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Application of singular value decomposition (SVD) in extraction of gravity components indicating the deeply and shallowly buried granitic complex associated with tin polymetallic mineralization in the Gejiu tin ore field, Southwestern China

Yongqing Chen [a,*], Lina Zhang [a], Binbin Zhao [b]

[a] School of Earth and Mineral Resource, China University of Geosciences, Beijing 100083, China
[b] Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

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ABSTRACT

The Gejiu tin polymetallic ore deposit, located at the westernmost end of the Cathaysia Block, is one of the largest tin polymetallic ore deposits in the world. It is associated with a magmatic-hydrothermal ore-forming system triggered by the deeply buried geological structures and concealed granites. A singular value decomposition (SVD) program on a MATLAB platform was effectively used to extract deeply buried geological information reflecting deep-seated geological structures and the concealed granites by decomposing gravity signals within the Gejiu tin polymetallic ore field. Firstly, the gravity signals were decomposed into a few components with different eigenvalues using a singular value decomposition (SVD) approach. Secondly, the thresholds between the eigenvalues of gravity components reflecting deeply and shallowly buried ore-controlling geological structures and/or geological bodies were established by a multifractal method. Finally, the images of gravity components reflecting deeply and shallowly buried ore-controlling geological structures and/or geological bodies were reconstituted. This yielded two layers of significant two dimensional singular value gravity component images that indicate deeply and shallowly buried ore-controlling geological structures and/or geological bodies, respectively. The deep layer of gravity component image reveals a negative gravity anomaly (I) which indicates that the granites exposed in the west ore field, bounded by the Gejiu Fault, may be extended to the east ore field at depth, forming concealed granites (Fig. 4). The shallow layer of gravity component image reveals a structural framework created by two groups of NW-trending and three groups of NE-trending positive gravity component images defining two negative gravity anomalies (I and II), which may reflect existence of the exposed granites in the western ore field (I) and the concealed granites in the eastern ore field (II) (Figs. 5 and 6). Almost all tin polymetallic deposits are located within the negative gravity anomalies (Figs. 4 and 5). This approach, combined with the identification of geochemical anomalies plays an important role in the discovery of deeply buried tin polymetallic ore deposits, including the 0.78 million tons of tin reserves over the last ten years.

1. Introduction

With decreasing of outcropped mineral deposits deep mineral exploration has been placed on the agenda (Zhao, 2007). It is well known that geophysical and geochemical anomalies are crucial clues for searching buried ore bodies. But these anomalies at surface caused by buried ore bodies are usually indirect and weak due to the shielding effects of the cover layer. Moreover, these anomalies are affected also not only by the burial depth, scale of ore bodies and petrophysical–chemical properties of cover layers but also by the superposition of anomalies from geological bodies (or ore bodies) with different petrophysical–chemical properties, depths and sizes, which lead to complexity of these anomalies. Therefore identification and extraction of the geophysical and geochemical anomalies associated with buried mineralization plays an important role in deep mineral exploration.

It has been demonstrated by recent studies that hydrothermal processes in the Earth's crust can result in ore deposits characterized by high concentrations of metals with fractal or multifractal properties (Agterberg, 1995; Cheng et al., 1996; Cheng, 2007a, 2007b; Mandelbrot, 1989; Schertzer and Lovejoy, 2004; Turcotte, 1997). This property of the high concentrations of metals is termed a singularity, and the hydrothermal processes are considered as singular processes (Cheng, 1999a, 2007a). Singularity can be defined and characterized in different ways. From a geological application point of view, singularity can be defined as a special phenomenon with anomalous energy release or material accumulation occurring within narrow spatial–temporal intervals (Cheng and Agterberg, 2009). For example, the ore-forming event associated

* Corresponding author.
E-mail address: yqchen@cugb.edu.cn (Y. Chen).

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with the Gejiu giant tin polymetallic deposits took place from 77.4 ± 0.6 Ma to 95.3 ± 0.7 Ma (about 18 Ma), and the magmatism of the granites associated with the tin polymetallic mineralization took place mainly from 77.4 ± 2.5 Ma to 85.8 ± 0.6 Ma, being only about 10 Ma (Cheng and Mao, 2010; Cheng et al., 2012, 2013a, 2013b). Singularity is a generic property and phenomenon of nonlinear natural processes that often generate end products which obey fractal or multifractal distribution and can be described by the power-law model (Cheng, 2007b, 2007c; Cheng and Agterberg, 2009). Power law relations may reflect self-similarity (scale independence) of the underlying, genetic processes (Agterberg, 1995). Generalized fractal self-similarity characterized by a power-law relationship can be expressed in the spatial or frequency domain (Chen et al., 2015a, 2015b). Several power law relationships are characterized in geophysical fields, such that the value of gravity or magnetic anomaly (f) is proportional to some power of distance (r), and this relationship can be expressed as follows:

$$f = Fr^{-N}, \tag{1}$$

Where F is an amplitude factor, and N is the scaling exponent or structural index depending on the properties of source. For a gravity sphere, $N = 3$; conversely, $N = 2$ for a gravity horizontal cylinder, and $0 \le N \le 3$ for other types of geological bodies. A power-law relationship between the power spectrum $P(\omega)$ of the causative physical properties (e.g., density or magnetization) and wavenumber ω: $P(\omega) \propto \omega^{-\alpha}$. Considering the fractal properties of gravity or magnetization, the power spectrum of potential field data can be rewritten as:

$$P(\omega) = C\omega^{-\alpha}\mathrm{e}^{-2\mathrm{d}\omega}, \tag{2}$$

where α is the scaling exponent, d is the burial depth of the geological body, and C is a constant. (2) can be written in logarithmic form as:

$$\log P(\omega) = C - \alpha \log \omega - 2d\omega. \tag{3}$$

The power spectrum for small depth is approximately proportional to some power of wavenumber, whereas the power spectrum for large depth acts as an exponential function of wavenumber. The rate of decay of the spectrum in model (2) can be approximated by combining two models with two parameters; the exponential model characterizes the linear decay rate, whereas the power-law model characterizes the nonlinear decay rate (Chen et al., 2015a, 2015b). In recent years Cheng and his research group (Cheng, 2012; Wang et al., 2011; Chen et al., 2015a, 2015b; Liu et al., 2013) developed Singularity Mapping Technique based on a density–area (C–A) fractal model and has been applied to extract weak gravity and magnetic as well as geochemical anomalies. From a fractal or multifractal point of view, a measure is denoted as $\mu(B_Q(\varepsilon))$ with the size ε located at Q, the object's fractal properties can be characterized by studying how $\mu(B_Q(\varepsilon))$varies with decreasing ε. $\mu(B_Q(\varepsilon))$ follows a power-law relationship with ε: $\mu(B_Q(\varepsilon)) \propto \varepsilon^{\alpha(Q)}$, where $\alpha(Q)$ is known as the coarse Hölder exponent, also termed the local singularity index (Chen et al., 2013). Cheng (1997, 1999b) proposed the following ratio of the logarithmic transformation of μ and ε to estimate the value of the singularity index.

$$\alpha_Q = \log(\mu(\varepsilon_1)/\mu(\varepsilon_2))/\log(\varepsilon_1/\varepsilon_2) \tag{4}$$

Where $\mu(\varepsilon_1)$ and $\mu(\varepsilon_2)$ are measures corresponding to ε_1 and ε_2, respectively. The singularity index acts as a high-pass filter and can be divided into three cases for evaluating gravity anomaly and detecting the density properties: $\alpha < 2$ indicates high density, $\alpha > 2$ indicates low density, and $\alpha \sim 2$ indicates the lithological contacts with different densities. Therefore singularity value decomposition based on multifractal is a crucial technique which can be applied to the decomposition of mixed gravity fields for investigation of specific geological structures such as faults, concealed granites and Moho discontinuity and in turn to extract geophysical and geochemical and geological anomalies associated with mineralization from their complicated geological backgrounds.

In this paper, the SVD based on multifractal model are used for decomposing the gravity data surveyed at scale of 1:200,000 of the Gejiu tin polymetallic ore field to extract gravity components (anomalies) which might reflect deeply and shallowly buried geological structures and geological bodies associated with the tin polymetallic mineralization in order to provide evidences for prospecting deeply buried ore bodies.

2. Principle and methodology

With the SVD, a data set X can be decomposed to be a series of eigenvalues. The SVD can be used for signal and noise separation (Glifford, 2005; Varbie et al., 2004). The eigenvalues derived by means of SVD represent fractal or multifractal distribution described with power-law function. Li (2005) used the multifractal SVD for feature extraction and anomaly identification for mineral exploration.

The singular value decomposition (SVD) is a factorization of a rectangular matrix X into orthogonal matrices

$$X = USV^T \tag{5}$$

Where U is a left eigenvector matrix, S is a diagonal matrix called singular value matrix and V^T stands for a transposition of the right eigenvector matrix. The singular values of X are the positive entries of S which can be entered in decreasing order along its main diagonal and are equal to positive square roots of the eigenvalues (λ_i) of the covariance matrices XX^T and X^TX. Thus

$$S = diag(\sigma_1, \sigma_2, \cdots, \sigma_r) \tag{6}$$

Where $r = rank(X)$, $\sigma_1 \ge \sigma_2 \ge \cdots \ge \sigma_r$, $\sigma_i = \sqrt{\lambda_i}$.

The singular value decomposition of X can be also written as follows:

$$X = \sum_{i=1}^{r} \sigma_i u_i v_i^T \tag{7}$$

where r is the rank of X, u_i is the ith eigenvector of XX^T, v_i is the ith eigenvector of X^TX, σ_i is the ith singular value of X, and $u_i v_i^T$ is an $m \times n$ matrix of unitary rank called the ith eigenvalue of X (e.g. the first eigenvalue, $\sigma_1 u_1 v_1$). According to formula (7), the original matrix X can be rebuilt with all of the eigenvalues. Also if some specific eigenvalues are selected, a sub-matrix can be reconstructed.

The singular values obtained by SVD method have features as follows: (1) they are distributed in decreasing order along main diagonal; (2) they represent different weighting coefficients of eigenvalues; and (3) their squared values (i.e. λ) are equivalent to power spectral density values in Fourier space (Li, 2005).

Relatively few eigenvalues contain the most energy of data set X. The percentage of each eigenvalue (P_i) can be calculated as the following formula (Li, 2005; Freire and Ulrych, 1988):

$$P_i = \frac{\sigma_i^2}{\sum_{j=1}^{r} \sigma_j^2} = \frac{\lambda_i}{\sum_{j=1}^{r} \lambda_j}. \tag{8}$$

3. Application and results

Various types of rocks with different density can lead to singularities of gravity anomalies. In fact, the reason that traditional data process methods based on linear theory like Fourier transform and geostatistics are unsuitable for processing singular data is just because of their nonlinear and nonstationary properties (Cheng, 2008, 2012). Singularity is of typical scale invariant and obey fractal or multifractal distributions. The singular values can be estimated for every location of geological bodies and used for characterizing the anomalies caused by buried geological bodies (Cheng and Zhao, 2011; Cheng, 2012). This may be reasons why SVD is more suitable than Fourier transform in extracting geophysical and geochemical anomalies associated with mineralization from their complicated backgrounds.

Gravity data play an important role in inferring deep-seated geological structures and delineating concealed geological objects such as buried intrusive bodies and ore bodies. Effective use of gravity fields, like other geophysical fields, depends on the establishment of a set of signatures that characterizes forms, sizes and depths, as well as masses of various geological objects and their relationship to mineralization (Pan and Harries, 2000). The most direct information acquired from gravity fields is the density of geological bodies. A strong Bouguer gravity anomaly indicates the presence of geological objects with higher average density than the materials surrounding them. Conversely, a weak Bouguer gravity anomaly indicates the presence of geological bodies with relatively low average density. Because of heterogeneity in the density of geological bodies created during complicated geological processes, even the same lithological unit in different spatial locations can cause different gravity anomalies, whereas different lithological units can produce similar gravity fields. This non-unique correspondence can cause some difficulties in inferring deep-seated geological structures and in delineating concealed geological objects. Thus, intrinsic geological and geochemical information is required. The intensity of gravity anomalies is related not only to the size, but also to the depth of geological bodies. The same scale and type of anomaly might be produced by different lithological units located at different depths. Different scales and types of anomalies are possibly associated with differences in both the lithology and buried depth of geological bodies. These complexities and difficulties mean that new information decomposition techniques are required to identify possible ore-bearing locations from huge amounts of geosciences data. Over the last ten years we have done some significant explorations in that application of SVD and multifractal methods in extraction of buried deeply mineralization information by decomposing geochemical and gravity data (Chen et al., 2006, 2007; Zhao and Chen, 2011; Chen and Zhao, 2012; Huang and Zhao, 2015).

3.1. Geological background and mineralization characteristics of the Gejiu tin polymetallic ore field

The Gejiu tin polymetallic ore field located on the west margin of the Cathaysia block occupies about 1600 km^2 (Fig. 1b). Bounded on the northwest side by the NE-trending Mile-Shizong Fault, it is adjacent to the Yangtze Block; and bounded on the southwest side by the NW-trending ASRR Fault, is adjacent to the Indo-China Block (Fig. 1a and b). This ore field is characterized by widespread Late Cretaceous igneous rocks.

The magmatism in the Gejiu area is represented by: (1) porphyritic granite; (2) equigranular granite; (3) gabbro; (4) granite with contained mafic microgranular enclaves; and (5) alkaline rocks and basic dykes. These intrusions are well exposed in the western part, but buried deeply in the eastern part (Fig. 1b). In the last few decades most research has focused on the porphyritic and equigranular granitoids that have a close spatial relationship to tin polymetallic mineralization. More recent studies have focused on the aspects of the petrogenesis, and evolution of the granitoids and gabbros in the Gejiu ore field. It has been concluded that

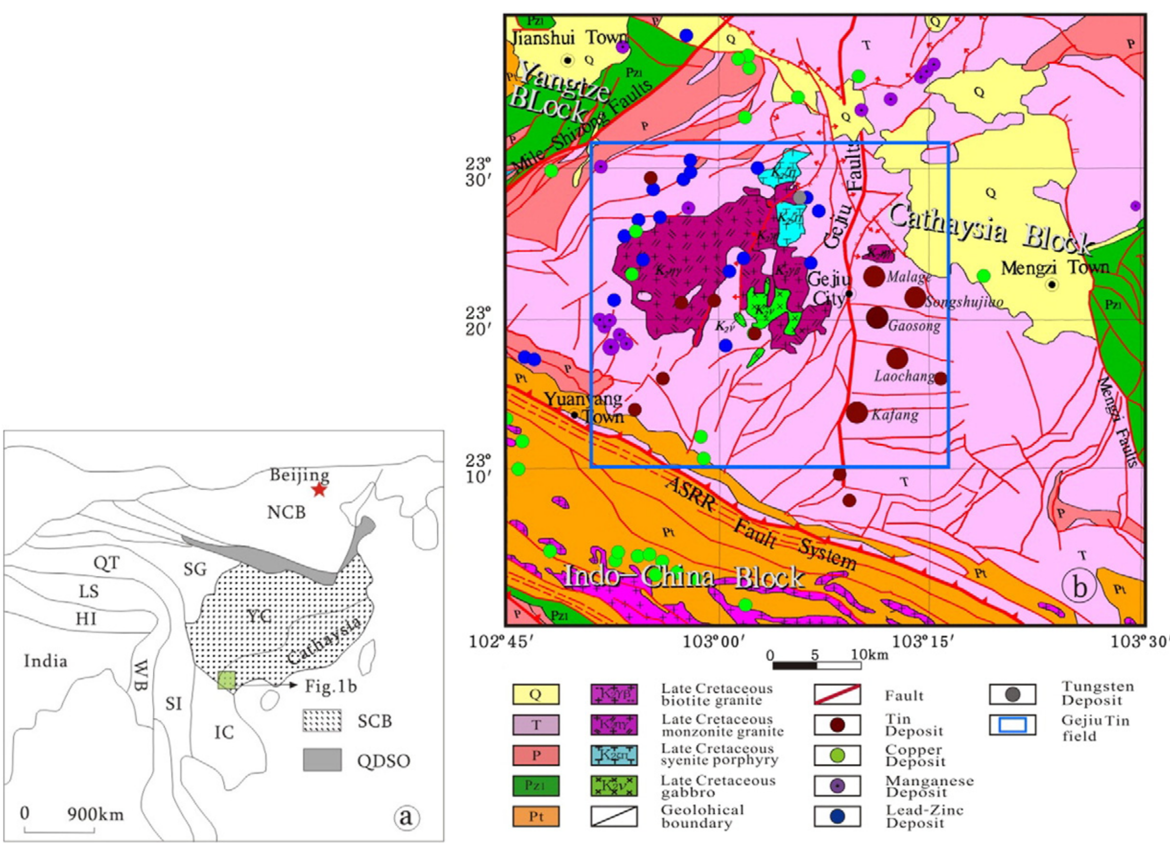

Fig. 1. (a) Geological outline map of eastern Asia, showing major tectonic units and tectonic location where the Gejiu tin polymetallic deposits are situated (from Cheng and Mao, 2010; Cheng et al., 2012, 2013a, 2013b); (b) simplified geological and mineralized map showing distribution of intrusive rocks, strata and various ore deposits in the Gejiu tin polymetallic ore field. SCB—South China Block; NCB—North China Block; YC—Sibumasu Block; QT—Qiangtang Block; SG—Songpan-Ganze Accretionary Complex; WB—Western Burma; HI—Himalaya Orogenic Belt; LS—Lhasa Block; QDSO—Qinlin–Dabie Subduction Orogenic Belt; Q—Quaternary sediments containing tin placer deposits; T—Triassic carbonate rocks embedded with basic volcanic rocks; P—Permian basalt embedded with clastic sedimentary rocks; Pz_1—Lower Paleozoic carbonate rocks embedded with sand rocks as well as shale; Pt—Proterozoic Ailaoshan group metamorphic rocks.

the granites experienced various degrees of fractionation, and the gabbro and some porphyritic granites were formed by interaction between crustal- and mantle-derived magmas. A widespread extension-related magmatic episode affected the entire region in the late Cretaceous, possibly as a lithospheric thinning, basaltic underplating and associated crustal melting result (Cheng and Mao, 2010; Cheng et al., 2013a). In conclusion, the crust–mantle interaction may play an important role in the formation of the granitic rocks.

The outcropped strata in the Gejiu area include mainly the Triassic Sedimentary Formation which consists of more than 3000 m of carbonate in the lower part, and the 1800 m to 2800 m thick fine-grained clastic and carbonate rocks with the intercalated basic lavas in the upper part. The most significant fault in the Gejiu tin polymetallic ore field is the NS-trending Gejiu fault. The Gejiu fault separates the Gejiu field into the eastern and the western sectors (Fig. 1b). In addition to this, other faults are the secondary faults, including the NE-trending, the NW-trending and the EW-trending faults.

The Gejiu tin polymetallic ore deposit is one of the largest tin deposits in the world. Ore reserves include 300 Mt of ~1% Sn ore, 300 Mt of ~2% Cu ore, and 400 Mt of ~3–10% Pb + Zn ore. The tin polymetallic deposit consists of five ore blocks, from north toward south, being named as the Malage Sn–Cu, the Songshujiao Sn–Pb, the Gaosong Sn–Pb–Zn, the Laochang Sn–W–Cu, and the Kafang Cu–Sn ones, respectively. There are four ore types in the tin polymetallic deposit, including greisen, skarn, stratabound cassiterite-sulfide and vein type ore. In each deposit the ore bodies typically occur in an extensive hydrothermal system centered on a shallow Late Cretaceous granitoid cupola. Metal zoning is well developed both vertically and horizontally over the entire field, from W + Be + Bi ± Mo ± Sn ores inside granite intrusions, to Sn + Cu-dominated ores at intrusion margins and farther out to Pb + Zn deposits in the surrounding host carbonate. This zoning pattern is similar to that of other hydrothermal deposits in other parts of the world, indicating a close genetic relationship between magmatism and mineralization (Cheng et al., 2012, 2013b). The complicated geo-processes including evolution-differentiation of the magmas and hydrothermal systems resulted in diversity of abovementioned mineralization.

3.2. Extraction of gravity anomaly information

The gravity data surveyed at grid of 2000 m × 2000 m for this study is provided by Yunnan Geological Survey. The total data resolution is $\pm 2.32 \times 10^{-6}$ m/s^2. The densities of the exposed geological bodies vary from 2.55 to 2.60 g/cm^3 for the granites, range from 2.68 to 2.72 g/cm^3 for the carbonate rocks, change from 2.98 to 3.10 g/cm^3 for the basic and ultra-basic rocks and 4.52 g/cm^3 for massive tin ore within the Gejiu field (Xiong and Shi, 1994).

The SVD is used for analyzing the gravity data surveyed at scale of 1:200,000 within the Gejiu tin polymetallic field (Fig. 2). It has been illustrated by Fig. 2 that the Gejiu ore field displays an irregular negative gravity anomaly with an extension in approximately EW–NE orientation. Freire and Ulrych (1988) defined low-pass X_{LP}, band-pass X_{BP}, and high-pass X_{HP} SVD image terms of the ranges of singular value used.

$$X_{LP} = \sum_{i=1}^{p-1} \sigma_i u_i v_i^T \tag{9}$$

$$X_{BP} = \sum_{i=p}^{q-1} \sigma_i u_i v_i^T \tag{10}$$

$$X_{HP} = \sum_{i=q}^{r} \sigma_i u_i v_i^T \tag{11}$$

The choices of p and q depend on the magnitudes of the singular values themselves. One of the properties of singular processes is the resulting power-law distribution. Here we will use the power-law to determine p and q. The main proposition supporting the non-linear theory and application of power-law models is that mineralization can result from some singular processes, and that mineral deposits can be regarded as the products of some singular processes, and that this singular processes may be characterized by power-law models (Cheng et al., 2009). The square of the singular values (i.e. λ) corresponds to the spectral energy densities of eigenvalues (Li, 2005). Thus, the sum of energy (i.e. a measurement of energy in spectral energy radius or scale) whose squared singular values are larger than λ_i can be written as follows (Li and Cheng, 2004):

$$E(\lambda | \lambda \geq \lambda_i) = \sum_{k=1}^{i} \lambda_k. \tag{12}$$

And its relevant proportion (P) is:

$$P(\lambda | \lambda \geq \lambda_i) = \sum_{k=1}^{i} \lambda_k / \sum_{t=1}^{r} \lambda_t. \tag{13}$$

λ and E (or P) may represent a fractal or multifractal (Li and Liu, 2003; Li and Cheng, 2004; Li, 2005)

$$E \propto \lambda^{\alpha} \tag{14}$$

or

$$P(\lambda | \lambda \geq \lambda_i) \propto \lambda^{\alpha} \tag{15}$$

Because of power law, the curve in log–log plot of λ–E can be separated into several segments due to different slopes. And the break points are p and q (sometimes can be separated into more than 3 segments). The reconstruction of some specific eigenvalues whose singular values in the same segment may be corresponding to specific geological processes.

With the multifractal and SVD methods, p, q in Eqs. (9)–(11) can be determined. The curve in log–log plot of λ–E of gravity signal in the Gejiu tin polymetallic ore field can be separated into three segments according to their different slopes, two break points, $p = 4$, $q = 12$ (Fig. 3). The right segment is made of ranking from λ_1 to λ_3 and the percentage of its energy is about 99.966% of total energy. The reconstructed gravity image with the sum from 1st to 3rd eigenvalues (Fig. 4) can be regarded as low-pass filtered image, which usually reflects buried deeply geological structure and geological bodies associated with the regional ore-forming background. The middle segment is made of ranking from λ_4 to λ_{12}, and the percentage of its energy is about 0.033% of total energy. The reconstructed gravity image with the sum from 4th to 12th eigenvalues (Fig. 5) can be regarded as high-pass filtered image, which usually reflects shallowly buried geological structures and geological bodies associated with the local ore-controlling factors. The left segment is made of ranking from λ_{13} to λ_{38}, and the percentage of its energy only takes up about 0.0012% of total energy, which might be originated from data errors without any geological significance.

4. Results and discussions

The reconstructed gravity component image from the 1st to 3rd eigenvalues is a low-pass filtered image which depicts the buried deeply geological structures and geological bodies. Taking −4 μm/s^2 as threshold value, two negative gravity component anomalies are delineated within the Gejiu tin polymetallic field and its neighboring area. One is an EW-trending negative gravity component anomaly (I) which may reflect a spatial distribution of the Gejiu granitic complex at depth (Fig. 4). The anomaly I indicates that the outcropped granites in the western Gejiu ore field bounded by the Gejiu fault have extended to the eastern

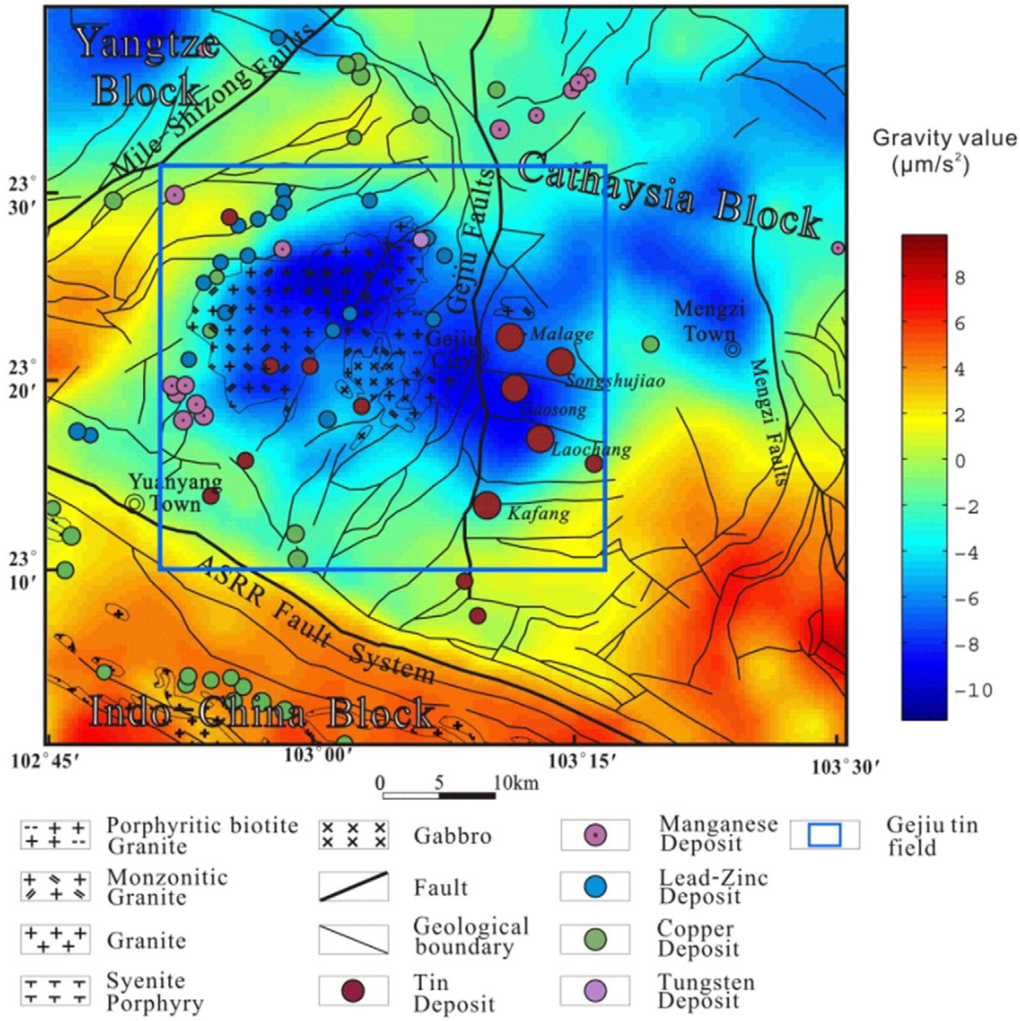

Fig. 2. Original gravity data map with simplified geological and mineralized units showing distribution of intrusive rocks and their gravity anomaly in the Gejiu tin polymetallic ore field.

Gejiu ore field, which has been manifested by drilling and mining engineering (Fig. 6). The various types of tin polymetallic ore deposits within the Gejiu ore field have a close spatial relationship with the granitic complex (Cheng et al., 2012, 2013b). Another negative gravity component anomaly (II) lies on the northeastern side of the anomaly I around which there are a few copper and manganese ore occurrences. The anomaly II is a new polymetallic resource potential area to be explored. The influence area of the granitic complex may be more than that of the negative gravity component anomalies I and II. According to the spatial distribution of the known tin polymetallic ore deposits, the influence area may be a ring one (III) with gravity component anomaly value varying from -2 μm/s^2 to 2 μm /s^2 around the granitic complex (Fig. 4).

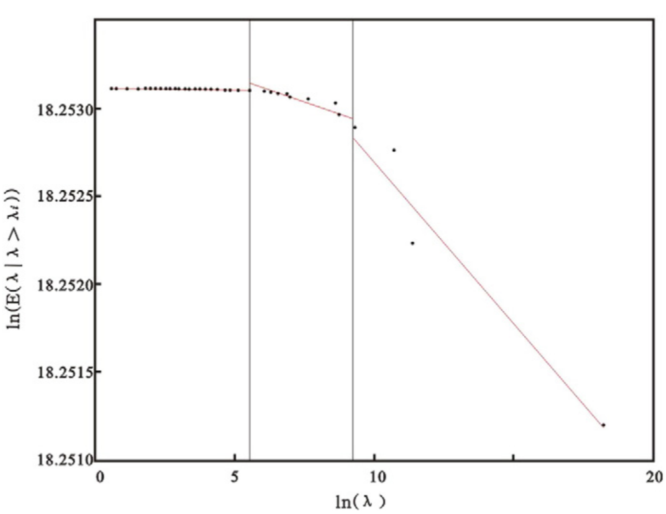

Fig. 3. ln–ln plot of λ–E with two break points of the gravity data in the Gejiu tin polymetallic ore field, $p = 4$, $q = 12$, $\ln(\lambda_4) = 9.24$, $\ln(\lambda_{12}) = 5.89$.

The reconstructed gravity component image from the 4th to 12th eigenvalues is a high-pass filtered image that depicts the shallowly buried geological structure and geological bodies within the Gejiu tin polymetallic field and its neighboring area (Fig. 5). Two negative gravity component anomalies (I and II) are surrounded by a positive gravity component anomaly framework which is made of three groups of NE-trending and two groups of NW-trending positive gravity component anomalies (Fig. 5). The two negative gravity component anomalies correspond to respectively the outcropped granites (I) in the western ore field bounded by the Gejiu fault and the buried granites (II) in the eastern Gejiu ore fields. The positive gravity component anomaly framework may be created from these different orientation of faults filled with basic intrusions such as the gabbro and/or basic dikes. The spatial distribution of almost all types of tin polymetallic ore deposits and the related granites within the Gejiu ore field are restricted by the positive gravity component anomaly framework. All large scale of tin and copper

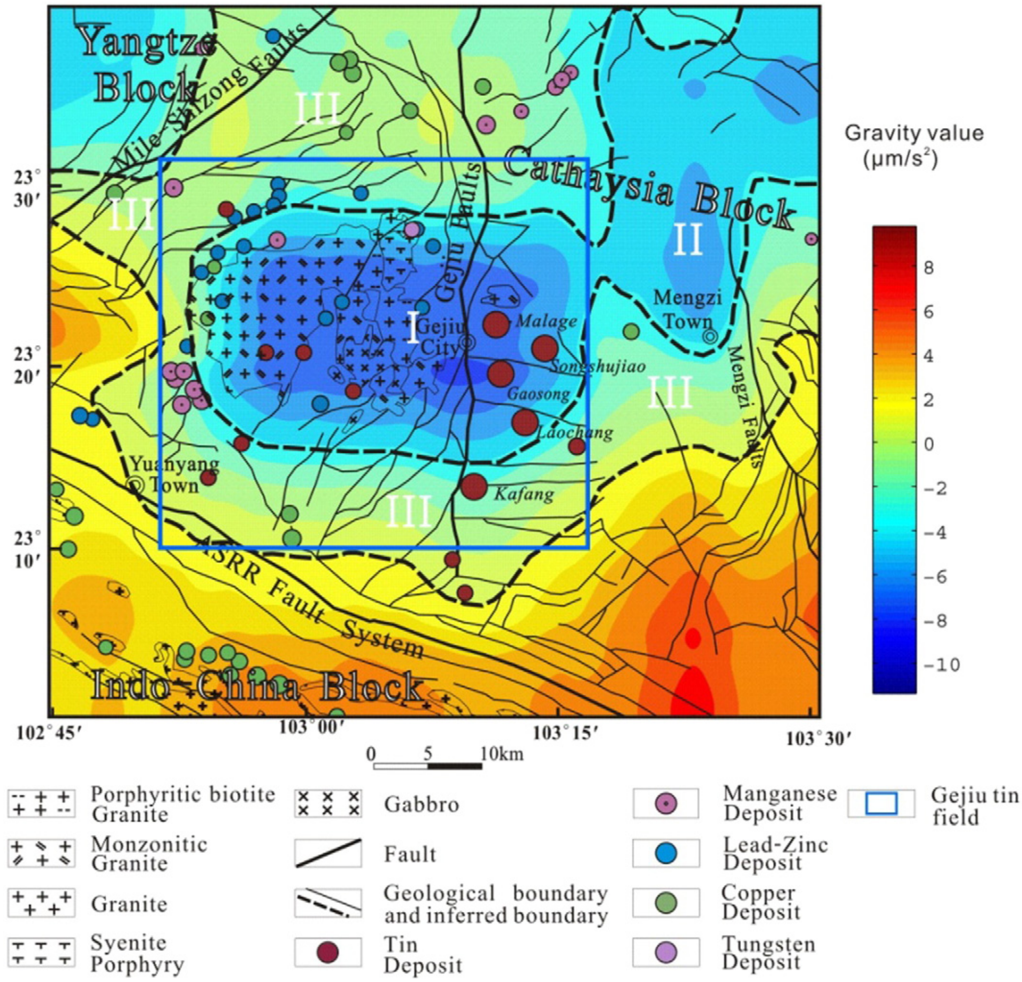

Fig. 4. Reconstructed gravity component image from the 1st to 3rd eigenvalues in the Gejiu tin polymetallic ore field.

deposits are situated at the concealed granites indicating negative gravity component anomaly II(Fig. 5). Taking a geological section along line AA′ in Fig. 5 yields a geological–geophysical pattern crossing the whole Gejiu tin-polymetallic field from north to south, which shows the relationship between the distribution of the granites with tin polymetallic mineralizations and the local gravity anomaly (Fig. 6). During about.

77.4 Ma–85.8 Ma, the Late Cretaceous intrusive complex intruded into the Triassic carbonate rocks with interlayers of basalt, forming four ore types such as greisen, skarn, stratabound cassiterite-sulfide and vein ore in the tin polymetallic field. The local gravity anomaly along the section AA′ reflects mainly the shape fluctuation of the granite complex, tectonics and mineralization. There is a gravity anomaly varying from 2 to 5.5 μm/s^2 from the Malage Sn–Cu ore block toward the Laochang Sn–W–Cu ore block with the shape of the granite complex swelling and the overlying carbonate rocks thinning, but from the Laochang Sn–W–Cu ore block to the Kafang ore block the local gravity anomaly ranging from −5.5 to 3 μm/s^2, displaying rising tendency without the overlying carbonate rocks distinctly thickening, which may imply that the local gravity anomaly variation is influenced not only by lithology but also by tectonics and mineralization.

5. Conclusions

The multifractal singular value decomposition (SVD) could effectively reveal the shallowly and deeply buried geological structure and geological bodies by decomposing gravity field. Combined with the ore-forming geological background of the Gejiu tin polymetallic field, the deeply seated ore-controlling geological factors and the shallowly seated ore-controlling factors could be extracted in proper sequence.

(1) The reconstructed gravity component image from the 1st to 3rd eigenvalues represents a low-pass filtered image which may indicate the buried deeply geological structures and geological bodies. There are two negative gravity component anomalies in the Gejiu ore field. The anomaly I indicates that the outcropped granites in the western Gejiu ore field bounded by the Gejiu fault have extended to the eastern Gejiu ore field at depth, forming one granitic complex. The various types of tin polymetallic ore deposits have a close spatial relationship with the granitic complex. Another negative gravity component anomaly (II) lies on the northeastern side of the anomaly I around which there are a few copper and manganese ore occurrences. The anomaly II is a new polymetallic resource potential area to be explored.

(2) The reconstructed gravity component image from the 4th to 12th eigenvalues represents a high pass filtered image that depicts the shallowly buried geological structures and geological bodies within the Gejiu tin polymetallic ore field and its neighboring area. The two negative gravity component anomalies correspond to respectively the outcropped granites (I) in the western ore field bounded by the Gejiu fault and the buried granites (II) in the eastern Gejiu ore fields. The positive gravity component anomaly framework may be created from these different orientation of faults filled with basic intrusions such as the gabbro and/or basic dikes. The spatial distribution of almost all types of tin polymetallic ore deposits and the related granites within the Gejiu ore field are

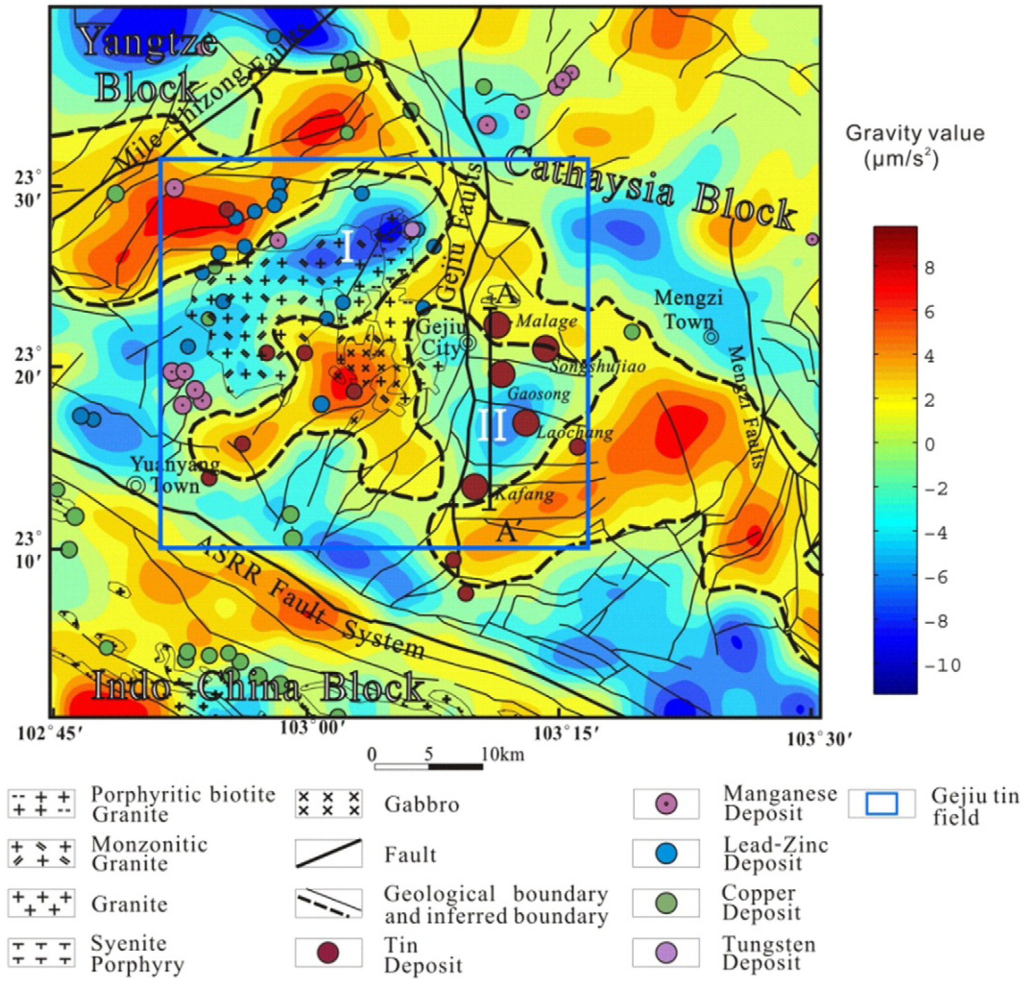

Fig. 5. Reconstructed gravity component image from the 4th to 12th eigenvalues in the Gejiu tin polymetallic ore field.

restricted by the positive gravity component anomaly framework. All large scale tin and copper deposits are situated at the concealed granites indicating negative gravity component anomaly (II).

(3) The Gejiu tin polymetallic ore deposits indicate a typical complexity which is controlled by multi-layers of ore-forming factors such as the granitic complex, faults and carbonates.

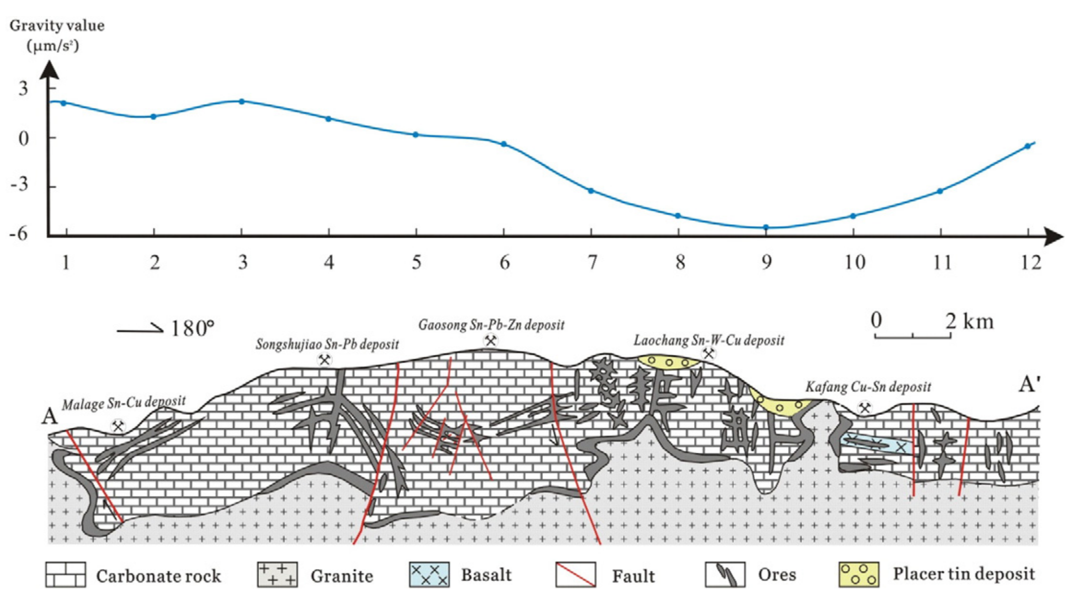

Fig. 6. Spatial relationships between granites, ore bodies and local gravity components in the Gejiu tin polymetallic ore field (modified from Cheng et al., 2012, 2013b).

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