kirschner and Teyssier (1994) extended the Reches model for brittle fault sets, to brittle-ductile shear zones as well as sets of en-echelon veins and kink-band arrays of all kinds. The structural context they interpreted in their paper (vein arrays from the White Range, central Australia) offers certain similarities with the one characterizing the Linglong mining district.

The eastern part of the Shandong Province, the Linglong-Jiaojia region (Figs. 1 and 2), also on a smaller scale, the Linglong (Fig. 4) and Jiaojia (Fig. 7) areas are characterized by eight sets of brittle faults and shear zones (Fig. 9). All these brittle fault sets were developed during the D5 and D6 deformational events discussed previously. As mentioned earlier, even the Tancheng-Lujiang and the Potouqing ductile

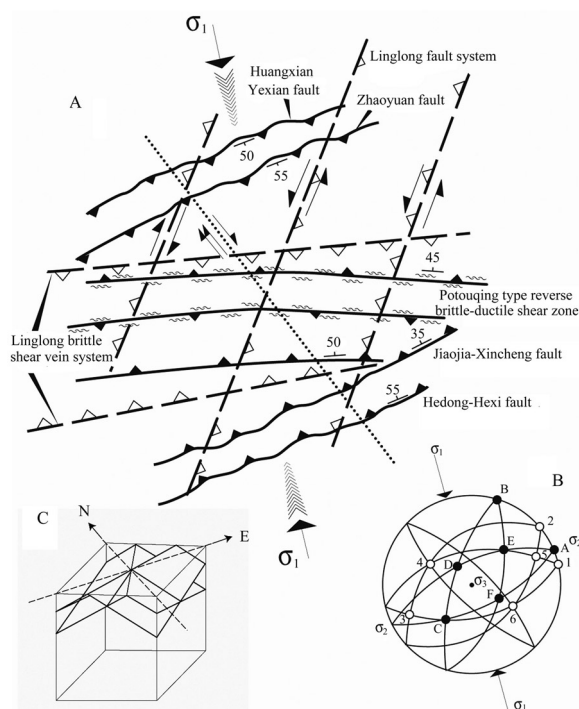


Fig. 9. Geomechanical modeling of the Linglong-Jiaojia area: A. Schematic structural modeling of the various shear zones and faults characterizing the area; B. the different shear zone and fault systems plotted in a stereonet as great circles with stress state indicated (lower hemisphere); C. schematic block diagrams and stereonets illustrating triaxial (3D) strain resulting fault systems on the theoretical and experimental basis (from Krantz, 1989).

fault zones were reactivated under brittle deformation conditions during that period. Almost each fault set of the region, striking in the same direction, shows fault planes dipping in opposite directions and evidence of oblique slip on most of them, except for a few cases (Lü Guxian and Kong Qingren, 1993) (Fig. 2). The eight sets of brittle faults and shear zones (Fig. 9) can be grouped into two superposed rhombic patterns. The first large rhombic pattern is established by the ENE trending fault sets (like the Potouqing) dipping N and S and by the brittle thrust oblique slip shear zones sets (like the Sanshandao, Jiaojia-Xincheng, Huanxian-Yexian, Zhaoyuan, Pingdu and others) striking N30°–40°E and dipping 30°–50°NW or SE shown in full line in Fig. 9B and the six intersection lineations between faults are numbered 1–6. The other smaller rhombic pattern is established by the NNE-trending (N10°–20°E) fault sets (like the Linglong fault system) dipping steeply E or W and the ENE-trending brittle reverse fault sets striking N65°–75°E and dipping 60°–70°N or S (like the Linglong shear veins) shown in dashed line in Fig. 9B and the six intersection lineations between faults are lettered A to F. Intersection lineations in C and E are common to both patterns implying that the family of the Potouqing fault set is related to the smaller rhombic pattern. These rhombic patterns were developed under reverse conditions (Fig. 9C) but were submitted to normal displacements during the final phase of the D6 deformational event (Fig. 9D).

So, the whole region is subdivided into rhombohedral blocks cut by other fault sets, forming, at different places, tetrahedral blocks. This can be observed from mega to macroscale throughout the region. Gold mineralization was introduced preferentially into the brittle fault sets striking N40°–50°E and dipping 40°NW and SE within tension and shear fractures developed inside these brittle shear zones (or fractured zones) in the Jiaojia area while in the Linglong area, the mineralization was deposited in the brittle fault sets striking N65°–75°E and dipping 60°–70°N and S including the Potouqing shear zone. The mineralization is localized into these large structures, within smaller faults and fractures (tension and shear) on a small to very small scale, mostly restricted to the Linglong granite.

#### 4.2 Brittle deformation and faulting mechanisms in the Linglong area

The shear veins, in which a large part of the gold mineralization was localized, show large variations in strike, from NNE to ENE, and dip in an opposite direction (SE and NW) so that they form anastomosed patterns both in plan and in section (Fig. 4). The southern boundary of this pattern of shear veins is

defined by the Potouqing brittle-ductile shear zone striking ENE to EW and dipping around 45°S, in which gold mineralization was also concentrated, while the northern boundary is characterized by a similar shear zone dipping N. These structures are cut by the unmineralized NNE Linglong fault system and the subparallel system of dykes both dipping E and W. On a large scale the shear fracture pattern was developed within a rhombohedral block defined by NNE and ENE fault systems (Figs. 2 and 9B). The shear fractures (mineralized veins and dykes) are arranged in zones of concentrated veining, on a kilometer scale, with anastomose around zones of unveined granite (Fig. 4A). The unveined zones show rhomboid forms, with their long diagonal trending approximately NE (Fig. 9B in dashed lines). This macroscopic anastomosing geometry on the order of several kilometers mimics the rhombohedral geometry produced by individual cross-cutting veins. This pattern shows certain similarities, on a larger scale, with the vein arrays from the White Range studied by Kirschner and Teyssier (1994) in their Fig. 6.

The shear fracture pattern may have resulted from the development of subsidiary conjugate brittle reverse faults of the Potouqing brittle-ductile reverse shear zone towards the end of the D5 brittle deformation event and intersected by the NNE Linglong fault system and subparallel system of dykes both dipping E and W, which dragged them during their sinistral displacement in the early phase of the D6 brittle deformation event. During the last phases, in which the stress field was reversed into a gravitational stress field, normal displacements were induced on most of them. The spatial attitude of these shear veins and the superposed brittle phase on the

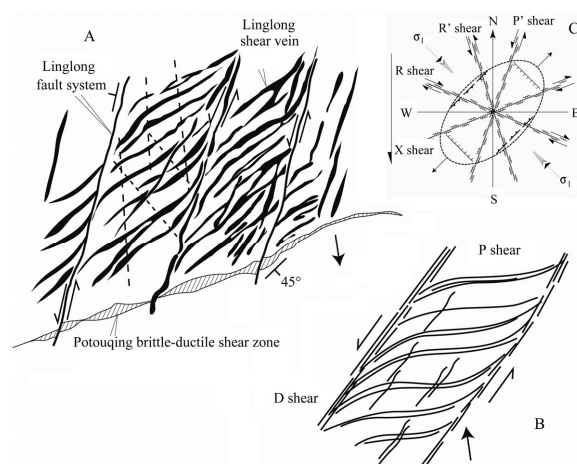


Fig. 10. Modeling of the development of the Linglong shear veins. A. Schematic shear vein systems and Potouqing shear zone in the Linglong area (not to scale); B. schematic mechanical development of the shear vein systems as P and D shears systems; C. Tchalenko's model (1970).

Potouqing ductile shear zone suggest that they were developed before the NNE Linglong faults and dykes systems that displaced them.

Another way to model the Linglong pattern of shear structures (fractures, dykes and veins) in relation with the NNE Linglong faults and dykes may be on the basis of the shear zone development model proposed by Tchalenko (1970) in which only P shears (at thrust attitude) and D shears (direction shears) were developed (Fig. 10). This situation was observed in shear fracture pattern and evolution in transpressional fault zones both in field studies and laboratory analogue simulations showing that shear zones dominated by P shears are diagnostic of a transpressional deformation regime (Keller et al., 1997). The P shears are characterized by a reverse shear movement like the Potouqing brittle-ductile shear zone, as if they were subsidiary structures, but the model has the advantage of being able to integrate the NNE shear veins and dykes as D or direction shears with the same strike as the Linglong faults. But this model presents certain difficulties because the P shears have the same dips and this is not the case for the shear veins. The NNE shears are barren dykes that cut through the shear veins and displaced them slightly, indicating that they were developed later than the veins. So, the first model is still the better one to explain the situation.

### 4.3 Brittle deformation and faulting mechanisms in the Jiaojia area

The Jiaojia area is characterized by several subparallel NE-striking brittle thrust shear zones dipping  $30^{\circ}$ – $40^{\circ}$  SE and NW in a conjugate pattern and a few ductile shear zones in the same direction but dipping around  $60^{\circ}$ – $70^{\circ}$  SE, as well as subvertical strike-slip faults trending NNE (Figs. 7A, B, 9 and 11). These various fault systems also define a pattern of rhombohedral blocks according to the Reches model.

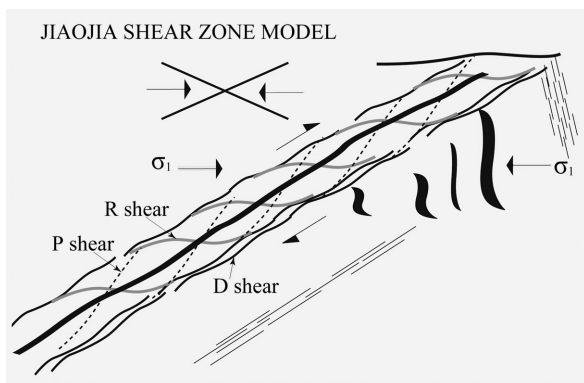


Fig. 11. Modeling of the brittle thrust shear zones showing how the Jiaojia No.1 alteration zone type ores and No.3 extensional ore bodies were developed (not to scale).

The gold mineralization and deposits are hosted in smaller-scale structures (tension and shear fractures) within the brittle thrust shear zones (Fig. 11).

Although ore bodies, on a regional scale, and mineralized quartz veins, on a smaller scale, seem to be randomly oriented, it is possible to relate their distribution and orientation in terms of the simple shear process of deformation under which they were developed in the model proposed by Tchalenko (1970) and detailed in Archambault et al. (1994), regarding the deformation process and the sequence in which the various fractures appear during the progressive deformation and failure of the rock media. In fact, the progressive shear failure development and evolution in brittle rocks characterized by inhomogeneous and non-coaxial strain distributions show that various fracture modes (tension and shear), which intervene in sequence during simple shear deformation and displacement (Fig. 12A), are influenced by the stress level (depth of burial) in their structural characteristics, showing more or less dilatancy (void openings) and extending to all scales. The sequence of shear and tension fractures with shear displacement are presented as follows: first, the conjugate Riedel shears (R and R') are developed at around  $20^{\circ}$  and  $70^{\circ}$  respectively with shear zone boundary, followed by the P shears in a thrust attitude inclined also at around  $20^{\circ}$  with the zone boundary but in the opposite direction; and finally the D (direction) shears are in parallel to the shear zone boundary (Fig. 11). The tension fractures (T fractures) can be developed at any moment during shear displacement, leading to the

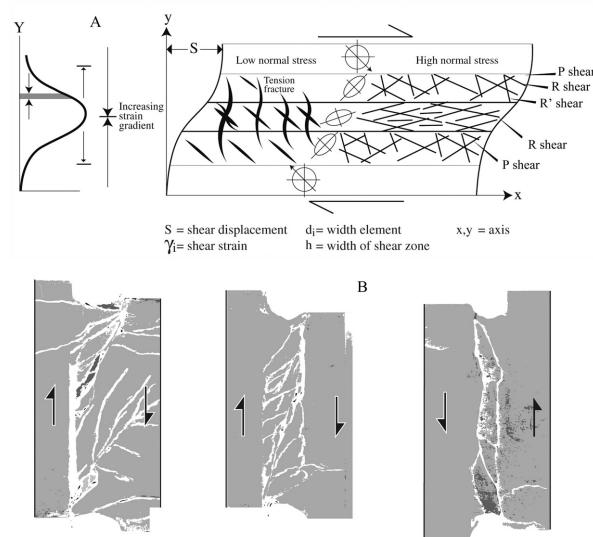


Fig. 12. The mechanics of brittle to brittle-ductile shear zone development: A. Progressive heterogeneous rotational deformation across the zone under simple shear; B. structural morphology of discontinuities and shears, in analog test specimens, in the shear zone after failure under three different applied normal stresses on the shear zones (after Archambault et al., 1994).

formation of en-echelon sigmoidal tension gashes, even on a large scale, as illustrated in Fig. 11. This model fits the Jiaojia shear zone adequately (Fig. 11) in which the relationships between these substructures are shown in an inset.

Simulations of brittle-ductile shear zones on rock-analog materials submitted to different stress levels were performed to study the progressive shear failure development and evolution in shear zones as well as the various fracture modes intervening in sequence during shear displacement under various applied normal stresses (Archambault et al., 1994). The resulting substructures (R and R', P and D shears as well as tension fractures) characterizing these simulated shear zones are illustrated in Fig. 12B. Boundary conditions and the limited length of the test specimens restricted shear displacements, so that very few P shears were developed while tension gashes, R and D shears are the most important features within these failure zones. The three specimens shown (Fig. 12B) were submitted, from top to bottom, to low, medium and high normal stress levels, respectively, simulating brittle to brittle-ductile behaviors within the fractured zones. The left hand side of Fig. 12B shows enlargement of a small portion of the fractured zones characterized by anastomosed pattern of the characteristic substructures within them. The simulation results are consistent with the Tchalenko's model of shear zone development and evolution with simple shear characteristics and shear displacement. This model allows definition of the spatial attitude (strike and dip) of the tension and shear fractures (joints, faults, smaller-scale shears) within the shear zones but not their frequency or spatial density distribution that resulted from a random process. The characterization of spatial distribution of the various types of discontinuities in shear zones on all scales can be done using geostatistical methods of analysis (Tavchandjian et al., 1997) or using scale-invariance fractal geometry of fracture systems (Main et al., 1990).

Most of the structural features observed in the Jiaojia and Linglong areas, on all scales, are consistent with the previous model and simulation tests. The Jiaojia-Xinchen as well as the Hedong, Hexi, Sanshandao and Madong brittle thrust shear zones (Figs. 7A and 7B) show the characteristic structural features (Fig. 12B) of the low to medium normal stresses (top and central specimens in Fig. 12B), corresponding to very brittle shear zones. In the Linglong area, the Linglong, Jiuqu, Dongfeng and Lingnan structural features of the gold deposits (Fig. 4) are more characteristic of the medium to high normal stresses acting on the shear zones and corresponding to brittle-ductile behavior (central and bottom specimens in Fig. 12B). Gold mineralization occurred

in the substructures of these shear zones through circulating fluids in openings created by dilatancy or increasing volume variation resulting from tension and shear movement in the rock media (Fig. 13).

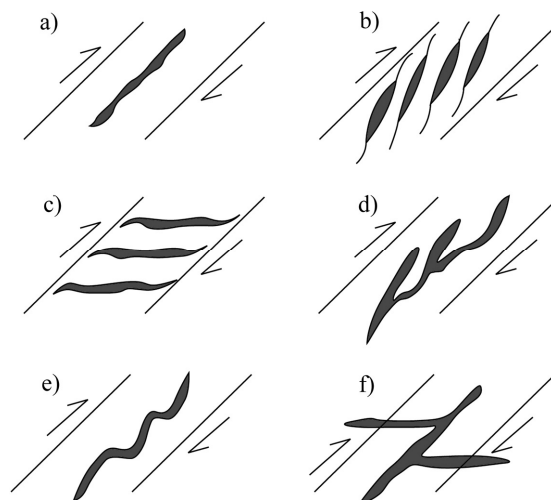


Fig. 13. Progressive rotational simple shear deformation and fracture (tension and shear) development in shear zones (modified from Robert and Brown, 1986) formed in the late-stage en-echelon types of gold quartz veins observed in the Linglong and Jiaojia mines. Quartz veins in: a) D shears; b) P shears; c) tension fractures; d) combination of R and P shears; e) combination of R and P shears; f) combination of tension fractures and D shears.

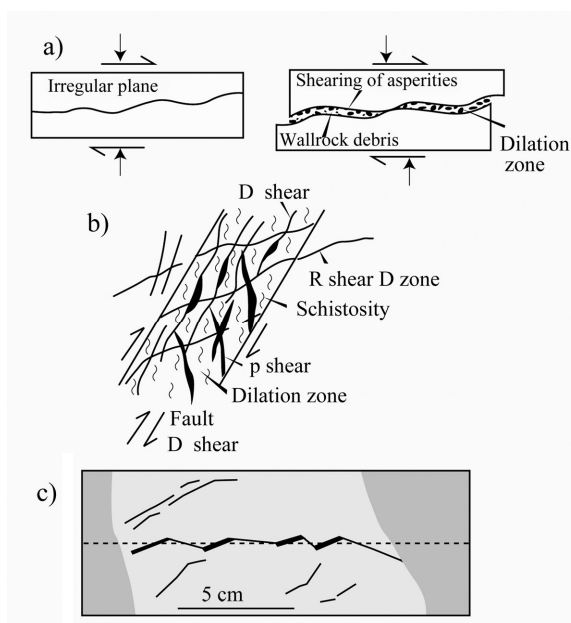


Fig. 14. Illustration of the dilation process on irregular shear planes: a) Initial and final stages of shear displacement on an undulating surface with wall rock debris inside dilated zones (after Guha et al., 1983); b) within the whole shear zone on the R, P and D shears after Tchalenko's model (1970); and c) a field example on a small scale.

#### 4.4 Dilatancy mechanisms and circulation of fluids

The above models of the Linglong and Jiaojia structural patterns characterizing the various gold deposits in these areas require a reference to the mechanics of dilation which created openings for fluid movement and ore concentration. The development of dilation zones (openings) is characteristic of geological structures (shear and fault zones) resulting from rock deformation associated with brittle to brittle-ductile failure. The expression of this dilatancy can take various forms. The first form resulted from microfractures developed during pre-failure deformation phase, at failure and during post-failure movements and dilatancy is expressed as openings created by en-echelon tension gashes (Figs. 12 and 13) or tensional fractures and may end in cataclastic zones associated with faulting and shearing. Another form of dilatancy resulted from pinch and swell structures caused by the overriding irregularities, waviness and undulations in faults and shear zone substructures (Figs. 13 and 14) or a mixture of these structures (Fig. 13). These dilatancy phenomena led to an increase in overall permeability of rock masses and the development of traps for mineralizing fluids. These openings are very important foci for localizing gold ore deposits and are very well documented in the literature (Bateman, 1950; Park and McDiarmid, 1964; Newhouse, 1942; to cite a few).

The progressive development of en-echelon tension gashes (the first type of dilatancy), within and in the immediate surroundings of very brittle low normal stress shear zones in relation to shear displacement, begins with en-echelon single tension fractures, followed by sigmoidal openings of these fractures and the superposition of new sets of tension gashes (Fig. 12A), and ends in the formation of breccia to cataclastic zones explained in Ramsay and Huber (1987). The mechanics of development of these tensional fractures was discussed in detail in Archambault et al. (1994). The progressive overriding of irregular planes (composed of valleys and waviness of various scales) (the second type of dilatancy) causing dilatant (openings) and contraction (sheared) area in faults and shear zone substructures (Figs. 13 and 14) channelized the circulation of the mineralizing fluids through the dilatant zones in which the pore fluid pressure will be lower than in the contraction zones, hence establishing a hydraulic gradient allowing the fluids to migrate. The mechanics of these phenomena can be explained by the application of a shear fracture dilatancy model, incorporating the dilation mechanisms in these zones, like the model developed by Ladanyi and Archambault (1970) and

applied to dilatant mineralized shear zones by Guha et al. (1983). These two types of dilatancy within shear zone substructures were observed both in the Jiaojia mine (Figs. 11 and 13) and in the Linglong mine (Figs. 10 and 13).

#### 4.5 Occurrence of mineralization in these structures

The relationships among the different types of shear zones, gold mineralization, temperature, depth of formation (confining pressure) and the morphology of ore bodies in the Linglong-Jiaojia area are illustrated in Fig. 15. The Jiaojia, Hedong, Hexi, Xincheng and Sanshanda mineral deposits are characterized by structures typical of shallow depth while the Linglong, Muping and Jiuqu ore bodies were deposited in structures characteristic of greater depth, where brittle-ductile deformation predominates, and finally the Lingnan ore body occurs at the transition between brittle-ductile and ductile deformation structures within the Potouqing shear zone.

The end of ductile phase activity of the Tancheng-Lujiang fault zone was evaluated at around 160 Ma (Lu Huanzhang et al., 1999) corresponding to the Linglong granite emplacement, followed by the other intrusions. The gold mineralization was introduced later on, around 110–120 Ma (Qiu et al. 2002), through a brittle to ductile deformation phase (D5 and D6 deformation events), superposed on the earlier ductile deformation structures. During that period, brittle-ductile shear zones were developed and the mineralization occurred in openings resulting from the dilatancy phenomena, on all scales, related to the substructures of these shear zones or disseminated in

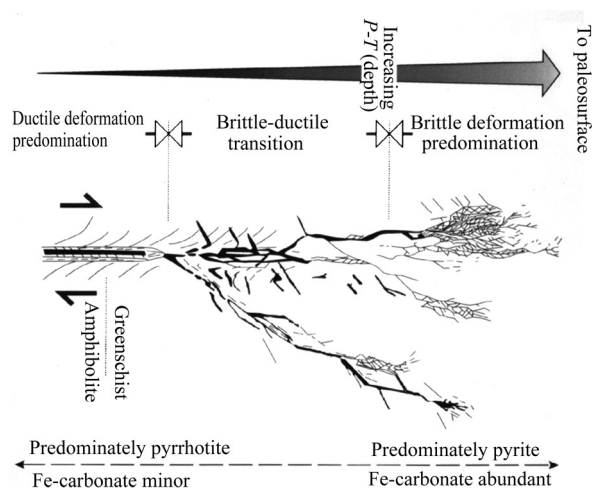


Fig. 15. The relationships among the different types of shear zones, gold mineralization, temperature, and depth of formation (modified from Colvine et al., 1988).

the dilatant rock massifs within or surrounding the shear zones, giving rise to the two types of gold mineralization: the lode gold or vein type and the disseminated gold or alteration zone type.

## 5 Conclusions

Faults and shear zones are the main structural features controlling gold mineralization, and dyke intrusion in the Linglong-Jiaojia region. The distribution of gold deposits is controlled by brittle to brittle-ductile shear zones located within the major shear zones and subsidiary structures. Most of the shear zones show evidence of superposed brittle and ductile deformation developed at different times in their history. The Linglong gold deposit is located in the Linglong granite and the Potouqing ductile shear zone and its related substructures controlled the mineralization emplacement. Under a simple shear regime, the fracturing formed an en-echelon fracture pattern and these fractures were filled by different types of dykes, gold-bearing quartz-pyrite veins and veinlets.

Lode gold deposits in the Jiaojia area occur in the brittle fault zones formed in a dominant simple shear deformation regime, mainly in the thrust attitude with a variable sinistral strike-slip displacement. The structural characteristics of these brittle shear zones are consistent with the tectonic NNW-SSE principal stress field orientation responsible for the Tancheng-Luliang fault zones in the vicinity of the Linglong-Jiaojia area. Under this stress regime, the Linglong granite was deformed heterogeneously in the shear zones in which R, P and D shears were developed and the gold mineralization filled these shears and formed the Nos.1 and 2 types of ore bodies in Jiaojia while extension developed en-echelon tensional fractures mineralized to form the No.3 type of ore bodies in the mine. The ENE fold axes in the region are also consistent with the same NNW-SSE-trending principal stress field orientation, so that these zones occurred as part of the major tectonic events in the province of Shandong.

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