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Basin-scale structure control of Carlin-style gold deposits in central Southwestern Guizhou, China: Insights from seismic reflection profiles and gravity data

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ABSTRACT

Carlin-style gold deposits are widely distributed in Southwestern Guizhou, China. Research has dominantly focused on deposit-scale geology and structural control of mineralization. The relationship between the gold deposits and regional structures, in particular their control on the formation and distribution of those deposits is less well understood. Here we use seismic survey and gravity data to reveal the basin-scale structure control of the gold deposits in central Southwestern Guizhou. The seismic reflection profiles show strong reflection horizons including Upper Permian coal measures, and Dongwu and Guangxi unconformities. The seismic data provide important evidence of the basinal structural style and the relationship between fault-related folding and the Carlin-style gold deposits. Regional gravity data also revealed several paleo-uplifts, which appear to control the distribution of Carlin-style gold deposits.

The Carlin-style gold deposits are spatially and temporally associated with fault-related folds. Based on their location, we classify the gold deposits into two types, (1) low-angle thrust-controlled deposits; and (2) high-angle reverse fault-related deposits. In the low-angle thrust-controlled deposits, main thrusts are listric, strike NW-SE and dip southwest. These thrusts detach into coal measures, tuffs and volcanic rocks and are bedding-parallel in the vicinity of the Dongwu unconformity. Gold ore bodies are found in the thrusts and characterized by cutting-layer veins near the surface and bedding-parallel veins at depth. The high-angle reverse fault-related deposits are located in the hinge of northeast-southwest-striking fault-related folds, with high-angle reverse faults near the hinge of folds crosscutting the Upper Permian coal measures, volcanic rocks and Dongwu unconformity, and then into the limestone of Middle Permian Maokou Formation. Ore bodies are bedding-parallel in anticline culminations where interlayer fracture zones in Upper Permian coal measures and volcanic rocks are generated by high-angle reverse faulting.

We consider that the formation of the gold deposits is part of the tectonic evolution in the area. The two sets of NW-SE- and NE-SW-striking fault-related folds were successively formed during the closure of eastern Tethys Ocean in Late Triassic, and major gold deposits formed in the fault-related folds. The Dongwu unconformity and faults provided conduits for ore fluid flow, and the coal measures and the tuffs of Dachang Member acted as detachment layers and hosts for ore deposition.

1. Introduction

Carlin-type gold deposits are characterized by sub-micro Au in solid solution or sub-micron particles in disseminated pyrite/marcasite in silty carbonate host rock (Cline et al., 2005). The largest districts of the Carlin-style Au deposits in the world are in Nevada, USA while Carlin-style gold deposits are present in Southwestern China, and they bear many similarities in tectonic settings, host rock and mineralization styles (Li and Peters, 1998; Hu et al., 2002; Peters, 2004; Peters et al., 2007; Cline et al., 2013).

Southwestern part of Guizhou Province, Southwestern China is a well-known metallogenic district of the Carlin-style gold deposits. Based on host rocks, the gold deposits in the area can be further divided into two sub-types: 1) Upper Permian coal measure- and volcanic rock-

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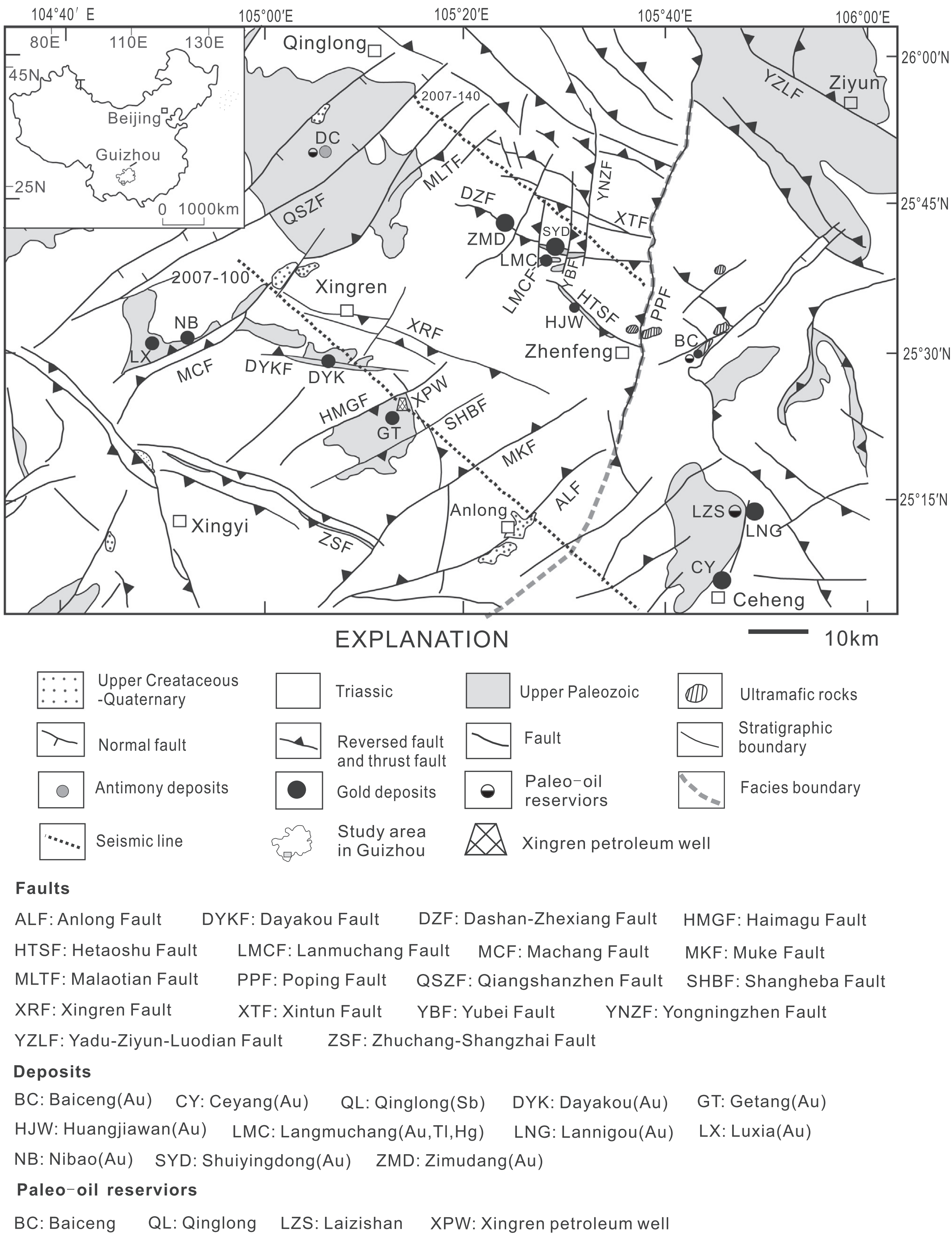

Fig. 1. Tectonic map of central Southwestern Guizhou, China, based on this study, a regional structural study (Wang et al., 1994) and two 1:200,000 regional geological reports (Zhang and Zheng, 1980). Two seismic lines (2007-10 Line, 2007-140 Line) are shown as dotted lines.

hosted deposits in the central part of the southwestern Guizhou, including Shuiyindong, Zimudang (ZMD), Getang (GT), Nibao (NB), Luxia (LX), Lanmuchang (LMC) and Dayakou (DYK) deposits (Fig. 1). Among them Shuiyindong deposit is the largest and has confirmed reserves of 263 metric tonnes (t) of gold (Tan et al., 2015); and 2) Middle Triassic flysch-hosted deposits in the eastern part of the southwestern Guizhou, including Lanigou (LNG), Ceyang (CY), Yata and Banqi deposits (the last two not shown in Fig. 1. as they are outside the research area). Among them the Lannigou deposit is the largest and has confirmed reserves of 126 t of gold (Su et al., 2017). The boundary between the two types of the gold deposits is also the transition zone between sedimentary facies of Upper Permian and Lower-Middle Triassic stratigraphy in the Zhexiang-Poping-Shipan area (Fig. 1). In this study we focus on the first type of the gold deposit (i.e., those located in the central Southwestern Guizhou).

The genesis of the Carlin-style gold deposits in the central Southwestern Guizhou is controversial and can be summarized into three different interpretations, which include pluton-related, sediment- and diagenesis-related, and syn-deformation-related ore forming processes:

Although there is no evidence of igneous activity in the vicinity of gold deposits, and minor mafic dikes occur far away from the gold deposits (Fig. 1), several researchers have proposed that deep magmatic hydrothermal fluids may have played an important role in metallogenesis. They suggested that tectonic setting switched in the central Southwestern Guizhou from compression to extension associated with ultramafic magma emplacement during the Yanshanian period. The hydrothermal fluids related to the ultramafic magmatic activities are considered responsible for the formation of the gold deposits (Liu and He, 1996; Zhu et al., 1997; Fang et al., 2008; Su et al., 2009). Some researchers have proposed that mineralization occurred during sedimentation-diagenesis (Liu and Liu, 1997) as most ore bodies are strata-bound (Tao et al., 2004; Xia et al., 2009). In contrast, other studies have proposed that ore formation is closely related to compressional deformation (Wang et al., 1994; Peters et al., 2007). This model is supported by structural data that show thrust faults (i.e., a type of reverse faults with a low dip angle) as important host-structures for the Carlin-style gold deposits, and gold deposits either occur in the thrusts or in the interlayer of fracture zones (Fu et al., 2008)

A better understanding of the regional structures and their relationship with the gold deposits in the region will help understand the ore genesis and help explorations for similar gold deposits. In this respect, geophysical data such as seismic surveys have the potential to reveal the structures related to the gold deposits in the region. In particular, the seismic reflection survey data can be used to resolve the geometry of fault-related folds (i.e., a fold that is directly related to fault activity, Brandes and Tanner, 2014) that are common in the Carlin-style gold deposits. The folds and faults can be continuously traced in the seismic profile from the surface down to ~3000 m deep. In addition, the seismic data provide further information about the presence of thrusts detaching into the coal measures of Upper Permian Longtan Formation, volcanic rocks of Dachang Member and Dongwu unconformity. Paleo-uplifts above the basin basement can also be identified by seismic profiles.

Two seismic reflection surveys for petroleum exploration were completed in 2007 in central Southwest Guizhou. These seismic reflection lines are NW-SE oriented with a total length of about 137.9 km. The first one is numbered as 2007-140 Line with a length of 49.6 km. This line passes through the Dashan-Zhexiang structural belt where the Shuiyindong, Zimudang, and Taipingdong deposits are located. The second line is numbered as 2007-100 Line with a length of 88.3 km, which transects the Machang structural belt where Nibao gold deposit is located, the Dayakou structural belt where the Dayakou gold deposit/occurrence is found and the Getang structural dome where the Getang gold deposit is located. The data collected from these two lines provide useful information about the structures that control gold deposits, in particular the relationship between fault-related fold structures and gold mineralization.

In this paper, we use seismic profiles and gravity data to reveal structures in overlying sedimentary strata and the architecture of host structure for the Carlin-style gold deposits in central Southwestern Guizhou. We further discuss the structural control of the gold deposits at basinal scale, including the tectonic evolution of the area, the age of the fault-related folds, the relationship between fault-related folds and gold mineralization, and the impact of paleo-uplifts on the distribution of the Carlin-style gold deposits in the region.

2. Tectonics of major gold deposits

The area containing gold deposits in central Southwestern Guizhou is bounded by four sets of major faults: Zhuchang and Shangzhai Faults (ZSF) in the south, Xintun Fault (XTF) in the north, Machang and Malaotian Faults (MCF and MLTF) in the west and Poping Fault (PPF) and sedimentary facies boundary in the east (Fig. 1).

Previous researchers suggested that central Southwestern Guizhou is part of the Yangtze Block (Ren et al., 1981). However, magnetotelluric (MT) and aeromagnetic surveys revealed that it is probably located in the South China Fold Belt (Yang et al., 1999; Ma et al., 2004). MT soundings further support the view that the basement of Southwestern Guizhou, with high conductivity and being integrated as Lower Paleozoic metamorphic rocks, is similar to the South China Fold Belt but different to the Yangtze Block where the basement consists of Proterozoic metamorphic rocks (Yang et al., 1999; Ma et al., 2004). The 2007-100 and 2007-140 seismic lines also show that the Lower Paleozoic succession in central Southwestern Guizhou is poorly reflective (see Figs. 3 and 4), therefore we interpret it as a folded and slightly metamorphosed basement. This is similar to the strata of eastern Southwestern Guizhou interpreted by previous seismic lines (Li et al., 2007; Hu, 2011). In contrast, the Lower Paleozoic strata in adjacent Southern Guizhou in the Yangtze Block, is strongly reflective and parallel to the overlying Upper Paleozoic strata in seismic lines. This is also confirmed by petroleum drilling data (Zhao et al., 1992; Hu, 2011).

Sedimentary horizons exposed in central Southwestern Guizhou include Middle Permian Maokou Formation, Upper Permian Dachang Member, Longtan, Changxing and Dalong Formations, and Lower Triassic Yelang and Yongningzhen Formations (Fig. 2; Zhang and Zheng, 1980; Wang et al., 1994). Most Middle Permian and underlying strata are not exposed in this area. Coal measures and Upper Permian volcanic rocks, Middle and Lower Permian limestone and dolomite, and Carboniferous Successions were intersected by Xingren petroleum well within Getang structural dome (see Fig. 9. Zhao et al., 1992). The Devonian strata are composed of limestone, dolomite and mudstone, whereas the Lower Paleozoic contains slightly metamorphosed and folded limestone and dolomite and slate exposed in Longlin Anticline in neighboring Guangxi (Wang et al., 1987; Zhao et al., 1992). Combining information of the exposed rocks of adjacent area and petroleum drilling data, the stratigraphic column of central Southwestern Guizhou is illustrated in Fig. 2.

The host rocks of the gold deposits in central Southwestern Guizhou include: (1) limestone conglomerate, volcanic breccia and tuff of Upper Permian Dachang Member that overlies Middle Permian Maokou Formation with an unconformity; (2) coal measures of Upper Permian Longtan Formation; and (3) carbonate rocks of Lower Triassic Yelang Formation. Upper Permian volcanic horizons are widely distributed in central Southwestern Guizhou. Altered volcanic breccia were first recognized in the bottom of Emishan basalt in Qinglong antimony deposit and termed "Dachang Member" (Zhang and Zheng, 1980). Subsequently, the Dachang Member was also associated with some gold deposits in the region, for example in Getang, Nibao, Shuiyindong and Zimudang (Hu et al., 2004; Tao et al., 2004; Liu et al., 2006).

Alkaline ultramafic dikes with an Ar-Ar age of 85 Ma (Su, 2002) and a SHRIMP U-Pb age of 84 Ma (Chen et al., 2009) occur near the Poping

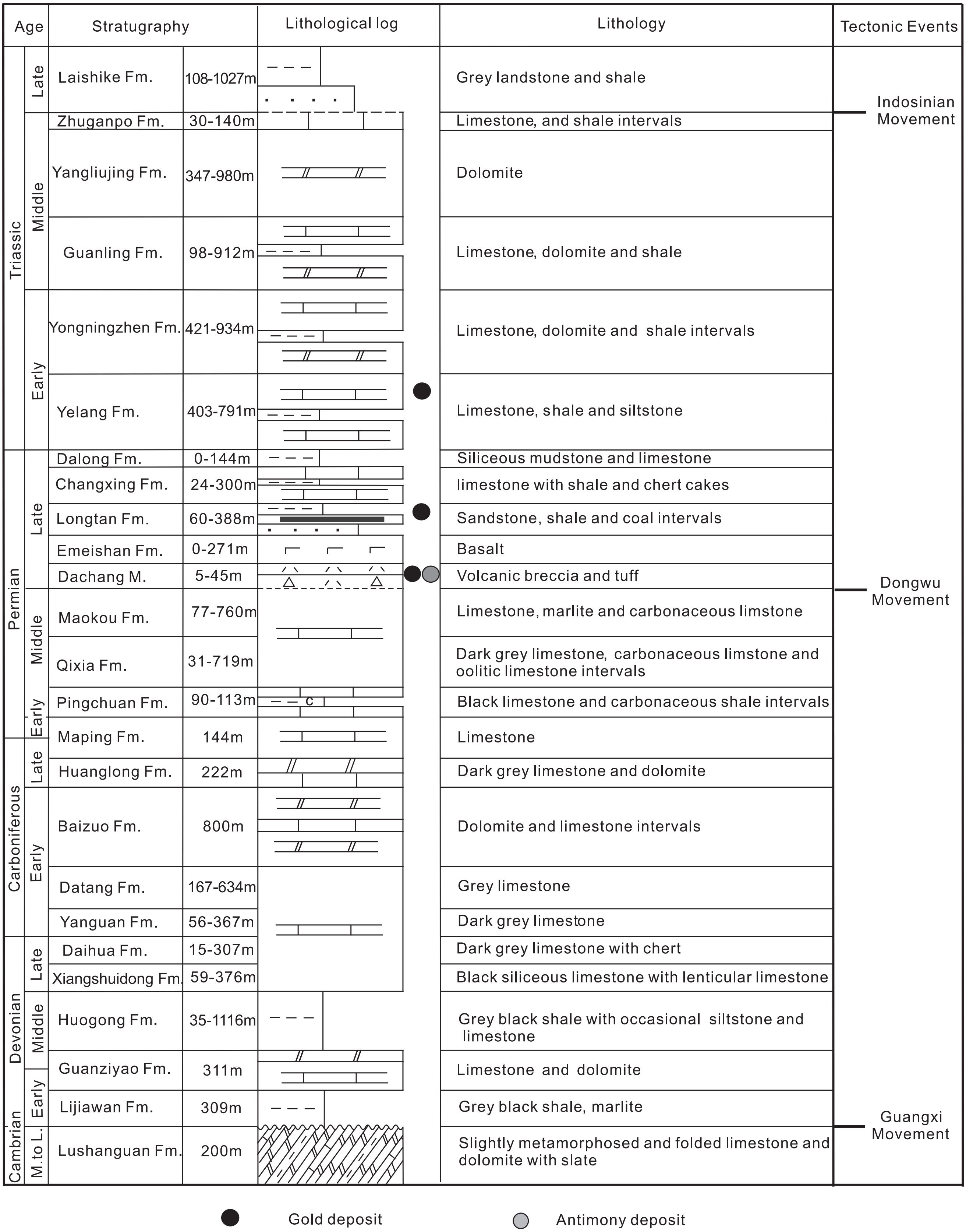

Fig. 2. The stratigraphic sequences of central Southwestern Guizhou based on the 1:200,000 regional geological map completed by Zhang and Zheng (1980), Xingren petroleum Well drilled by Dian-Qian-Gui Petroleum Exploration Bureau in 1958 in Getang structural dome (Zhu and Yang, 2007), the regional geology of Guizhou province (Wang et al., 1987) and Petroleum Geology of Yunnan, Guizhou and Guangxi Provinces (Zhao et al., 1992).

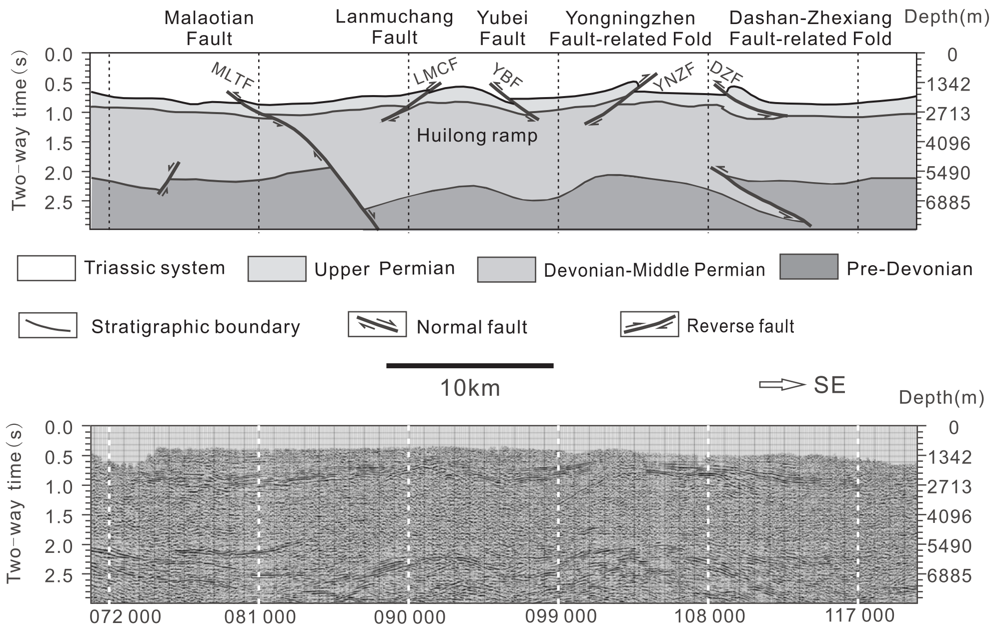

Fig. 3. Interpretation section of seismic line 2007-140 showing deep (from surface down to about 7 km) structural characteristics of Dashan-Zhexiang fault-related fold that hosts Shuiyindong and Zimudang gold deposits, and Huilong structural ramp, where Lanmuchang thallium-mercury-gold deposit occur. Using TWT-V (Two-Way Time -Velocity) model of Nanpanjiang basin, the average velocity for the seismic wave at a given TWT was obtained and then, using H = VT/2, the depth (H) of the structures were calculated (Hu, 2011).

Fault in Upper Permian and Triassic systems. The rock types include pyroxenite, biotitite, peridotite and cryptoexplosive breccia (Wang et al., 1994).

Two groups of faults, trending northwest-southeast (NW-SE) and northeast-southwest (NE-SW) separately, have been identified in the central Southwestern Guizhou. Almost all Carlin-style gold deposits are distributed in the folds related to these two fault systems, such as Shuiyindong and Zimudang gold deposits in the Dashan-zhexiang fault-related fold, Getang gold deposit in the Getang structural dome, Nibao gold deposit in the Machang fault-related fold and Lanmuchang thallium-mercury-gold deposit in the Huilong ramp structure.

The structures observed in the region were formed during the geodynamic evolution of the South China Fold Belt, which experienced of extensions during Devonian to the middle Triassic, to compressional features during Indosinian Orogeny, and extension again in Yanshanian period. Earlier studies suggested that the Carlin-style gold deposits formed in Yanshanian Orogeny (Hu et al., 2002); however the recent geochronology data indicate that the gold deposits may have formed during Indosinian Orogeny. For example, Re-O_S ages of arsenian pyrite from Shuiyindong gold deposit are 235 ± 33 Ma (Chen et al., 2015), and from Lannigou gold deposits are 193 ± 13 Ma and 204 ± 19 Ma (Chen et al., 2007, 2015), respectively. There is also no genetic relationship between intrusions in Nanpanjian-Youjiang Basin and the gold deposits in the region (Zhu et al., 2017).

3. Interpretation of seismic data for major gold deposits in central Southwestern Guizhou

High-quality 2D seismic reflection data have been collected during the 2007-100 and 2007-140 seismic survey in 2007. The interpretation of these two survey lines is based on regional stratigraphy (Zhang and Zheng, 1980) and Xingren Petroleum well drilled to a depth of 2934.9 m where it intersected at Lower Carboniferous beneath the Getang gold deposits (Zhu and Yang, 2007).

Acquisition of seismic reflection data and processing method: Deep seismic reflection profile (several to tens of kilometers) in recent years has been used to reveal the crustal architectures and regional structures that hosts the mineral deposits and prospects (Drummond et al., 2006; Willman et al., 2010; Faure et al., 2011; Korsch et al., 2012; Manzi et al., 2013; Gibson et al., 2016). Seismic method is also used for the exploration for mineral deposits in the area where igneous and metamorphic rocks predominate (Chopping et al., 2010; Malehmir et al., 2014). In contrast, shallow (several hundred meters to several kilometers) seismic profile in sediment rocks, although widely used for petroleum exploration, has not been used for understanding the ore-field to deposit scale structures in mineral deposit research. The seismic data used in this study, originally undertaken for petroleum exploration, provided information about the structures that control the gold deposits in the region. Explosives were used as seismic source, with group interval of 20 m and reception number of trace of 540 and multiplicity of 90. The data are collected with 408XL-type digital seismic instrument, and poststack time migration sections (Figs. 3 and 4) were generated with ALPHA/GRISYS processing codes. For the shallow rock layers (e.g., coal seams), main frequency is 40–60 Hz, vertical and horizontal resolution of 26 m and 530 m, respectively. For middle to deep layers, main frequency is 28–45 Hz, with vertical and horizontal resolution of 39 m and 1678 m, respectively.

Two seismic reflectors can be recognized (Figs. 3 and 4). We interpret the deeper reflector as Guangxi unconformity interface between Lower Paleozoic and Lower Devonian. Strong reflections above the unconformity indicate the mudstone of Lower Devonian, and disorder reflections under the interface indicate a slightly metamorphosed, folded limestone and dolomite with slate of Lower Paleozoic. The lower reflector is interpreted as Dongwu unconformity between Middle and Upper Permian, while strong reflections overlying on the unconformity indicate Upper Permian coal measures and non-reflections indicate carbonate rocks of Middle Permian. Huge non-reflections between two unconformity surfaces are interpreted as carbonate rocks of Devonian, Carboniferous, Lower and Middle Permian. These interpretations are also based on the data of the Xingren petroleum well (Zhu and Yang, 2007).

Two structural styles are identified in seismic profiles: compressional structures (e.g., reverse faults including low-angle thrust faults and high-angle reverse faults, and related folds) developed in Upper Permian and Lower Triassic, and extensional structures (e.g., normal faults, horsts and grabens) developed in Lower Devonian above Guangxi unconformity and Lower Palaeozoic metamorphic basement. In the following sections we will use the seismic data to show that the Carlin-style gold deposits in central Southwestern Guizhou, such as the Zimudang, Shuiyindong, Taipingdong, Nibao, Getang and Dayakou deposits, are controlled by fault-related fold structures.

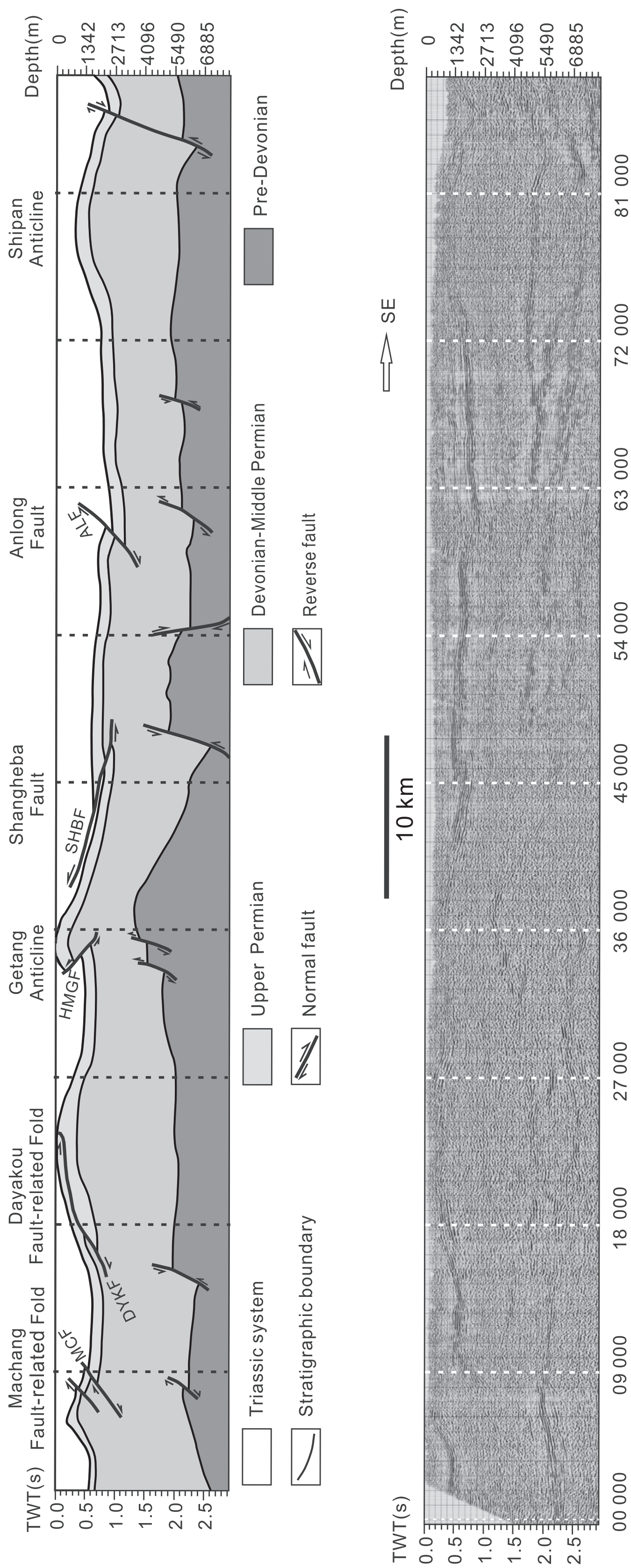

Fig. 4. Interpretation section of seismic line 2007-100 showing a large paleo-uplift below Getang gold deposit and a thrust in Dayakou gold occurrences. The TWT-V model is noted in Fig. 3.

3.1. Gold-bearing, NW-SE-trending fault-related fold belt

NW-SE-trending fault-related fold structures in central Southwestern Guizhou are characterized by linear distribution with strike lengths of tens of kilometers, the longest one being the Zhuchang-Shangzhai structural belt with a strike length of 70 km (Table 1). These fault-related folds are composed of a southwest-dipping first-order fault, which we define as a thrust fault, and an asymmetric fault-related fold in the hanging wall block. The Carlin-style gold deposits mainly occur as bedding-parallel veins at depth in both hanging wall and the thrust.

3.1.1. Gold deposits in Dashan-Zhexiang structural belt

On the surface, the NW-trending Dashan-Zhexiang Fault-related Fold consists of the Dashan-Zhexiang Fault (DZF; dipping SW 15–35°) in the north, and Huijiabao Fold in the south (Fig. 5b). This structure belt has been crosscut by several later NE-trending faults. The fold is located in the hanging wall of the thrust, with the oldest Dachang Member exposed in the hinge zone. It has gently-dipping north limb (dipping angle 15–35°) and steeper south limb (dipping angle 60–70°).

Eleven gold deposits have been found in this structural belt. From west to east, they are Laowangqing (LWZ), Zimudang (ZMD), Taipingdong (TPD), Xiangbahe (XBH), ZK42002, Shuiyindong (SYD), Xionghuangyan (XHY), Puzilong (PZL), Zaofanshan (ZFS), Beiyinpo (BYP) and ZK45301 (Fig. 5a). Dashan-Zhexiang structural belt contains proven resources of 420 t Au (Liu et al., 2010; Tan et al., 2015; Su et al., 2017). The strike lengths of ore bodies in Zimudang gold deposit vary from 850 to 1000 m while the thicknesses of the ore bodies vary from 0.7 to 25 m burial depths of 400–500 m. The average grade is about 5.95 g/t Au and prospective reserves are about 80 t Au (Su et al., 2017). The strike lengths of ore bodies in Shuiyindong gold deposit vary from 500 to 800 m and ore-body thicknesses vary from 2.23 to 3.33 m. The average grade is about 5 g/t Au and prospective reserves are about 263 t Au (Tan et al., 2015; Su et al., 2017).

Tectonites have developed in host rocks and occur as veins near the surface. Tectonites can be classified into three zones of cataclasite in sides, conglomerate in middle and fault gouge in core (Wang et al., 1994; Du, 1999). At deeper levels, the bedding-parallel ore bodies are located in gently dipping thrust. Minor structures such as joints, small folds and tectonic breccia are also found in ore bodies and host-rocks (Wang et al., 1994; Tao et al., 2002). In prospecting line 0 of Zimudang deposit, first-order Dashan-Zhexiang thrust fault dips southwest in previous research (Wang et al., 1994).

Taipingdong gold deposit has proven Au reserves of 29 t (Liu et al., 2010). We consider the structural characteristics of this deposit are similar to the Zimudang gold deposit. Dashan-Zhexiang thrust has extended into coal measures and controls many orebodies in two walls around the thrust (Fig. 5b). Shuiyindong gold deposit occurs in the core of Huijiabao asymmetric anticline (Fig. 5c). Individual ore bodies are bedding-parallel and the deposit is believed to be strata-bound (Liu et al., 2006); however, many small compressional structures such as minor reverse faults, drags and tectonites were also found in ore bodies and host rocks of Dachang Member and coal measures of Longtan Formation (Hu et al., 2004). This may indicate that Dashan-Zhexiang thrust fault has detached into coal measures of Longtan Formation and volcanic rocks of Dachang Member (Fig. 5c).

2007-140 seismic line intersects the east end of Dashan-Zhexiang fault-related fold to the south of Zhexiang town (Fig. 1). The interpretation of the seismic profile (Fig. 6a) reveals the Dashan-Zhexiang low-angle thrust fault: it dips steeply southwest in surface, however at depth the dip progressively becomes shallower, and it finally detaches along the Dongwu unconformity surface. The seismic profile also shows that thickness of coal measures strata is doubled compared to the original thickness around the thrust fault. This is probably caused by thrust related duplication along the Dashan-Zhexiang thrust fault (Fig. 6a). The structural features in the geological section of Zimudang

Table 1
List of fault-related folds controlling gold deposits in central Southwestern Guizhou.

Structures	Length (km)	Dip, angle of fault	Exposed lowest Fm	Gold Deposits
Dashan-Zhexiang	30	SW, 35-5°	Dachang	11 deposits, e.g., Shuiyindong, Zimudang, Taipingdong, etc.
Zhenfeng	28	SW, 60° (surface)	Dachang	Gold occurrences
Dayakou	25	NE, 45-5°	Longtan	Gold occurrences
Zhuchang-Shangzhai	70	SW, 60-70°	Longtan	Gold occurrences
Machang	62	NW, 60°	Dachang	Nibao, Luxia
Getang	25	SE, 60°	Maokou	Getang
Huilong	10	NW, 60°	Longtan	Lanmuchang (thallium-mercury–gold)

gold deposit (Fig. 6b) are well revealed in the seismic profile (Fig. 6a), and this deposit is predominantly controlled by a thrust-related fold structure. The distribution of the ore bodies follows the shape of the thrust which dips steeply at shallow level and more gently at depth. Note that the Triassic rocks consist of massive limestone layer that have no effective wave impedance and are non-reflecting, therefore the feature of Huijiabao antilcine is not obvious in Triassic strata in the seismic profile.

Based on the above analysis we consider that Dashan-Zhexiang fault-related fold belt is composed of Dashan-Zhexiang Fault and Huijiabao Fold and has a strike length of 30 km. Dashan-Zhexiang Fault, the southwest-dipping first-order thrust fault has a dip angle between 5° and 35°. Huijiabao anticline, comprising a steeply dipping northeastern limb (forelimb) and gently dipping southwestern one (back limb), is located above Dashan-Zhexiang thrust fault.

3.1.2. Gold occurrences in Dayakou fault related fold

Gold occurrences in Dayakou structure belt are located about 10 km southwest of Xingren. The East-West trending Dayakou structure includes Xinzhai anticline and Dayakou Fault (DYKF) that dips 40–50° north and has a 25 km strike length. Located in the hanging wall of the Dayakou Fault, the Xinzhai anticline has gently-dipping (15–30°) north limb, and steep south limb (~50°). The oldest rock in the hinge zone is Longtan Formation.

Previous mapping shows that gold mineralization occurs in a fracture zone along Dayakou Fault as lenses and irregularly shaped bodies. Compressional structures such as small reverse faults and fault breccias are common in the mineralized zones. The tectonites show a clear horizontal zonation across the fault, with cataclasite formed along the sides, breccias in the middle and fault gouge or schist formed in the thrust's core. Although mineralization is common in the fault belt, the grade is low (Fig. 7b; Hao, 2007).

The 2007-100 seismic line passes through the eastern part of Dayakou structure. The seismic migration profile shows that Dayakou Fault is located on the northern side of Xinzhai anticline. Our interpretation shows that Dayakou Fault is a low angle thrust that has locally thickened the strata by about 2–3 times near the core of the anticline (Fig. 7a). The fault is relatively steep near the surface but is a gently dipping thrust fault at depth. This interpretation is consistent with the previous discovery of compressional structures in the mineralized zones (Hao, 2007; Liu et al., 2016) and we consider that the local structures are controlled by the much larger Dayakou Fault as imaged by the seismic survey.

3.2. Gold-bearing NE-SW-trending fault-related fold belts

The seismic data also reveal that ore deposits occur in NE-SW-trending structures in interlayer fracture zones generated by high angle reverse faults which do not detach in the coal measures but cut them instead. The NE-SW trending faults cut across NW-SE trending faults, suggesting that the former formed later, as shown on the geological map (Fig. 1; Zhang and Zheng, 1980; Wang et al., 1994). The gold deposits related to these fold belts will be discussed below.

3.2.1. Gold deposits in Machang structural belt

The NE-trending Machang fault-related fold belt consists of two large reverse faults and Nibao anticline. On the surface the Machang Fault (MCF) dips northwest at 50°. The NE-trending Hongya, Erlongxibao and Nibao Faults in the Nibao Gold district are parallel to the Machang Facult with Hongya, Erlongxibao Faults dipping NW at 50–60°, Nibao Fault dipping SE at 45°. Located on the hanging wall of the Machang Fault, the Nibao anticline is an asymmetric with gently-dipping NW limb (10–20°) and steeper SE limb (40–50°). The oldest rock exposed at the hinge zone is Maokou Formation.

Nibao and Luxia gold deposits are located within the Machang fault-related fold belt (Fig. 1). The ore body of Nibao gold deposit is 100–200 m long, 1–15 m thick and has a grade of 4–10 g/t Au (Tao et al., 2002), totaling 97 t (Sheng et al., 2016). The ore bodies are bedding-parallel and have been interpreted as a strata-bound deposit controlled by lithology and stratigraphy (Tao et al., 2004). Some researchers have found structural features such as small reverse faults, small folds and joints in the ore bodies and host rocks (Tao et al., 2002; Hu et al., 2004).

Our interpretation of the 2007-100 seismic migration line shows similarities with the cross-section of Nibao gold deposit by Wang et al. (1994), both at depth and near the surface (Fig. 8). The forelimb (southeast limb) of the fold is composed of several parallel northwestern dipping faults and tectonic wedges that have caused disorder to the reflection Permian coal measure in the southeast limb. Although the reflection is poor in the massive carbonate rocks of Lower, Middle Permian and Carboniferous strata, we can identify a fault-plane wave that may have been generated by Machang Fault (Fig. 8). Therefore, we consider the Machang Fault to be a high-angle first-order reverse fault, which has cut the Lower, Middle Permian and Carboniferous strata. Other faults such as the Hongyan, Erlongqiangbao and Nibao faults in Nibao gold deposit are likely to be the second order faults. This structural feature of high angle faults in Nibao gold deposit is significantly different from the low-angle thrust faults in Zimudang deposit, Shuiyindong deposit and Dayakou gold occurrence. The previously described small-scale reverse faults and fold structures are probably the result of interlayer gliding associated with reverse faulting of Machang high angle reverse fault (Hu, 2011).

3.2.2. Gold deposits in Getang dome structure

The Getang dome structure consists of Getang dome and two NE-trending reverse faults. The two faults dip southwest with 30–40° on the surface. The oldest rock exposed in the center of the Getang Dome is Maokou formation.

The Getang gold deposit occurs within the Getang dome (Figs. 1 and 9). Ore bodies at Getang deposit range from 400 to 1000 m in length and 2.5 to 4.3 m in thickness. Getang contains about 25 t Au reserves with an average grade of about 5 g/t Au (Peters et al., 2007).

The Getang gold deposit has also been interpreted as a strata-bound deposit with bedding-parallel ore bodies where mineralization was believed to be controlled by stratigraphy and lithology (Yang, 1992; Wang and Mou, 1998). However, some investigators described the interlayer structures in the ore bodies and host rocks as volcanic breccia of Upper Permian Dachang Member and coal measures of Longtan

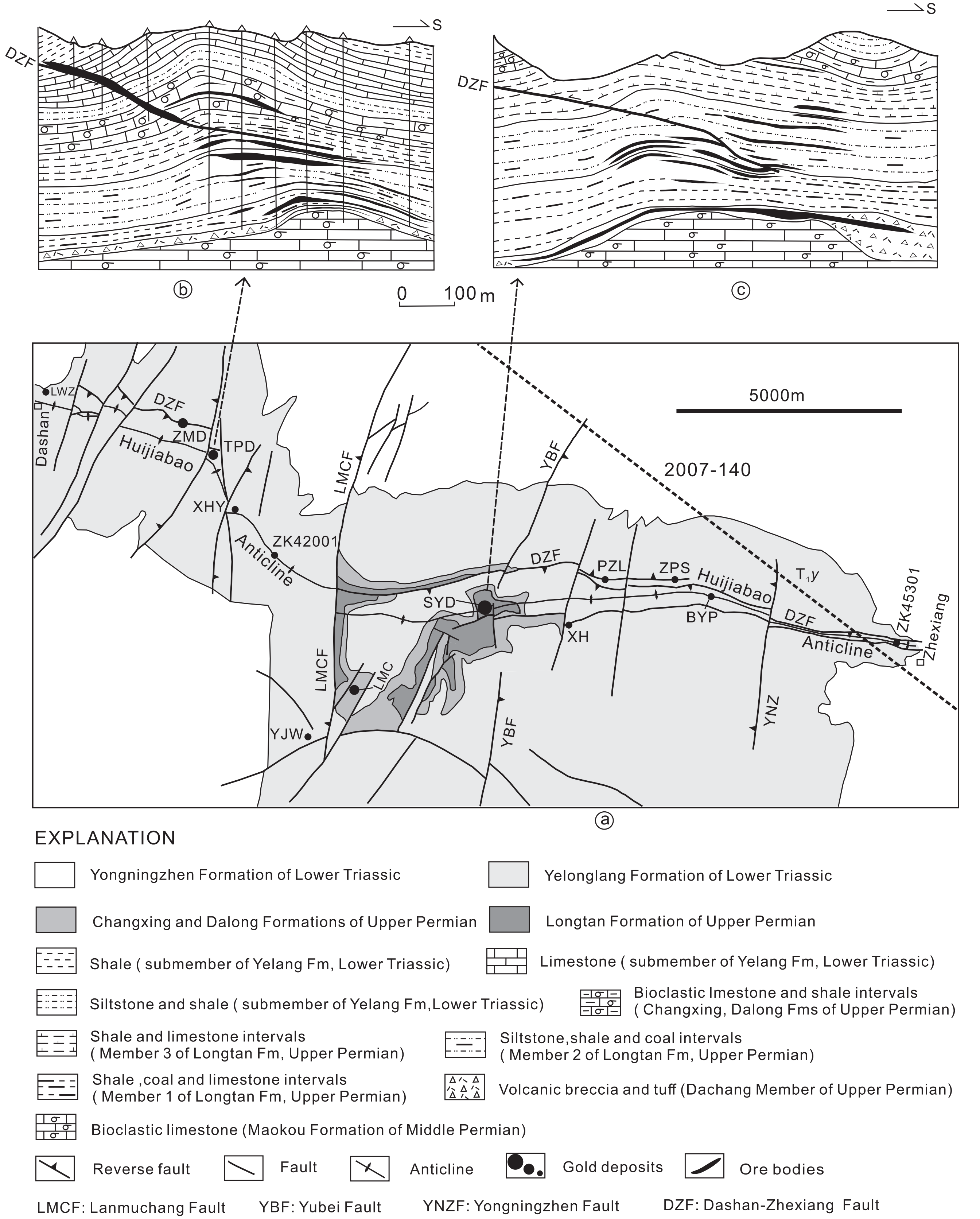

Fig. 5. The geological map of Dashan-Zhexiang fault-related fold and gold deposits (a, modified from Liu et al., 2006); Geological section of prospecting line 263 in Taipingdong gold deposit (b, modified from Liu et al., 2012) and Geological section of prospecting line 7 in Shuiyindong gold deposit (c, modified from Liu et al., 2006). The fault numbering and stratigraphy are the same as in Figs. 1–4. The abbreviations of gold deposits are noted as follows, B: Beiyinpo, LMC: Lanmuchang, LWZ: Laowangqing, PZL: Puzilong, SYD: Shuiyindong, TPD: Taipingdong, XBH: Xiangbahe, XHY: Xionghongyan, YJW: Yangjiawang, ZFS: Zaofanshan, ZMD: Zimudang.

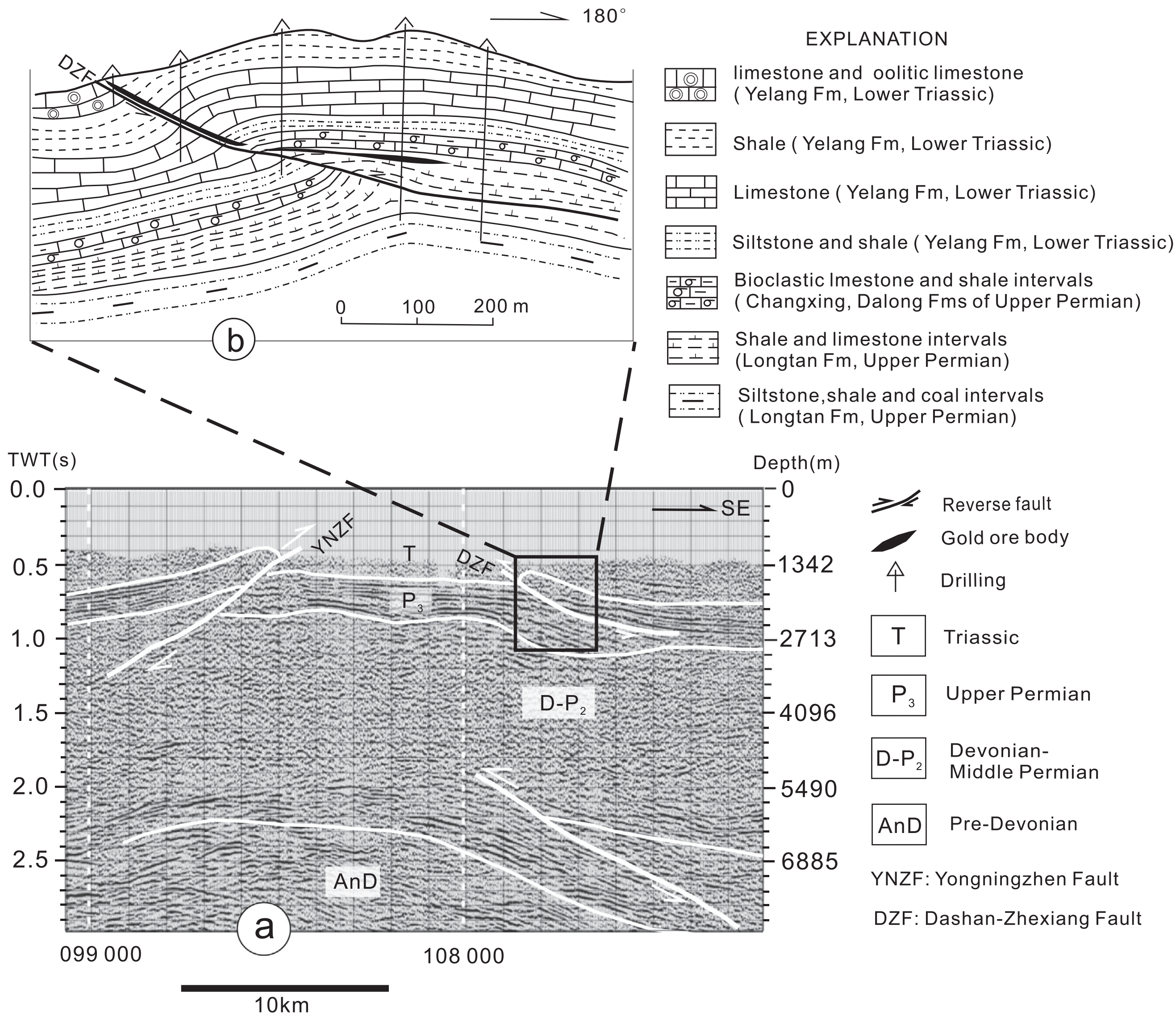

Fig. 6. Interpretation of the seismic profile and geological section of Huijiabao anticline. (a) Interpretation of the seismic migration profile of Dashan-Zhexiang fault-related fold belt. The scale on the left is two-way travel time in seconds of seismic wave, and the scale on the right is depth in meters from surface. (b) Geological section along prospecting line 7 of Zimudang gold deposit (modified after Du, 1999). The seismic line intersects the Dashan-Zhexiang fault-related fold belt to the 18 km east of Zimudang gold deposit.

Formation. These structures include small asymmetric folds trending NE-SW and dipping southeast, 5–10 m length reverse faults dipping southeast, and structural breccias and joints trending NE-SW in ore bodies and wall rocks (Wang et al., 1994; He et al., 1997).

The 2007-100 seismic line reveals that Getang anticline, where gold deposit occurs, is bounded by Haimagu high-angle reverse fault (HMGF) on northwest limb and Shangheba low-angle thrust fault (SHBF) on southeast limb. These two NE-SW trending faults dip southeast and cut the coal measures and the volcanic rocks of Upper Permian (Fig. 9), then extend into the limestone of the Middle Permian. The interlayer structures are also probably caused by reverse faulting.

3.2.3. Lanmuchang thallium-mercury-gold deposit in Huilong structural ramp

Huilong structural ramp consists of NE-trending Huilong anticline bounded by two NE-SW striking faults: The Lanmuchang Fault (LMCF) is in the west dipping NW at 45°, and the Yubei Fault (YBF) in the east dipping SE at 40°. The Huilong anticline has gently-dipping limbs at 10–20°. The oldest rock exposed is Dachang Member.

Lanmuchang thallium-mercury-gold deposit is located near Huilong town, about 4 km south of Shuiyindong gold deposit (Figs. 1. and 5). This deposit occurs on the Huilong structural ramp. The deposit lies to the east of Lanmuchang Fault and its bedding-parallel ore bodies occur in the interlayer fracture zones in the coal measures of Upper Permian Longtan Formation (Fig. 10b). The lengths of the ore bodies vary from 60 to 240 m, with width from 40 to 80 m and thickness from 2 to 5 m (Zhang, 2007). Tl reserves are 500 t with average grade of 0.011% Tl, including high grade ore of 1–5% Tl, and average Hg grade of 0.19%. Two gold ore bodies were discovered in thallium-mercury-gold deposit in 2003–2005, with length of 150 m, thickness of 1.5 m and Au average volume of 1.5 g/t–2.5 g/t, and reserves of 1.5 t of Au. The interlayer fractures were also found in gold ore bodies (Zhang, 2007).

The 2007-140 seismic line passes through the northern part of Huilong structure where the outcrop is Triassic strata. We can clearly identify the architecture (Fig. 10), which includes a ramp structure that is composed of two NE-SW-trending reverse faults (Lanmuchang Fault in west and Yubei Fault in east) and a fold. These high-angle reverse faults crosscut strongly-reflective coal measures of Longtan Formation. In addition, the seismic profile shows an uplift overlying the basement and some intraformational folds, which indicate interlayer movement (Fig. 10a). This is consistent with the interlayer structures documented by Zhang (2007) in ore bodies of Lanmuchang thallium-mercury-gold

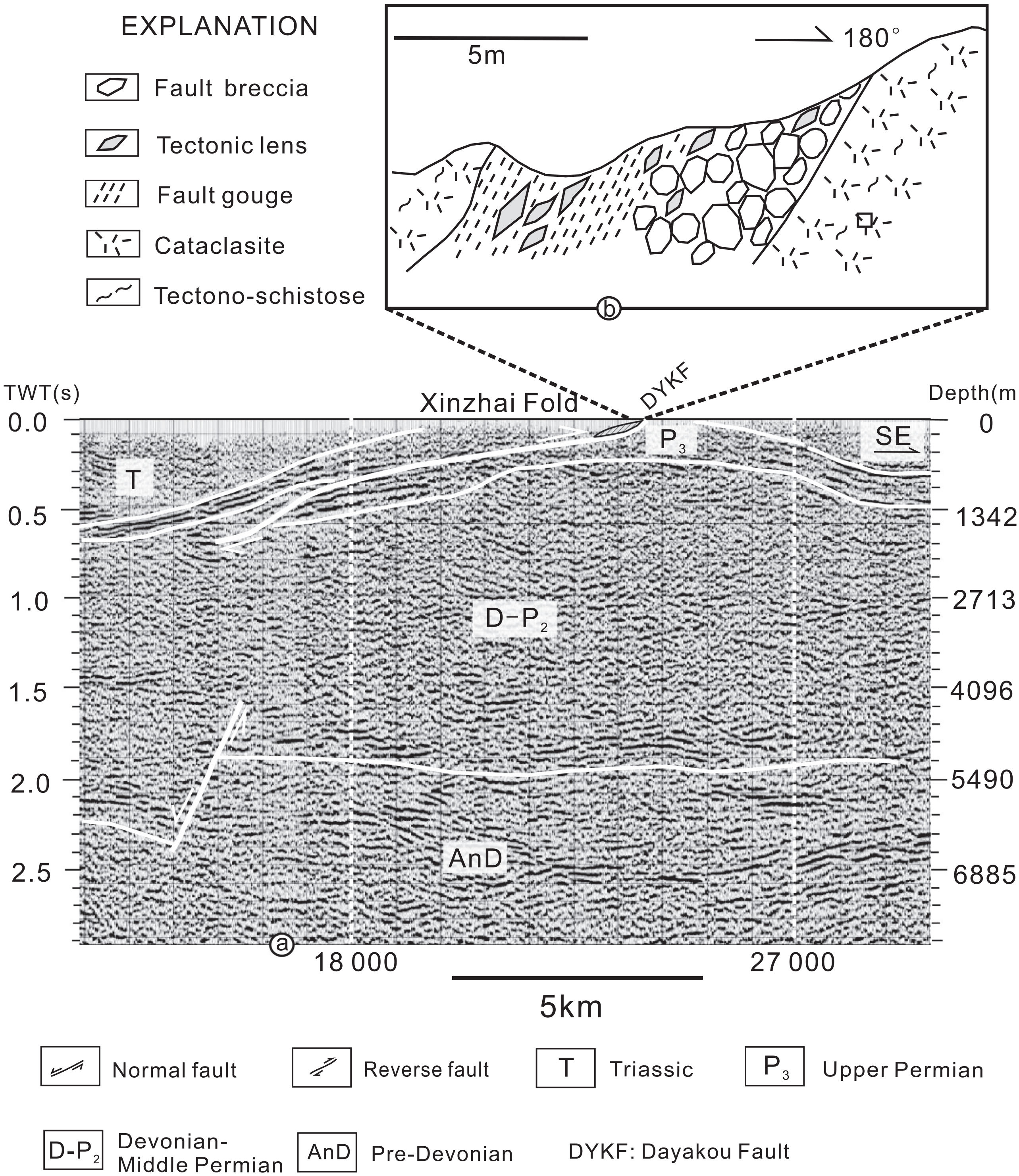

Fig. 7. Interpretation of the seismic profile for Dayakou structure. The seismic profile shows that P_3l thickness in the core of the fold is two times thicker than normal as a result of thrusting (a). There is a good zonation of tectonite in Dayakou thrust fault (b, Hao, 2007). The site of the seismic line across Dayakou thrust is about 5 km east of the Dayakou gold occurrences.

deposit. These interlayer structures, and the Lanmuchang thallium-mercury-gold deposit, are likely to be associated to reverse faulting.

In summary, the above interpretation demonstrates that the gold deposits in central Southwestern Guizhou are controlled by regional faults and fault-related folds. Based on their locations in fault-related folds in the seismic profiles, the gold deposits in the area can be divided into two sub-types: low angle thrust fault-controlled and high angle reverse fault-related deposits.

For low angle thrust fault-controlled deposits (such as Shuiyingdong, Zimudang and Dayakou etc.), the thrust is characterized by steep dip angles of 30°-40° at shallow level and low dip angles (less than 5°) at deeper level where it detaches in coal measures, tuffs and along Dongwu unconformity. In these deposits, thrust fault-related folds always occur on the hanging wall of the thrust. Their limbs are asymmetric in the cross section of the thrust folds: the forelimb near the thrust dips steeply (60°–70°) whereas the back limb away from the

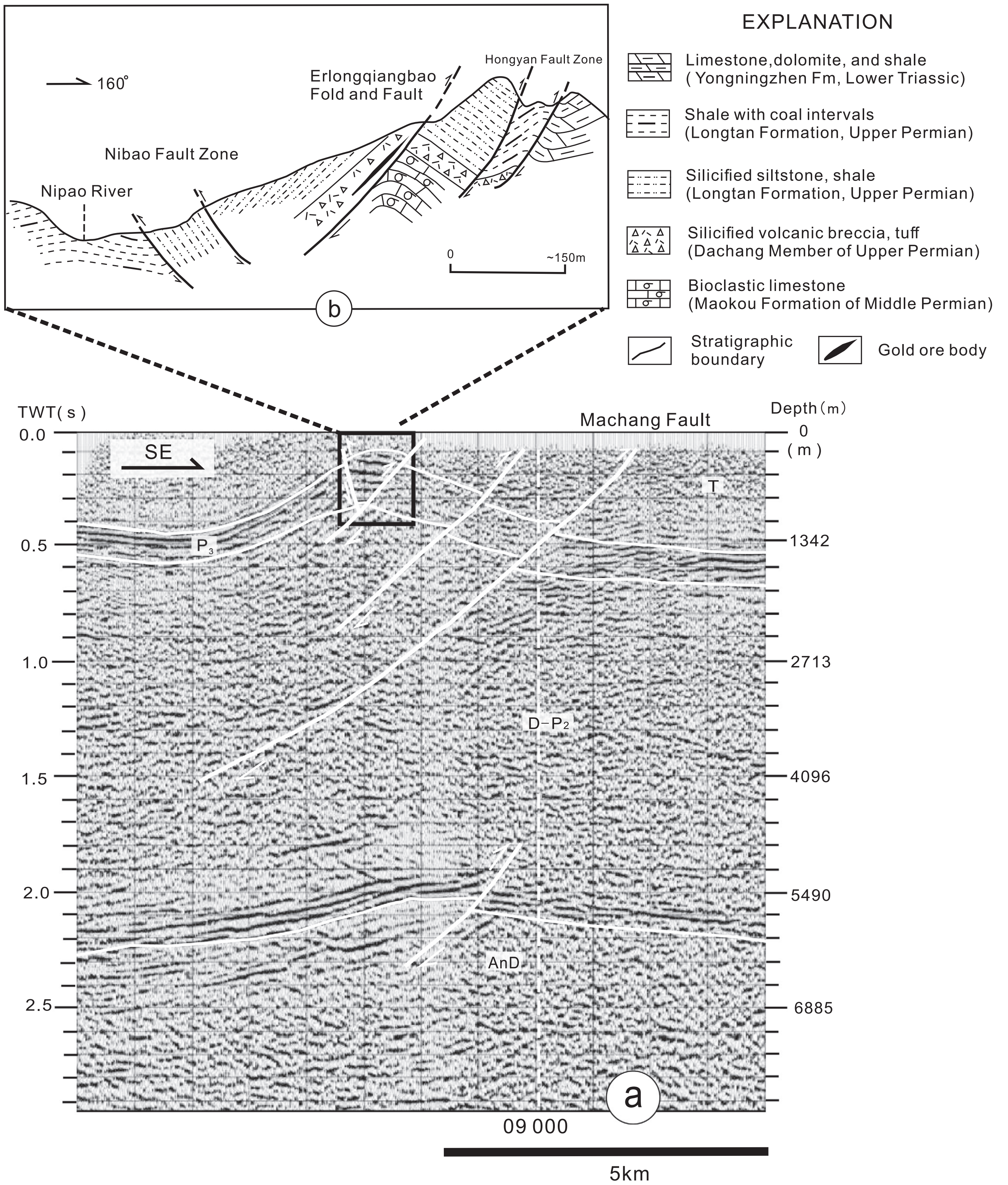

Fig. 8. Seismic profile and geologic section of Nibao gold deposit: (a) interpretation of seismic profile of Machang fault-related structure (left-hand scale is two-way travel time of seismic wave, right-hand scale is depth from surface). The seismic line is located 20 km southwest of the Nibao deposit; (b) Geological section of Nibao gold deposit (modified from Wang et al., 1994). The legends in Fig. 8a are the same as in Fig. 7a.

thrust dips gently (20°–40°). Gold ores occur as veins cutting the strata at shallow depths of the thrusts and as bedding-parallel veins at depth of the thrusts, such as the gold deposits in Dashan-zhexiang thrust fault related fold.

The high-angle reverse fault-related gold deposits (such as Nibao and Getang) occur in interlayer structures caused by high-angle reverse faults and are characterized by bedding-parallel ore bodies, such as at Nibao and Getang deposits. In reverse fault-related gold deposits, the reverse faults always dip steeply, extend downward and cut Upper Permian coal measures, Dongwu unconformity and Middle Permian

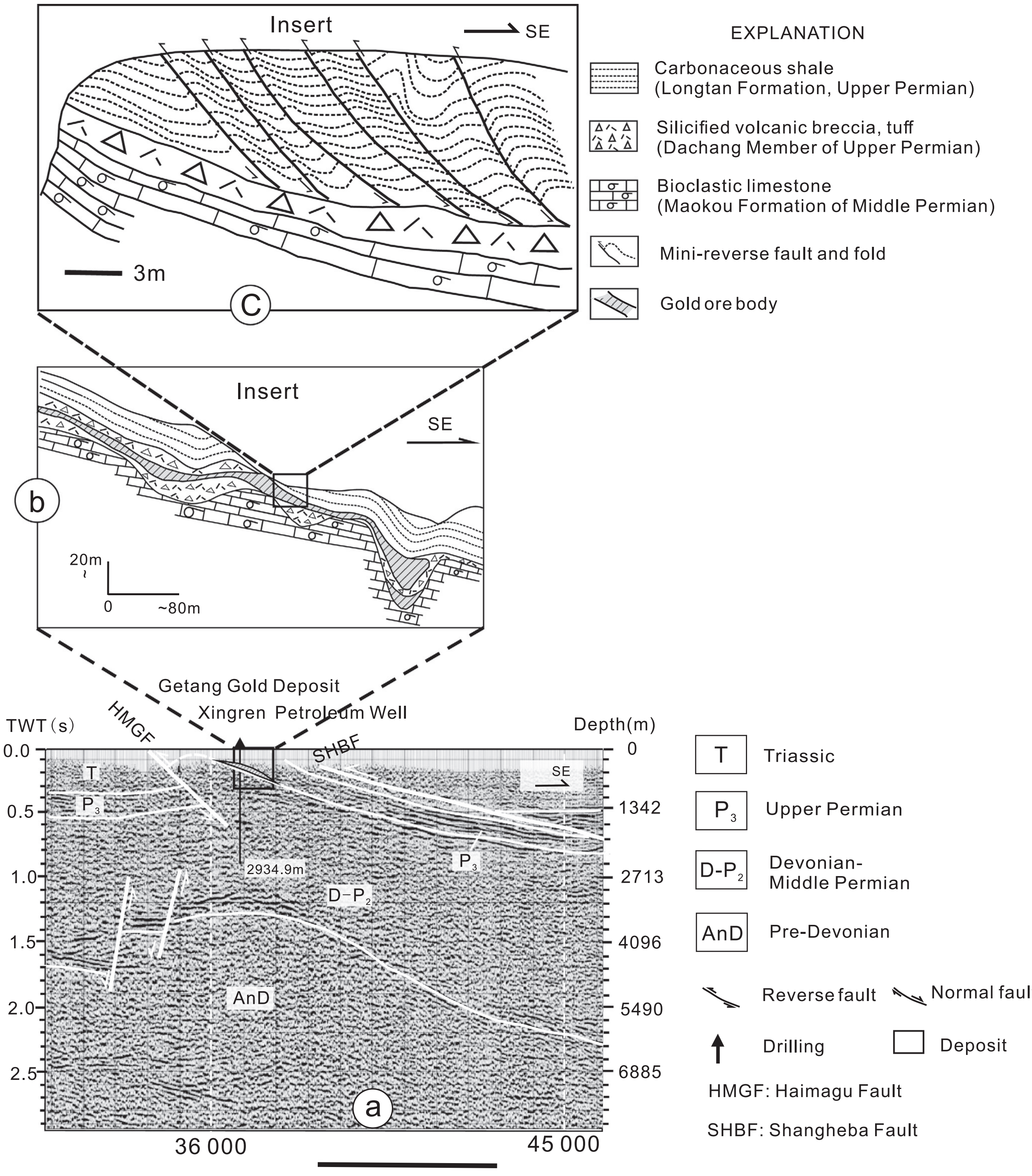

Fig. 9. The seismic profile and geological section of Getang gold deposit. (a) Interpretation of the seismic profile (The scale on the left vertical axis is two-way travel time in seconds of seismic wave, and the scale on the right is depth in meters from surface); (b) Geological section along prospecting line 3 of Erlongkou in Getang gold deposit (modified after Wang et al., 1994). (c) Mini- reverse faults and folds in the ore body (modified after He et al., 1997).

limestone. No gold deposit is found in these high-angle faults so far.

4. Interpretation of gravity data for central Southwestern Guizhou

4.1. The residual gravity anomaly

In 1980s and 1990s, Geophysical Exploration Teams of Yunnan, Guizhou and Guangxi Provinces completed a 1:200,000-scale gravity survey in central Southwestern Guizhou and adjacent area. Based on the reprocessed gravity data, Sinopec Shengli Oilfield mapped the residual gravity anomaly of this area. The density model for different overlying strata and basement has been re-established based on the large quantity of samples (totaling 20,583) collected from the surface and drill cores. The densities of the Triassic, Permian, and

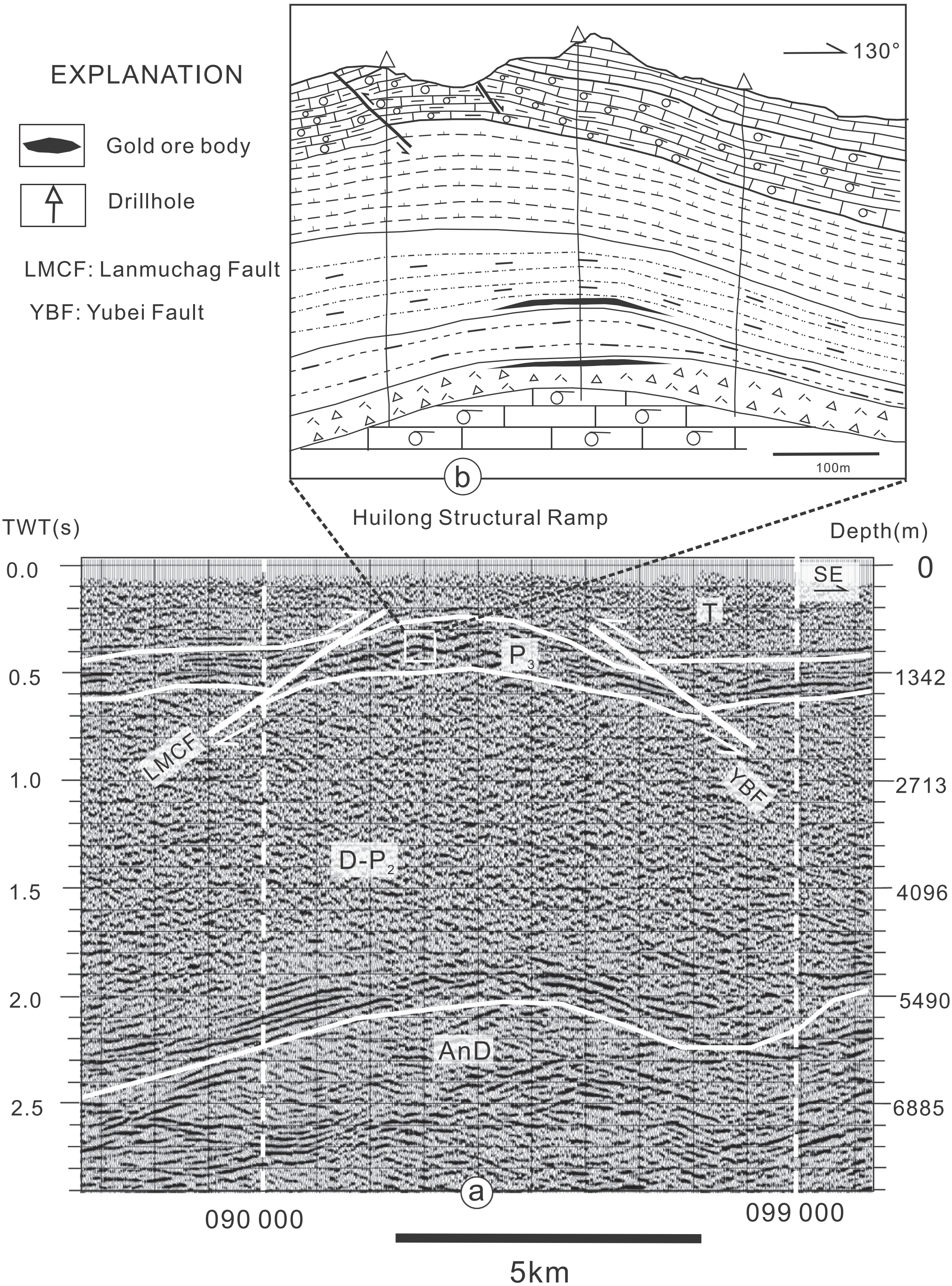

Fig. 10. The seismic profile (a) and geological cross-section (b) showing the structure of the Lanmuchang thallium- mercury-gold deposit. The 2007-140 seismic line passes through the northern part of the Huilong ramp which contain the deposit. The geological cross-section (b) of the Lanmuchang thallium-mercury-gold deposit is from (Zhang, 2007). Other legends for this figure are the same as in Figs. 5 and 9.

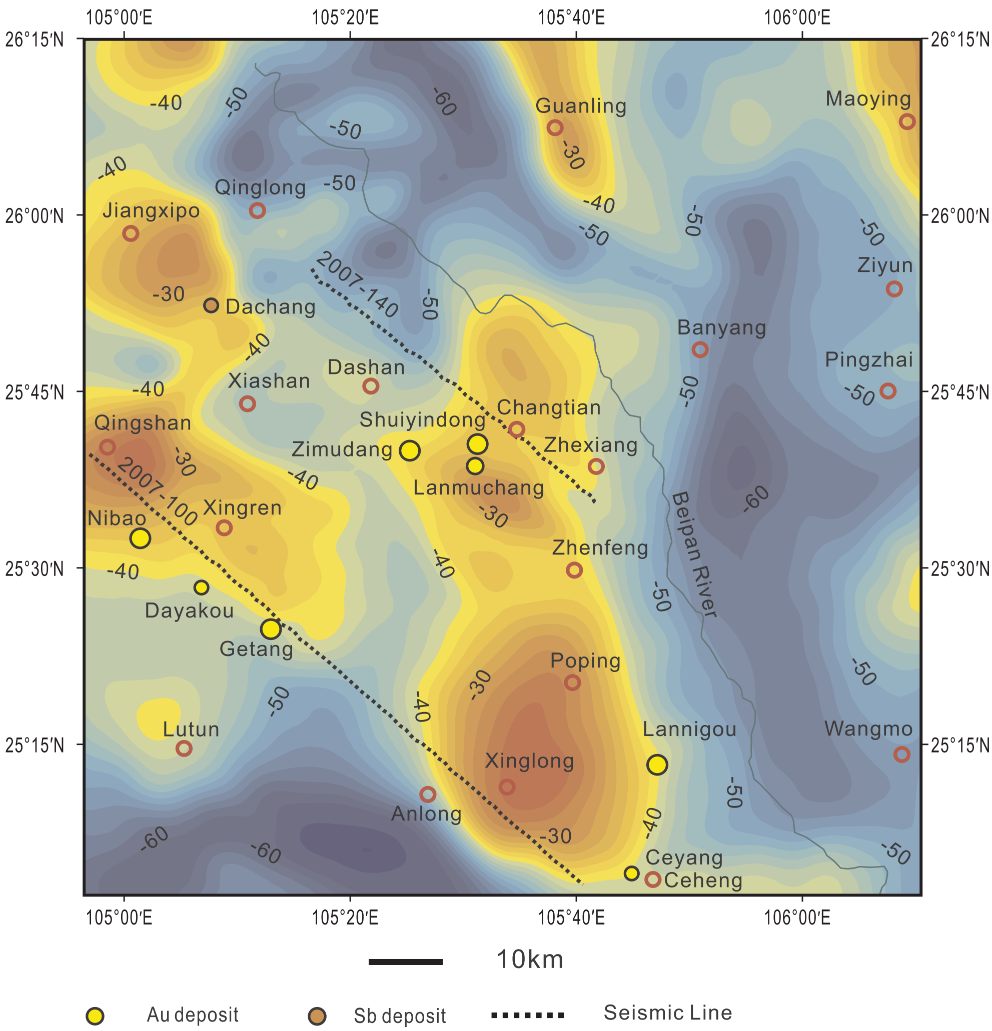

Fig. 11. The residual Bouguer gravity anomaly map (intervals of − 10 mGal) of the basement and distribution of gold and antimony deposits in central Southwestern Guizhou. The map reveals that most Carlin-type deposits occur in areas of high Bouguer gravity anomaly (red and yellow color), inferred to be anticlines or paleo-uplifts in the sedimentary basin. Modified from unpublished report (Li et al., 2007). The seismic profile lines are also marked for comparison.

Carboniferous strata (2.66–2.72 g/cm^3) are generally higher than the value (~ 2.62 g/cm^3) of Devonian, Silurian and Ordovician lithologies, except the Lontang Formation with density of 2.52 g/cm^3. The Cambrian rocks, the basement of in the area has the highest density of 2.74 g/cm^3. The difference of the density values are due to the different rock types in the region (Table 1). The gravity anomaly for each rock layer was calculated and corrected using the Parker–Oldenburg's algorithm and Fugro LCT Gravity and Magnetic software. The terrain-corrected Bouguer gravity data are presented as 2 × 2 km grid with spatial resolution of 5′ × 5′, allowing the identification of the gravity anomaly caused by a 9 km geological body (Li et al., 2007).

The residual gravity anomaly map of the Cambrian basement shows that three high gravity anomaly are identified with background values > − 40 milligal in central Southwestern Guizhou, namely Jiangxipo-Dachang, Qiangshan-Xingren, and Changtian-Xinglong anomalies (Fig. 11). Because the rock density of the basement in the region is higher than overlying strata, these positive anomalies are interpreted as basement paleo-uplifts (Fig. 11; Li et al., 2007). The characteristics of three paleo-uplifts are summarized in Table 2.

These paleo-uplifts identified by the gravity data are also recognisable in the seismic reflection data. For example, the 2007-140 line shows clear uplift under the Lanmuchang Fold to the north of Shuiyindong deposit, and 2007-100 line also shows the uplift near Getang deposit (Figs. 9–11). These uplifts have probably started to form during the Guangxi Movement in the late stage of early Palaeozoic era, and developed further during intensive activities of extension in early Devonian. The gravity data also show that, the paleo-uplifts affected the uplifting of the overlying strata, in particular the shape of the bottom boundary of the Triassic, with round-shaped and elongated Upper Permian dome structures that are consistent with the underlying uplifts of the basement (Fig. 1; also Hu, 2011). The gravity data also show that the paleo-uplifts also shaped the outline of the overlying strata, in particular the contour of bottom boundary of Triassic sequences, In this area the dome structures in the Upper Permian rocks are spatially consistent with the paleo-uplifts in the basement (Fig. 1) (Hu, 2011).

Table 2
Characteristics of paleo-uplifts in central Southwestern Guizhou.

Paleo-uplift	Length (km)	Width (km)	Area (km^2)	Depth of basement top (m)	Gold deposits or Occurrences
Jiangxipo-Dachang	35	17	600	absence	Dachang (antimony and gold)
Qiangshan-Xingren	> 40	20	> 800	3200	Getang, Nibao, Luxia, Dayakou
Changtian-Xinglong	75	30	2400	5800	Zimudang, Shuiyindong, Lanmuchang, Lannigou, Ceyang

4.2. The paleo-uplifts and distribution of Carlin-style gold deposits

Fig. 11 shows that almost all the Carlin-style gold deposits in the region are located either on the top or along the slopes of the paleo-uplifts revealed by the gravity data. For example, Qinglong antimony deposit occurs in Jiangxipo-Dachang paleo-uplift; Nibao and Getang gold deposits, and Dayakou gold occurrence are located in Qiangshan-Xingren paleo-uplift; Zimudang, Taipingdong, Shuiyindong, Lanmuchang, Lannigou, and Ceyang gold deposits are all on Changtian-Xinglong paleo-uplift (Fig. 11). Our interpretation of the seismic profiles also reveals that there are more underlying paleo-uplifts in gold deposits such as Zimudang (Fig. 6), Nibao (Fig. 8), Getang (Fig. 9) and Lanmuchang (Fig. 10) gold deposits. Based on the seismic data, these paleo-uplifts have been estimated to extend to a depth of 5–7 km below the surface, and affected the distribution of the gold deposits. Liu et al. (2002) also suggested that the paleo-uplifts control the distribution of the gold deposits in the Napanjian-Youjiang basin.

The evolution of these paleo-uplifts is related to tectonic movements in central Southwest Guizhou. At the end of Silurian, Guangxi or Late Caledonian tectonic movements happened in a triangle area of Dian (Yunnan) – Qian (Guizhou) – Gui (Guangxi) and Dian – Qian - Gui paleo-land was formed (Zhao et al., 1992; Ma et al., 2004). This paleo-land is considered to have formed as a result of collision between the South China Ocean in the north and the Huaxia plate in the south (Ma et al., 1995; Qiu et al., 1996, 1999; Wu, 2001). In Southwestern Guizhou, some highlands were formed by erosion at the end of Silurian and then buried by the Devonian marine transgression. They became buried hills or paleo-uplifts, such as Jiangxipo-Dachang, Qingshan-Xingren and Changtian-Xinglong paleo-uplifts as mentioned before, and affected the post-Devonian sea floor terrain and structures (Li et al., 2007; Hu, 2011).

In the southwest Guizhou surrounding area, the paleo-uplifts also have impacts on the distribution of oil and gas reservoirs (Fig. 1). Examples include the paleo-oil reservoir of Qinglong Antimony deposit (QL) above the Jiangxipo-Dachang paleo-uplift (Wang et al., 2017), the Xingrenjing paleo-oil reservoir (XPW) on top of the Qingshan-Xingren paleo-uplift, and Laizishan (LZS) and Baiceng (BC) paleo-oil reservoir on top of Changtian-Xinglong paleo-uplift (Zhao et al., 1992; Gu et al., 2012). This indicates that the paleo-uplifts may have facilitated the migration of oil and gas.

5. Discussions: the collisional orogeny, fault-related folding and ore formation

Previous studies rarely link the formation of the Carlin-style gold deposits in the Southwestern Guizhou with collisional orogeny and fault-related folding. Our analysis of the seismic survey data show that the Carlin-style gold deposits in the area are controlled by the fault-related folds in the upper levels of the sedimentary basin. The gravity data also show close spatial relationship between the gold deposits and the paleo-uplift features in the basement rocks. This suggests that the formation of the gold deposits be related to the evolution of the regional structures. Combining previous tectonic understanding, we further infer that gold-bearing fault-related folds are related to the Indosinian Orogeny of the Yue Hai Orogenic Belt located in the south of the study area.

As shown in Fig. 12b, Southwestern Guizhou Depression and Nanpanjiang Depression are parts of the Nanpanjiang-Youjiang Basin (II in the Fig. 12b) that are bordered by four major faults: Shizong-Mile Fault (SMF), Yadu-Ziyun-Luodian Fault (YZLF), Pingxiang-Dongmen Fault (PDF) and Funing-Napon Fault (FNF). The Southwestern Guizhou Depression includes central and western Southwestern Guizhou, and the Nanpanjiang Depression includes southern and eastern Southwestern Guizhou, Southeastern Yunnan and Northwestern Guangxi (Zhao et al., 1992). To the south of Nanpanjiang-Youjiang Basin is the western section of Yue Hai Orogenic Belt (Fig. 12b).

The tectonic evolution of the Southwestern Guizhou can be divided into three major periods: Devonian to Middle Permian characterized by rift-type basins along passive continental margin (Liu et al., 2001; Hu, 2011), Late Permian to Middle Triassic rift-type basin in back-arc (Guo et al., 1983; Wang et al., 1986), and Late Triassic foreland basins and thrusts (e.g., Mou and Wu, 1990; Chen, 1994; Qin et al., 1999).

The geodynamic evolutionary processes of the Southwestern Guizhou can be categorized in the following six stages (Fig. 12a, based on Ma et al., 2004):

1) Dian-Qian-Gui paleo-land formed by collision between South China ocean in the north and Huaxia plate in the south in late Caledonian (bottom of Fig. 12a);
2) The Babu-Phu Ngu and Xiangpa-Tunchang Ocean (part of east Tethys Ocean) began to open in the Devonian and reached its maximum in the Carboniferous. A sequence of black carbonate rocks and black mudstones deposited in central Southwestern Guizhou, forming the source rocks of the hydrocarbon in the region (Zhao et al., 1992, 2006);
3) The Babu-Phu Ngu and Xiangpa-Tunchang oceanic crust subducted to south and began to close in the Permian, and a suite of deep-grey and light-grey carbonate rocks and mudstones deposited in the region;
4) The closure of Qinfang Rift Trough led to the uplift of Dian-Qian-Gui area and Dongyun unconformity. Dongwu Movement also caused the breakdown of Yangtze Block and massive volcano eruptions. The volcanic breccia and tuff with high background Au content deposited in the region, followed by a suite of tidal-flat coal seams and carbonate rocks on the platform from Late Permian to Early Triassic;
5) The Babu-Phu Ngu and Xiangpa-Tunchang oceans subducted further to the south, and volcanic and sedimentary rocks were scraped and accreted onto the North Vietnam Black (Ma et al., 2004). The Nanpanjian depression was a part of a flysch basin, with intrabasinal platforms developed. Southwestern Guizhou depression, further to the north, is located in carbonate platform in Middle Triassic;
6) Yangtze Block was collided by an accretionary wedge. A foreland basin and then fault-related folding developed in the Southwestern Guizhou and adjacent area, with major gold deposits forming in fault-related folds in Late Triassic.

The NW-SE- and NE-SW-trending tectonic framework in central Southwestern Guizhou and its adjacent area has a complex tectonic history as shown in Fig. 12, being related to tectonic mode switches (Lister and Forster, 2009). From the Devonian to the middle Triassic, the region was affected by the eastern Tethys Ocean. The extensional tectonic settings gave rise to NW-SE-striking normal faults such as Yadu-Ziyun-Luodian Fault Belt (YZLF) and Zhuchang-Shangzhai Fault (ZSF), and NE-SW-striking normal faults such as Shizong-Mile Fault Belt (SMF), Machang Fault (MCF), Poping Fault (PPF), Anlong Fault and Yongningzhen Fault (YNZF) (Fig. 1; Zhao et al., 1992; Liu et al., 2001). These normal faults switched to reverse faults during Indosinian Orogeny. As we can see from the seismic profile, the features of normal faults are kept at depth in the reverse faults, such as Malaotian Fault and an unnamed fault in the east to Shipan anticline (Figs. 3 and 4). A normal fault could be easily identified beneath the Yadu-Ziyun-Luodian reverse fault at depth by some MT lines (Zhu and Yang, 2007).

The tectonic evolution in the region is also related to the closure sequence of the eastern Tethys Ocean in the late Indosinian Orogeny (Wu, 2001; Ma et al., 2004). At first, the collision of Babu-Phu-Ngu and Xiangpa-Tunchang ocean bordering China and Vietnam occurred in the northwest segment in the late Triassic (Wu, 2001; Ma et al., 2004), and formed five sets of thin-skin structures, such as Dayakou, Xingren, Zhenfeng, Dashan-Zhexiang, and Xintun fault-related fold belts in central Southwestern Guizhou. Later, the collision took place in northeast segment from Tunchang in Hainan Island to Changle in Fujian Province and formed NE-SW-striking faulted-related fold structures

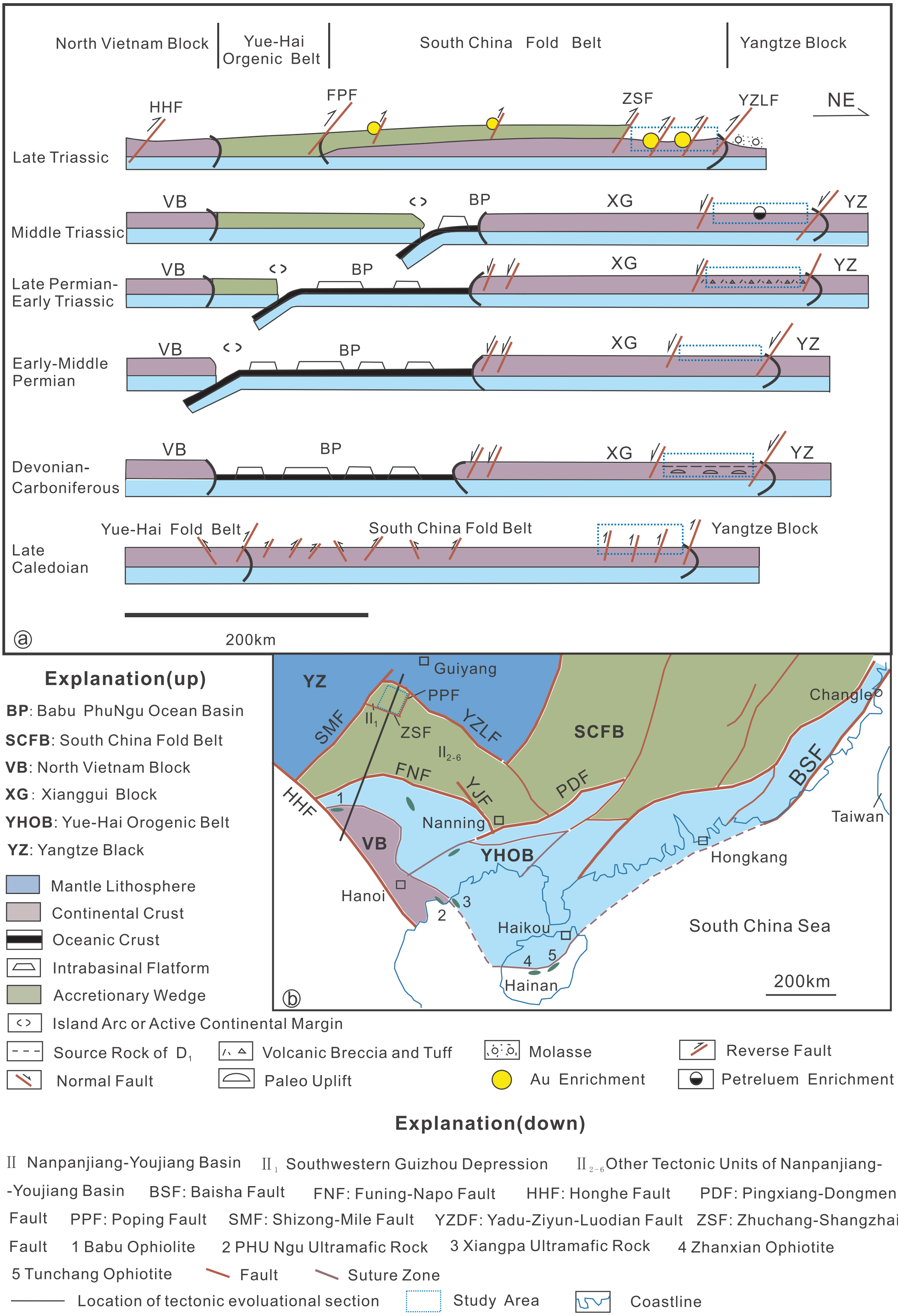

Fig. 12. Schematic diagram of plate-scale cross sections showing the tectonic evolution of gold mineralization in central Southern Guizhou, modified after Ma et al. (2004).

(Charusiri et al., 1995; Wu, 2001; Ma et al., 2004). Those NE-SW-striking faults inherited the dips of pre-existing normal faults and have no preferred dip directions, some dipping to northwest, some to southeast, and some forming ramp-fault-related fold such as Huilong ramp structure (Fig. 3). The formation sequence of the fault-related fold structures with variable strikes and dips is confirmed by the observations that NE-SW-striking faults crosscut NW-SE-striking thrusts (Fig. 1).

The tectonic evolution of the region has facilitated the formation and distribution of the Carlin-style gold deposits. The extensional tectonics during Devonian to Middle Permian further developed the paleo-uplifts in the region (Li et al., 2007), which helped migration and accumulation of hydrocarbon during Indosinian Period. Dongwu Movement between Middle and Late Permian caused intensive volcanism in Yangtze Craton and surroundings (Luo et al., 1988), with volcanic sediments deposited in Dachang Member with Au contents of 40–50 ppb (Tao et al., 2002; Hu, 2011), providing the source of Au for the Carlin-style gold deposits. Indosinian Movement (~235 Ma) between Mid-Triassic and Late-Triassic is an important event that facilitated the formation of oil-gas reservoir and the gold deposits. Several oil/gas reservoirs have formed during this period in the central Southwestern Guizhou (Zhou, 1999, Wang et al., 2017). Those hydrocarbon reservoirs are suggested to have acted as reducing agent in the reaction of the thermochemical sulfate reduction (TSR) to provide reduced sulfur needed to form the metal sulfides in the gold deposits (Gu et al., 2010; Wang et al., 2017).

The tectonic mode switched to compression during Indosinian Orogeny changed the normal faults to reverse faults and thrusts in the region. Those faults, and widespread Dongwu unconformity, can provide effective conduits for the ore fluid flow for the formation of the gold deposits, as suggested by previous studies (Wang and Mou, 1998; Li et al., 2000, 2004; Tan et al., 2015). The coal measures and tuffs of Dachang Member, with poor rheological properties, may play important role in the formation of the fault-related folds and gold mineralization by acting as detachment layers and a host for ore deposition.

It is interesting to compare the tectonics of the Carlin-style gold deposits in the study area to those in Nevada, USA. Detailed comparisons of the gold deposits in two districts have been well documented (e.g., Li and Peters, 1998; Hu et al., 2002; Cline et al., 2013) and will not be repeated here. It is notable that although in both locations the gold deposits are located in orogenic belts and spatially related to hydrocarbon reservoirs (Hulen and Collister, 1999; Gu et al., 2012), gold mineralization in Nevada occur during Cordilleran Orogeny with changes from compression to extensions (Cline et al., 2005, 2013), such as primarily along high-angle Tertiary normal faults (Yigit et al., 2003). In contrast, the Carlin-style gold deposits in China (hence the term style, as opposed to type) formed during compression, and occur mainly in thrusts and related folds (e.g., Peters et al., 2007) during Indosinian Orogeny as discussed in this study.

6. Conclusions

Combining reflection seismic profile, residual gravity anomaly and regional geology data, we have analyzed the structures controlling the Carlin-style gold deposits, in particular the relationship between fault-related fold structures and gold mineralization in central Southwestern Guizhou.

The gold deposits are controlled by NW-SE- and NE-SW-striking fault-related fold structures. These deposits can be classified into two types based on the spatial relationship between the gold deposits and fault-related fold structures. The first type is low-angle thrust-controlled gold deposits found in low-angle thrusts which have a high angle near the surface. The second type is high angle reverse fault-accompanied gold deposits in interlayer fracture zones caused by high-angle reverse faults which always dip steeply both on the surface and at depth. Gravity data shows that the Carlin-style gold deposits are distributed on and around the paleo-uplifts in the region.

The formation and distribution of the gold deposits are part of the tectonic evolution in the region, with tectonic switching from extension to compression during Indosinian Orogeny. In the late Triassic to early Jurassic, central Southwestern Guizhou was a part of a compressional geological environment, in which NW-SE- and NE-SW-trending fault-related fold structures formed, probably caused by the closure of the eastern Tethys Ocean.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.oregeorev.2017.09.011.

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