Structural features and metallogenesis of the Carlin-type Jinfeng (Lannigou) gold deposit, Guizhou Province, China

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ABSTRACT

Jinfeng, previously known as Lannigou, is the largest Carlin-type gold deposit in the Yunnan–Guizhou–Guangxi region in southwestern China. Gold mineralization in the Jinfeng deposit is almost entirely fault-hosted and structurally controlled, with very little disseminated ore occurring in the adjacent host rocks. The structural elements in the Jinfeng deposit can be subdivided into 3 groups comprising NS-, NW-, and NE-striking faults and folds, with NW-striking structures controlling the overall framework of the deposit. Four tectonic stages have been recorded in the Jinfeng area, i.e., rifting, orogenic compression, lateral transpression, and lithospheric extension. A series of contemporaneous normal faults, such as the N-striking and east-dipping F1 and F7 faults developed along the edges of a carbonate platform during basin rifting (D2–T1). These structures provided an initial framework for subsequent basin evolution, and also represent the principal hydrothermal conduits. A gradual change of the compression direction during the orogenic stage (T3) from NE to E–W to NE–SW, gave rise to the NW-striking structures, including large, tight to overturned folds such as the Huangchanggou synclinorium and associated thrusts such as the F3 fault. The development of these orogenic, predominantly NE-dipping structures, as well as accompanying NE-striking dextral shear and transform faults (such as the F2 fault) along the margin of the Laizishan Dome established the structural pattern of the deposit area. The NW-striking folds were refolded by NE-striking superimposed folds during post-collisional lateral transpression (J1) and NW–SE directed compression. Oblique stress distribution gave rise to NS-trending compression and EW-trending extension, with dilational zones developing at the intersection of the F2 and the F3 faults east of the Laizishan dome. It is these dextral- and sinistral-normal dilational zones in which gold was precipitated during the main ore-forming event at Jinfeng. Following the main ore stage lithospheric extension occurred during the Yanshan stage (J2–K) resulting in minor reverse faults that in places cut pre-existing structures. The above four main structural deformation stages mirror the evolution of the Youjiang Basin from inception to basin inversion and post-orogenic collapse and renewed extension. Significant gold metallogenesis at Jinfeng occurred during the transition from collisional compression to extensional tectonics in the early Jurassic, and is focussed into intersections of F2 and F3 and fault splays adjacent to F3. This structurally controlled gold metallogenic model is likely to be applicable to analogous settings elsewhere in the Yunnan–Guizhou–Guangxi triangle area, and has implications for the targeting of Carlin-type gold mineralization in this region.

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1. Introduction

The Jinfeng (also known as Lannigou) gold deposit is located within Zhenfeng County of the southwest Guizhou Province, which forms part of the ‘Golden Triangle’ region covering southwest Guizhou, southeast Yunnan and northwest Guangxi in southwest China (Fig. 1). The deposit was discovered in 1986 by members of the Institute of Regional Geological Survey, Guizhou Bureau of Geology and Mineral Resource (BGMR) while testing an Au anomaly which was delineated in the course of 1:200,000 scale geochemical stream sediment surveys undertaken between 1984 and 1986 by the Institute of Geophysical and Geochemical Exploration of the Guizhou BGMR. Geological prospecting between 1987 and 1993 by the 117th Geological Team of the Guizhou BGMR proved up gold resources and reserves of over 75 tonnes with an average grade of 5.1 g/t Au at a cut-off grade of 2 g/t (Luo, 1998). Metallurgical difficulties, however, hampered interest in, and development of, the world-class resource. Sino Gold Mining Ltd. began to participate in the exploration and mining of the Jinfeng deposit in 2001. By April 2008, drilling and underground development
had outlined an ore reserve of 3.5 million ounces (Moz) of gold with an average grade of 5.2 g/t Au. The deposit, which remains open at depths below 1000 m, is estimated to contain at least 5.3 Moz Au mineral resources at an average grade of 4.5 g/t Au (Sino Gold Mining Ltd, 2008), making Jinfeng one of the largest known gold deposits in southwestern China. At present (2011), the Jinfeng deposit is mined by Eldorado Gold Corporation through the acquisition of Sino Gold Mining Limited in December 2009.

As one of the largest and most representative Carlin-type gold deposits in the 'Golden Triangle' region, the Jinfeng gold deposit has been studied continuously since it was discovered in 1986. Geological, metallurgical and geochemical characteristics of the Jinfeng deposit bear many similarities with the Carlin-type deposits of the Great Basin in Nevada, USA (Chen et al., 2007; Cline et al., 2005; Hu et al., 2002; Ilichik et al., 2005; Li and Peters, 1998; Luo, 1993; Peters et al., 2007; Zhang, 1997; Zhang et al., 2003).

The Jinfeng gold deposit is a typical fault-controlled deposit (Luo, 1993), but there are also several discrepancies in terms of deposit-scale structural features, its geological evolution, and controls on mineralization. In view of the economic importance of the Jinfeng gold deposit, and its relevance for the understanding of deposit models in the 'Golden Triangle' region, this paper aims at providing a detailed review of deposit- and district-scale structural features that control the continuity and geometry of ore domains, assessing the structural evolution, and placing it in a tectono-metallogenic context. A better understanding of structural ore controls will provide a basis for focusing exploration programs in the Jinfeng district, and for improving and revising deposit models in the 'Golden Triangle' region.

2. Regional geological setting

The 'Golden Triangle' covers part of the Youjiang Basin, with an area of 50,000 km² of significant gold endowment extending for about 400 km in E–W direction, developed primarily on the southwest margin of the Yangtze Block ('YZB' in Fig. 1). Several first-order structures such as the Shizong–Panxian and Ziyun–Du'an faults controlled basin subsidence through crustal extension and rifting at the end of the Caledonian tectonic cycle (Fig. 1).

2.1. Geotectonic evolution of the Youjiang Basin

The evolution of the Youjiang Basin can be divided into four main stages: (1) rifting and development of a back-arc basin from the Early Devonian to the Early Triassic; (2) orocinal bending and foreland
basin development in the Mid-Triassic; (3) compression and orogeny in the Late Triassic; (4) post-orogenic lateral compression and extension in the Early Jurassic to Cretaceous (Guangxi BGMR, 1985; Zeng et al., 1995; Zhang and Jiang, 1994).

Development of the Youjiang Basin in the southwestern Yangtze Block commenced in the Paleozoic. A series of NW-striking and NE-striking normal faults formed in response to crustal extension and rifting associated with the opening of the Paleo-Tethys Ocean in the Early Devonian. These normal faults shaped the Youjiang Basin and gradually gave rise to a pattern of graben-platform segmentation separated by normal faults. Within the grabens, deep-marine facies pelite, siliceous rock, chert and limestone, as well as voluminous basic and intermediate volcanic rocks were deposited. Fossiliferous shallow water facies carbonates dominated sedimentation on the intercalated platforms (Guangxi BGMR, 1985). In the late Permian, the Ailaoshan and intermediate volcanic rocks were deposited. Fossiliferous shallow water facies carbonates dominated sedimentation on the intercalated platforms (Guangxi BGMR, 1985).

Within the Youjiang Basin, giving rise to the Funing–Napo arc, which resulted in the transformation of the Youjiang Basin into a back-arc position, with voluminous mafic–acid magmatism in the Funing–Napo arc, and deposition of thick turbidite sequences in the basin (Guangxi BGMR, 1985; Zeng et al., 1995; Zhang and Jiang, 1994).

At the end of the Early Triassic, the Indo-China Block and the Paleo-Pacific Plate collided with the South China Plate, giving rise to the Funing–Napo arc, which resulted in the transformation of the Youjiang Basin into a back-arc position, with voluminous mafic–acid magmatism in the Funing–Napo arc, and deposition of thick turbidite sequences in the basin (Guangxi BGMR, 1985; Zeng et al., 1995; Zhang and Jiang, 1994).

Following the peak of Indosinian tectonics in the Early Jurassic, the regional tectonic stress field across the newly formed Youjiang orogenic belt gradually changed from compression to lateral compression. During this time, a large-scale thrust nappe with a southeast direction developed between the carbonate platform of the Yangtze passive continental margin and the overlying terrigenous detrital rock units in what is now southwest Guizhou (Suo et al., 1993).

Extension during the Jurassic and Cretaceous led to the formation of small fault basins and minor magmatic activity throughout the orogenic belt. Although no geochronological constraints are available, the evolution of the Youjiang Basin suggests that hydrothermal activity and gold deposition in the Golden Triangle region took place, possibly partially linked to thermal activity, during the Yangshanian (from ca. 200 Ma to 66 Ma) and involved basin dewatering in response to uplift and compression, in a tectonic setting similar to that of the Shannxi–Gansu–Sichuan gold-rich region (Chen, et al., 2004; Mao, et al., 2002, 2005).

In this regard, the tectonic setting of these two areas in China is distinct from the Great Basin in Nevada, which developed as a basin-range province inboard of an active accretionary orogenic margin (Arehart et al., 2003; Cline et al., 2005; Hofstra and Cline, 2000; Li and Peters, 1998; Peters et al., 2007).

2.2. Sub-tectonic units of the Youjiang Basin and controls on gold mineralization

The Youjiang Basin is subdivided into two separate subtectonic units which display differences in terms of their stratigraphic sequences, lithology, and structures, relative to the position of the Poping Thrust Nappe (Fig. 1) (Suo et al., 1993; Wang et al., 1994). Accordingly, Carlin-type gold deposits within the basin can be divided into two subclasses as per below.

The unit northwest of the Poping Thrust Nappe belongs to the Yangtze passive continental margin which comprises a shallow-marine carbonate rock association interbedded with terrigenous detrital rocks (Longtan Formation and Yelang Formation) and volcanic rocks proposed to be a part of the Permian Emeishan flood basalt (Han et al., 1999; Wang, 1990). The major structures in the unit are open, large-scale folds with several groups of small-scale faults. The anticlinal cores of these large-scale structures provided favorable locations for gold mineralization, but with lithology clearly having an influence on the distribution of the ore. The impure carbonates and volcanic (pyroclastic) rocks are important gold-bearing units and host several strata-bound deposits such as Getang, Zimuand, Shuiyindong, Nibao, and Shaguochang (Han et al., 1999; Liu et al., 2006).

The stratigraphic sequence located to the southeast of the Poping Thrust Nappe is dominated by a typical deep-marine facies terrigenous clastic rock succession in the Youjiang Basin termed the Laizishan Sequence by Wang (1990) and Han et al. (1999). The lower portion of this sequence comprises a thin layer of carbonates, siliceous rock, mudstone and pyroclastics, and the upper portion is composed of terrigenous detrital turbidite. The major structures are synsedimentary normal faults, tight isoclinal folds and overturned to recumbent folds, and associated thrusts. Carlin-type deposits are distributed along the faulted margins of the isolated carbonate platforms. The typically vein-like orebodies are hosted by calc-terrigenous detrital rock units, and are developed along high-angle faults. Representative gold deposits include Jinfeng (Lannigou), Banqi, Yata, Gao-long, Jin-ya, and Ming-shan (Han et al., 1999; Luo, 1993; Zhang, 1997).

3. Geological characteristics of the Jinfeng deposit

The Jinfeng gold deposit is located in the northern Youjiang Basin (Fig. 1). Based on its geological characteristics, it has been interpreted by previous workers as a Carlin-type analogue that formed close to the faulted contact between an isolated carbonate platform and a terrigenous detrital host rock unit (Fig. 2) (Li and Peters, 1998; Luo, 1993; Zhang et al., 2003).

There are two different stratigraphic units apparent in the area of the Jinfeng deposit (Fig. 2). The western part is represented by a Carboniferous–Permian platform of thickly bedded shallow-marine carbonate rocks composed of the Carboniferous Maping Formation, lower Permian Qixia and Maokou Formation, the upper Permian Wujiaaping Formation, and a middle-late Permian reef limestone. The eastern part comprises strongly folded and thrusted terrigenous detrital sediments of deep-marine facies belonging to the mid-Triassic Xinyuan, Xuman, Niluo and Bianyang Formations. The early Triassic Luolou Formation (thickly bedded limestone of platform marginal slope facies) overlies units of the Wujiaaping Formation in the northwest of the deposit region.

The majority of the ore-bearing stratigraphic units belong to the Bianyang and Xuman Formations, with the latter being dominant in the deeper sections of the deposit. The Bianyang Formation (T₄by) comprises turbidites with a thickness of more than 400 m. The principal lithologies are grey, moderately bedded fine-sandstones interbedded with thinly-layered mudstones. Bouma sequences and geotonal structures are commonly observed. The Xuman Formation 4–3 (Tₓxm⁴–³) reaches a thickness of over 250 m. Dark grey, thick-bedded to massive mudstone and siltstone with a few interlayered sandstone lenses are prevalent in this formation.

There are no exposures of igneous rocks at surface in the mine district. The nearest intrusive rocks are meta-aluminous ultramafic–mafic dykes which crop out ca. 25–30 km to the NNE of Jinfeng. These dykes have been dated by the SHRIMP zircon U–Pb method at 84 ± 1 Ma (Chen et al., 2009a). It remains unclear whether magmatism is genetically linked to gold mineralization due to the lack of exposure and relevant age constraints.
The Jinfeng gold deposit itself can be divided into two ore blocks separated by the NE-striking F2 fault, with the Rongban ore block to the northwest and the Huangchanggou ore block to the southeast (Fig. 3). Ore bodies are dominantly associated with the NW-striking F3 fault in the Huangchanggou ore block (accounting for 81% of the current reserve) and at the intersection of F3 and F2.
The No. 1 orebody, the largest in the deposit to date with an average grade of 6.5 g/t Au, is hosted by a fractured alteration zone along the NW-striking F3 in Huangchanggou ore block (Fig. 3). The surface exposure of this orebody is about 500 m in length with a vertical continuity in excess of 1000 m and remaining open to the SE. The on average 8 m thick orebody strikes 295° and dips NNE, with the dip angle varying from 55° to vertical and, in places, overturned (Fig. 4). It has a SE-pitch with an angle of 55° along the intersecting line with the F2 Fault. Additional orebodies include the Rongban ore block, which consists of more than ten individual ore bodies that are characterized by their small size, low gold grades and poor continuity.

The principal host rocks in the Jinfeng deposit are calc–arenite, calc–siltstone and minor calc–mudstone. The matrix between sand clasts contains abundant primary carbonate of sedimentary origin (sparry calcite and dolomite). The high calcareous content of the detrital rocks is a dominant and critical feature of the Jinfeng deposit, and resembles those of most Carlin-type gold deposits in the Great Basin of Nevada (Cline et al., 2005; Hofstra and Cline, 2000; Su et al., 2009; Zhang et al., 2003).

The dominant primary style of ore consists of pyrite and minor arsenopyrite disseminated sparsely throughout the host rock. Other ore types include vein, stockwork, banded and brecciform assemblages. The content of metallic sulfides in the ore bodies is less than 5%, with pyrite and arsenopyrite most abundant. Pyrites are zoned, with early As-poor cores embedded in As-rich rims (arsenian pyrite) within which gold occurs as sub-microscopic (<0.2 μm) grains (Chen et al., 2009b; Douglas, 2006; Zhang, 1997). Minor sulfides include stibnite, realgar, orpiment, cinnabar, galena, sphalerite and chalcopyrite, but their total volume remains below 0.2% and none of these minerals contain appreciable concentrations of gold (Wu, 1992).

Hydrothermal alteration and mineralization types include silicification, pyritization arsenopyritization, stibnitization, cinnabarization, realgarization, calcification and argillisation. Of these, silicification
and pyritization are the most common types (Douglas, 2006; Zhang, 1997).

Fluid inclusion analysis by Zhang (1997) indicated that the ore-forming fluids at Jinfeng were low-salinity (3.9 to 6.4 wt.% NaCl equiv.), H₂O–CO₂–CH₄ mixtures with temperatures of 170° to 275 °C and pressures of 1400–2400 bar. The δ³⁴S composition of pyrite varies from +10.1‰ to +12.6‰, which has been interpreted by Zhang (1997) to reflect derivation of the sulfur from wallrocks. The δ¹³Cᵥ of vein calcite ranges from −3.6 to −0.1‰, indicative of carbon derivation from carbonates of the wallrock; δ¹⁸Oᵥ of quartz veins range from 22.7‰ to 26.1‰, which indicates that the ore-forming fluids have a mixed meteoric to metamorphic water signature (Zhang, 1997; Zhang et al., 2003).

Initial geochronological data for Jinfeng yielded inconsistent results with ages of 259 ± 27 Ma from Rb–Sr dating of fluid inclusions in quartz and calcites in main ore-forming stage veins determined by Hu et al. (1995) considered geologically meaningless. Su et al. (1998) obtained better constrained mineralization ages of 105.6 Ma from Rb–Sr dating of fluid inclusions in quartz and calcites, and an 82–83 Ma age from quartz fission-track dating was published by Zhang and Yang (1992). More recently, Re–Os dating of 9 arsenian pyrites from ores yielded an isochron age of 193 ± 13 Ma (Chen et al., 2007) which was interpreted by these authors to represent ore formation at Jinfeng during the transition from collisional compression to transpressional–extensional tectonics.

4. District-scale structural features

District-scale structures refer to structural elements that extend throughout an area of about 40 km² around the Jinfeng deposit. Relevant data were captured using structural mapping (at a scale of 1:2000) of surface exposures and structural cross-section interpretations based on existing drilling data.

Two different structural units, i.e. the (Laizishan) carbonate platform in the west and the turbidite-hosted basin in the east, can be distinguished in the Jinfeng district (Fig. 2). Due to the competence contrast of the two dominant lithological types, the structural style varies significantly between the carbonate platform and the turbidite-hosted basin at the district scale.

4.1. District-scale folds

The Laizishan carbonate platform in the western portion of the district is dominated by a major NE-striking open anticline with a cylindrical shape. Second-order folds are undeveloped and the strata remained flat-lying to gently dipping.

In the eastern part of the district NW-striking folds are dominant. Close to the platform margin the turbidites have been folded into a series of major, tight to overturned multiple anticlines and synclines, among which the Huangchanggou synclinorium and Lintan anticlinorium are the dominant features in the south, with the Niluo synclinorium and Gaoliu anticlinorium dominating in the north (Fig. 2). Away from the platform margin, the folding is less intense.

Early N-striking faults are mainly developed in the Anbao area, such as the Anbao synclinorium and Kongfang anticlinorium, which display tight, isoclinal to overturned folding. These folds are overprinted by both NW- and NE-striking faults.

The NE-striking folds are generally represented by locally developed outcrop-scale anticlines and synclines superposed on the above-mentioned N- and NW-striking major fold structures. The Jinfeng mine district is 18–22 km away from the front of the Poping Thrust Nappe (Fig. 1) with the trend of NE-striking fold perpendicular to the thrusting direction of the thrust nappe. Therefore, the principal stress direction of the two structures is consistent and probably resulted from the same tectonic event in the early Yanshanian.

4.2. District-scale faults

Geological mapping illustrates the presence of three groups of faults in the district. These strike N, NW, and NE, respectively (Fig. 2).

The N-striking faults mainly occur in the western part of the mine district, with the so-called F1 fault developed along the T/P unconformity, and the F7 fault, a steeply-dipping contemporaneous growth fault. These faults were repeatedly reactivated during extension and inversion of the Youjiang Basin.

The NW-striking faults, which are associated with the development of NW-striking folds, represent the most extensively developed faults in the district, and include the F3, F5, F14, and F70 faults adjacent to the deposit, as well as the Banchang regional fault in the northeast of the district (Fig. 2). These faults developed as thrusts during the orogenic period and were subsequently reactivated as normal faults with a dextral strike-slip component. The Banchang fault corridor consists of a major fault and a series of secondary small faults in its hanging wall, forming an imbricated fault system that caused thrusting of the lower middle-Triassic Xinyuan Formation limestone and mudstones over sandstones of the upper middle-Triassic Bianyang Formation. Folds in the hanging wall and footwall of the fault are mostly asymmetrical with axial planes dipping NE, indicating that thrusting occurred from NE to SW. However, ‘Z’-shaped folds can be observed in some parts of the hanging wall (Fig. 5), suggesting that the hanging wall of the Banchang fault moved in a normal sense (i.e. downwards) at a later stage. This notion is consistent with the structural deformation history of the deposit itself [discussed below], suggesting that orogenic compression was followed by post-collisionsal normal-faulting and strike-slip transpression.

The third group of NE-striking faults commonly accompanies the NW-striking faults. They are widely developed but generally limited in scale, with the F2 and F12 faults being typical examples. This group of faults has a characteristically steeply-dipping orientation with a strike-slip component and commonly overprints the other two groups of faults.

![Fig. 5. A secondary small fault in the Banchang fault corridor with 'Z'-shaped folds in the hangingwall suggesting subsequent downthrow.](image-url)
5. Deposit-scale structural analysis

Deposit-scale structures refer to those structures situated within the limits of the deposit and near-mine area covering about 2 km². The Jinfeng deposit is located in the core of the first-order Huangchanggou synclinorium (Figs. 2, 3). The individual ore bodies are hosted along thrust faults (such as F3) that are situated at the transitional section between secondary order anticlines and synclines.

Fig. 6. Preferred orientations diagram of poles to the axial plane (left) and hinge (right) of folds (lower hemisphere stereographic projection). A — Folds across the entire deposit; B — NW-striking folds; C — NE-striking folds; D — Drag folds adjacent to the F3 fault.
5.1. Deposit-scale folds structure

Mine-scale geological mapping (approx. from 1:500 to 1:1000) has shown that the secondary folds within the first-order Huangchanggou synclinorium are well developed with variable morphology. Systematic measurement (Fig. 3) and projection of fold elements (Fig. 6-A) illustrate that the structural pattern of the Jinfeng deposit is controlled by NW-striking folds and minor NE-striking folds.

5.1.1. NW-striking folds

The Huangchanggou synclinorium is a large overturned syncline 3 km long and 1 km wide with several sub-anticlines and sub-synclines. These second-order folds are dominantly NW-striking with NE-dipping axial planes and dominant dip angles 45°–65°, and generally shallow plunging axes (Fig. 6-B).

Using the Huangchanggou outcrop ore section as an example (Fig. 7), a second-order anticline is situated close to the hanging wall of the F3 fault. At the 730–740 m level of the open pit (top in Fig. 7), the bedding on both limbs of the fold has a normal orientation. At greater depth, the core of the fold becomes tighter with the limbs nearly isoclinal (Fig. 7-A) and with well-developed “Z” shaped third-order folds (Fig. 7-B). Usually, progressive thrusting rotated and overturned the early folds and exposed bedding to later folding, and synthetic and antithetic layer-parallel shear. At the 100–300 m level, an overturned syncline with generally shallow SE plunges in the hanging wall of the F3 fault is apparent from the interpretation of cross-section (Fig. 4).

In the footwall of the F3 fault, two overturned second-order synclines and one overturned anticline are exposed at surface, with multiple smaller folds also well developed. Within the overturned anticline, the bedding on the NE limb is upright and near vertical (Fig. 7-D). In the core of the second-order anticline, third-order “M” type folds are well developed, and “Z” type folds are visible on the overturned SW limb (Fig. 7-E). Moreover, the fourth-order “M” type folds are well developed on the core of the “Z” type folds (Fig. 7-E).

The above demonstrates that folding with similar geometry can be distinguished over at least four scales in the Huangchanggou synclinorium, reflecting the intense nature of progressive deformation during orogenesis.

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Fig. 7. Haul road cut showing the features of folds and faults in the Huangchanggou ore block. A — Core of tight overturned anticline (secondary order) on the hanging wall of the F3 fault; B — Parasitic folds (third order) associated with an anticlinorium in the hanging wall of the F3 fault; C — Tight overturned syncline (secondary order) on the footwall of the F3 fault. Noting that the bending direction of bedding on the left side suggests subsequent normal slipping of the F3 fault; D — Section of the F20 fault and its hanging wall with overturned anticline on which overturned limb is near vertical and mineralized; E — Parasitic folds (third order) on the limb of a secondary order overturned fold, and fourth-order “M”-type folds which developed in the core of a third-order fold.

Fig. 8. NE-striking folds with steep hinge dip angles that refolded the limb bedding of NW-striking folds. (All other symbols are as per Fig. 7).
5.1.2. NE-striking folds
The NE-striking folds are extensively developed throughout the Jinfeng deposit. These folds are characterized by the following features:

(1) In contrast to larger-scale NW-striking folds which can be recognized only by mapping except where higher-order parasitic folds are present, the scale of NE-striking folds is limited to widths of less than 10 m and can be recognized more readily in outcrop.

(2) NE-striking folds commonly refolded the limb bedding of NW-striking folds (Fig. 8) to the effect that NE-striking folds preferentially have near-vertical axial planes (Fig. 6-C) with hinge dip angles varying from 5° to 80°, and dip to the SW or NE as a function of changes in attitude of limbs of the interfering NW-striking folds.

(3) The majority of NE-striking folds are simple open folds, unlike the multiple-order, tight and overturned NW-striking folds. Although NE-striking folds complicate the geometry of NW-striking folds, they generally do not disrupt the general pattern of the NW-trending, first-order structural trends.

5.1.3. Nature and timing of folding events
The complexity of folding described above illustrates that at least two generations of folding occurred at Jinfeng.

The older NW-striking folds with NE-dipping axial planes and shallow SE-plunging axes are characterized by large-scale, multiple-order, tight and overturned structures, implying approximately NE-SW compression (thrusting from basin to platform) during orogeny. Progressive deformation and increasing shortening led to faulting and overturned folds.

The younger NE-striking folds with steep dipping axial planes and variable hinge dipping angles are characterized by simple, open and small-scale structures, indicating approximately NW-SE directed compression during the final orogenic stage.

The superposed relationship of NE- and NW-striking folds distinctly reflects their timing relationship (Fig. 9), and implies a near orthogonal stress field giving rise to an NE-NW interfering structural pattern in the Jinfeng deposit.

5.2. Deposit-scale faults
Three groups of faults, i.e. N-, NW- and NE-striking, can be distinguished from deposit-scale mapping. N-striking faults are repeatedly activated faults. Large-scale NW-striking reverse faults are commonly accompanied by the NW-striking folds described earlier. The NE-striking faults extend for shorter distances, have a strike-slip component and commonly are offset along folds.

5.2.1. N-striking faults
The N-striking faults (e.g., F1, F7) are located adjacent to the carbonate platform (Fig. 2). The F7 fault generally dips to the east, but the dip angle is highly variable and ranges from near vertical in the north (Laowuji and Gaolu area) to more shallow in the southern area (Rongban, Huangchanggou). The fault is zoned with lensoid sandstones and cleaved mudstones well developed in the centre of the fault, contains overturned and recumbent folds, rootless folds next to the fault, and flexure bedding along the edge (Fig. 10). A geological cross-section (lower portion of Fig. 2) and an interpreted cross-section from IP (Fig. 11) clearly show that the hanging wall of the F7 fault contains younger strata of the Bianyang Formation, whereas the older Xuman Formation or upper-Permian Wujiaping Formation occur in the footwall. This juxtaposition indicates that the fault developed as a normal fault and resulted in several hundred meters offset of the strata on either side of the fault. In contrast, the Rongban ore section demonstrates that the hanging wall of the fault contains a...
closed overturned anticline with NE-dipping axial planes, indicating that the fault has a reverse sense of movement; this suggests that the growth fault with a normal sense of movement was inverted to a thrust during orogenesis. At the outcrop scale, abundant reclined folds occur along the strike of the fault (Fig. 10). These parasitic folds have the same axial planar and hinge attitudes, being similar to the F7 fault geometry, indicating that these folds formed by bedding shearing following inversion of the fault. Overall, the F7 fault is an example of a repeatedly reactivated, inverted, strike-slip structure that recorded the entire evolution of the Youjiang Basin from its initial extension to inversion and closure.

Trenching and drilling in the Rongban area has shown that mineralization along the F7 fault near the surface is uneconomically low (<1 g/t). However, at depths of 50 m to 300 m the grade increases up to 2–7 g/t but remains limited to narrow widths when compared to the main ore-bearing NW-striking F3 fault (discussed below). We infer that due to its protracted evolution the F7 fault may have acted as a long-lived conduit for ore-bearing fluids rather than providing an efficient trap.

5.2.2. NW-striking ore-bearing faults

The NW-striking faults, including F3 and its subparallel structure (splays) such as F6, F20, represent the dominant ore-hosting faults at Jinfeng. The F3 fault is one of the principal ore-controlling faults hosting about 81% of the overall gold reserves. The fault is cut by the NE-striking F2 fault and as such can be divided into two parts (Huangchanggou and Rongban respectively) (Fig. 3). The width of the fault zone is generally between 5 and 15 m but reaches up to 30 m. The fault strikes 295° and generally dips to the NE with an angle from 65° to 85° but can be locally overturned within the uppermost 50 to 100 m (Figs. 4, 7). Lateral migration of economic gold mineralization is restricted to the host rocks that are adjacent to this fault zone (Fig. 12), which suggests that shearing was active at the time of mineralization.

The brittle-dominated fracture zone along the F3 fault is well developed, with porphyroclase and breccia comprising wallrock and early cataclasite with intense silicification overprinted by calcite-quartz veins. A weakly developed preferred fabric can be noted in the brecciated fragments and the matrix, with minor folded banding in

Fig. 11. 2D_IP geophysical section showing the figures of carbonate rock platform and boundary faults (F7) with steep dip angle and large offset of the hangingwall.

Fig. 12. Adit plane map (left: CD38 at 640 m level) and drillhole cross-section (right: ZK1107 in line No.11) showing economic gold mineralization is limited to within the sheared F3 fault with small lateral migration into the host rocks adjacent to the fault (after No.117 geology team of Guizhou BGMR, 1993).
fractures (Fig. 13), indicating a reverse sense of shear associated with compression. In some outcrop sections of the fault zonation can be observed with the centre dominated by breccias and lenses, and wallrock bands along the selvages (Fig. 14). Host strata in both the hanging wall and footwall are typically intensely folded (Fig. 7). Micro-structures in fault-associated host rocks have generally characteristic of non-preferred fabrics, which suggests an extensional environment during mineralization. However, in places cleavages are developed on breccia bodies causing elongation of quartz crystals, as well as sub-grain development, pressure solution textures and/or preferred grain orientation (Fig. 15), suggesting semi-ductile deformation did occur during compressing.

The F3 fault has undergone at least two different stages of development. That is, the structure initially formed as a typical thrust related to intense overturned folding associated with compression and shorting (Fig. 7). The large horse-stone remaining the pattern of intense overturned folds and the structural lenses with preferred fabric developed in fracture zone suggest an intense thrusting of the F3 fault (Fig. 13).

Thrusting of the F3 fault was followed by right-normal-slip faulting as indicated by drag folds such as those mapped in the Huangchanggou ore block where a large number of upright plunging folds are developed on both side of the F3 fault (Figs. 14-C, 16, 17). These folds have axial traces that parallel the strike of the F3 fault and near-vertical axial planes (Fig. 6-D), and are clearly different from the folds formed by NE–SW compression during the early stages of deformation (Fig. 14-B). In contrast to the NW-striking folds which dip to the NE and have near-horizontal hinges that match the compressing and thrusting of F3, hinges of drag folds are near vertical (Fig. 6-D, Fig. 16) and match the dextral strike-slip of the F3 fault. In addition, these drag folds are only developed within about 30 m on both sides of the F3 fault, which indicates a close relationship between drag folds development and the fault. An overprinting relationship exists also between the drag folds and NW-striking folds. That is, the closer to the F3 fault, the steeper the dip angle of the axial plane and hinge of drag folds are, suggesting modification from early NW-striking folds (Fig. 16). Drag folds are better developed in the hanging wall than in the footwall of the F3 fault, which indicates the displacement of hanging wall may have been greater than that of the footwall. This observation matches the inferred kinematics of the F3 fault where the hanging wall underwent extension relative to the cross-cutting F2 fault which displays opposite kinematics.

The F3 fault also displays a net normal displacement which can be distinguished directly from the movement of host rock strata along exploration cross-sections (Fig. 4). However, this normal displacement conflicts with the structural pattern of the overturned folds and abundant structural lenses observed in F3 fracture zones indicative of reverse shearing typically associated with compression (Fig. 13). The normal sense of the F3 fault therefore is considered to record extension subsequent to compressional deformation. For example, several small-scale folds of different orientation can be observed in the footwall of the F3 fault. These folds display hinge zones with axial planes that dip to the west, which is inconsistent with the orientation of normal NW-striking folds with NE-dipping axial planes (Fig. 18). This discrepancy indicates that subsequent normal slip modified the earlier main folds, thus altering the character of earlier parasitic folds. This later movement may have been too weak to leave a mark on the major structures but at least one limb of an overturned syncline next to the F3 fault has been widened (Fig. 7-C), further suggesting that a downslide sense of movement occurred following the formation of compressional reclined folds. This later downslide sense matches the features of the Banchang Fault (Fig. 5).
The above analysis shows that the F3 fault is a thrust fault which developed during early NE–SW compression, but evolved into a dextral strike–slip normal fault during subsequent deformation.

5.2.3. NE-striking ore-bearing faults

Compared to the NW-striking faults, NE-striking faults are relatively minor in scale. The fault planes are nearly vertical, with well-developed striking slip kinematics. The F2 fault is a representative NE-striking fault.

The F2 fault strikes NE–SW and dips steeply to the SE, but in some outcrops can be shown to also dip to the NW. The width and intensity of mineralization of the fracture zone vary significantly along strike. That is, the F2 fault actually is a broad shear zone up to 10–20 m wide (Fig. 19-A), and hosts a zone of significant, steeply east-plunging mineralization at the intersection of the F2 and F3 faults. In contrast, the fracture zone decreases to less than 1 to 2 m in width along segments of the fault away from the intersection with the F3 fault, with only weak mineralization and alteration developed (Fig. 19-B).

Similar to the F3 fault, the F2 fault contains well-developed breccia zones, cataclasites and structural lenses of host rock. Some rocks within the fault display characteristics of ductile deformation. For example, mylonites display a flow structure and preferred fabric (Fig. 20-A). Porphyroclasts of mylonites contain strongly silicified sandstone, with the matrix composed of asphaltene rocks, carbonaceous shales, and mudstones (Fig. 20-B). Owing to the strong silicification that occurred during the main ore-forming stage, the silicified porphyroclasts suggest that ductile shearing continued after the ore-forming stage.

An oblique normal and dextral sense of shearing along the F2 fault can be readily recognized by the displacement of the F3 fault and associated strata (Fig. 3), as well as by the drag folds having a steep plunge within or near the shear zone (Fig. 19-A,C). However, in underground exposures the F2 fault has an oblique reverse sense of shearing with asymmetric folds also containing a moderate to steep plunge.

Conflictive shearing directions within the F2 fault or shear zone possibly reflect different deformation events but are interpreted here as representing the result of conjugate deformation along structures intersecting an oblique stress field. That is, at the same time when dextral strike slip-normal faulting occurred along the F3 fault, a corresponding sinistral strike slip sense of displacement occurred along the F2 fault.

Significantly, higher grade mineralization occurs in the shear fabric of the F2 fault and associated folds, suggesting that the mineralization was dominantly associated with movement along the F2 structure. Furthermore, extensive mineralization occurs along the intersection of the F2 and F3 faults, with the extent of gold mineralization along strike and away from this intersection limited. This observation

![Fig. 14. Cross-section at the 720 m level pit of the Huangchanggou ore block showing the zoned F3 fault and folds formed during different tectonic stages. A — Zoned F3 fault with ore shoot in centre and lower-grade ore with remnant bedding on both sides; B — Fold with shallow hinge indicating a NE–SW compression during the D2 deformation phase; C — Drag folds with steep hinge suggesting a dextral strike–slip of the F3 fault during the D3 deformation phase.](image_url)

![Fig. 15. Microstructure in fault rock within the F3 fault indicating semi-ductile deformation; Sample F3-3, transmitted light, polarized light (left) or crossed polarizers (right). A — View illustrating the oriented arrangement and pressure solution within quartz grains; B — Quartz grains elongated and bent into wave-forms.](image_url)
suggests that mineralization may be associated with dextral strike slip-normal faulting of the F3 fault and sinistral strike slip shearing of the F2 fault.

5.2.4. Near-horizontal faults

In addition to the above-mentioned three principal groups of faults, some local-scale, near-horizontal and undulating faults also exist in the Jinfeng area. The lateral extension of these faults is limited and commonly these structures thin out vertically. These near-horizontal faults cut all of the above-mentioned faults and folds with the displacement generally remaining below 10 to 20 m (Fig. 21). Based on the slip direction of marker beds, the warping direction of hanging wall strata and the splay of fracture zones associated with these faults, the kinematic sense of the near-horizontal faults is inferred to be thrusting from NE to SW. Although this sense of movement is similar to that of the NW-striking compressional faults, the near-horizontal faults are clearly late-stage and therefore considered to represent the final tectonic reactivation in the region.

6. Structural evolution of the jinfeng deposit

6.1. Characteristics of structural deformation

From the above analysis, the structural deformation features of the Jinfeng deposit, within the context of the Youjiang orogenic belt, can be summarized as per the following:

(1) The general structural pattern is a combination of folds and faults and is characteristic of a fold–fault structural belt. The intensity of both the faulting and folding increases from the centre of the basin to its boundaries and the carbonate platform (see cross-section in Fig. 2).
(2) Folding is dominant at a regional-scale and expressed via linear complex folds, with axial planes dipping towards the basin. These regional-scale NW-striking folds are characterized by intense horizontal, inclined to overturned and convolute folds which are refolded by younger outcrop-scale, simple and upright plunging or vertical NE-striking folds.

(3) Faulting is dominated by major NW-striking thrust faults; these are parallel to the axial trace of complex folds, and minor strike-slip faults that are orthogonal to the thrust faults. Major ore-bearing NW-striking faults underwent complicated structural movement. That is, these faults are thrust faults accompanied by complex folds that developed early during orogeny in the Indo-Chinese epoch, as well as dextral strike slip-normal faults accompanied by superposed folds later during oblique Yanshanian post-collisional compression-transpression. Mineralization in the jinfeng deposit is related to dextral strike slip-normal faulting of NW-striking faults.

The structural evolution implies that the NW-trending fold–fault belt was formed during the Indo-Chinese Orogeny, and was modified by NE-trending structures that developed during the Yanshanian epoch.

6.2. Evolution of the ore-forming structures

The structural evolution of the Jinfeng gold deposit is summarized in Table 1 and illustrated in Fig. 22. A series of contemporaneous normal faults, such as the F1 and F7 faults which strike N–S and are east-dipping in the deposit, formed around the edges of the carbonate platform during the rifting stage (D2–T2) of the Youjiang Basin. These faults provided the primary weak structural foliation for subsequently developing structures (Fig. 22-A). Due to the presence of the N-trending Laizishan dome, the compression direction during the collisional stage (T3) changed gradually from east→west to northeast→southwest, giving rise to the prominent NS- and NW-striking structural elements such as strongly overturned folds and reverse faults. The accompanying NE-striking shear fault such as the F2 fault with a dextral sense of...
shearing also formed during this stage (Fig. 22-B). The principal compression direction during the post-collision stage (J1) was northwest-southeasterly, refolding of earlier folds into NE-striking superimposed folds. Compression in a northwest-southeast direction gave rise to east-west extension which resulted in sinistral and dextral strike-slip normal movement along the F2 and F3 faults, respectively. The ore-bearing fluid and gold mineralization were introduced into areas of extension at this stage (Fig. 22-C). Mineralization was followed by lithospheric extension during the late Yanshanian (J2) which produced minor late-stage reverse faults (Fig. 22-D).

The structural analysis described herein suggests that mineralization occurred late during lateral post-collisional transpression during the Yanshanian, and generally agrees with the ages of Re–Os dating of arsenian pyrite reported by Chen et al. (2007). Regional structural analysis shows that the deposit is located about 18 km southeast of the Poping Nappe frontal belt, a large-scale sheeted thrust nappe in southwestern Guizhou. The thrust direction of the nappe is southeast, which agrees with the main compressional stress direction of NE-striking folds that formed during the mineralization stage at Jinfeng demonstrating that these two processes occurred during the same tectonic event. These NE-striking folds are superimposed on the principal NW-striking structures and represent the strongest tectonic deformation phase following the Indo-Chinese Orogeny. Ultrabasic rocks in the Zhenfeng and Baiceng area are intruded into the hanging-wall and footwall of the Poping Nappe (Suo et al., 1993; Wang et al., 1994), indicating that mineralization at Jinfeng probably occurred prior to ultrabasic magmatism that was related to lithospheric thinning in the late Yanshanian at about 80 to 60 Ma (Chen et al., 2009a).

7. Structural control on ore formation

There is a strong relationship between faulting and gold mineralization in Jinfeng from the outcrop observations and also from assay data. That is, the bulk of the gold mineralization is confined to major structures, such as the F3 and F2 faults, as well as related splays such as the F6 and F20 faults with apparently limited migration of ore into the adjacent sedimentary horizons (Fig. 12). This is different from the Shuiyindong deposit in Guizhou and Carlin-style gold deposits in Nevada where significant lateral migration of ore fluids and gold mineralization occurred along planar lithological contacts (Liu et al., 2006).

The importance of structural control on mineralization is apparent in the Jinfeng gold deposit, with the following features considered critical for the formation of a major deposit of this type:

(1) A structural trap formed by orogenic thrusting. The structural trap can be generated by any favorable structural association that is able to provide an impermeable barrier. Figs. 3 and 4 illuminate that this is the case for the F5 thrust fault and Lintan anticline. The F5 fault is a 3 to 5 m wide thrust fault with a gentle-moderate dip angle and consisting of fine-grained breccia infill with abundant argillaceous (up to 50 vol. %) fragments. This fault-related rock is considered unfavorable for fluid flow. Due to the thrusting of F5, mudstone in the hangingwall has been thrust upward and covers Bianyang Formation in the footwall, thus providing an efficient barrier for upward moving gold-bearing fluids.

(2) Extensional structural setting

The change of the F3 fault from a thrust during the collisional stage to a right-lateral strike-slip normal fault during the post-collision stage, combined with the intersection with the F2 fault, provided a dilational zone (Fig. 22-C) that enabled the formation of an ore body associated with the F3 fault, with dimensions of 550 m along strike and continuing to depths of over 1000 m. The F20 fault and associated anticlines in the hanging wall provided another efficient ore-hosting mechanism. Under compressional conditions, the two limbs of the overturned anticline formed a zone that was unfavorable for
### Table 1
Structural/tectonic evolution of the Jinfeng (Lannigou) gold deposit.

<table>
<thead>
<tr>
<th>Phase of deformation</th>
<th>Approximate geologic epoch</th>
<th>Folding</th>
<th>Faulting</th>
<th>Main stress direction in ore area</th>
<th>Mineralization</th>
<th>Tectonic evolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>D4</td>
<td>J₂–K (175 to 65 Ma)</td>
<td>Undeveloped, kink folds</td>
<td>Minor near-horizontal thrusting dipping to NE</td>
<td>NE–SW compression</td>
<td>None</td>
<td>Extension of lithosphere</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reactivation of D2 stage faults, right slipping normal faulting of F3, sinistral strike–slip of F2. Regional large-scale thrust nappe</td>
<td>NW–SE compression</td>
<td></td>
<td>Lateral transpression</td>
</tr>
<tr>
<td>D3</td>
<td>J₁ (200 to 175 Ma)</td>
<td>Outcrop-scale, NE-striking, small simple upright folds with axial-trace perpendicular to the boundary between basin and platform, and superimposed on the D2 stage NW-striking folds</td>
<td>NW–SE shortening, reactivation of D2 stage faults, right slipping normal faulting of F3, sinistral strike–slip of F2. Regional large-scale thrust nappe</td>
<td>NW–SE compression</td>
<td>Main phase</td>
<td>Orogenic compression</td>
</tr>
<tr>
<td>D2</td>
<td>T₃ (228 to 200 Ma)</td>
<td>Regional-scale, NW-striking, intense horizontal inclined-overturned-convolute complex folds with axial plane dipping towards basin (NE)</td>
<td>Large-scale low-intermediate angle thrusting fault dipping towards basin, with corresponding high-angle dextral strike–slip normal faulting (transform fault)</td>
<td>NE–SW compression</td>
<td>Weak (?)</td>
<td>Orogenic compression</td>
</tr>
<tr>
<td>D1</td>
<td>D₂–T₂ (398 to 228 Ma)</td>
<td>Locally developed slumping, folding</td>
<td>High-angle contemporaneous normal fault dipping towards basin (NE)</td>
<td>E-W extension</td>
<td>None</td>
<td>Rifting; basin inception</td>
</tr>
</tbody>
</table>

Fig. 22. Interpreted structural evolution of the Jinfeng (Lannigou) gold deposit.
developing dilational space, but a superimposed normal slip motion during the post-collision stage caused the upright limb to splay and generate a dilatant zone suitable for gold precipitation (Fig. 23). The structural development also suggests that gold mineralization occurred relatively late in the deformation history.

(3) Intersection of major faults
A distinct geometric feature of the Jinfeng gold deposit is that the thickest and highest-grade ore bodies are located at the intersection of major faults with different strike orientation. For example, the intersection of NW-striking and NE-striking faults such as the F3 and F2 fault hosts a wedge-shaped ore shoot that is 40–60 m in width, 100 m long, and more than 200 m down dip (Fig. 3). Likewise, the shallow pitching intersection between faults with different dip angles in cross-section, such as the F3 and F20 faults, or the F3 and F7 faults at depth, also host significant ore shoots (Fig. 4).

8. Summary
The ‘Golden Triangle’ region of China represents a gold-endowed region of global significance. The Jinfeng gold deposit has strong analogies to the Carlin deposits of the Great Basin in Nevada USA, but is also distinguished by some marked differences that include the lack of causative intrusions at Jinfeng, the somewhat higher temperature of ore-bearing fluids (up to 275 °C), lack of associated epithermal mineralization, and a possible difference in the fluid sources (metamorphic and/or magmatic for Carlin deposits versus metamorphic-meteoric in the Jinfeng deposit; Zhang et al., 2003). From a structural–tectonic view point, the formation of the Jinfeng deposit was governed by the following:

(1) Jinfeng is a fault-controlled gold deposit with the most significant gold mineralization located within fault zones. Geometry and kinematics of faults constrained the shape, thickness and grade of orebodies as well as their plunge and pitch directions.

(2) The structural elements in the Jinfeng deposit can be subdivided into 3 groups of N-, NW-, and NE-striking faults and folds. Among these, the NW-striking folds and faults which developed during the orogenetic period control the structural framework. The NW-striking F3 fault developed as a thrust during orogeny but subsequently transformed into a right-lateral-slip normal fault during post-collision lateral transpression.

(3) Four tectonic evolution stages are recorded in the Jinfeng area, i.e. rifting, orogenic compression, lateral transpression, and extension of the lithosphere. The basin-bounding normal faults which developed during basin rifting (D2–T3) determined the initial structural make-up and subsequent basin evolution, and these faults represented also the principal hydrothermal conduits. NW-trending structural elements (folds and associated faults) which developed during orogenic compression (T3) established the structural pattern in the deposit. The NW-striking folds were refolded and formed NE-striking superimposed folds during post-collisional lateral transpression (J3). The F3 fault was reactivated by dextral slip and normal faulting, creating dilation at the intersection of the F2 and the F3 fault, and it is these extensional spaces in which gold was precipitated. Extensive gold mineralization occurred during the structural transition from collisional compression to extensional tectonics, and was focussed into intersections between the F2 and F3 faults, and fault splays adjacent to the F3 fault.

(4) The structural traps formed by thrusting of faults during orogenic shortening and the splay setting that developed during post-collision lateral transpression represent the principal mechanisms controlling gold mineralization at Jinfeng.

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References


