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Construction, Test and Application of a Tungsten Metallogene Named MGW11: Case Studies in China

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Abstract: Geochemical gene is a new promising concept proposed recently in the discrimination and traceability of geological materials and is also a useful tool to recognize geochemical anomalies in mineral exploration. Based on the lithogenes of LG01 and LG03, geological materials can be classified into nine types of LG_CR compositionally. With respect to geological materials with 11 types of LG_CR, in order to eliminate the lithological influence and to further narrow the prospecting target area, a tungsten metallogene named MGW11 is proposed for geochemical tungsten exploration after the tungsten metallogene MGW. Six weathering profiles of 11 types of LG_CR developed on granitic intrusions in different areas in China are selected to test the stable properties such as heredity and inheritance of MGW11 and MGW. The results indicate that MGW11 and MGW metallogenes illustrate stable properties during rock weathering regardless of weathering degrees, although gene variations of MGW11 and MGW are also observed during extreme weathering. Based on the regional geochemistry survey data in the Lianyang area in south China, where stream sediments are mostly 11 types of LG_CR compositionally, geochemical maps of mineralization similarities of MGW11 and MGW are contoured, and the anomaly areas are determined on the mineralization similarity value of ≥40%. Comparing the tungsten deposits and anomaly areas determined on MGW11 and MGW metallogenes spatially, a total of six polymetallic W deposits recognized in the study area are all located in the anomaly areas. Therefore, mineralization similarities of MGW11 and MGW can be viewed as useful integrated indices on geochemical tungsten exploration. In areas with 11 types of LG_CR compositionally, anomaly areas determined on the MGW11 are smaller than those on the MGW, which indicates that MGW11 is more efficient than MGW in targeting W deposits during tungsten prospecting because of the elimination of the lithological influence.

Keywords: geochemical gene; MGW; LG_CR; mineralization similarity; Lianyang

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1. Introduction

Geochemical gene is a new promising concept proposed recently in the discrimination and traceability of geological materials [1,2] and is also a useful tool to recognize geochemical anomalies in mineral exploration [3,4]. Geochemical gene is proposed and illustrated firstly as a lithogene [5] named LG02, then followed by lithogenes called LG01 [6] and LG03 [7], gold metallogene (MGAu) [3], and tungsten metallogene (MGW) [4], and REE (rare earth elements) genes called REEG01 and REEG02 [6]. Therefore, there are a total of seven geochemical genes reported till now, which were introduced and reviewed by Gong et al. [1] recently.

With respect to lithogenes LG01 and LG03, their gene properties of heredity and inheritance during weathering have been tested on lots of weathering profiles developed over different lithological rocks in different climate zones in China [6–8] according to the similar gene criterion of ≥80% on gene similarity [1]. Their application in classifying

geological materials is useful and suitable for fresh and altered rocks and weathered products such as soils and sediments [2]. The classification method is introduced here briefly. The ideal acidic rock in China (a virtual rock sample represented by the elemental abundance of acidic rock in China compositionally) has the same gene code of 10202020202 on LG01 and LG03, and the ideal basic rock in China also has the same gene code of 12020202020 on these two lithogenes [6,7]. The gene similarity of a sample relative to the ideal acidic rock is called the sample's acidic similarity and can be labeled as R_{Acidic}. According to this definition, the R_{Acidic} of the ideal acidic rock in China is 100%, while the R_{Acidic} of the ideal basic rock in China is 0%. Geological materials can be classified into three groups acidic-like composition with $R_{\text{Acidic}} \geq 80\%$ labeled 1, intermediate-like composition with R_{Acidic} between 75% and 25 labeled 2, and basic-like composition with $R_{\text{Acidic}} \leq 20\%$ labeled 3. In order to integrate the classification results of LG01 and LG03, LG_CR (classification results of lithogenes) with a double-digit is proposed by Wu et al. [2]. The classification result of LG01 is put as the first digit, and the result of LG03 is the second digit. There is a total of nine types theoretically of LG_CR classified based on LG01 and LG03 as 11, 12, 13, 21, 22, 23, 31, 32, and 33 types. The 11 types of LG_CR of a sample indicates that the values of R_{Acidic} of LG01 and LG03 of the sample are all $\geq$80%. Therefore, the result of LG_CR can be used to classify geological materials [2].

With respect to the metallogenes of MGAu and MGW, their gene properties of heredity and inheritance during weathering have also been tested in China [3,4]. The ideal geochemical background samples (all indicator elements are clearly lower than their immobile elements in gene spectral lines) have the same metallogene code of 10202020202 on MGAu and MGW. In contrast, the ideal ore samples (in which indicator elements are enriched clearly in gene spectral lines) will have the same metallogene code of 12020202020 on these two metallogenes. Like the above mentioned on lithogenes, the gene similarity of a sample relative to the ideal ore sample is called the sample's mineralization similarity and can be labeled as R_{IdealOre}. According to this definition, the R_{IdealOre} of the ideal ore sample is 100%, while the R_{IdealOre} of the ideal background sample is 0%. The application of metallogenes is that their R_{IdealOre} can be viewed as an integrated index of recognizing geochemical anomalies for mineral prospecting, and the mineralization similarity (R_{IdealOre}) value of 40% can be viewed as the criterion to discriminate samples with or without mineralization [1,3,4]. Although the metallogenes have been used well in geochemical exploration [4,9], the anomaly area determined on the R_{IdealOre} is commonly too large than deposit areas, which is unfavorable to targeting deposits promptly and precisely during prospecting. This large anomaly area determined on R_{IdealOre} resulted from the elemental reference values during the metallogenes' construction. The reference values are determined by the elemental abundances of acidic, intermediate, and basic rocks in China. Therefore, the R_{IdealOre} index is applicable to geological materials ignoring the lithology of basic-like, intermediate-like, or acidic-like compositions. If the target deposits, such as tungsten deposits, are located in the acidic-like composition area, such as the 11 types of LG_CR area, the determined anomaly areas on the R_{IdealOre} of MGW are certainly larger than the target area. Therefore, a tungsten metallogene aiming at 11 types of LG_CR materials should be constructed to substitute the MGW to determine anomaly areas more efficiently.

In this paper, a tungsten metallogene named MGW11 aiming at 11 types of LG_CR materials is constructed firstly. Then the heredity and inheritance properties of MGW11 are tested on lots of weathering profiles developed over 11 types of LG_CR rocks in different climate zones in China. Finally, the R_{IdealOre} of MGW11 is used to determine geochemical anomaly areas in the Lianyang area of south China, and the results are compared with those derived from the MGW.

2. Construction of MGW11

A geochemical gene is commonly constructed on five steps as a selection of elements, determination of reference values, spectral line and codes, calculation of similarity, and sequence of elements [1,3]. On the basis of the MGW metallogene proposed by Gong et al. [4],

the selected elements and their sequences of MGW can be adopted to construct the new tungsten metallogene named MGW11 here. In addition, the methods of coding spectral lines and calculating gene similarities are also adopted during the construction of the MGW11. Therefore, the main task or key step to construct the MGW11 is the determination of reference values for each selected element.

In MGW and MGAu metallogenes, reference values are determined on the abundances of five geological materials in China, which are acidic rock, intermediate rock, basic rock, soil, and stream sediment [10]. The reference values of the six immobile elements, Ti, Th, Nb, Zr, La, and Y, were calculated as

$$C_{\text{ref}} = 10^{(\lg C_{\text{min}} - 0.1)} \quad (1)$$

where C_{ref} is the reference value and C_{min} is the minimum abundance of each element in the five materials [3]. While references values of the five indicator elements as Cu, W, Sn, Zn, Mo in MGW were calculated as

$$C_{\text{ref}} = 10^{(\lg C_{\text{max}} + 0.1)} \quad (2)$$

where C_{max} is the maximum abundance of each element in the five materials [4]. The spectral lines of MGW of the five materials are listed in Figure 1a. The gene codes of the five materials are the same as 10202020202, which is the ideal background material's metallogene code.

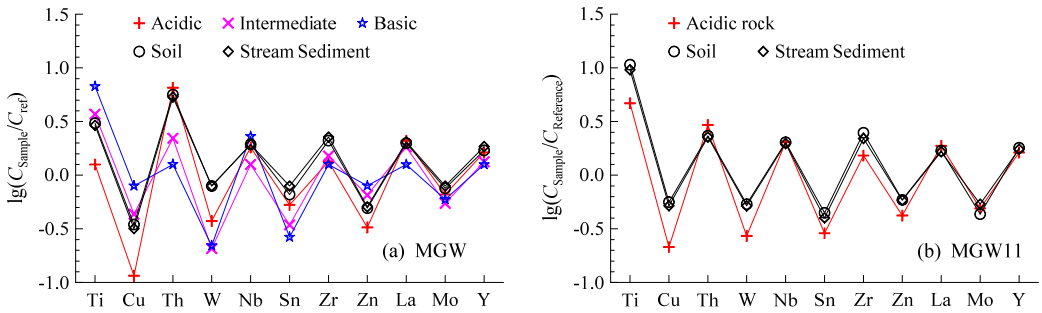


Figure 1. Spectral lines of MGW (**a**) and MGW11 (**b**) metallogenes for geological materials in China. Sample data in (**a**) are from Chi and Yan [10] and data in (**b**) are from Chi and Yan [10], Hou et al. [11], Xiang et al. [12] respectively.

With respect to the MGW11, reference values are determined on elemental abundances of a total of 190 geological materials in China, including 85 records of acidic rocks from Chi and Yan [10], 48 records of soils from Hou et al. [11], and 57 records of stream sediments from Xiang et al. [12] which are all 11 types of LG_CR compositionally. The reference values of the six immobile elements, Ti, Th, Nb, Zr, La, and Y, were calculated as

$$C_{\text{ref}} = 10^{(\lg C_{\text{min}} + 0.1)} \quad (3)$$

The references values of the five indicator elements, Cu, W, Sn, Zn, and Mo, in MGW, were calculated as

$$C_{\text{ref}} = 10^{(\lg C_{\text{max}} - 0.1)} \quad (4)$$

where C_{ref} is the reference value and C_{min} and C_{max} are the minimum and maximum abundances of each element in the 190 materials in China. The spectral lines of MGW11 of the three materials are listed in Figure 1b with the same gene code of 10202020202, which is the ideal background material's gene code. The elemental sequence and reference values of MGW and MGW11 are listed in Table 1.

Table 1. Reference values for tungsten metallogenes of MGW and MGW11.

Gene Elements	Ti	Cu	Th	W	Nb	Sn	Zr	Zn	La	Mo	Y	References
Sequence No.	1	2	3	4	5	6	7	8	9	10	11	–
MGW	1406	69.2	2.22	2.27	8.26	3.78	119	138	19.1	1.06	13.5	Gong et al. [4]
MGW11	378	37.4	4.94	3.13	7.4	6.95	105	107	21.3	1.43	13.5	This study

Note: Unit in μg/g.

If a sample of 11 types of LG_CR is mineralized during tungsten ore-forming processes, indicator elements will be enriched relative to the other six immobile elements. If the five indicator elements were all enriched clearly, the sample would have the MGW11 code of 12020202020 and is called the ideal ore sample. Therefore, the MGW11 similarity between the ideal ore and the ideal background sample is 0%. As aforementioned, the genetic similarity between a sample and the ideal ore is called the sample's mineralization similarity labeled as R_{IdealOre}, which can be used as an index to discriminate a geological material as an anomaly or background sample. The 40% value of the R_{IdealOre} was suggested as the criterion to discriminate samples with or without mineralization or to classify anomaly or background samples [3,4] which is also adopted here to the MGW11 gene.

3. Test of MGW11

3.1. Materials

The test of a geochemical gene focuses on stable properties such as heredity and inheritance during rock weathering [1]. Here six weathering profiles of 11 types of LG_CR are selected from literature to test the properties of the MGW11. The six weathering profiles are labeled as DH31, TL19D04, LHK55, and LC19 from northeast to southwest in China and LY18D13 and LY18D06 in Liangyang area of south China (Figure 2, Table 2).

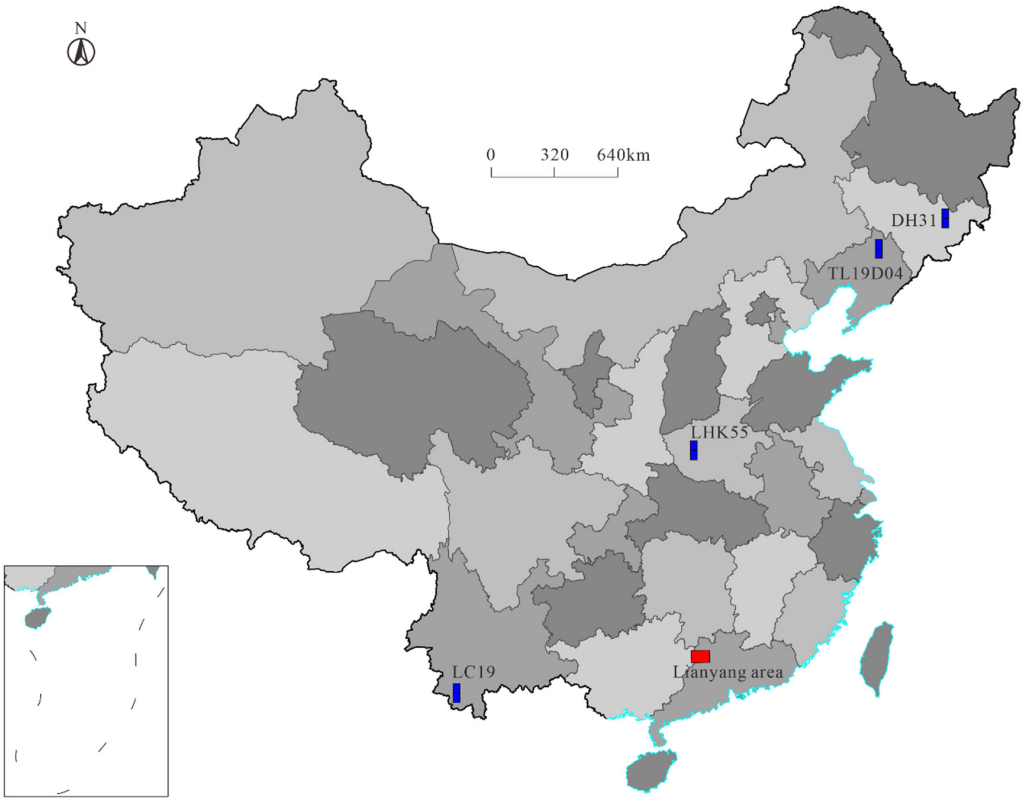


Figure 2. Locations of weathering profiles and Lianyang area in China. LY18D13 and LY18D06 weathering profiles are located in Lianyang area.

Table 2. Information on weathering profiles.

Profiles	Parent Rock	Longitude	Latitude	Depth (m)	Sample Count	References
DH31	Monzogranite	E 128°22′22″	N 43°18′44″	11	13	[8]
TL19D04	Monzogranite	E 123°56′44″	N 42°26′16″	6	9	[13]
LHK55	Granite	E 112°07′09″	N 33°49′06″	5.2	11	[14]
LC19	Granite	E 100°18′05″	N 22°12′24.2″	14	20	[15]
LY18D13	Granite	E 112°15′57.6″	N 24°23′00″	14.6	23	[16]
LY18D06	Granite	E 112°4′26.76″	N 24°9′39.96″	25	29	[17]

The DH31 profile (E 128°22′22″, N 43°18′44″) developed over the Dunhua monzogranite in a temperate monsoon climate. The depth of DH31 profile is ca. 11 m, and 13 samples are collected sequentially from the topsoil downward to the monzogranite. Details, including descriptions, elemental concentrations, and the analytical qualities of these samples, can be found in Reference [8]. The TL19D04 profile (E 123°56′44″, N 42°26′16″) formed on the Tieling monzogranite in a temperate continental monsoon climate. The depth of TL19D04 profile is ca. 6 m, and 9 samples are collected sequentially from the topsoil downward to the monzogranite. Details of these samples can be found in Reference [13]. The LHK55 profile (E 112°07′09″, N 33°49′06″) developed over the Taishanmiao granite in a warm temperate continental monsoon climate. The depth of LHK55 profile is ca. 5.2 m, and 11 samples are collected sequentially from the topsoil down to the granite. Details of these samples can be found in Reference [14]. The LC19 profile (E 100°18′05″, N 22°12′24.2″) formed on the Lincang granite in a subtropical monsoon climate. The depth of LC19 profile is ca. 14 m, and 20 samples are collected sequentially from the topsoil down to the granite. Details of these samples can be found in Reference [15].

The LY18D13 profile (E 112°15′57.6″, N 24°23′), developed over the Lianyang granite in a subtropical monsoon climate. The depth of LY18D13 profile is ca. 14.6 m, and 23 samples are collected sequentially from the topsoil down to the granite. Details of these samples can be found in Reference [16]. The LY18D06 profile (E 112°4′26.76″, N 24°9′39.96″), also developed over the Lianyang granite, is ca. 25 m, and 29 samples are collected sequentially from the topsoil down to the granite, which details including descriptions, elemental concentrations, and their analytical qualities can be found in Reference [17].

3.2. Results

Based on the reported elemental concentrations of samples from each weathering profile, weathering indices including CIA and WIG, acidic similarities (R_{Acidic}) of LG01 and LG03 lithogenes, samples' similarities relative to the top soil and the bottom bedrock, mineralization similarities (R_{IdealOre}) of MGW and MGW11 metallogenes are calculated for each weathering profile and illustrated in Figures 3 and 4.

The CIA (chemical index of alteration) was developed by Nesbit and Young [18] in reconstructing paleoclimate from Early Proterozoic sediments, and the WIG (weathering index of granite) was proposed by Gong et al. [19] to describe the weathering degrees of weathered granitic products in the absence of CO_2 contents. The calculation methods used here were detailed and described by Wu et al. [8]. The calculation methods on gene codes and similarities used here can be found in Reference [1]. Acidic similarities (R_{Acidic}) of LG01 and LG03 in each profile were calculated firstly to check whether their products are 11 types of LG_CR or not. The gene similarity (R) of samples is calculated relative to their bedrock (heredity property) labeled as R_{Bedrock}, their top soil (inheritance property) labeled as R_{Topsoil}, and the ideal ore (mineralization similarity) labeled as R_{IdealOre} respectively in each weathering profile (Figures 3 and 4).

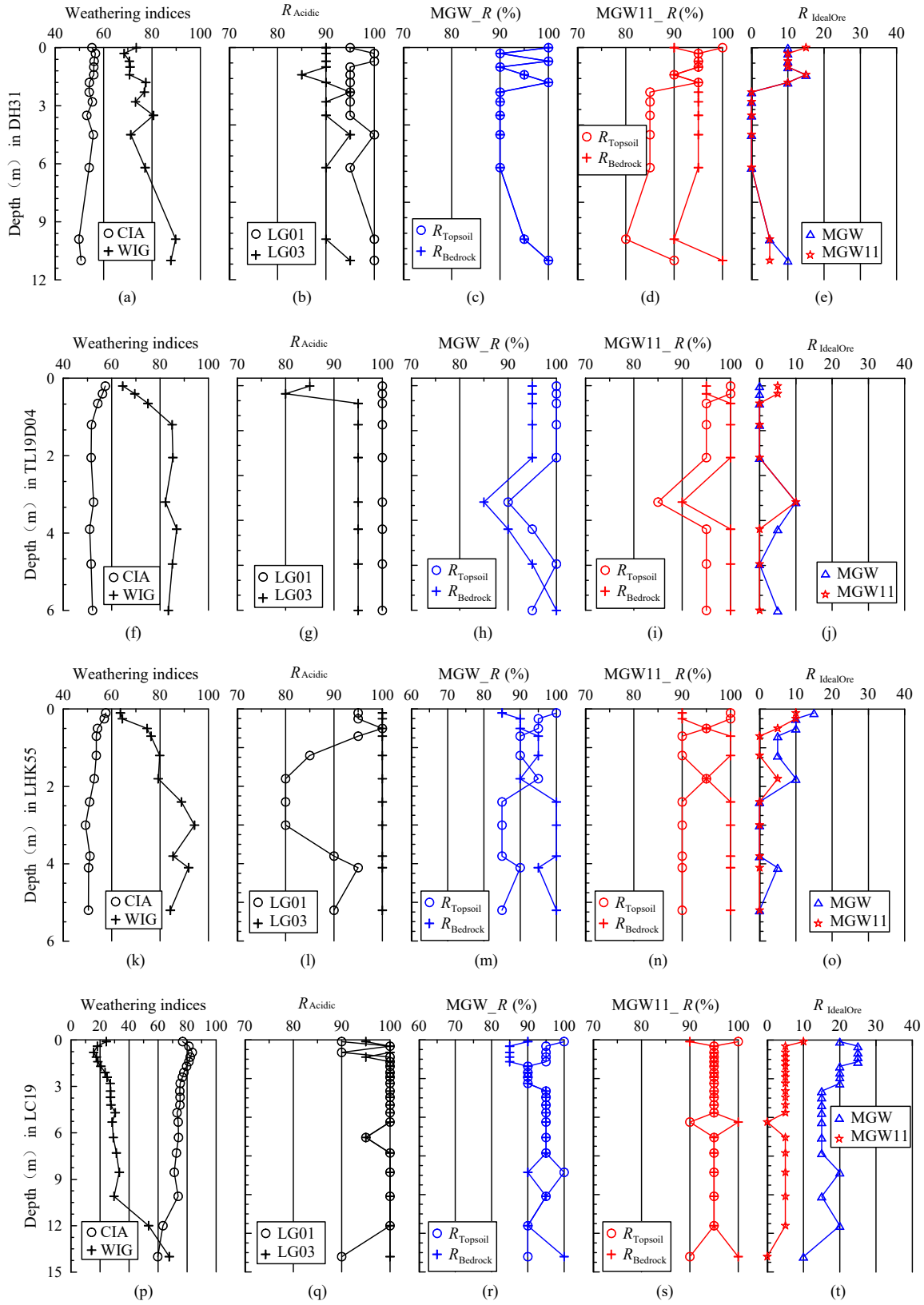


Figure 3. Weathering indices and gene similarities of samples from weathering profiles of DH31, TL19D04, LHK55, and LC19. (**a**–**e**) are the weathering indices, acidic similarities, similarities of MGW, similarities of MGW11, and mineralization similarities respectively in profile DH31. (**f**–**j**) are those in profile TL19D04, (**k**–**o**) are those in LHK55, and (**p**–**t**) are those in LC19.

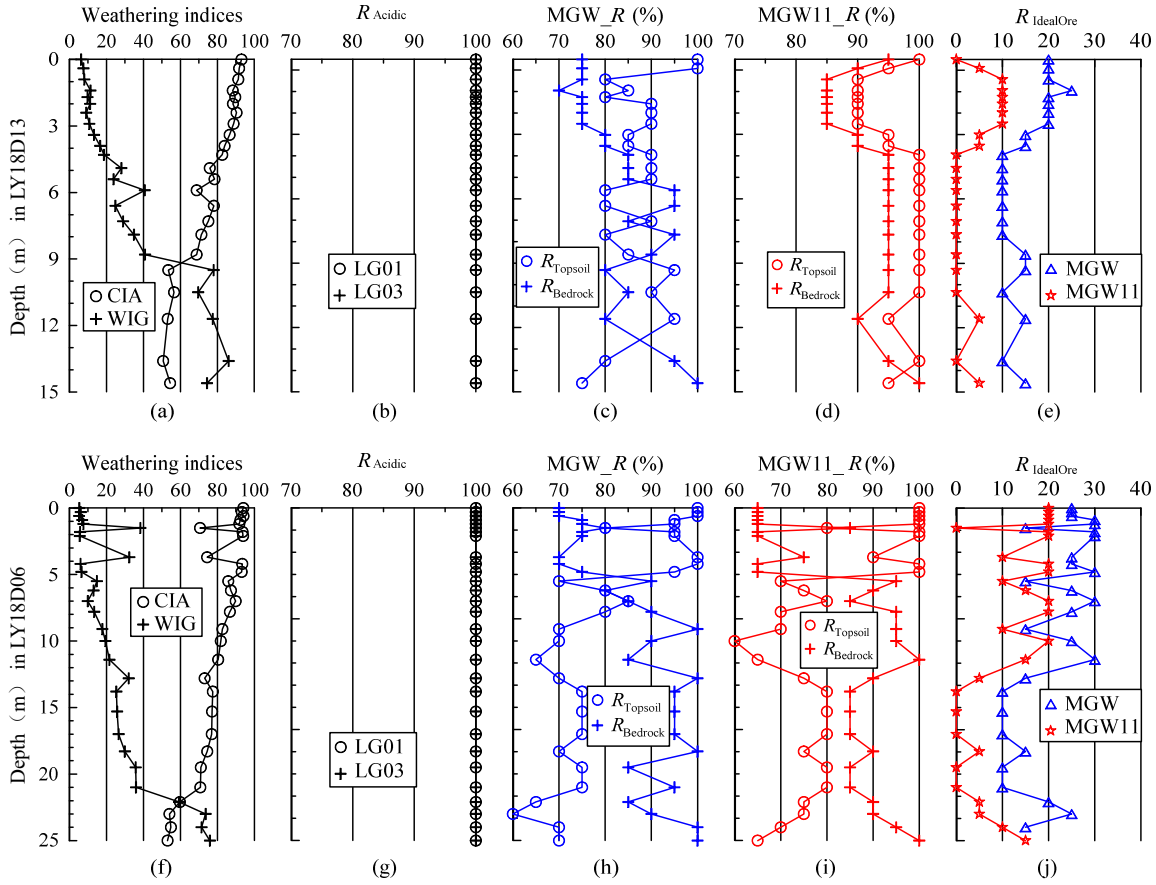


Figure 4. Weathering indices and gene similarities of samples from weathering profiles of LY18D13 and LY18D06 in Lianyang area. (**a**–**e**) are the weathering indices, acidic similarities, similarities of MGW, similarities of MGW11, and mineralization similarities respectively in profile LY18D13. (**f**–**j**) are those in profile LY18D06.

The CIA values of samples from DH31, TL19D04, and LHK55 profiles range from 49.8 to 56.6, from 50.9 to 57.4, and from 49.2 to 57.6, respectively (Figure 3a,f,k). The WIG values of samples from these three profiles range from 68.5 to 89.8, from 64.6 to 86.9, and from 63.6 to 94.3, respectively (Figure 3a,f,k). According to the classification values of 60 and 80 on CIA [20] and values of 20 and 60 on WIG [6,8], these three profiles have undergone incipient weathering. While CIA values of samples from LC19, LY18D13, and LY18D06 profiles in south China range from 53.0 to 94.1, from 59.8 to 83.6, and from 50.7 to 93.1, respectively (Figures 3p and 4a,f). The WIG values from these three profiles in south China range from 5.2 to 76.0, from 15.6 to 67.8, and from 6.3 to 86.1, respectively (Figures 3p and 4a,f). These values indicate that the profiles in south China have undergone extreme weathering.

The R_{Acidic} of samples from all profiles vary from 80% to 100% on LG01 and LG03 (Figures 3b,g,l,q and 4b,g). According to the classification method proposed by Wu et al. [2], which is also introduced above, samples from the six weathering profiles are all 11 types of LG_CR compositionally.

In Figure 3, all values of $R_{Bedrock}$ and $R_{Topsoil}$ of MGW and MGW11 in the four profiles of DH31, TL19D04, LHK55, and LC19 are ≥80% which indicates good heredity and inheritance of MGW and MGW11 metallogenes in each profile (Figure 3c,d,h,i,m,n,r,s). Values of $R_{IdealOre}$ on MGW are all ≤25%, and values of $R_{IdealOre}$ on MGW11 are all ≤15% (Figure 3e,j,o,t). This indicates that all samples from these four profiles are background samples (rather than anomaly samples) according to the discrimination criterion of 40% of $R_{IdealOre}$.

In Figure 4, values of $R_{IdealOre}$ on MGW are all ≤30%, and values of $R_{IdealOre}$ on MGW11 are all ≤20% (Figure 4e,j). This indicates that all samples from weathering profiles

in the Lianyang area are also background samples according to the discrimination criterion of 40% of $R_{IdealOre}$.

In the LY18D13 profile, values of $R_{Bedrock}$ and $R_{Topsoil}$ of MGW11 (Figure 4d) are all ≥85% which indicates stable heredity and inheritance of MGW11. Except for some upper soil samples, values of $R_{Bedrock}$ of MGW are higher than 80% (Figure 4c), which indicates good heredity of MGW except for some variations in the upper soils with extreme weathering degrees. On the other hand, values of $R_{Topsoil}$ of MGW are higher than 80% except for only the bottom bedrock sample (Figure 4c), which indicates a good inheritance of MGW, excluding the bottom bedrock sample.

In the LY18D06 profile, values of $R_{Bedrock}$ of MGW and MGW11 are ≥80% except in some upper soil samples (Figure 4h,i) with extreme weathering degrees, which indicates good heredities of MGW and MGW11 except in some variations in the upper soils. However, values of $R_{Topsoil}$ of MGW and MGW11 are higher than 80% only in the upper soils (Figure 4h,i), which indicates good inheritance of MGW and MGW11 only in upper soils and gene variations appear relative to the lower or parent samples in this profile.

In summary, stable properties such as heredity and inheritance of MGW11 and MGW are verified in six weathering profiles which are all 11 types of LG_CR compositionally and are all geochemical background samples with different weathering degrees. However, gene variations of MGW11 and MGW are also observed in some extremely weathered samples. With respect to the MGW, MGW11 shows better stability in the 11 types of LG_CR geological materials.

4. Application of Geochemical Exploration in Lianyang Area

The main aim of constructing the tungsten metallogenes such as MGW and MGW11 is to determine geochemical anomalies using their mineralization similarities ($R_{IdealOre}$) as an integrated index for tungsten exploration. With respect to the MGW, MGW11 should be more precise on anomaly determination in the tungsten mineralized area with geological materials of 11 types of LG_CR compositionally on its construction. Therefore, the Lianyang area in south China is selected here to test or illustrate the applications of MGW and MGW11, where some tungsten deposits have been found, and geological materials such as stream sediments are most 11 types of LG_CR compositionally.

4.1. Geographical and Geological Settings

The Lianyang area is located in south China with an area of ca. 5400 km^2 ranging from E 111°47′24″ to E 112°40′12″ with a distance of 90 km from west to east and N 24°02′24″ to N 24°34′48″ with a distance of 60 km from north to south (Figure 5a), which is situated in a typical subtropical monsoon zone with a humid climate. The mean annual temperature is ca. 15.5~20.4 °C. The annual rainfall is ca. 1500~2200 mm, most of which falls in summer, according to the public network data. The topography in the Lianyang area is characterized by foothills, and the elevation is low in the middle, high in the north and south, and with a value of 50 to 1900 m a.s.l. Soils are thickly developed, and the regolith thickness commonly varies from 10 to 25 m depending on the relief. The land is commonly covered by crops or arbors.

The strata in the study area belong to Cambrian, Devonian, Carboniferous, Permian, Triassic, Jurassic, and Quaternary periods, respectively, which petrological descriptions are illustrated briefly in Figure 5a as notes. Faults are mainly trending N-S in the center and NE-SW in the northwestern, and NW-SE in the northeastern. The main intrusion in the study area is the Lianyang granitic complex in which two types of lithology can be recognized gradationally: the medium-grained biotite granite as the main body and the medium-coarse-grained porphyritic-like biotite granite outcropped locally [21].

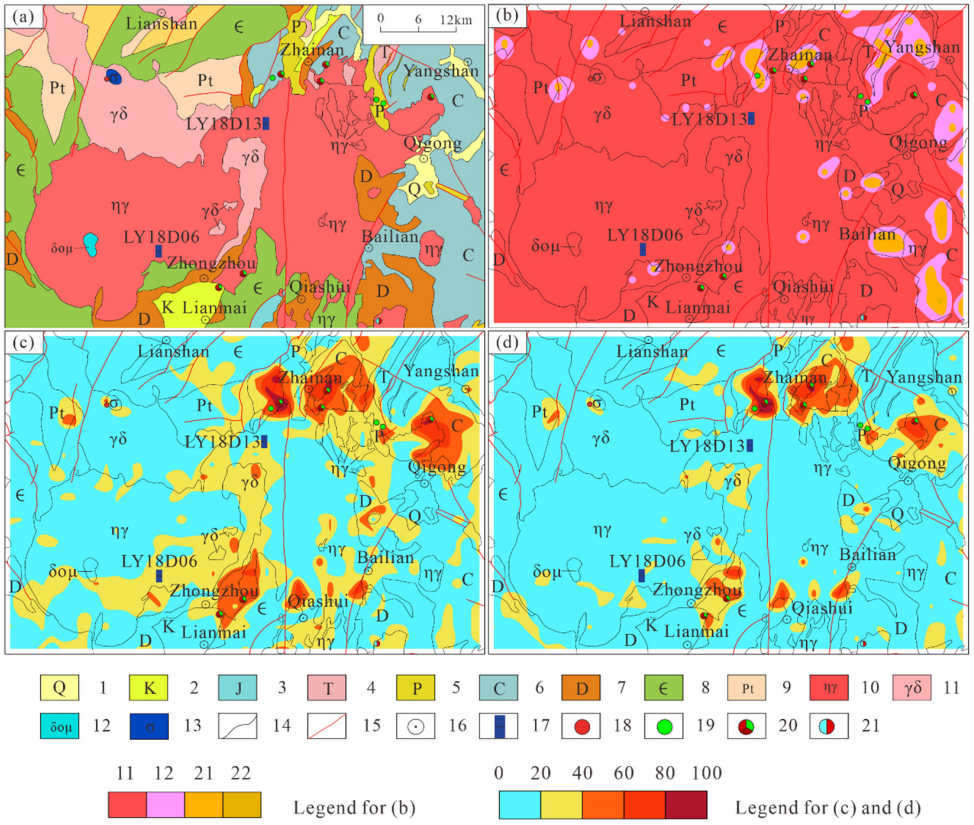


Figure 5. Geological map of Lianyang area (**a**) and geochemical maps of the LG_CR (**b**), $R_{IdealOre}$ of MGW (**c**), and $R_{IdealOre}$ of MGW11 (**d**). Figure 5a is modified after the G49 with a scale of 1:1000,000 from China Geological Survey with notes are as the followings. 1—Quaternary sand and gravel mixed with clay silty sand; 2—Cretaceous sandy conglomerate, pebbled sandstone and siltstone; 3—Jurassic sandstone, siltstone, grit stone and mudstone; 4—Triassic limestone and mudstone; 5—Permian limestone and mudstone; 6—Carboniferous dolomitic limestone and dolomite; 7—Devonian sandstone and dolomitic limestone; 8—Cambrian sandstone, slate and siltstone; 9—Proterozoic sandstone, siltstone and slate; 10—Monzogranite; 11—Granodiorite; 12—Quartz-dioritic porphyrite; 13—Peridotite; 14—Petrological boundary; 15—Fault; 16—Main residential place; 17—Locations of LY18D13 and LY18D06 weathering profiles; 18—Au deposit; 19—Cu deposit; 20—Polymetallic W deposit; 21—Mo-Fe deposit.

Six polymetallic W deposits have been recognized in the study area [22], although they have not been receiving much attention [23]. The polymetallic W deposits are mainly distributed around the Lianyang granitic complex contacting with strata and faults (Figure 5a). Among the six polymetallic W deposits, three deposits are located in the north margin of the Lianyang granitic complex near the Zhainan town, two deposits in the south margin of the Lianyang granitic complex near the Zhongzhou town, and one in the northeast margin of the Lianyang granitic complex near the Yangshan town. In addition, three Cu deposits, one Au deposit, and one Mo-Fe deposit are also recognized in this area [16,24].

4.2. Materials, Results and Discussion

In the Lianyang area, a total of 1393 geochemical records (or samples) of stream sediments were retrieved from the database of the RGNR (Regional Geochemistry–National Reconnaissance) project [12]. In this project or database, stream sediment is the sampling media with a scale of 1:200,000 and was analyzed with 10 major components (SiO_2, Al_2O_3, Fe_2O_3 or TFe_2O_3, K_2O, Na_2O, CaO, MgO, Ti, P, and Mn) and 29 trace elements (W, Sn, Mo, Bi, Cu, Pb, Zn, Cd, Au, Ag, As, Sb, Hg, Li, Be, Sr, Ba, B, F, V, Cr, Co, Ni, Zr, Nb, Th, U, Y, and La) [25].

Based on the geochemical data of each record which represents an area of four square kilometers, the gene codes and their acidic similarities (R_{Acidic}) of LG01 and LG03 are calculated on the GGC software [1] firstly. Then the LG_CR results of the 1393 samples are derived according to the method proposed by Wu et al. [2]. The geochemical map of the LG_CR in the Lianyang area is illustrated in Figure 5b. Although nine types of LG_CR can be classified theoretically on double-digit numbers based on the acidic similarities of LG01 and LG03 lithogenes, only four types are recognized in the Lianyang area as 11, 12, 21, and 22 types. The 11 types of LG_CR are dominant in the whole study area, and the other types of 12, 21, and 22 are located sporadically in the east and north of the area. Therefore, the Lianyang area can be viewed as an area of 11 types of LG_CR compositionally by and large.

Based on the geochemical data of the 1393 records, the gene codes and their mineralization similarities (R_{IdealOre}) of MGW and MGW11 are calculated. The geochemical maps of the R_{IdealOre} of MGW and MGW11 in the Lianyang area are illustrated in Figure 5c,d. In these maps, the blue areas with $0 \leq R_{\text{IdealOre}} \leq 20$ can be viewed as the normal background area, the yellow area with $20 < R_{\text{IdealOre}} < 40$ can be viewed as the higher background area, and the red area with $40 \leq R_{\text{IdealOre}} \leq 100$ are the anomaly areas for tungsten exploration. Furthermore, the anomaly areas can be divided into three zones; the outer zone with $40 \leq R_{\text{IdealOre}} < 60$, the middle zone with $60 \leq R_{\text{IdealOre}} < 80$, and the inner zone with $80 \leq R_{\text{IdealOre}} \leq 100$ (Figure 5c,d).

By comparing the deposits and the anomaly areas spatially in the Lianyang area, we can find that a total of six polymetallic W deposits in the study area are all located in the anomaly areas determined on the R_{IdealOre} of MGW (Figure 5c) and MGW11 (Figure 5d). This indicated that the mineralization similarities of MGW and MGW11 can be viewed as useful integrated indices on geochemical tungsten exploration.

With respect to the three Cu deposits in the study area, one is located in the anomaly area, one is near the anomaly area, and one is in the background area determined on MGW (Figure 5c) and MGW11 (Figure 5d). With respect to the Au deposit and the Mo-Fe deposit in the study area, the Au deposit is located in the higher background areas determined on MGW and MGW11 (Figure 5c,d), and the Mo-Fe deposit is located in the background areas (or higher background area determined on the MGW in Figure 5c and normal background area determined on the MGW11 in Figure 5d. This indicates that the mineralization similarities of MGW and MGW11 are invalid in Cu, Au, and Mo (Fe) geochemical exploration.

By comparing the anomaly areas locating the six tungsten deposits, we can find that the areas determined on the MGW11 are all smaller than the anomaly areas determined on the MGW, especially in the south and northeast margins of the Lianyang granitic complex. This is helpful in targeting the tungsten deposits efficiently in geochemical exploration and is consistent with the aim of this study. Therefore, the mineralization similarity of MGW11 is an integrated index for recognizing the tungsten anomalies, which eliminates not only the closure effect of compositional data such as the spider diagrams [26] and elemental correlations [27] but also the weathering and lithology influences during geochemical exploration.

In addition, two anomaly areas are determined in the south margin of the Lianyang granitic complex near the Qiashui town, both on the MGW (Figure 5c) and on the MGW11 (Figure 5d) with outer and middle anomaly zones (or $R_{\text{IdealOre}} \geq 60\%$) which may be potential targets for further tungsten prospecting.

5. Conclusions

(1) A tungsten metallogene named MGW11 is proposed for geochemical tungsten exploration in areas with 11 types of LG_CR compositionally.

(2) The MGW11 and MGW metallogenes illustrate stable properties such as heredity and inheritance during weathering of rocks with 11 types of LG_CR compositionally regardless of weathering degrees. However, gene variations of MGW11 and MGW are also observed during extreme weathering.

(3) The mineralization similarities of MGW11 and MGW can be viewed as useful integrated indices on geochemical tungsten exploration. In areas with 11 types of LG_CR compositionally, anomaly areas determined on the MGW11 are all smaller than those on the MGW because the MGW11 eliminates the lithological influence on recognizing tungsten anomalies during tungsten prospecting.

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