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Application of a shallow seismic reflection method to the exploration of a gold deposit

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Abstract
The shallow seismic exploration method has been used extensively in petroleum exploration and geological engineering, but whether or not it is suitable for solid-ore exploration is still uncertain since solid ore deposits are usually irregularly shaped. The application of this shallow seismic exploration method to the Yangji-Shan gold deposit in south China is, however, an example of a successful attempt to determine subsurface structure and find potential orebodies using the technique. In combination with the study of regional metallogeneic characteristics, shallow seismic exploration can provide a potential approach to locating and exploring solid mineral resources. Industrial drilling has verified the interpreted results for the gold orebodies at Yangji-Shan.

Keywords: shallow seismic exploration, solid mineral resources exploration, gold deposit, ore exploration

1. Introduction

The shallow seismic exploration method has been used extensively in petroleum exploration and geological engineering, particularly in karst regions. However, whether or not it is suitable for solid-ore exploration is still speculative since solid ore deposits usually occur as irregularly shaped bodies (e.g., gold deposits outcrop as veins, keels and other shapes). It is necessary to increase the resolution of the seismic data in order to carry out solid-ore investigations into gold, silver, copper and other mineral resources. This paper describes a case study in which the shallow seismic exploration method was used to investigate the subsurface structure of the Yangji-Shan gold deposit in Jiangxi Province, south China. The aim of the study was to test the feasibility and suitability of the shallow seismic exploration method in exploiting other solid ores.

The shallow seismic exploration procedure is principally divided into the following three stages: data acquisition, processing and interpretation. Using basic geological observations, we attempt to interpret geologically the seismic profiles obtained, which show various lithological interfaces. By means of comparison and discrimination of waves in the time domain, structural forms and contact relationships of the reflected layers, as well as the distribution of faults etc, can be determined. However, the accuracy of these geological interpretations is always affected by certain factors, for example, the arrangement of the field observation system, the method of primary data collection, the method of data processing and the selection of parameters. Therefore, due to the complexity of the geological processes involved, in the course of exploration for solid mineral resources, especially gold and copper, there are several factors that must be very carefully considered. First, study of the metallogenic and geological conditions is important. Second,

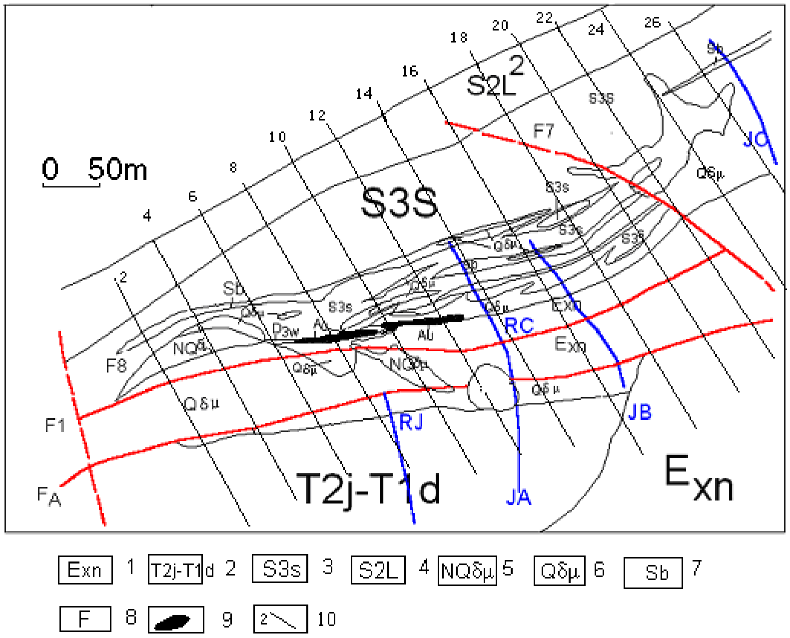

Figure 1. Geological sketch of the Yangji-Shan gold deposit. 1. Tertiary (E); 2. Middle-Lower Triassic (T_2-T_1); 3. Upper Devonian (D_3); 4. Middle-Upper Silurian (S_2, S_3); 5. Quartz dioritic porphyrite ($Q\delta\mu$); 6. Cryptoexplosive breccias ($NQ\delta\mu$); 7. Crush zone (Sb); 8. Orebody (Au); 9. Fractures (F); 10. Seismic profiles (JA, JB, JC, RJ).

the selection of shallow seismic profiles, which relies on the fundamental geology, is critical. Finally, seismic results must be compared with real mining data to test the feasibility of the developed shallow seismic exploration technique.

2. Geological and metallogenic conditions of the Yangji-Shan gold deposit

2.1. Geological characteristics

The Yangji-Shan gold deposit is located in the southern Yangtze block in south China, adjacent to the boundary between the Yangtze and Cathaysian blocks. Geographically, this is about 2 km east of Rui-Chang County, Jiangxi Province. The area of gold mineralization is about 1 km long in the E–W direction and about 0.4 km wide in the N–S direction. Structural analyses from previous studies (Zhang 1992, Chen *et al* 1999) have shown that the Yangji-Shan gold deposit lies on the southern flank of the Dachong–Dingjiashan compound anticline (figure 1). It is separated from the Niaoshijie-Saihu faulting basin by ENE-trending faults. From north to south, the outcropping strata include Silurian, Devonian, Carboniferous, Permian and Triassic sedimentary rocks which are predominantly shallow-marine grey and grey-green clastic rocks, and minor intercalated siltstones and fine sandstones.

The sedimentary rocks experienced strong later silicification in the ore area, either as a result of the gold mineralization process or the emplacement of quartz dioritic porphyrites. Tertiary red sandstone–conglomerates developed in the south-eastern area. The strikes of the Palaeozoic strata vary, following the regional structural line (figure 1). ENE-to NE-trending fractures are predominant in the ore area with minor NW- and near-NS-trending faults. Among these is the ENE-trending fault, F_1, which traverses the whole area and has played an important role in the formation and development of the mineralization. This fault is considered as an ore-hosting conduit of the Yangji-Shan gold deposit. Moreover, interlayered crush zones and lateral fractures of the trunk faults are also well developed. There are two ENE-trending trunk fractures, F_1 and F_A. F_A is now a tensile-shear fault and was active prior to diagenesis, which led to a non-sequence in the strata on the south side. The displacement of the fault is about 0.4–0.5 km (unpublished data from Northwest Jiangxi Geological Team, 1985). F_A is still active in the Tertiary and along the fracture zone where the Tertiary basaltic magmas erupted. This fracture acted as an ore-conducting and magma-conducting structure in the ore area, as the gold ores and mineralization outcrop in the fracture zone.

Current mining of the gold deposit is limited locally to the region between exploration lines 5–14. However, it is unclear whether the eastern peripheral areas are suitable for gold mineralization and exploration. We have applied the shallow seismic exploration method in this area with the aim of locating and investigating new mineral resources and potential gold ores.

2.2. Metallogenic characteristics

This section focuses on the tectono-metallogenic process, i.e. the process of mineralizing fluid migration and mechanism of gold localization. The major characteristics of tectono-metallogenesis of the Yangji-Shan gold deposit are summarized as follows.

The structural deformation and gold mineralization have migrated in a common NNE direction. For instance, all ore-bearing drill holes are located to the north of fault F_1, indicating a directional tectono-metallogeneic migration. This means that gold has migrated and concentrated either along one flank of the fracture or from the centre to the periphery under the tectono-thermal dynamic conditions that prevailed in the Yangji-Shan area at the time of deposition (Zhang 1992, Cui 1995, Chen *et al* 1998). Fault F_1 had cut through the Silurian and Triassic systems by the end of the early Indosinian–early Yanshanian episode; a quartz diorite and quartz dioritic porphyrite zone about 20 km in length is exposed along the fault. These igneous rocks experienced intense compression and shearing. In the ore area, fault F_1 is not only an ore-conducting structure but also the ore-hosting site, together with the surrounding secondary *en échelon* plumose fractures. Later tectonic activity along fault F_1 resulted in the structural deformation of the orebodies and might have displaced the existing orebodies into several segments.

The gold mineralization clearly shows characteristics of isometry. At the current mining site, the orebodies occur as lenses and are distributed in a right-handed direction. Each lens is about 20 m long and 5–8 m wide. According to three-dimensional analysis, orebody number 5 outcrops in a lenticular shape, declining from east to west. At the midsections, −12 m and −60 m, orebody number 5 consists of two segments of high-grade ore: one is located between exploration lines 7 and 8 and the other is located above −60 m, between exploration lines 10 and 12. According to the results obtained from drill holes and structural analysis of the orebodies, the two segments of high-grade ore extend to the −204 m and −156 m midsections, respectively. In general, the fraction of an orebody that is revealed at different depths is strictly controlled by the regional structure (Zhai and Yao 1992, Chen *et al* 1999).

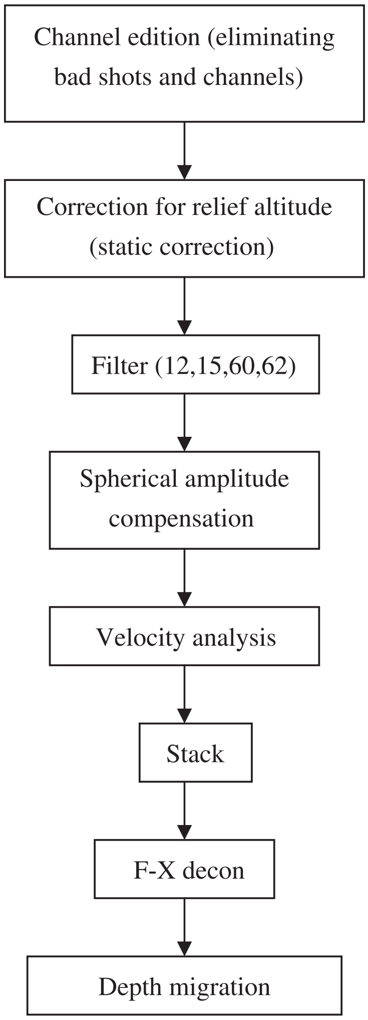

Figure 2. Data processing flow diagram.

3. The shallow seismic exploration method

Based on the characteristics of the Yangji-Shan region mentioned above, a multifold seismic acquisition system has been adopted to collect data in the field. Four surveying profiles were designed to meet our geological investigation target and detailed locations are shown in figure 3. The acquisition system is set up with a shot-leading geometry. For each shot, the weight of dynamite is 350–400 g. The shot interval is 10 m. Each shot record consists of 24 channels with a receiver interval of 5 m. The offset between the shot and the first receiver is 30 m. The recording length includes 2048 samples with a sampling rate of 0.4 ms.

Data processing includes pre-processing, static correction, filtering, velocity analysis, NMO correction, stack, noise attenuation and depth migration. A multifold stack technique is adopted. This can attenuate multiples and various interference waves, and hence greatly improve the signal-to-noise ratio of a seismic profile. It also provides more accurate velocity parameters determined from a common-midpoint gather. The detailed procedure for data processing is summarized in figure 2.

4. Geological interpretation

The results of two seismic exploration profiles (RJ and JB) are illustrated in figures 3 and 4, respectively. It is clear that a volcanic channel exists adjacent to exploration lines 8–12. Since it is possible to distinguish between the seismic velocities of different objects, the seismic velocity structures for different lithologic layers are discontinuous and they all converge towards the location of current mining activity. These features extend from −100 m to −1200 m. The geological interpretation of the seismic profile between lines 14 and 15 indicates that a crush zone exists in the contact region above −450 m between the Permian–Triassic strata and a quartz dioritic porphyrite intrusion, and the width of this crush zone is small. Below −450 m, a soft band extends downwards to −600 m. This is interpreted as an ore-bearing magmatic channel probably composed of ore-bearing cryptoexplosive breccias. Below −600 m, Silurian sandstones occur in this region. In the northern section of the profile, a concealed sack-shaped pluton is located between −400 m and −600 m, forming a clear boundary with the wall rocks. A magmatic channel is present above the pluton.

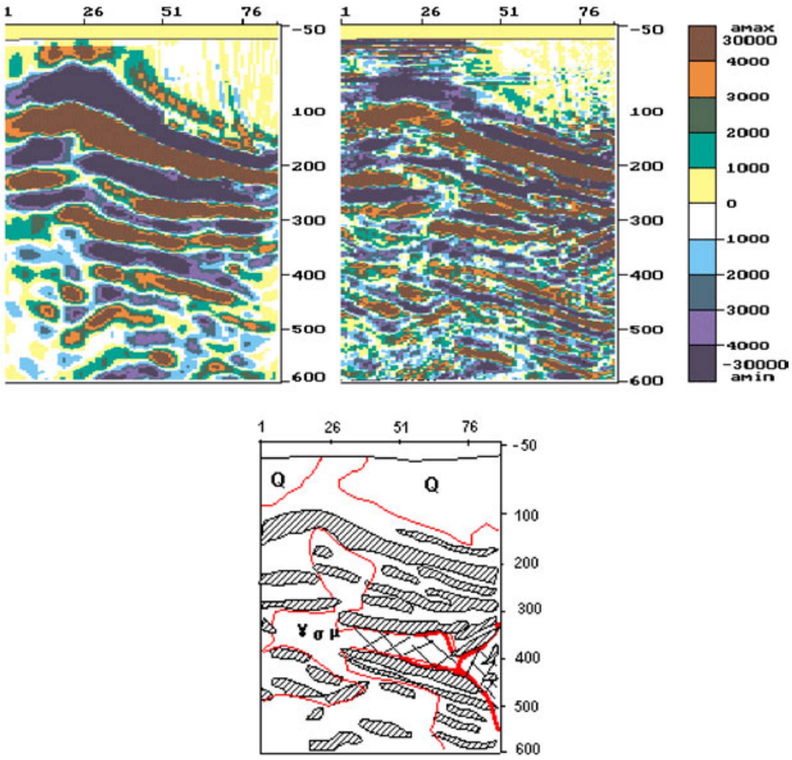

Figure 3. Shallow seismic profile above −600 m altitude for line RJ and the interpreted image (exploration line 10). The upper right-hand figure shows the section after improving the resolution. The dark line above the section shows the surface relief. The depth scale is in metres and the horizontal axis shows the CDP number at intervals of 2.5 m.

A quartz dioritic porphyrite intrusion, 1–2 m wide, outcrops on the surface along line 16. The width of the intrusion increases gradually downwards and is also sack-like; it clearly intrudes into the structural crush zone. According to the general metallogenic characteristics of the Yangji-Shan gold deposit, such a crush zone, intruded by dioritic porphyrites, is a favourable site for gold mineralization and deposition. This conclusion is in good agreement with the results of gold-abundance contouring in the area. The combined results indicate that the gold mineralization of the Yangji-Shan deposit is closely related to a volcanic structure (a volcanic channel). The latter is one of the controlling factors of gold concentration in the region.

Based on the general characteristics of tectono-metallogenesis of the Yangji-Shan gold deposit, we now describe in detail the shallow seismic profiles of −430 m.

(1) Both the crush zones and magmatic channel are potential sites for gold mineralization. The magmatic channels act as passages for the migration of ore-bearing fluids and the crush zones provide space for gold precipitation.

(2) A concealed magmatic channel adjacent to lines 8–12 also exists. In figure 4, the discontinuous extension of different lithologic layers, all of which converge towards the current mining sites (at the northern end of the profiles), suggests the existence of a magmatic channel. This feature extends downwards from −100 m to −1200 m.

(3) The shallow seismic profile beneath lines 14 and 15 shows that a contact region exists between the wall strata and a pipe-like object, which extends downwards from −450 m to −600 m. A crush zone occurs along this pipe-like object. This is possibly a contact zone between cryptoexplosive breccias (or quartz dioritic porphyrites) and sedimentary strata. It is reasonable to infer that such a crush zone associated with cryptoexplosive breccias might be a favourable site for gold deposition.

(4) The seismic profiles indicate the possible existence of other cryptoexplosive breccias (or quartz dioritic porphyrites) at −600 m, where the contact region between the inferred igneous rocks and the wall rocks clearly contains a crush zone. If our conclusion is correct, this locality might be another favourable site for gold mineralization.

5. Ore prediction and test

Based on the geological results presented above, we point out the possibility that gold orebodies may occur between lines 14 and 16 in the Yangji-Shan site. With this in mind, three holes have been drilled to test our seismic results. The drill hole ZK14–4 is located on line 14 and the drilling depth is 308.58 m. Sulfide ores in cryptoexplosive breccias are encountered at depths of 233.35–237.90 m (corresponding to altitudes of −165.87 to −170.43 m). The average gold abundance is 13.45×10^{-6} with the highest value being 24.88×10^{-6}. In the drill hole ZK13–1, the gold orebody is about 7 m thick

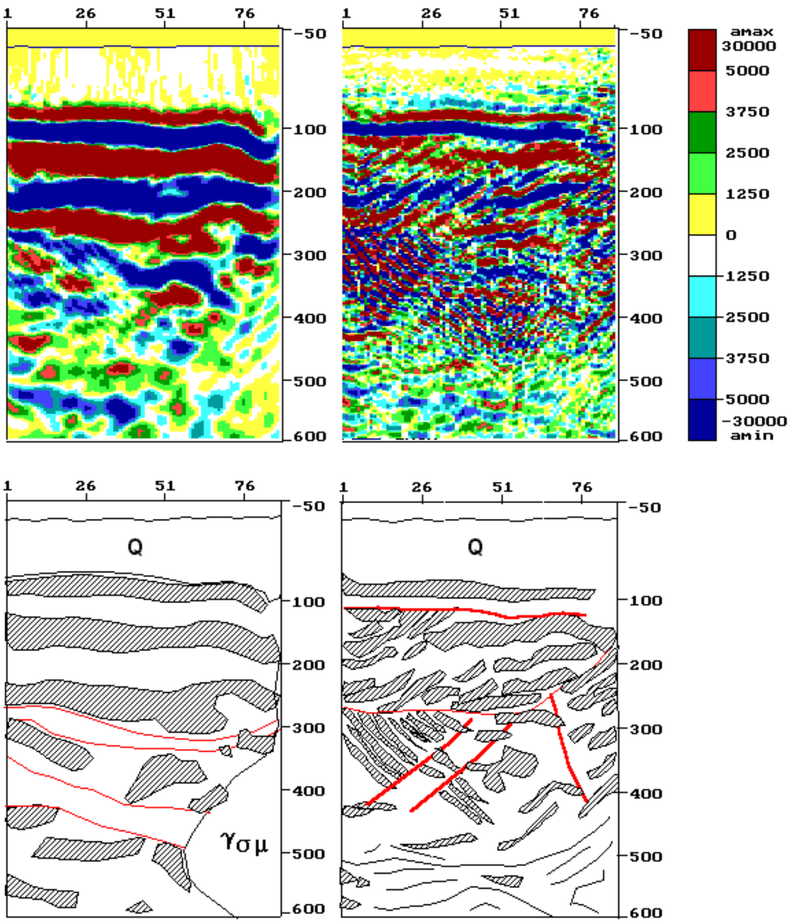

Figure 4. Shallow seismic section interpretation images of exploration line JB in the Yangji-Shan gold deposit (exploration line 14).

and occurs between 113.76–121.04 m. The average gold abundance is 1.9×10^{-6} where the highest value is 10×10^{-6}. The drilling data indicate that other new industrial orebodies exist in the Yangji-Shan gold deposit.

6. Conclusions

The new shallow seismic exploration method can be used for solid-ore exploration only if the seismic data resolve the solid mineral resources. The successful application of the shallow seismic exploration method to the Yangji-Shan gold deposit in south China demonstrates that the determination of subsurface structure and potential orebodies is possible using this technique. In combination with the study of regional metallogenic characteristics, the shallow seismic exploration method has potential for the discovery and exploration of solid mineral resources.

Acknowledgments

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