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Deep Structural Framework and Genetic Analysis of Gold Concentration Areas in the Northwestern Jiaodong Peninsula, China: A New Understanding based on High-Resolution Reflective Seismic Survey

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Abstract: The gold concentration areas in the northwestern Jiaodong Peninsula constituted an important gold metallogenetic region in Eastern China during the Mesozoic. The deep geological bodies' texture characteristic is important for exploring the resources thoroughly and understanding the metallogenic process. The detailed textures were revealed using high-resolution seismic profiles through the three major ore-controlling structures-Sanshandao fault zone, Jiaojia fault zone and Zhaoping fault zone. This study aims to establish a deep structural framework of this area. Based on their formation mechanism, the fault structures developed in the area can be divided into regional and local fault structures. The structural styles are characterised by superimposing their compressional, strike-slip and extensional multi-stage activities. The crust is cut by vertical structures corresponding to a left-lateral strike-slip fault system on the surface. Nearby these structures are the arc-shape structures formed by multi-stage magma intrusions into the upper crust. Bounded by the Tancheng–Lujiang and Muping–Jimo fault zones, the current Jiaodong block, developed a series of NE-trending strike-slip fault systems, was probably formed by the assemblage of several obliquely aligned blocks. The intensive magmatism and hydrothermal activity between the blocks induced large-scale mineralisation. It provides a new angle of view for understanding the cratonic destruction and large ore-concentration formed during the Mesozoic.

Key words: ore concentration area, deep exploration, strike-slip faults, Sanshandao fault zone, cratonic destruction, Shandong

1 Introduction

Large-scale mineralisation of the endogenic gold deposits in eastern North China occurred during the Mesozoic (Yang et al., 2003；Yang L. Q., 2014a, b, 2016；Deng and Wang, 2016；Hao Ziguo et al., 2016). Based on existing isotope chronology data, the large-scale gold mineralisation in Eastern China occurred during three periods: 200–160 Ma, ~140 Ma and 130–110 Ma (Mao Jingwen et al., 2003). The mineralisation was especially intense in the 130–120 Ma period (Yang et al., 2001, 2003; Li et al., 2012; Li et al., 2013; Wang Ronghu et al., 2008; Yu Xuefeng et al., 2012; Yang et al., 2014a, b; Zhu Rixiang et al., 2015). The largest gold concentration area in the Northwestern Shandong Peninsula, namely the Zhao–Lai gold concentration area, located in the Jiaobei Block (Fig. 1), typifies the mineralisation during this period, and has been extensively studied (Deng Jun et al, 1996; Li Houmin et al., 2003; Hou Minglan et al., 2006; Wang et al., 2014; Wang et al., 2015; Yang L. Q., 2014b, 2016, 2017). The overall mineralisation endowment of the area is approximately 5000 t (Song Mingchun et al., 2014; Yu Xuefeng et al., 2016; Yang et al., 2016).

Most of the goldfields in the Zhao–Lai gold concentration area are spread along three linear and almost

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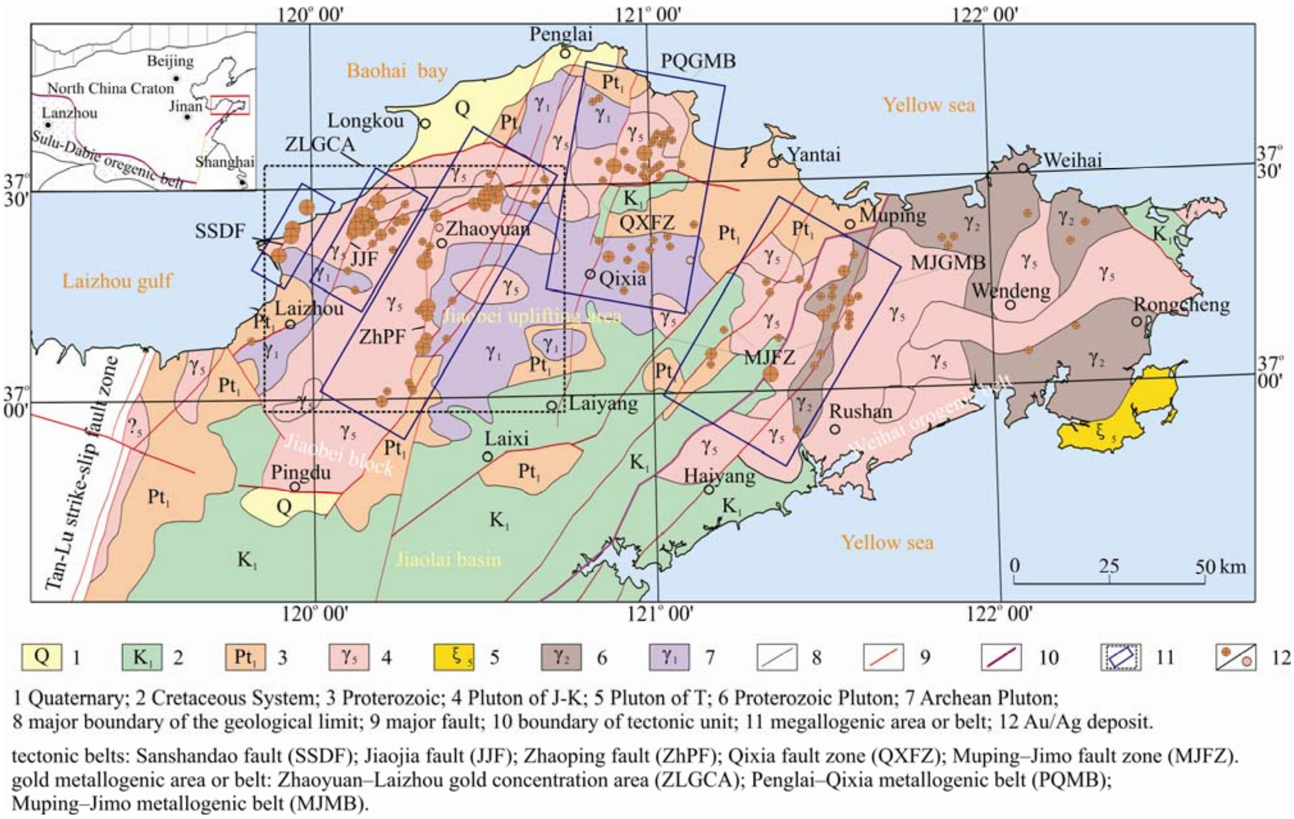


Fig. 1. Distribution of the gold metallogenic belt in the Jiaodong area.

parallel fault zones: the Sanshandao Fault Zone, the Jiaojia fault zone and the Zhaoping fault zone. These zones form the major gold concentration area of the Jiaodong gold province (Fig. 1). According to the drilling results, the ore zones hosted by these faults continue to underground depths of 2000 m or more (Song Mingchun et al., 2011, 2015; Yu Xuefeng et al., 2016). The latest drilling activities of the Shandong Institute of Geological Sciences in 2017, which focused on the ore-hosting structure (the deep extension of Jiaojia Fault), revealed ore body at depth of 2810 m. However, the metallogenic model and genetic mechanisms in this area remain contentious (Song Mingchun et al., 2013；Yang Liqiang et al., 2014b；Goldfarb, 2014). Hence, the characteristics of the deep-crust compositions, the structural framework and their relationship, especially, the patterning and formation of the structures during the geological processes, are significant for deep exploration and for understanding the metallogenic processes.

By measuring the high-resolution reflective seismic profiles in the Zhaoyuan–Laizhou Gold Concentration Area (ZLGCA), this study characterised the crustal textures and structures from the Sanshandao fault zone zone to the Zhaoping Fault Zone. Combining the results with surface geological information, it then establishes a preliminary structural framework of this area. The deep detection results revealed a series of NE-trending strike-slip faults distributed through the area, many of which cut through the crust with small surface displacements. This type of fault probably fractured the crust or lithosphere, forming rising conduits for magma and fluid. The magmatic activities and metallogenic fluid induced and controlled by the faults then connected the three main faults (the Sanshandao Fault, the Jiaojia fault zone and the Zhaoping fault zone) in the gold concentration areas, generating the main metallogenic zone in this area. By elucidating this mechanism, we can better understanding the formation process of the large ore concentration area in the eastern North China Craton during the Mesozoic.

2 Geological Setting

The Jiaobei Block, located in the back-arc area caused by subduction of the present-day Pacific plate, occupied the southeastern margin of the North China Craton in the Mesozoic. It neighbours the Weihai orogenic belt at the eastern end of the Sulu–Dabie orogen (Liu et al., 2003, 2005) to the southeast and the Luxi block to the west, where it is separated by the Tancheng–Lujiang Fault Zone (Fig. 2). The Jiaobei Block can be divided into two major areas with different tectonic developments and topographical features: the Jiaobei uplift area in the north

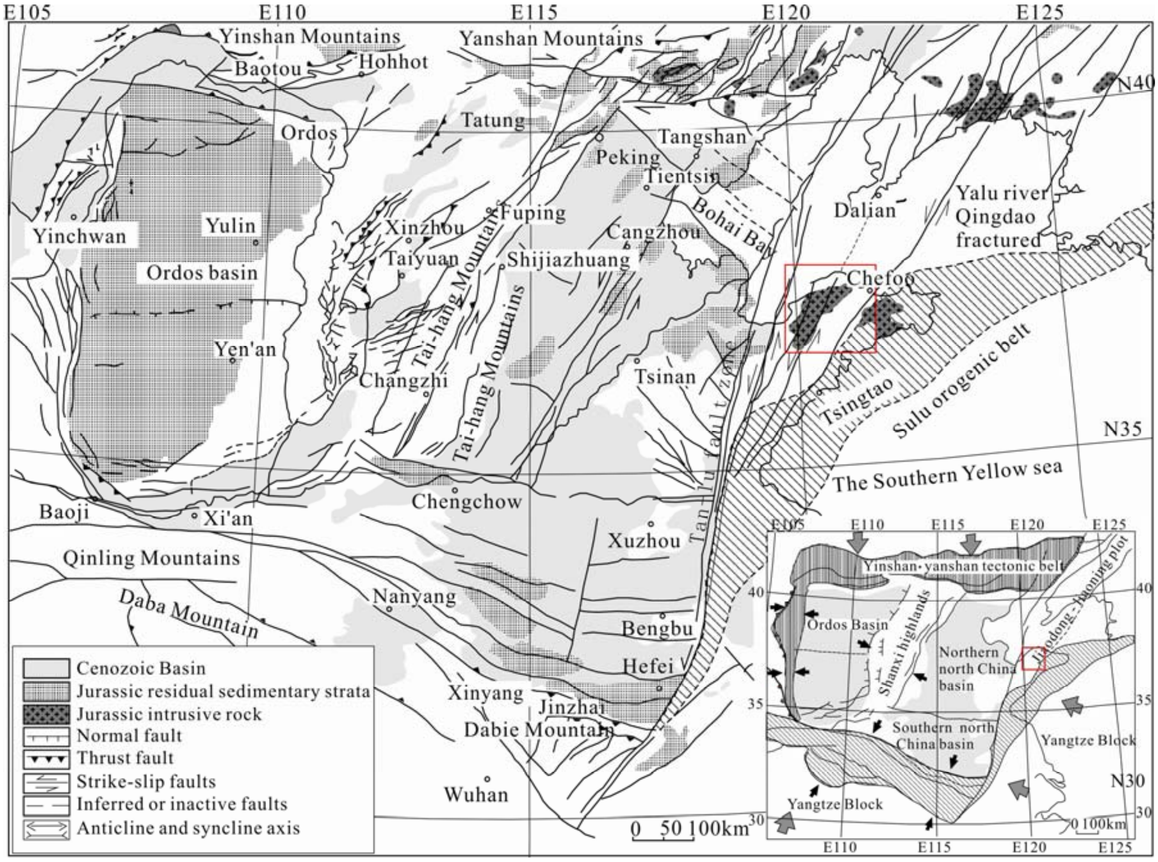


Fig. 2. Geotectonic location and tectonic system in the study area during the Jurassic (revised after Zhang et al., 2008a, b).

and the Jiaolai depression area (Jiaolai Basin) in the south.

The Jiaobei Block is an important component of the North China Craton. It has a long geological evolutionary history with multi-stage magmatic and structural developments (Liu et al., 2013). From the Archaean to the Proterozoic, the continental block formed by gradual growth, increase and amalgamation from the continental nucleus and unification of blocks (Bai and Dai, 1994; Li Junjian et al., 2010). In the Mesozoic the North China Craton amalgamated with the Yangtze Craton, and the Paleo–Tethys tectonic domain transformed to the Pacific tectonic domain (Zhang Guowei et al., 2004; Liu et al., 2015a, 2015b).

The geological evolutionary processes in the Jiaobei Block during the Mesozoic and Cenozoic have always been focal points of geological research. These processes are complicated by the superimposition of multi-stage tectonic movements and complex tectonic traces (Zhu and Xu, 1994). A series of geological events, including the amalgamation of the northern and southern continental blocks in the early Mesozoic, the destruction of the eastern North China Craton, the left-lateral strike-slip of the Tancheng–Lujiang Fault Zone and the oblique subduction of the Paleo-Pacific plate to the Eurasian plate, have been recorded in different geological bodies in this area. From the Mesozoic to the current era, the tectonic regime was correspondingly transformed from the Paleo–Tethys tectonic regime to a marginal Pacific tectonic regime. Accordingly, the EW and NE-trending structures became superimposed in the Jiaodong area.

The Jiaobei Block is mainly composed of Precambrian crystalline basement rock, including the Neoarchean greenstone formation, tonalite–trondhjemite–granodiorite, the Paleoproterozoic Jingshan Group and Fenzishan Group (Geng Ke et al., 2016). The earliest isotopic age is 2.9 Ga (Wan et al., 2015). The basement rock is locally covered by the Neoproterozoic Penglai Group, which comprises a series of clastic and carbonate sedimentations. Sedimentation was largely absent from the Cambrian to the Jurassic (Li Junjian et al., 2010). The Yanshan movement then produced large-scale magmatic activities and fault basins. The Yanshanian granites in the Jiaobei uplift area have been traditionally divided into three suites: the Linglong suites, the Guojialing suites and the Weideshan suites. The Linglong suites (Late Jurassic) are mainly composed of medium-grained metaluminous to slightly peraluminous biotite granite with ages of 160–156 Ma. They are usually subdivided into four units, namely, the Yunshan Pluton, the Cuizhao pluton, the Guojiadian and Biguo Pluton and the Linglong Pluton. The Guojialing suite (first-stage early Cretaceous) is mainly composed of porphyritic hornblende–biotite granodiorite, monzodiorite and adamellite, with ages of 130–126 Ma (Wang et al., 1998; Guan Kang et al., 1998; Zhang Lianchang et al., 2002). The Weideshan suites (second-stage early Cretaceous) are mainly composed of pyroxene hornblende diorite, diorite porphyrite and monzodiorite with ages of 116–113 Ma (Goss et al., 2010). They include the Aishan Pluton and the Weideshan Pluton, among other features. Numerous mafic–intermediate dikes dated at 124–120Ma are also distributed in this area.

The main surface features of the Jiaobei Block are folds, faults and ductile shear zones. Most of the fault structures developed within the epistructure or mid-epistructure facies, which typically formed by brittle or ductile–brittle deformation of rocks that were uplifted and depressed or dislocated in the Mesozoic and Cenozoic. The current structural framework is dominated by NNE- or NE-trending faults, interspersed with NW- or EW-trending faults. From west to east, the major NNE- and NE-trending fault structure zones are the Sanshandao Fault, the Jiaojia Fault, the Zhaoping Fault, the Fengyi–Leyuan Fault (FYLYF), the Cunliji Fault and the Qixia Fault (Fig. 1).

Thus far, the Mesozoic gold deposits have mainly been discovered in the Jiaobei uplift zone and the northeastern margin of the Jiaolai Basin. Three gold metallogenic zones or belts are spread along the faults: the ZLGCA, the Penglai–Qixia Gold Metallogenic belt and the Muping–Rushan Gold Metallogenic belt (Fig. 1).

3 Data Acquisition and Methods

3.1 Method of data acquisition and profiles processing

The texture and geological processes within the deep geological bodies in major ore-concentration areas are pivotal topics in geological study. On the lithosphere scale, the various textures and compositional materials formed by geodynamic processes in the crust leave numerous ‘geological traces’ or ‘earth fingerprints’ that can be identified. These textures and characteristics in deep geological bodies reflect the occurrences, developments and terminations of geological effects. High -resolution reflective seismic survey is an effective geophysical method for finding such evidences and reconstructing past processes.

This study collects and analyses four seismic profiles with common depth-point stack profiles. Three of these profiles (the mainlines) extend approximately along the 107° direction, nearly perpendicular to the Sanshandao Fault, the Jiaojia Fault and the Zhaoping Fault. The longest profile starts from the northeastern part of the Sanshandao Gold Deposit and terminates at the eastern end of the Biguo Pluton, located east of the Zhaoping Fault. The C–D profiles (Figs. 3 and 4) connect the Sanshandao Fault, Jiaojia Fault zone and Zhaoping Fault Zone. One profile is 60.90 km long and runs through the Linglong suites, including the Guojiadian and Biguo plutons. Two of the other lines pass through the middle section of the Zhaoping Fault Zone, near the Dayingezhuang goldmine site and south of Zhaoyuan county. All three profiles are connected by a crossline.

During the data acquisition, the arranging style was 5990–10–20–10–5990 with a 20-m group spacing, a 40-m shot spacing and 150-fold. The deep-layer information was obtained by deep-well blasting with an up-scaled blasting charge (the normal blasting charge in down-hole excitement is 8 kg). Single wells were 16 m deep and big shots with a 10-kg blasting charge were placed at 200-m intervals. The split spread mode was adopted with a 12-s recording length and a 2-ms sampling interval.

The data were processed by focusing on the field statics, pre-stack noise attenuation, wavelet coherence processing and a detailed velocity analysis. After frequency-division processing, the horizontal stack profile, dip-moveout (DMO) stack profile, horizontal migration profile and DMO migration profile were obtained, along with the corresponding frequency-division and time-division profiles.

3.2 Interpretation of Results

3.2.1 Fault structures in the upper and middle crust

(1) X-shape conjugated fault system

The seismic profiles revealed a conjugated brittle fault through the distribution area of the Linglong suites in the shallow crust. Many conjugated X-shape fault surface waves were found in the 0–2 s range of the C–D profile. These fault waves are characteristic of the Linglong suites, indeed, of the Guojiadian Pluton.

Most of the reflection waves resulted from one or two groups of seismic events with a weak continuity. The event relics obviously extend along a certain direction before suddenly jumping. These reflection waves were identified as reflections of fault plains, sometimes corresponding to outcrop faults.

The formation of this set of faults was associated with magmatic intrusion and uplift from the deep part. They are expected as conjugated faults formed when the maximum principle stress is perpendicular to the surface. The same structural pattern was found by surface observation (Fig. 5). However, the faults exhibit different developmental levels and different shapes. The X-shape patterns appear on the central top of the pluton. Along the sides of the pluton, the pattern is a direct or inverted Y-shape.

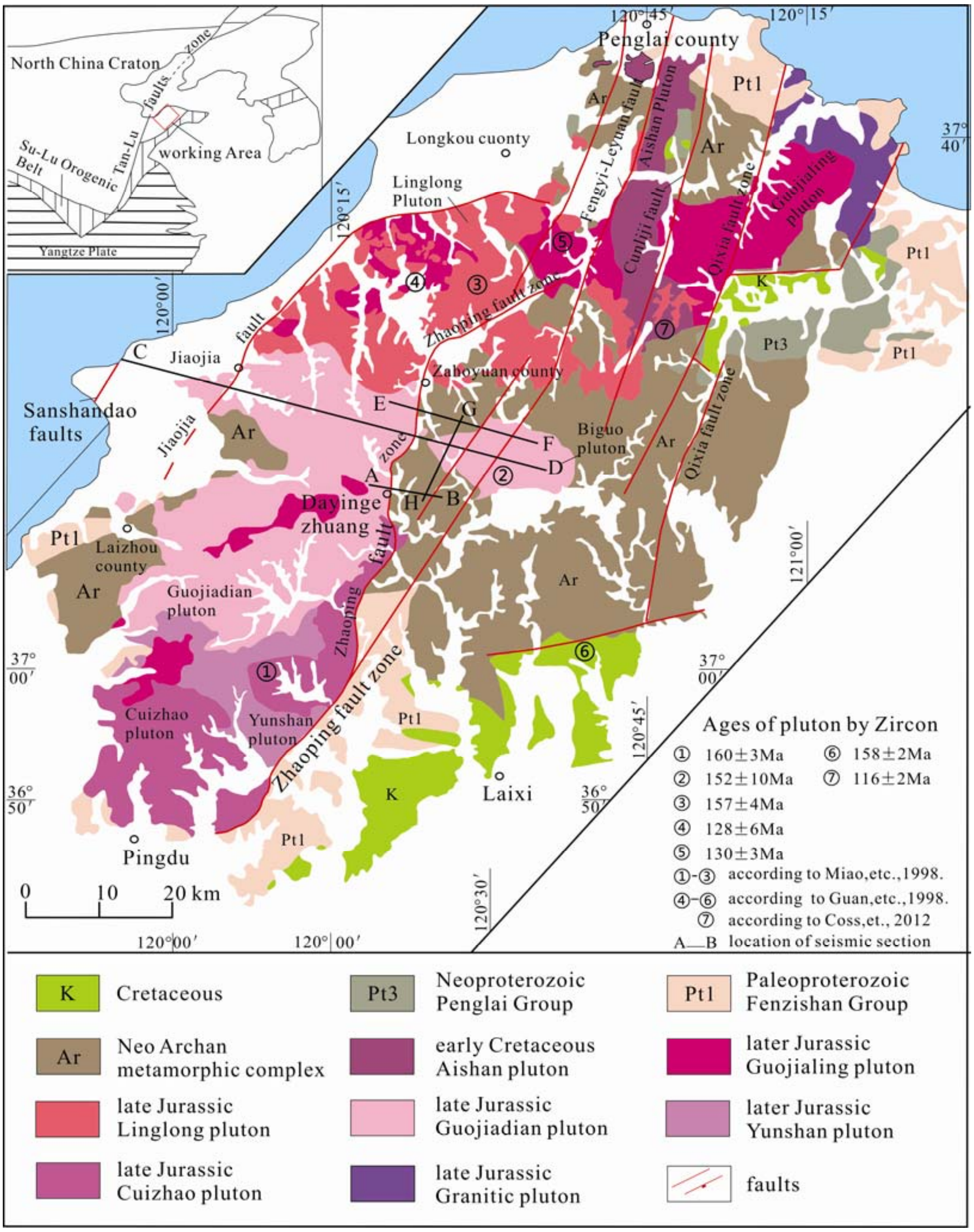


Fig. 3. Geological sketch and profile location in the study area.

(2) Listric fault group dipping to the SE

In the profiles, the Sanshandao Fault (Fig. 6) and Zhaoping Fault appear as large listric faults dipping to the SE. The dip angles gradually become gentle in the deep regions. The faults extend to 4 s in the dip direction, forming the regional large-scale structures.

In the deep part of the Sanshandao Fault, the slivers of metamorphic basement show thrusting movements along with the fault surfaces. However, the fault crop near the Sanshandao Deposit shows normal mylonite fault features. This suggests multi-stage activities of the fault and reverse directions of the movements in different stages.

Multi-stage magmatic intrusion activities have occurred beneath the Zhaoping Fault. In the deep part of the fault, the shape is turbulent because the plutons have contacted their wall rock in some zones. Similar listric-shaped faults with a similar spatial distribution appear in the Guojiadian Pluton between the Jiaojia and Zhaoping Fault zones. Most of these faults are largely extended in the dip direction and cut through the Linglong suites (in which the Guojiadian Pluton resides). Their properties are not clearly revealed.

(3) Structural patterns of Sanshandao Fault and Jiaojia Fault

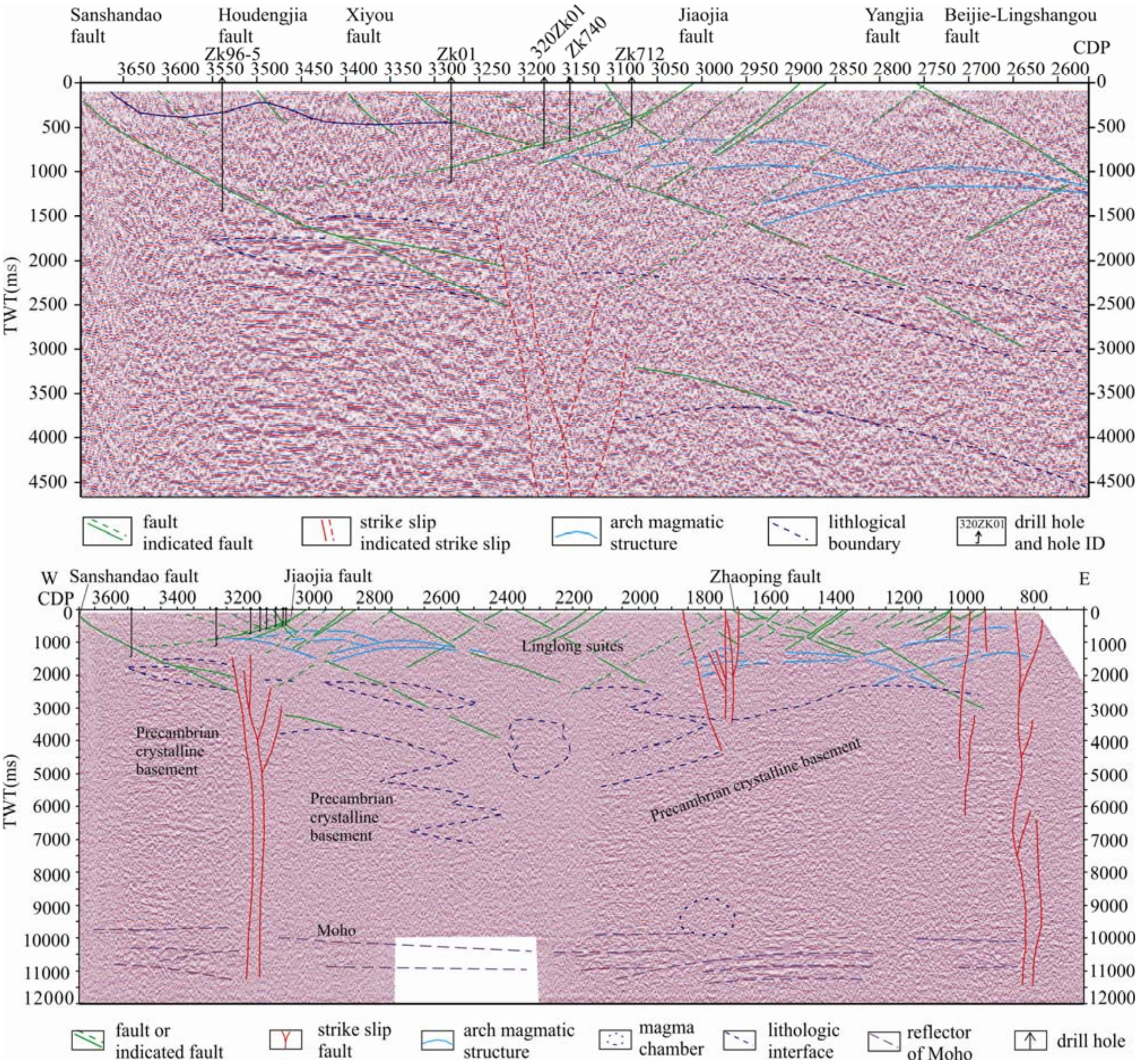


Fig. 4. Time profile (a) and geological interpretation (b) of survey line C–D.

Fig. 5. The filled quartz veins in conjugated X shape in the Linglong pluton.

The combined pattern of Jiaojia Fault and Sanshandao Fault is anticipated as an X-shape, a Y-shape, or an inverted Y-shape. The structural relationship between Jiaojia Fault and Sanshandao Fault was investigated in-depth in two seismic profiles, one crossing the drill hole ZH96-5 completed by Shandong Gold Group Co., Ltd., which profiles the depth of Sanshandao Fault, the other crossing the 3266.06-m deep drill hole ZK01 completed by Shandong Institute of Geological Sciences, which profiles the depth of Jiaojia Fault. Hence, the relationship between the two faults was profiled by a seismic section calibrated with drill holes.

Throughout the depth of Jiaojia Fault, the drill hole Zk01 cut through the fracture plane from ca. 2720 m to ca. 2810 m. The facture plane comprises an alteration zone, a fault gouge, cataclasite and other fracture features. Near the fracture plane is tectonic rock. However, as the Jiaojia Fault is poorly imaged in the reflection seismic section, it was calibrated by the boreholes (e.g. Zk712, Zk740, 320Zk1, Zk01) spreading along the section, and characterised by several sets of continuous weak reflection zones formed by minor events. This observation is consistent with the geological appearance of the main structural zone in the drilling core, which is composed of cataclasite several hundred metres thick. The lack of a continuous impedance surface in the structural zone implies a seismic wave. In fact, owing to cataclasis, the physical properties of the whole structural zone and the surrounding rocks vary widely.

The deep Sanshandao Fault extends to the SE over a long distance, cutting through Linglong- stage granite batholiths before plunging into the metamorphic basement. The Jiaojia Fault zone dips toward Sanshandao Fault. At greater depths, the dip angle gradually becomes gentle and the two faults meet approximately underneath CDP3530, with a nearly horizontal extension between CDP3330 and CDP3530. Thus, a reverse Y-shape (Fig. 6) presents in which Sanshandao Fault is the primary fault with the larger deep extension and Jiaojia Fault is the subsidiary fault cut down by Sanshandao Fault in the deep part. Interestingly, Sanshandao Fault, Jiaojia Fault and Zhaoping Fault are all connected in the deep part with vertical structures cutting through the crust (which may be deep-cutting strike-slip faults).

3.2.2 Magmatic intrusion structures

Owing to the homogeneity of magmatic rocks and the absence of reflection interfaces, the seismic waves within the pluton have a ‘transparency’ property which can potentially distinguish the distributions of the magmatic rocks from those of metamorphic rocks. Meanwhile, multi -stage magmatic activities give rise to different magmatic intrusions. From the reflection interfaces at the contact zones of these magmatic intrusions, one can estimate the stages of magma activities.

The seismic profiles running through the Linglong suites (the Guojiadian Pluton) reveal many mushroom-shaped single- or double-layered arcuate reflection interfaces within the pluton (Fig. 7). These interfaces are similar to the arch-structures mentioned by Yang Wencai et al. (2005), and the strong-reflection bright spots of double-layered domes (Lu Zhanwu et al., 2014). Lu interpreted these structure as magma chambers upwelled by magma from deep to the middle crust.

Successive stages of such reflections are evident in the profiles. The reflections are matched to fault structures at both sides or above the reflection. This kind of reflection is considered as an intrusive structure formed by magmatic intrusion and resembles that of magmatic bodies. Together with their attached faults, the arc structures at the different stages were cut and transformed by each other. Consequently, the later arcuate interfaces present a complete and clear shape, whereas the earlier ones are discontinuous and indistinct.

The arcuate reflection mostly distributes along the western and eastern sides of the Linglong suites. At the east side, it lies beneath the Zhaoping Fault and the Biguo pluton. At the west side, it lies beneath the Jiaojia Fault and its adjacent areas. Based on their distribution regularity and formation sequence, these reginal magma activities likely occurred after the Linglong stage and possibly in the Guojialing or Weideshan stage.

3.2.3 Strike-slip faults

The strike-slip faults are mainly characterised by shear sliding of the geological bodies along with the fault surfaces. Large strike-slip faults are usually composed of deep erect ductile shear zones and shallow brittle fault systems. Seismic exploration exploits the impedance differences at the gentle-angle interfaces formed by strata or layer-like geologic bodies. As the Jiaodong area lacks sedimentary cap rocks, strike-slip faults with high dip-angles are difficult to detect in the seismic profile. Nevertheless, the finely conditioned outcrops and the detailed regional mapping in the study area provide sufficient and reliable foundations for identifying the strike-slip faults.

In the C–D profile, deeply cut strike-slip fault systems appear in the CDP 750–1010 and CDP1700–1900 ranges at the eastern side of the Guojiadian Pluton. At the west side of Guojiadian Pluton, a vertical structure runs from the upper to lower crust between CDP3100 and CDP3250. This structure is considered as another strike-slip fault covered by Quaternary rock. The strike-slip faults at CDP800 and CDP3200 should run through the whole crust. The seismic wave sets exhibit a turbulent fabric near the strike-slip faults, indicating a disordered texture of the geological bodies involved in the faults. The textures and structures at both sides of the fault are mostly discontinuous. Meanwhile, the strike-slip faults are associated with obvious lower-velocity zones in the velocity profiles. In the A–B profile (Fig. 8), strike-slip faults are observed at CDP1450 and CDP1850–1950, with deep cutting and discontinuous fabrics at both sides of the faults. The CDP1850–1950 fault corresponds to the southern segment of the surface Fengyileyuan Fault. On the surface, the metamorphic basement and elliptical Biguo pluton are left-laterally dislocated by Fengyileyuan Fault and a series of fault bundles arranged in echelon

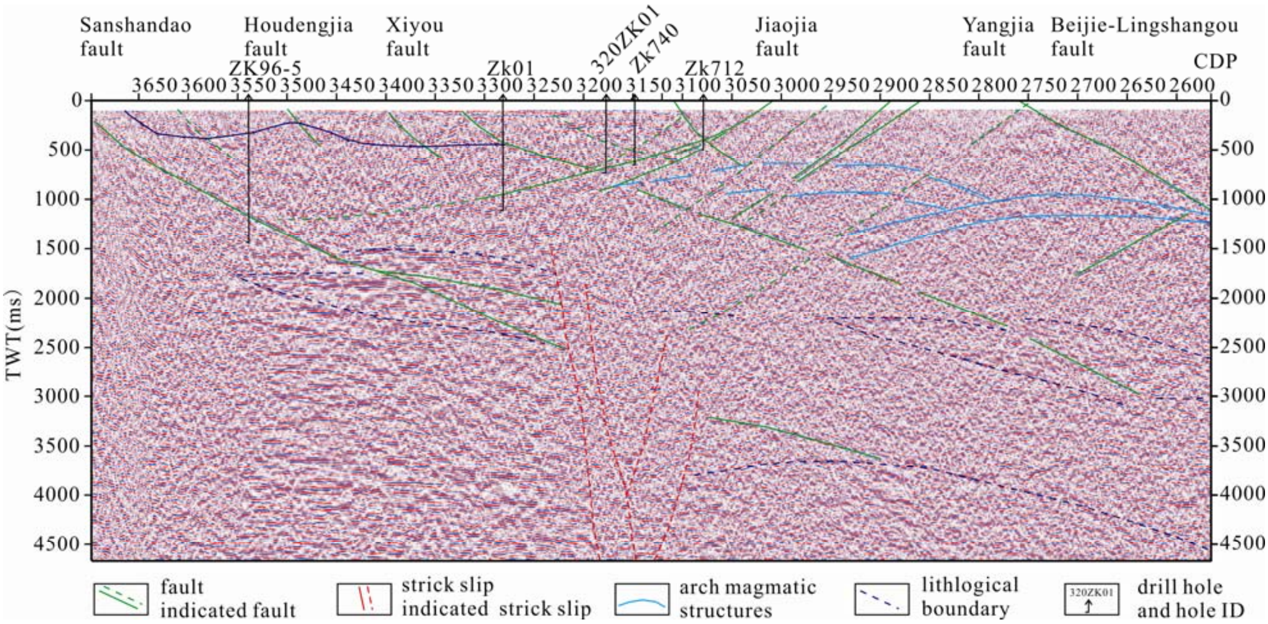


Fig. 6. Features of the deep structures between Sanshandao Fault and Jiaojia Fault.

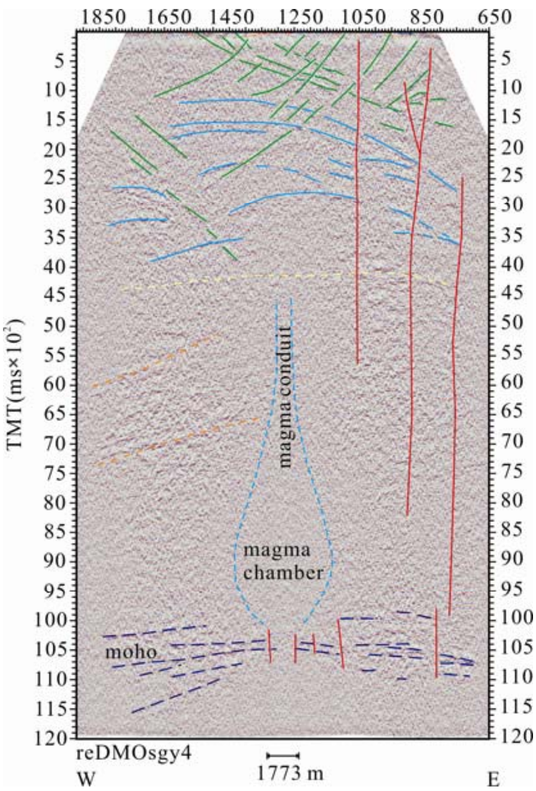


Fig. 7. Interpretation of the time profile of seismic measurements along survey line E–F.

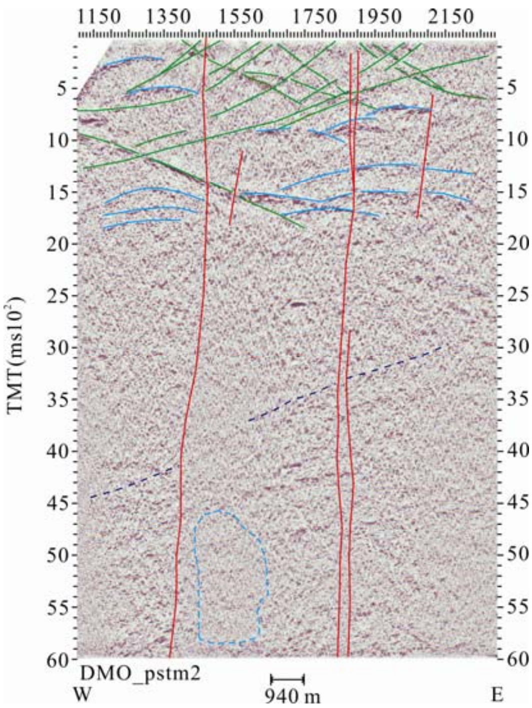


Fig. 8. Geological interpretation on the time profile of survey line A-B.

form. The strike-slip distance is typically small and the obvious left-lateral dislocation is approximately 1.5 km in the Biguo pluton. The seismic survey confirmed that the strike-slip faults extend to the bottom of the crust in the C–D profile, corresponding to fracture of the Moho discontinuity and vertical dislocation.

3.2.4 Shape of the Linglong suites and their bottom interface

The surface of the research area includes Linglong-stage granites from Guojiadian Pluton and Biguo Pluton, which intruded during the later Jurassic. Intrusive stocks and dike swarms are also distributed in the Linglong suites. Most of the stocks are Guojialing-stage granodiorites formed during the early Cretaceous. The dike swarms are characterised by a wide compositional spectrum including lamprophyric, basaltic, dioritic, granodioritic and granitic dikes from the later Jurassic to the early Cretaceous.

Above 1 s, the fabric of the seismic wave sets is dominated by nearly transparent reflections in the magmatic-rock zone. The obvious interface at 1.5–3.0 s in the C–D profile is sourced from the different seismic-wave fabrics in that depth region. Considering the seismic-wave characteristics (Yang Wencai et al., 2007) and the regular spatial distribution of the geological bodies, this interface likely separates the magmatic rocks from the metamorphic rocks. Similar interfaces formed by fabric differentiation appear at approximately 4.5s in the E-F profile and at 3.0–4.5 s in the A–B profile. Based on current knowledge, this interface is inferred as the bottom interface of the Linglong suites (Figs. 6 and 7). Furthermore, the Linglong suites (being composed of different plutons) present as a large layer-like batholith suggestive of gravity inversion (Zeng Hualin et al., 1999). The batholiths contain arcuate multi-intrusive structures supported by extensional faults with magma emplacement. They are underlain by the metamorphic crystal basement.

3.2.5 Metamorphic crystal basement and Precambrian inclusions

The North China Craton is an ancient continental block area. Precambrian metamorphic rocks are widely distributed in the Jiaodong area, which occupies the southeastern margin of the North China Craton. The metamorphic facies of the exposed rocks on the surface are amphibolite to granulite (the latter belongs to the Neoarchean greenstone area). The ancient geological history suggests that Precambrian metamorphic rocks dominate the crustal rock components in this area. Meanwhile, many of the reflection sets in the seismic profiles are attributable to parallel and multi-group vertical seismic events with medium amplitude, low frequency and great continuity. These events are evenly distributed beneath or at the eastern and western sides of the Guojiadian Pluton. A similar reflection set in the Sulu area was evaluated as paragneiss (Yang Wencai et al., 2007). Based on their spatial distribution characteristics and the composition of their reginal geological bodies, the seismic facies in the present study were attributed to metamorphic rocks of Precambrian origin. In most profiles, the seismic events of such geological bodies are mainly horizontal from the bottom interface of the magmatic rocks to the Moho discontinuity, forming a series of layer-like reflection interfaces. Inclusions with these reflection characteristics were found in the Guojiadian Pluton. Consistent with these findings, giant metamorphic inclusions are always present in the outcrops of the Linglong suites.

3.2.6 Dipping structures in the middle and lower crust

A number of dipping structures appear in the metamorphic-rock area of the middle and lower crust at both sides of the Linglong suites. These dipping structures exhibit long extensions, good continuity and certain dip directions (Figs. 4 and 6). The dipping structures at both sides of the C–D profile dip toward the pluton centre. The vertically intersecting mainlines and crossline near the Zhaoping Fault Zone in the seismic profiles indicate a lentoid form of the geological bodies enclosed in the dipping structures.

3.2.7 The Moho discontinuity

Strong-reflection zones appear at 9.5–11.5s in the seismic profiles of every survey line (Figs. 4 and 6). The seismic fabric is characterised by a certain thickness of lower-frequency strong multi-phase reflection, discontinuous distribution of seismic events and strong amplitude. From the regional contrast, this thickness is inferred as the seismic reflection of the Moho discontinuity.

The Moho discontinuity in the seismic profiles presents as a stratified geological body with a certain thickness, a flat-top interface and reflection-free areas below the bottom interface. In the C–D profile, the Moho discontinuity exhibits gaps and thrusts in the extensional direction, revealing compressional dislocation. The reflection-free areas in the crust corresponding to the vertical gaps in the Moho discontinuity are inferred as strike-slip faults or magma conduits (Fig. 7).

3.2.8 Magma chambers or magma conduits

The metamorphic-rock areas show sacciform and branched reflection-free areas above the gaps in the Moho discontinuity, which partially correspond to high-velocity bodies in the velocity profiles. Considering the characteristics of the seismic facies in the top magmatic-rock area, these geological bodies are interpreted as rising magma conduits or magma chambers accompanying the strike-slip faults (Fig. 7). Most of these magma chambers lie underneath an extension at depths below 7.5 s.

3.2.9 Building of the structure framework

The C–D profile connects the Sanshandao fault zone, the Jiaojia fault zone and the Zhaoping fault zone. Its total length (60.9 km) runs through the Linglong pluton at a strike direction of 107°. The profile consists of two segments with recording times of 10 s and 12 s (TWT) respectively, clearly revealing the textures and structures of the deep geological bodies in the gold concentration areas of the northwestern Shandong peninsula. The horizontal and vertical zonalities in the crust, caused by the compositional and structural distribution of the geological bodies, are also revealed, along with the massive distribution features of the metamorphic and magmatic rocks in this area (Fig. 4).

Based on the above-mentioned knowledge, the C–D profile was interpreted to form a structural framework of the study area. The framework includes the fault structures in the middle and upper crust, the magmatic intrusion structures, the bottom boundary of the Linglong suites, the strike-slip faults, the dipping structures in the middle and lower crust, the metamorphic crystalline basement of the Precambrian, the Moho discontinuity and the magma chambers and conduits.

Three horizontal zonalities can be distinguished from the upper crust to the Moho discontinuity: the Linglong Suits distributed at the top of the upper crust, the Precambrian metamorphic basement (forming the middle zonality from the upper to lower crust) and the Moho discontinuity at the bottom. The framework covers the basement of the whole crust in this area. Structures and traces of magma activities with different shapes were also distributed through different levels. The main features in the upper crust are dominated by large listric faults dipping to the SE. Most of these features occupy similar spatial extents, with conjugated X-shaped faults observed in some features.

From west to east, the C–D profile exhibits vertical structures and strike-slip faults at both sides of the Linglong suites, cutting through the crust. These features are associated with the broken Moho discontinuity. Around the strike-slip faults, many of the intrusive stocks in the Linglong suites are genetically related to the conjugated X-shape faults and some listric faults, confirming a similar mechanism to that of local metamorphic-core complexes. Thereby, a deep structural framework of the study area was preliminarily established.

4 Discussion

Large-scale mineralisation in the Mesozoic has a complex geodynamic background. Mao Jingwen et al. (2003) concluded that the first, second and third major mineralisation periods were sourced from amalgamation and collision orogenesis of the North China and Yangtze Craton, the tectonic regime transformation from the Paleo–Tethys tectonic domain to a marginal Pacific tectonic domain and large-scale delamination of the lithosphere, respectively. Chen Yanjing et al. (2004, 2013) summarised the spatial and temporal distribution rules of the Mesozoic gold deposits in the greenstone terrain within the North China Craton. Inferring that the gold deposits arose from plate collision, they proposed a tectonic model of collisional orogeny based on metallogeny and fluid flow (the CMF model). Hu Shouxi et al. (2001) proposed that large-scale Mesozoic metallogenesis in the North China Craton was a long-distance effect of westward subduction of the Pacific plate. In a metallogenic model of gold deposits, Zhu Rixiang et al. (2015) considered the gold deposits of the early Cretaceous in the North China Craton as decratonic, which essentially distinguishes them from the orogenic gold deposits in the metallogenic tectonic background that sources the metallogenic fluid. They associated the latter with magmatic activity induced by cratonic destruction in an extensional background.

Aside from the main mineralisation periods, gold was deposited in minor mineralisation periods of the Mesozoic. Examples are the Guilaizhuang gold deposit in the Luxi block at 178–188 Ma (Yu Xuefeng et al., 2009a, 2009b), whose metallogenic period was constrained by the age of strata and ore-forming magma, and the Dongping gold deposit in the Hebei province, with a metallogenic age of 187±0.3 Ma (Jiang and Nie, 2000).

Theories of metallogenesis in the Mesozoic are diverse and the metal deposits are complex and difficult to interpret. However, all of these theories are controlled and constrained by geological processes and their related geotectonic settings.

4.1 Geotectonic settings and geological process in Jiaobei block

By establishing the spatial and temporal framework of the structural movements in a certain area during a certain geological period, we can reconstruct the tectonic evolution processes. The geotectonic setting and its evolutionary process underlie the dynamic mechanism and the stress-field characteristics of the recovered geological processes.

The main geological events related to Jiaobei block in the Mesozoic were the amalgamation of the North China Craton and Yangtze Craton in the Indo–Chinese epoch and the subduction of the ancient pacific plate beneath the Eurasia plate（Seton et al., 2012; Zahirovic et al., 2014, 2016). Corresponding to these events, the Jiaobei block, the Luxi block and the Jiaonan–Weihai Orogenic belt were amalgamated by the Tancheng–Lujiang fault zone, which is the major left-lateral strike-slip fault in Eastern China.

The three geological bodies underwent different geological processes before convergence and experienced the same processes after becoming adjacent to each other. Their structural styles were synthesised by structural evolution during different periods. Consequently, the three bodies exhibit widely different structural styles, degrees of structural development and degrees of magmatic activity coupled with the structural movements. The Jiaobei block is structurally similar to the Luxi block, but possesses its own distinctive characteristics.

4.2 Regional stress-field characteristics and structural traces in the Mesozoic

4.2.1 South–north compression and structural traces in the Indo–Chinese epoch

The Indo–Chinese movement occurred from the Triassic to the early period of the Early Jurassic within a geotectonic environment of amalgamation, collision and orogenesis between the Yangtze Craton and the North China Craton. The stress field in this period was characterised by a nearly south–north compression. In the Luxi area, the structural styles were open-to-tight folds and thrusting structures striking nearly EW in the Paleozoic.

The Jiaobei block is characterised by the deformation of middle-to-shallow structural facies. The structural styles are dominated by foliations of the metamorphic rocks in the Precambrian and large-scale, open compound longitudinal folds extending in EW direction. The structure is typified by the Qixia anticlinorium. A series of folds and boundary shear zones formed by thrusting movements around 210–180 Ma are also observed. A hinge line extends nearly east–west through the Weihai uplift in the Sulu orogenic belt, located in the eastern part of the Jiaobei block (Zhang Hongyuan et al., 2007).

4.2.2 Oblique compression and structural traces of the ancient Pacific plate in the Yanshanian

During the Yanshanian movement, subduction of the ancient Pacific plate in the NW direction formed the NE–SE-trending compressional tectonic environment within the continental margin arc of the western Pacific (Kusky et al., 2014). The structural stress fields from the late Jurassic to early Cretaceous underwent alternative transformations of the compressional–extensional stress regime. The changes in the structural stress field are described in Table 1.

The above stress-field characteristics controlled the regional structural development, forming different structural types and combinations of structural styles. A series of fault structures extending in the NE, NNE and NW directions match the stress characteristics and graben basins controlled by the extensional faults are widely distributed in the Luxi and Jiaodong areas.

The NW–SE-trending compression occurred from the late Jurassic to the early Cretaceous. The Jiaolai basin extended in the NW–SE direction during the first-stage early Cretaceous and in the EW direction during the late period (120–100 Ma). The NW–SE-trending compression shortened and deformed the Jiaolai basin, and induced another left-lateral strike-slip movement of the Tancheng–Lujiang fault zone.

The above structural styles accord with the Neocathaysian structural lithofacies characteristics of the Yanshanian movement in the Jurassic to Cretaceous described by Lv Guxian et al. (2011), who summarised the Neocathaysian structural systems. They are also consistent with the lithospherical texture of Eastern China, which is dominated by NE-trending structures and exhibits a conjugated relationship between the NE and NW directions within the fault systems (Ma Zongjin et al., 1999).

4.2.3 Movements of the Tancheng–Lujiang Fault in the Mesozoic and the left-lateral strike-slip faults in Jiaobei block

The major strike-slip fault in Eastern China is the Tancheng–Lujiang Fault. The strike-slip along this fault was transformed by intercontinental collision during 240–220 Ma and the following left-lateral strike-slip (Zhang and Dong, 2008a, b). From the middle and late Jurassic to the early Cretaceous (165~135 Ma), it was also subjected to compressional strike-slip activities accompanied by the thickening of lithosphere and crust in the Eastern North China Plate. Left-lateral strike-slip fault systems and Tancheng–Lujiang rift basin was developed during the 120–95 Ma period. The structural stress field became an NS-trending extension from the late Cretaceous to the Paleocene and had transformed into a NE–SW trending compression by the late Paleocene (Zhang Yueqiao et al., 2008a; Liu et al., 2007, 2013, 2017; Zhou Yaoqi., et al., 2015; Müller et al., 2016).

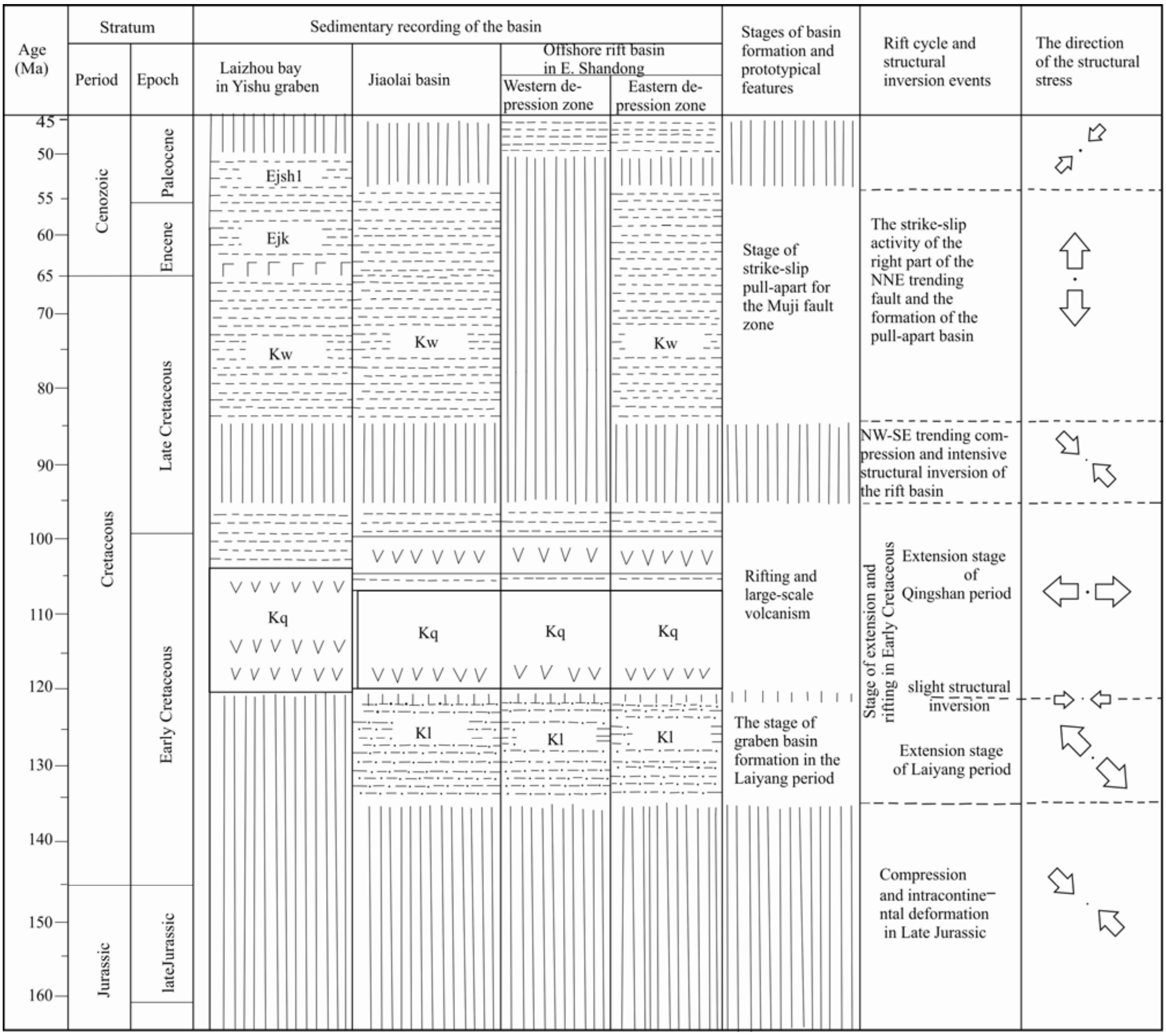
The present study suggests that the left-lateral strike-slip mechanism forming the Tancheng–Lujiang Fault zone also generated a series of strike-slip faults or fractures at different levels in the geological bodies near the fault zone. In the Jiaobei block, some of these features are reflected by strike-slip fault bundles with small strike-slip distance cutting through the crust. This mechanism probably dominated the magmatic activities and distribution of metallogenesis in the Jiaobei block during the Mesozoic.

4.3 Building of a structural framework in the uplift area of the Jiaobei block

4.3.1 Surface characteristics of structures in the uplift area of the Jiaobei block

Consistent with the structural evolutional process and

Table 1 Evolutional sequence of the sedimentology, tectonics, and magma in Jiaolai Basin and its adjacent areas (revised from Zhang et al., 2008b)



the stress-field characteristics in the Mesozoic, the structural framework of the Jiaobei block surface is mainly characterised by the superimposition of EW-trending structures and NE structures with a NW-trending structure (Fig. 9).

The EW-trending structures are dominated by large compound folds formed by the SN- trending compression, which present as foliations of the Precambrian metamorphic rocks. The typical fold structure is Qixia anticlinorium. The fold axes are dislocated by NE- and NNE-trending faults. Parts of the NE-trending faults exhibit the characteristics of the strike-slip faults. Most of the NW-trending fault structures bounded by the NE-trending faults have dislocated those faults. Therefore, the NW-trending faults should have formed at the same time or later than the NE-trending ones.

The endogenic gold deposits consistently match the structural developments at the structurally superimposed positions of the NE-trending and EW-trending structures. The gold deposits in the Jiaobei uplift area follow a zoned distribution in the EW direction and a stringy distribution in the NS direction. The Sanshandao, Jiaojia and Zhaoping faults are all characterised by left-lateral transpression.

The deposits controlled by the transpression show a regional regularity of lateral prostration, which accords with the left-lateral strike-slip. When the deposit-controlling faults strike in the NE or NNE direction and dip to the NW, the ore bodies are pitched in the SW direction. For instance, the ore-body group in the Jiaojia Fault zone pitches by 45–60° in the SW direction.

All ore bodies controlled by faults striking in the NE or NNE direction and dipping in the SE direction are pitched

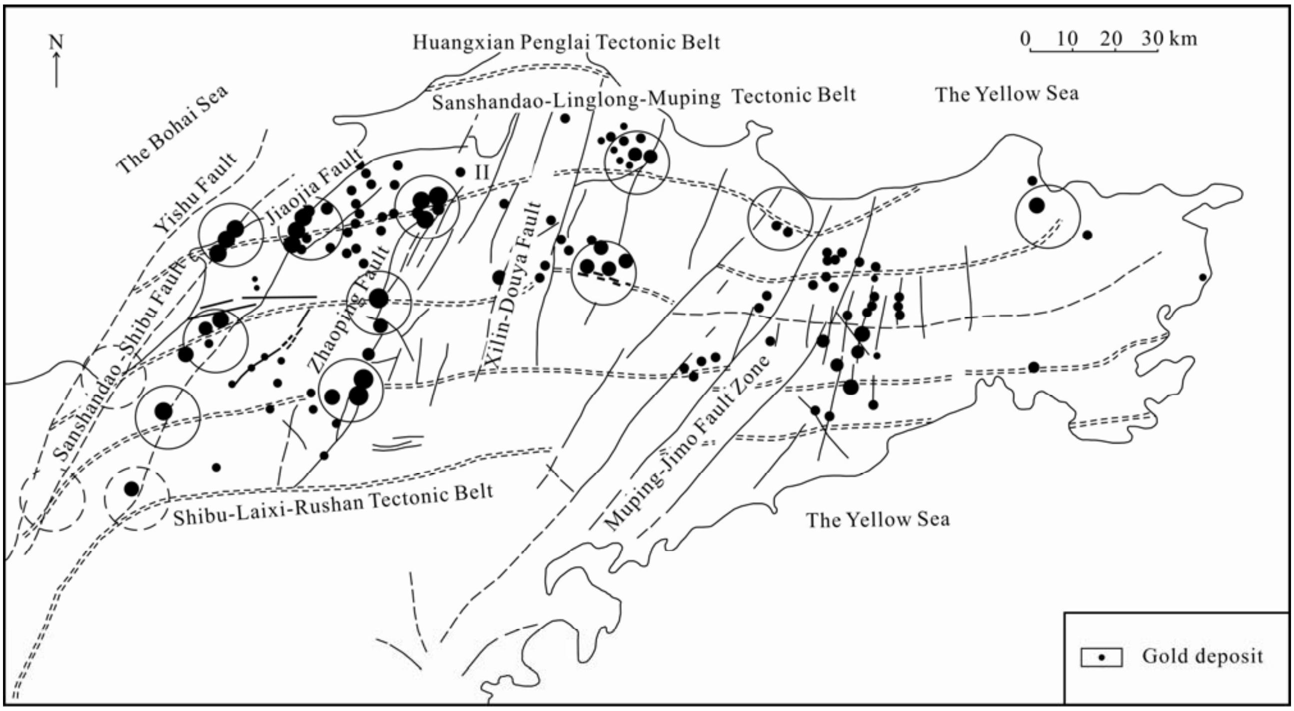


Fig. 9 Metallurgical regularity of gold deposits and the structural framework in the Jiaodong area (revised from Li et al., 2005)

by 40°–65° in the NE direction, as evidenced along the Sanshandao Fault. The ore bodies pitch to the SE when the ore-controlling faults strike and dip in the NNW and SW directions, respectively (for example, the Fanjiabu gold deposit). Meanwhile, ore bodies controlled by NNW-striking and NE-dipping faults pitch to the NW; an example is the Majiayao gold deposit in Qixia. The NW-trending extensional faults, such as the Shiqiao ore-controlling fault in Pingdu with an approximate striking direction of 310° NW, are extensional faults with high dip angles. The ore bodies controlled by these faults are extremely unobvious and present as nearly erect columnar bodies. The ore-controlling faults might have resulted from regular structural openings under the uniform stress environment during the metallogenic epoch. Despite their different faulting orientations, all faults exhibit a regular moving trail that obliquely droops within the left-lateral upper wall. Such features usually form under slack tensile stress.

4.3.2 Deep structural framework and process

The geological bodies crossed by the profile locate in the Mesozoic magmatic area. The surface is dominated by the Linglong pluton in the late Jurassic. As the NW-trending compression, NE-trending strike-slip and NW–SE trending extension changed within the Regional stress field, many structural styles were formed in the Linglong pluton. Based on the changing regional stress field and the sequence and distribution regularity of the geological bodies formed by the structural and magmatic activities, a structural framework and evolutionary process was proposed for the Jiaoxibei area (Figs. 10 and 11).

The crust and lithosphere were also fractured by the thrusting structure in the early NW- trending compressional environment. The structural styles formed by the crustal fracture accorded with the mode of the Neocathaysian structural lithofacies system summarised by Lv Guxian et al. (2011). The main structural type was the NE-trending left-lateral transpressional strike-slip fault.

The large-scale left-lateral strike-slip in the Tancheng–Lujiang fault zone is not merely the movement relic of the main structural zone. Substructures formed by the same mechanism should be widely developed within the geological bodies on both sides of the Tancheng–Lujiang fault. For example, the eastern and western sides of the Linglong pluton cut through the left-lateral strike-slip fault of the whole crust. This fault type is dislocated left-laterally on the surface of the EW-trending fold axes, and the plutons were formed in the metamorphic crystal basement at an early stage. The deep part corresponds to the fracture, dislocation and superimposition of the Moho discontinuity, which accompanied the development of the supporting NW-trending extensional-shear fault. The Mesozoic plutons are distributed in the intersecting region of the two sets of faults.

Under the extensional environment in the NW–SE direction, the extended strike-slip fault surface can form

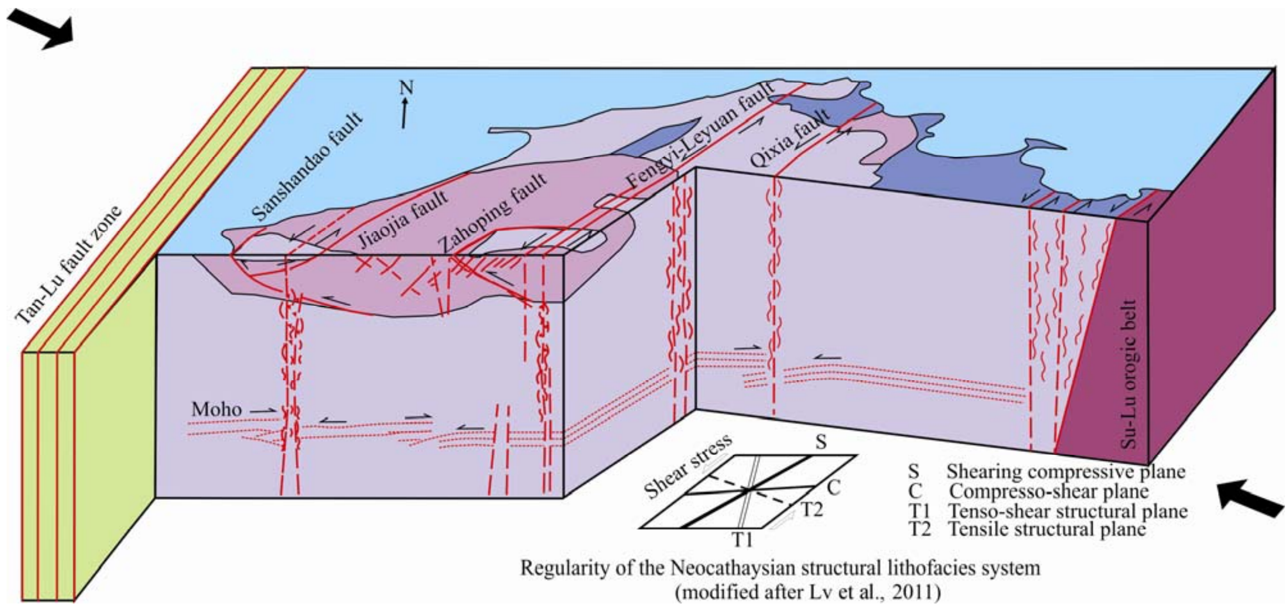


Fig. 10. Structural framework model of the Jiaoxibei block under compressional deformation in the late Jurassic.

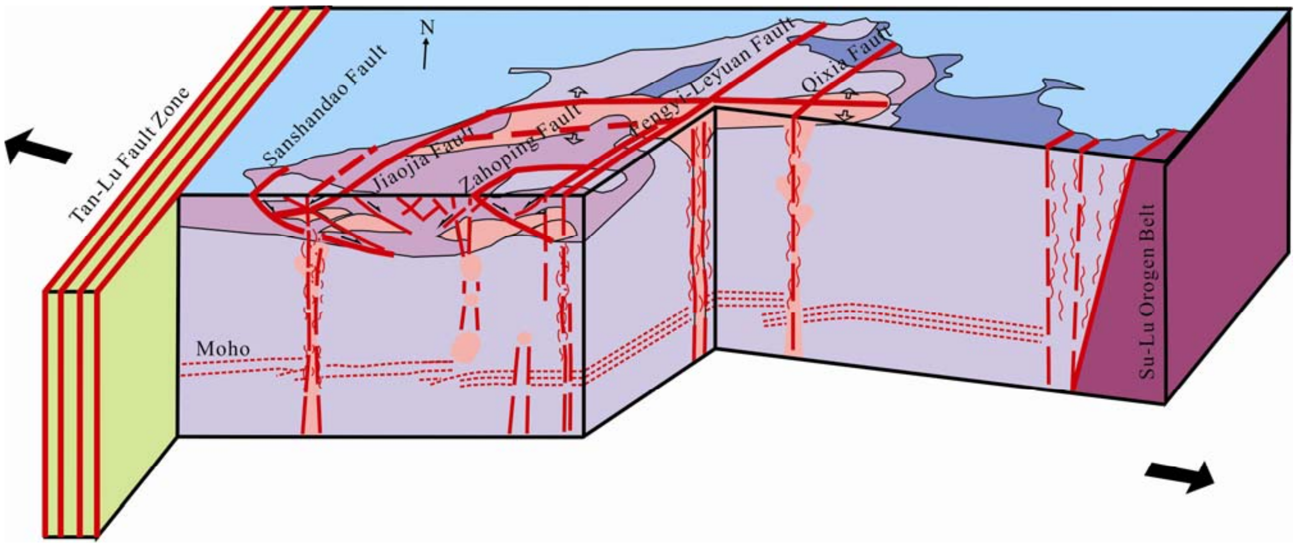


Fig. 11. Mode of structural magmatic activities in the inner extensional environment of the Jiaobei Block during the extending and rifting stage of the early Cretaceous.

rising conduits for magma. Accordingly, a complex zone of magmatic rocks extending in the NE direction can form. This zone can then superimpose on the extensional mechanism at both sides of the magmatic-rock area, forming a series of listric faults. The occurrence of listric faults, which constitutes the supporting extensional structure formed by the pluton intrusion, is related to the pluton location. Also, the regional extension in the NW–SE direction can reactivate and reinvert the pre-existing structures, forming a series of listric faults dipping to the SE. This kind of large-scale, long-distance fault structure is known as a regional fault structure. However, the faults are developed with high angles in the shallow segments and low angles in the deep segments determined by the forming mechanism. The faults become gently sloped when extending to a certain depth along the dip direction. Consequently, they disappear in the middle and upper crust.

According to the seismic profiles, the above-described structural-magmatic process occurred in several stages. The structural-magmatic activities in the later period were superimposed on the previous activities, obviously transforming the pre-existing structures and magmatic bodies. Consequently, the characteristics of the pre-existing structures were obscured. This mechanism is consistent with the known multi-stage activities in the magmatic and faulting structures developed in the study area.

4.4 Strike-slip faults, structural rock-control and the ore-controlling effect

This study reaffirmed the structural effects of strike-slip faults on the eastern and western sides of the Linglong pluton. The fault bundles with small strike-slip distance in the eastern part of the Linglong pluton are aligned obliquely in the NE direction and vertically cut through the whole crust. Therefore, they provide suitable rising conduits for magma and hydrothermal fluids. Through the vertical shear mechanism, the strike-slip faults cause intensive destruction and transformation of the geological bodies. Similar phenomena were observed in the South Yellow Sea basin (Lv Xiuxiang et al., 2016; Pang Yumao et al., 2017).

Faults with similar characteristics are widely distributed in the Jiaodong area. Examples are the Qixia fault controlling the Zangjiazhuang basin, the Taocun fault cutting the Yashan pluton and the Jinniushan fault. This fault series is characterised by high dip-angle and inverted dip direction along the extensional orientation.

Many gold or polymetallic deposits are distributed adjacent to the fault zone. Therefore, the Jiaodong geological body is probably bounded by a deep-cutting strike-slip fault and was formed by the amalgamation of several blocks.

The intensive magmatic and hydrothermal activities between the plutons induced large-scale mineralisation. The ore-forming materials were enriched and mineralised in the extensional faults, then connected with the strike-slip faults. The possible multi-phase, multi-stage formation processes and activities of the faults led to multi -stage magmatic activities in this area. The above findings provide new insights into the late Mesozoic texture formation of geological bodies and the geological phenomena in the Jiaodong area.

5 Conclusions

The seismic profiles running through the Sanshandao, Jiaojia and Zhaoping faults reveal the deep textures and structures in the Jiaodong area. The study findings, based on seismic profile interpretation and the surface geological data, are summarised below.

(1) The exploration length of the profiles is 12 s. From top to bottom, the geological bodies were identified as the Linglong pluton and its bottom boundaries, the metamorphic crystalline basement without fabric differentiation and the Moho discontinuity. Single- and double-layered arc structures formed by magmatic intrusions from the upper crust, accompanied by intrusive uplift and detachment structures on both sides of the pluton, were also identified.

(2) The Linglong pluton exhibits a saucer-shaped profile. Multi-stage magmatic intrusions with X-shaped conjugated faults are developed in the shallow layers.

(3) The profiles revealed several sets of listric faults dipping to the SE; representative examples are the Sanshandao and Zhaoping faults. The Sanshandao Fault may have been compressed and thrusted during the early period and extensionally detached in the late period. The formation and activity of the faults extending in the NE direction and dipping to the SE are possibly associated with regional compression and extension trending in the NW–SE directions.

(4) As the reflection interfaces of the Jiaojia Fault are unclear, the fault line was determined by borehole calibration. In deeper regions, the Jiaojia Fault obliquely intersects the Sanshandao Fault. All of the above faults exhibit crustal shallow-layer structures with a declining dip angle at large depths.

(5) The eastern and western sides of the Linglong pluton exhibit an ultracrustal strike-slip fault (bundle) cutting through the whole crust. The strike-slip fault bundles in the eastern part of the Zhaoping Fault dislocated the Neoarchean metamorphic rocks and the surface of the Biguo pluton in the late Jurassic. The dislocation corresponds to the fracture of the Moho discontinuity and the magma chamber in the deep lower crust. This fault zone might be crucially significant, as it controls the distribution of the magmatic and hydrothermal activities in the region, and probably provides the main passageways for rocks and ores.

(6) As indicated in the seismic profiles, the geological bodies are structurally characterised by superimposed compression and extension, with dominant NW–SE trending compression. Consequently, the crust or lithosphere was shortened and fractured. Thrust faults developed in the shallow segments, while thrusting superimposition of the Moho discontinuity developed in the deep segments.

The fractured blocks extending in the NE direction were left-laterally and tranpressionally slid in the direction perpendicular to the fault surface, forming a series of left-lateral strike-slip faults with a small strike-slip distance. Magma was activated during the extensional period and rose along with the fracture surface. Locally developed conjugated X-shaped extensional structures were matched with magmatic intrusion and emplacement. In the later developmental period, the pre-existing faults caused by compression were superimposed by the NW–SE trending extension of the regional stress field, forming regional listric faults dipping to the SE.

Combined with the regional geological characteristics, the above phenomena suggest that the NW-trending transpression induced a series of compressional, extensional and transpressional fault systems with comparatively complete fracture surfaces. This development was followed by a rock fracture mechanism over the whole crust (lithosphere) of the Jiaobei block, which is bounded by the Tancheng–Lujiang and Muping–Jimo fault zones. The transpressional NE-trending fault surfaces are fully developed in the Jiaodong area. The fault surfaces were sheared and dislocated in the direction perpendicular to the surface, forming a series of strike-slip fault systems that cut the Jiaobei block and induced explosive, large-scale magmatic activities and mineralisation in the Jiaodong area. The strike-slip fault system is a branch or cogenetic substructure, the Tancheng–Lujiang fault.

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