Remote-sensing ore prediction in and around the Linghou copper-polymetal deposit, southeastern China

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Abstract. Taking advantage of the band-ratioing operation, principal component analysis (PCA), and multifractal model, the OLI image was employed to extract iron-stained and hydroxyl alteration in and around the Linghou copper-polymetal mine. Findings showed that the extraction results successfully bypassed the interferences caused by the quite thick vegetational and sedimentary covers, and can accurately locate the Linghou diggings, as well as several suspected ore spots. This study may have contributed a useful case study for in-depth geological remote-sensing analysis.

1. Introduction
It is believed that remarkable is both the advantage and weakness of geological remote-sensing. Remote-sensing technology relies mostly on the capability of the sensor to register spectral signatures and other geological features related to mineral deposits, so the information that came out after analyzing an image was pretty significant but it cannot direct us exactly to what we are looking for. It gives us a good idea of where we should do further research so that we can focus on a specific area instead of wasting resources in places where the possibility of any positive findings is very slim, but allows only the identification of sites with likely occurrence of hydrothermal alteration, without providing a necessary spectral resolution to identify specific minerals because of the broad band configuration of TM/ETM+, particularly in SWIR [1]. Nevertheless, there is no denying that remotely sensed data seem more and more attractive to ore geologists, because it can delineate not only the ore – cause alteration, but also a variety of ore - controlling factors like structure quickly and macroscopically, although remotely sensed geological information is in essence rather weak and susceptible to extrinsic disturbance, e.g., rock-weathering, complex terrain, atmospheric influence, mixed-pixel effects, vegetation, and etc. [2].

The Linghou copper deposit surveyed in this paper is located in northwestern Zhejiang province, southeastern China, densely vegetated even in winter, but abundant in copper-polymetal deposits. Few people have devoted their efforts to remote sensing ore - prediction in this heavily vegetated and...
sediments-covered area, which is, as expected, a more mobile and flexible prospecting approach. It is, however, the focus of our research.

2. Geological Setting
The Linghou Cu-polymetal deposit is located in the eastern Qin-Hang metallogenic belt between the Yangtze and Cathaysian blocks, concretely in western Zhejiang province, eastern China. Several large ore deposits, associated with Mesozoic intrusive rocks, have been discovered here, including Dexing porphyry Cu-Mo-Au, Zhangshiba Pb-Zn, Dahutang porphyry W, Tongcun porphyry Mo(-Cu), Anji skarn-porphyry Fe-Pb-Zn-polymetal, Pingshui Cu, Lizhu iron polymetallic deposits, and so forth.

The Linghou ore deposit (119°11′45″E, 29°29′30″N) is a medium-scaled Cu-Pb-Zn-polymetallic mine that is identified as a sedimentation-hydrothermal reworked deposit [3]. The surrounding strata are mainly upper Devonian and middle to upper Carboniferous, namely the quartz sandstone, sandstone-bearing shale, fine sandstone, and limestone (including the marble and dolomite). Notably, parts of them, especially the carbonate rocks, were strongly altered and metamorphosed. The wall-rock alteration in chronological order appears: calc-silicate (skarn) and phyllic alteration, silification and carbonate alteration. Therein, the phyllic alteration characterized by disseminated sericite and quartz, with minor pyrite and chalcopyrite is well developed within the causative granites; Silicification characterized by quartz in ores or quartz + pyrite + chalcopyrite veins in the strata and granites is closely linked to Cu-Au-Ag mineralization. Carbonate alternation, characterized by earlier recrystallization of dolomite + calcite associated with the Cu-Pb-Zn mineralization, and later calcite clusters in a hydrothermal calcite cave near the ore-bodies, and calcite (+galena) veinlets across the ore and granites, is quite common. Magmatic intrusion and mineralization are obviously controlled by faulted structure which is mainly the product of Mesozoic tectonic movements.

3. Data Collection and Quality Control
The multispectral image (see figure 2) was collected from Landsat 8 OLI_TRIS digital products that are freely downloadable from http://glovis.usgs.gov/. There are eleven bands within an OLI image, and six of them are employed in this article: Band 2 (Blue) with bandwidth: 0.45−0.51 μm, Band 3 (Green): 0.53−0.59 μm, Band 4 (Red): 0.64−0.67 μm, Band 5 (near-infrared, NIR): 0.85 μm−0.88 μm, Band 6 (short wave infrared 1, SWIR 1): 1.57−1.65 μm, and Band 7 (SWIR 2): 2.11−2.29 μm. The Row/Path of the chosen image is 40/119, Data of acquisition: April 14, 2013. Cloud Cover: <0.49%, Sun Azimuth: 128.679°, Sun Elevation: 61. 757°, Spatial Resolution: 30m, Earth-Sun Distance: 1.003009 AU, and Image Quality: 9.

4. Analysis of Multispectral Image

4.1. Pretreatments
Before geochemical analysis, several pretreatments like cutting, atmospheric correction, geometric correction, radiometric calibration, and orthorectification were carried out. At the same time, waters with NDVI (Normalized Difference Vegetation Index) between -0.079 and 0.05 were erased for subsequent analysis, which accounts for ~27.19% of the total area; however it is impossible to completely eliminate the interferences (false anomalies) caused by settlements, (concrete and asphalt) roads, factory buildings, and so forth by using a single pixel-value threshold. In addition, in order to negate as much as possible the effect from illumination conditions related to topographic relief everywhere, the ratioing approach was thus introduced. According to Sabins [2], the band-ratios 4/2 and 6/7 of the OLI image can help to extract iron (Fe⁺) stained and hydroxyl (OH) wallrock alteration, respectively; while the ratio band 5/band 4 leads to an enhancement of vegetation information. With masking, these three ratioing images (bands) were consequently put into the principal component analysis (PCA).

4.2. Principal Component Analysis (PCA)
Aim of PCA is to produce uncorrelated output bands, to segregate noise components, and to reduce the dimensionality of datasets. Normally multispectral data bands are highly correlated, while the principal components (PCs) transformation is used to the output bands. This is done by finding a new set of orthogonal axes that have their origin at the data mean and that are rotated so the data variance is maximized. Actually, PC bands are linear combinations of the original spectral bands, producing more colorful composite images than their spectral color-composite counterparts because the data are uncorrelated. Here the PCA was conducted on the ENVI 5.1 platform. From table 1, based on the principle of statistics, the first principal component (PC1) can shed light on vegetational spectral signature, which contributes nearly 97% of the total variance. PC2 may highlight the iron-stained anomaly, and its contribution of variance is only 2.0%. PC3 turns out to be a reflection of the hydroxyl alteration, contributing less than 1% of the variance. The alteration anomaly patches bands might occur in the lighter colored areas according to reference [4].

| Eigenvalue | PC1     | PC2          | PC3          |
|------------|---------|--------------|--------------|
| Band 6/7   | 0.245006| -0.046941    | 0.968385     |
| Band 4/2   | -0.188566| 0.977446    | 0.095088     |
| Band 5/4   | -0.951007| -0.205901   | 0.230629     |

4.3. Extraction of Alteration Anomaly

As exhibited in figure 1, we used the conventional “average + standard deviation” method to delineate the iron-stained anomaly (in PC2 band), and “average plus 1.5-fold standard deviation” to expose the hydroxyl anomaly (in PC3 band). After the median filtering and field reconnaissance, we noticed that the resulting anomaly patches can cover most of the non-vegetated areas (bare fields), and the most striking Fe-stained “alteration” seems to be a reflection of rubified soil widely distributed in this region, likewise, the delineated hydroxyl alterations are more like a reflection of ordinary quaternary clay minerals (and the illumination intensity everywhere). Due to the topographic relief, most Fe-stained anomalies appear on montanic sunny sides, and many OH⁻ anomalies on the night sides.

4.4. A Further Exploration based on Fractal Model

From above, because of a variety of interference objects, especially the very thick coverage, most anomalies already known are identified as false anomalies, and further information about alteration and metallogenesis seems to be reluctant to detect [5]. According to Cheng [6], a singular physical process could result in anomalous amounts of energy release or material accumulation within a narrow spatial-temporal interval. Alteration and Mineralization can be regarded as a type of singular process due to large amounts of material accumulation and element enrichment, and is thus multifractally distributed [7]. Inasmuch I assume that the hydrothermally altered anomalies closely associated with mineralization is a fractality as well, and have a separable fractal dimension, so that the ore-causing anomaly and the false one can be discriminated. It is possible that the fractal model can act as a new
method determining a more accurate threshold of anomaly, instead of the traditional “mean+n-fold standard deviation” method.

Actually, previous researches have explicitly shown that multifractals can be used to describe ore grade distributions \([8]\), to separate geochemical anomalies, to depict the concentration distribution in the crust as revealed by geochemical survey \([9]\), and many other aspects about geology. If so, it might be very useful for remote sensing ore exploration in regional terrains with good vegetation.

![Figure 2. The spatial distribution map of the alteration anomalies. Note that the iron-stained anomaly threshold is \(-0.000225\) (average) \(+0.028606\) (standard deviation of) \(= 0.028381\), while the hydroxyl threshold is \(-0.000104\) (average) \(+1.5 \times 0.015072\) (standard deviation) \(= 0.022504\).]

In accord with Cheng \([6]\), a fractal model, i.e., a power-law function, could be represented approximately in the following form:

\[
N(r) = Cr^D
\]  

(1)

Where \(r\) is the characteristic linear measure, in figure 3 it stands for the logarithmic pixel-values; \(C\) constant of proportionality (prefactor parameter); \(D\) is known as the generalized fractal dimension, and \(N(r) = N(\geq r)\): number or summation of objects with characteristic linear measurement \(\geq r\). In fact, a lot of geological-geochemical phenomena possess such scale invariance properties, which include rock fragments, faults, earthquakes, eruptions, mineral resources, and oil pools. Their corresponding frequency distributions possess scale-invariant characteristics and can be described as power-law distribution.

Taking logarithms of the equation (1), we have equation (2):

\[
\ln N(r) = -D \ln r + \ln C
\]  

(2)

As shown in figure 3, a plot of \(\ln N(r)\) versus \(\ln (r)\) can produce several straight lines with different slopes, namely fractal dimensions, \(D_1, D_2, \ldots\). For a single straight line, by means of liner least-square regression analysis and the data set \((N(r_i), r_i)\) \((i=1, 2, \ldots N)\), we can evaluate the estimate of the parameter \(D\); while for two straight lines segments fitted by least squares with two slope \(D_1\) and \(D_2\), one dividing point can be determined by the optimum least-square regression method as equation (3), namely the residual sum of squares (RSS).
\begin{align}
\text{RSS} &= \sum_{i=1}^{l_{0}}[\ln N(r_i) + D_1 \ln r_i - \log C_1]^2 + \sum_{i=10}^{N}[\ln N(r_i) + D_2 \ln r_i - \log C_2]^2 \to \text{Min} \\
\text{Where } r_{i_0} \text{ is a dividing point defined as the threshold.} \\
\text{The corresponding computer programme based on MATLAB is found in Zhao }^{[10]} \text{, and in a similar manner, slopes of several scale-invariant segments, as well as the thresholds (} T_n, n=1, 2, 3 \ldots {) \text{ between them, could be figured out.} }
\end{align}

**Figure 3.** the ln \( r \) versus ln \( N(r) \) schema. For (a), only the brightest pixels with the pixel-value above “average+1.5-fold standard deviation” in the PC2 band were involved in the fractal calculation; for (b), the threshold was set as “average + twice standard deviation” in order to eliminate in advance the pixels unrelated to mineralization. \( N_1 \) represents the percentage of the number of pixels falling into the first fractal segment (\( D_1 \)) taking up the total pixels involved. In a similar fashion we can understand the meaning of \( N_2 \) and \( N_3 \).

**Figure 4.** The spatial distribution map of Fe-stained and OH\(^{-}\) anomalies. Note that by visual interpretation, the first iron-stained anomaly (Level II) threshold is \( T_1 \) in figure 3a, while the second one (Level I) is \( T_2 \) in figure 3b. The OH\(^{-}\) threshold is \( T \) in figure 3b. The geological base map (1:250 000) is quoted from Zhao \(^{[10]}\).

Figure 3 records spectral multifractal characteristics in PC2 and PC3 bands (images). After ground-truthing and visual interpretation, I found that \( D_1 \) always corresponding to a very large controlling areas, e.g., in PC2 band, pixels in \( D_1 \) accounts for about 84.46% of the total pixels involved in the
calculation; while in PC3 band, this percentage is about 95.09%, within which there is no obvious mineralization and alteration occurring, particularly most false anomalies in figure 2 are automatically filtered out. As displayed in figure 4, there are six suspected ore-associated areas: iron stained anomalies in (1), which are scattered and smaller in area, have turned out to be agricultural lands, so does the abnormal area (6); (2) is a large-scale bedrock (limestone) out-cropped area, or a quarry; (3) & (5), having a coexistence of Fe stained and hydroxyl anomalies, are proved to be constructions (actually concrete is rich in Fe), and clearings in between and around, however, these anomalies should not be ignored because they are very close to the Linghou mine; finally, (4) having the most significant anomaly happens to be the center of the Linghou diggings. From above, we can come to the conclusion that the segments $D_1$ of PC2 and $D_2$ of PC3 are more like a reflection of mineralization, while $D_2$ of PC2 (PC3?), namely the scattered anomalies around Linghou, perhaps has a sense of ore prediction. According to Zhao [10], nearby the Linghou mine, there are several concealed copper-polymetallic ore-spots like the small-scale Shiershan deposit (119°13′40″E, 29°31′33″N)—close to (6), the small scale Baisha Au-Cu-Pb-Zn deposit (119°11′47″E, 29°29′21″N)—close to (4), the Shanwu Cu-Fe ore-spot (119°13′19″E, 29°30′10″N)—abnormal indications appear when the threshold falls to approximately 0.04, which are, however, accompanied by a lot of false anomalous pattern-spot all over the map, and etc. On the other hand, the presence of vegetation cover, rapid urbanization, extensive weathering and recent non-consolidated deposits, together with the phenomena [11]: different objects with the similar spectral responses and the same object having different spectral features, may hinder the detection of alternative anomalies more or less thus a further ground truthing is indispensable [12].

4.5. Discussion

Hydrothermal alteration and mineralization, as natural geological processes, exhibit spatial pattern with fractal property [13], e.g., Cheng and Li [14] proved the multifractality of Landsat TM bands (except band 6) and accomplished hydrothermal alteration mapping of Au/Cu mineralization in the Mitchell-Sulphurets ore district, Canada. The PCA method is devoted to the appraisal of low and gentle anomalies or indistinct weak anomalies, it, unfortunately, ignores the fact that multifractal properties of geological landscapes including remote sensing information have become widely recognized recently [8], and cannot separate these spatially intertwined fractals or mono-fractals (ranges of scale-invariant): $D_1$ is a reflection of regional, large-scale fractal clustering, where systematic and non-altered factors play a leading role; while $D_2$, $D_3$ can reflect local and ore-related fractal clustering characteristics. Zhao et al. [10] pointed out that the scale-independent segment corresponding to mineralized alteration is always a result of distinct geological and geochemical mechanisms which are much more efficient, and is thus separate from other segments with significantly different slopes, in which non- and false anomalies occur. Inasmuch comparing figure 3 with 4, at the cost of anomalous area, we can find that the fractal method used to classify DN (digital number) values in the satellite imagery is apparently more targeted and essential than traditional approaches.
According to field geological investigation, there are two phases of ore alteration in this deposit: the first one is relating to silicification, sericitization, kaolinitization, pyritization and etc., developing within the quartz-sandstone zone which is the footwall relative to the mother lode (figure 5) and associated with submarine exhalation or hot spring [3], we found such alteration and mineralization at 29°29′17.04″N, 119°12′5.69″E, not far from the unique senior-level Fe-stained area in figure 4, due to a thick burial depth however, there is no more remotely-sensed anomalies shows occurring nearby. The second one is mainly skarnization and marbleization (figure 6) accompanying Cu-Pb-Zn-polymetal minerals, which has a close bearing on the Mesozoic granodiorite-porphyries. These alterations develop around the intrusion-related apophyses which is the hanging wall relative to the mother lode. Because the samples in figure 6 were sampled underground, together with the seriously vegetated ground surface, it is impossible for remote sensing signals to capture these information.

Seemingly, authentic hydrothermal anomalies have two crucial characteristics: 1) authentic Fe-stained and hydroxyl anomalies derived from an identical granitic-hydrothermal ore system overlap or surround each other, which are associated with the zoning of hydrothermal alteration. Besides, because Fe, whose Clark number is about 6.71% (FeOT), is an extremely abundant element, the coexistence of both alterations are actually in expectation [15]. 2) authentic anomalies show fractal clustering distribution that is characterized by a spectrally separable dimension, unlike false anomalies dispersively distributed all over the region, because in most cases the ore-caused alterations are spatially intrusion-centered.

5. Discussion and Conclusion
Multispectral remote sensing imagery could be taken advantage to ore prediction at three aspects: 1, OH- (hydroxyl) alterative extraction; 2, Fe (iron)-stained alterative extraction; and 3, visual interpretation of ore-controlling geological factors like structure. This paper focused mainly on the former two. The “band-ratioing + PCA + fractal analysis” were applied for anomaly-extracting, and findings showed a satisfactory result that the ore-caused anomaly patches of different types, namely the favorable areas for ore-prospecting, are always ore- or intrusion- centered and overlap each other. Anomalies delineated by traditional methods, on the other hand, are punctate and dispersively distributed in space, rather than centrally distributed like a typical magmatic-hydrothermal mineralized system does [16]. In sum, this article outlined some of the challenges in using Landsat-class data for ore prediction in the badly covered area and how they can be preliminarily overcome.

References
[1] Cavalli R M, Laneve, G, Fusilli L, Pignatt S, Santini F and Fernandezprieto D 2009 Remote sensing water observation for supporting lake victoria weed management Journal of Environmental Management 90 (7) 2199-211
[2] Sabins F F 2009 Remote sensing for mineral exploration Ore Geology Reviews 14 (3-4) 157-83
[3] Zhang D H, Wang K Q, Zhu Y D 2013 Project paper of “regionally metallogenic regularity
and prediction of copper-polymetal deposits in the west-middle section of the Jiang-Shao collision-orogenic belt” (Beijing: China University of Geosciences)

[4] Mozafar R, Dehghani M, Gingerich J and Durocher C 2006 Mineral potential mapping in khoy-oshnavieh area of NW Iran, using landsat etmand aster images Journal of Geological Society of Iran 1(1) 43-51

[5] Hamut T and Zhang X F 2009 A study on the extraction of alternative anomalies information from ETM remote sensing image of arid area Geological Review 25(5) 291-98

[6] Cheng Q 2007 Mapping singularities with stream sediment geochemical data for prediction of undiscovered mineral deposits in gejiu, yunnan province, China Ore Geology Reviews 32(1-2) 314-24

[7] Zuo R, Cheng Q, Agterberg F P 2009 Application of singularity mapping technique to identify local anomalies using stream sediment geochemical data, a case study from gangdese, tibet, western China Journal of Geochemical Exploration 101(3) 225-35

[8] Blenkinsop T 2015 Scaling laws for the distribution of gold, geothermal, and gas resources Pure & Applied Geophysics 172(7) 1-12

[9] Agterberg F P 2007 Mixtures of multiplicative cascade models in geochemistry Nonlinear Processes in Geophysics 14(3) 201-09

[10] Zhao B 2015 A Comparative Study of Enrichment Regularity of Ore-forming Elements between Zhexi (western Zhejiang province) and Nanling Regions, along the Qin-hang Metallogenic Belt in southeastern China (Doctoral Dissertation of China University of Geosciences (Beijing))

[11] Köhler P and Huth A 2010 Towards ground-truthing of spaceborne estimates of above-ground life biomass and leaf area index in tropical rain forests Biogeosciences 7(3) 2531-43

[12] Ahmadian N, Ghasemi S, JeanPierre W 2016 Comprehensive study of the biophysical parameters of agricultural crops based on assessing landsat 8 OLI and landsat 7 ETM+ vegetation indices Giscience & Remote Sensing 53(3) 337-59

[13] Shahriari H, Ranjar M and Honarmand M 2013 Image segmentation for hydrothermal alteration mapping using PCA and concentration-area fractal model Natural Resources Research 22(3) 191-206

[14] Cheng Q and Li Q 2002 A fractal concentration–area method for assigning a color palette for image representation Computers & Geosciences 28(4) 567-75

[15] Rudnick R L and Gao S 2003 Composition of the Continental Crust Treatise on geochemistry 3 1-64

[16] Cooke D R, Hollings P and Walshe J L 2005 Giant porphyry deposits: characteristics, distribution, and tectonic controls Economic Geology 100(5) 801-18