Using geochemical imaging data to map nickel sulfide deposits in Daxinganling, China

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Abstract

Nickel sulfide deposits occur in ultramafic rocks in the Daxinganling area, China; however, the prospectivity of these deposits has received little attention. This study transformed rasterized regional 1:200,000 geochemical data into spectral-like data and then used hyperspectral tools of the spectral angle mapper (SAM) to classify possible ultramafic lithologies and the multirange spectral feature fitting (MRSFF) method to classify prospective areas that are similar to a typical Gaxian Ni deposit. The prospective area map generated by the MRSFF implies the possible occurrence of ultramafic rocks classified by the SAM method. These results confirm the suitability of this innovative approach for prospectivity mapping of Ni sulfide deposits.

Keywords Spectral-like · Geochemical data · SAM · MRSFF · Ni sulfide deposits

1 Introduction

Major Ni sulfide deposition occurred globally between the Archaean and Triassic, and these deposits are often associated with ultramafic rocks (e.g., komatiitic volcanic flows and/or related intrusions) and tholeiitic rift-related Ni–Cu–Cr sulfides in layered intrusions [1]. Prospective criteria for sulfide deposits have been developed, e.g., the creation of exploration guidelines for Ni sulfide deposits in Australia [1–5], in which geochemical characterization remains critical.

In Daxinganling, China, the recent identification of the medium-scale Gaxian Ni sulfide deposit occurring in ultramafic rocks suggests that the prospectivity of Ni sulfide is closely related to that of ultramafic rocks. However, ultramafic rocks are relatively difficult to locate due to heavy vegetation, relatively small-scale serpentinization, and extensive weathering. A 1:200,000 regional geochemical survey of this region has been completed, which includes

the analysis of 39 elements and oxides and provides a solid foundation for prospecting and exploration.

In recent years, spectroscopy has emerged as a new method to identify regional lithologies. The use of multi-spectral and hyperspectral data to identify lithologies can be based on either the analysis of all spectral bands or the investigation of bands with specific absorption characteristics, both of which can be completed using image processing software. The spectral angle mapper (SAM) method is used to analyze the whole wavelength range [6–8], while the multirange spectral feature fitting (MRSFF) method is used to analyze multiple spectral bands with specific absorption characteristics [9, 10].

Traditionally, geochemical prospecting is based on geochemical anomalies [11]. In recent years, pattern recognition [12] has been used to study metallogenic systems, that is, to identify the geochemical distribution pattern of mineralization by considering enrichments and depletions at the same time [13, 14]. Then, the whole mineralization process is simulated. These approaches need some new

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functions (operations) for pattern recognition. The SAM and MRSFF methods are essentially pattern recognition tools; the former is equivalent to the cosine similarity measure (CSM) and has been applied in mineral prospectivity mapping [15, 16].

The main aim of this study was to provide a prospective area for Ni sulfide deposits in the Daxinganling area using the idea of pattern recognition. Rasterized regional geochemical data were treated as spectral-like data, and the SAM algorithm was used to identify the locations of ultramafic rocks, while the MRSFF algorithm was used for the prospective areas for Ni sulfide deposits.

2 Geological setting and geochemical data

2.1 Location and tectonic setting

The Daxinganling region is located in northeastern China (Fig. 1) and adjoins Russia to the north and Mongolia to the west. Daxinganling is located at the eastern end of the Central Asian orogenic belt, sandwiched between the North China plate and the Siberian plate [17]. The crystalline basement is composed of Precambrian strata, which were metamorphosed from a series of felsic volcanic rocks and carbonate rocks in an active continental margin tectonic setting. The cap rock is a combination of Paleozoic clastic and carbonate rocks. Wide areas are covered by volcanic rocks from the Late Jurassic to Early Cretaceous, within which two large volcanic eruption cycles can be classified. The early cycle began with mafic rock emplacement and ended with felsic volcanic eruptions. The second cycle formed only mafic volcanic rocks. Intermediate-mafic and intermediate-felsic volcanic rocks dominate in the region, with ultramafic rocks accounting for only a very small proportion.

2.2 Regional ultramafic rocks and Ni sulfide mineralization

Most ultramafic rocks in Daxinganling are found within ophiolite belts. Ultramafic rocks in the north belong to the Xinlin-Tayuan-Toudaoqiao ophiolite belt, which is characterized by peridotite, lherzolitic, pyroxenite, gabbro, basalt, and komatiite. The ophiolites are intermittently exposed and mostly dismembered. The Xinlin ophiolite includes a typical rock sequence, which from top to bottom includes [18] a mixed serpentine belt, a chlorite talc schist belt, metamorphic peridotite (serpentinite), layered sedimentary rocks, a sheeted complex, and metamorphosed basalt rocks.

The newly discovered medium- to large-scale Gaxian Ni sulfide deposit (Fig. 1) is located in the

Xinlin-Tayuan-Toudaoqiao ophiolite belt. It lies to the west of the Jifeng-Huanyu ductile nappe zone, an area that has experienced significant tectonic activity. The rocks occur within a Ni sulfide deposit that includes peridotite, hornfels, marble, altered marble, granite, and diabase.

Ni mineralization is present in the lower part of the pyroxene peridotite, with the occurrence, scale, and form of ore bodies strictly controlled by ultramafic rocks. The main types of mineralization include pentlandite, pyrrhotite, and pyrite. Metallogenic minerals are scattered or disseminated thin veins. The deposit can be classified as a magmatic liquation sulfide Ni deposit that underwent later hydrothermal alteration [20]. The ore consists of low-grade nickel and is low in copper. Nickel ore was identified in ore-bearing drill hole ZK002. Pyroxene peridotite nickel was observed at 0 to −145 m (mean Ni grade of 0.20%), a Ni grade of 20% was identified at a depth of 101 m, and Ni mineralization with a grade of 0.13% was identified at −145 m to −234 m, which was sandwiched by nickel ores with a Ni grade up to 0.21%. The deposit can be classified as a medium- to large-scale nickel deposit.

2.3 Geochemical data

A 1:200,000 geochemical survey based on stream sediments has been completed across most of the Daxinganling area. The mean sampling density was one station per 4 km², with several samples collected near each station integrated into a single sample. Sampled materials were passed through a 40-mesh sieve before they were sent for laboratory analysis. The contents of 39 elements were analyzed, including seven major elements (Al, Ca, Fe, K, Mg, Na, and Si) and 32 trace elements (Ag, As, Au, B, Be, Ba, Bi, Cd, Co, Cr, Cu, F, Hg, La, Li, Mn, Mo, Nb, Ni, P, Pb, Sb, Sn, Sr, Th, Ti, U, V, W, Y, Zn, and Zr) [21]. Twenty-four elements (Al, Ba, Ca, Co, Cr, Cu, Fe, K, La, Mg, Mn, Nb, Ni, P, Pb, Si, Sr, Th, Ti, V, Y, Zn, and Zr) were analyzed simultaneously using an X-ray fluorescence spectrometer, and the other 15 elements were analyzed by atomic fluorescence, atomic absorption, emission spectroscopy, polarography, laser fluorescence, and selective ion electrode methods [22].

3 Methods

Several steps were adopted to determine the prospective areas of Ni sulfide deposits. First, regional geochemical data were rasterized and treated as spectral-like data. Then, the SAM method for accurately identifying ultramafic rocks was applied. After locating the possible areas where ultramafic rocks may occur, we used the MRSFF method to classify the areas with alteration characteristics similar to those of typical Ni sulfide deposits.

Fig. 1 Tectonic framework (a) and distribution of lithologies (b, after Meng et al. [19]) in the Daxinganling area. EX=Erguna-Xingan microcontinent; SN=Songnen microcontinent; JS=Jiamusi microcontinent; HB=North China plate; DMF=Dunhua-Mishan fault;

①=Mongol-Okhotsk suture zone; ②=Solon-Hegenshan fault; ③=Xilamulun River fault; ④=Yilan-Yiton fault; and ⑤=Fushun-Mishan fault

3.1 Pre-processing of geochemical data

Data in this study were taken from a 1:200,000-scale regional geochemical database. The geochemical data were rasterized using the “rasterize point data” drop-down menu in ENVI software (version 4.4, Research Systems, Inc., Boulder, CO, USA). ENVI is a tool for imaging

and geographic information system (GIS) processing. Its gridding function uses Delaunay triangulation of a planar set of points. After the irregularly gridded data points were triangulated, they were interpolated to a regular grid. Interpolation with a linear quintic polynomial was chosen to enable the resulting surface to pass through all given data points, and the value of each point does

not change [23]. In our study, the output projection was determined, and the output X/Y size was selected as 1000 m (i.e., the spatial resolution of the rasterized images was 1000 m). After the above steps, images of single elements were formed (e.g., Fig. 2). To use a spectroscopic approach, geochemical elements were organized according to families in the periodic table, as these elements possess similar chemical properties on Earth (i.e., Li, Na₂O, K₂O, Be, MgO, CaO, Sr, Ba, Y, La, Th, U, Ti, Zr,

V, Nb, Cr, Mo, W, Mn, Fe₂O₃, Co, Ni, Cu, Ag, Au, Zn, Cd, Hg, B, Al₂O₃, SiO₂, Sn, Pb, P, As, Sb, Bi, and F).

3.2 Conversion of geochemical images into spectral-like images

Rasterized data were transformed to spectral-like data using ENVI software, in which a wavelength was assigned to each element to run the MRSFF method. For example,

Fig. 2 Example of a geochemical image (Li contents in ppm) for the Daxinganling area

the first element (Li) was assigned a value of 0.1 μm , the second (Na) was assigned 0.2 μm , and so on until all elements had been assigned a wavelength.

As geochemical data differ significantly from reflectance data (some by more than 1), they need to be normalized. Minimum–maximum normalization was calculated by the following formula:

$$EC_{\text{out}} = (EC_{\text{original}} - \min_c) / (\max_c - \min_c),$$

where EC_{original} is the original content of an element/oxide in the image, $\min_c$ is the minimum value of the element, $\max_c$ is the maximum value of the element, and EC_{out} is the output value. After the calculation, the data values were normalized between 0 and 1.

The emulated spectra (i.e., the spectra of geochemical elements) of the Gaxian deposit (e.g., Ni sulfide deposits) were extracted by locating previously identified deposits on the 1:200,000 regional geological map. The geographical coordinates at the central position of a deposit were extracted, and the “Z profile” method was used to extract the relevant emulated spectra from the spectral-like data.

The positions of known ultramafic rocks, including Xinlin, Gaxian, Moguqi, Fanbaotu, and Manhakacha, were also extracted from the 1:200,000 geological map. However, as the ultramafic rocks in Xinlin, Gaxian, and Fanbaotu were not concentrated in continuous pixels, they were further subdivided (e.g., Xinlin1 and Xinlin2 represent two separate ultramafic rocks in the Xinlin area). The emulated spectra of ultramafic rocks were extracted from the geochemical images (Table 1). Based on normalized geochemical images and the resulting emulated spectra (Fig. 3), we found that only Xinlin1, Gaxian2, and Xinlin2 had low SiO_2 contents in the stream sediments of ultramafic rocks. For the other previously mapped ultramafic rocks, the relatively high SiO_2 contents in the stream sediments suggested ultramafic rocks on a small scale (i.e., a pixel) and associated wall rocks with higher SiO_2 .

3.3 Application of SAM

The SAM method was used to classify the lithologies using geochemical images. The SAM method measures similarity by calculating the angle between two spectra and treating them as vectors in n -dimensional space, with n equal to the number of bands [6, 7]. The same principle can be applied to geochemical data as long as the geochemical data have been transformed into spectral-like data. We treated the geochemical spectra as vectors in multidimensional space (with the number of dimensions equal to the number of elements), which allowed the angle between the reference emulated spectra and pixel spectra to be calculated and provided a measure of the similarity. The SAM

method was applied to all geochemical images, with the threshold of the angle fixed at a value of 0.1, and an angle larger than this value was not classified. The generated rule images were then used for emulated spectral analysis and post-classification.

The emulated spectrum of Xinlin2 was selected as the reference spectrum because it was enriched in Mg and Al but low in SiO_2 , while the spectral angles of Xinlin1, Gaxian1, Gaxian2, Moguqi, Fanbaotu1, Fanbaotu2, and Manhakacha were used for comparison. The SAM method was applied to four groups of image types: images using all 39 elements and oxides with their original concentrations, a subset of 21 elements and oxides (K, Be, Mg, Ca, Sr, Ba, Th, Ti, Zr, Mo, Co, Ni, Ag, Au, Al, Si, Sn, Pb, P, As, and Bi) with their original concentrations, all 39 elements and oxides using normalized values, and the subset of 21 elements and oxides using normalized values. The 21 elements and oxides of the subset were selected according to whether the normalized value of any emulated spectrum was greater than 0.8 or less than 0.2; here, a value larger than 0.8 means enrichment in the element, whereas a value lower than 0.2 means depletion in the element (Fig. 3). The SAM method was operated using standard procedures, and four rule images were created.

The spectral angles were extracted and compared with the cumulative frequency percentages of the rule images (Table 2). The cumulative frequency percentage was a parameter that could be used to count the area suitable for the classification; for example, the cumulative frequency percentage for the Xinlin1 ultramafic rocks was 0.0053, meaning that only 0.53% of the total areas could have a smaller spectral angle of less than 0.1086. The spectral angles were lower for the subset of 21 elements and oxides with normalized values, which were ultimately used for the SAM classification (Fig. 4).

3.4 Application of MRSFF

Spectral feature fitting (SFF) is a commonly used strategy for discriminating ground targets using hyperspectral imagery analysis; the technique is an absorption feature-based method that compares the fit of image spectra to reference spectra using a least-squares technique [9]. MRSFF is an improvement on the treatment of several spectral wavelength ranges and the assignment of corresponding weights and can yield a better performance [24]. When the main metallogenetic elements are treated as absorption features, MRSFF can be used to identify ore-bearing altered rocks and relate them spatially to prospective areas.

The emulated spectra of Gaxian2 were chosen to represent the geochemical characteristics of the deposits. The spectra of Gaxian2 had high concentrations of Mg, Ca, Sr,

Table 1 Elemental concentrations from stream sediments collected in areas that contain ultramafic rocks. Na, K, Mg, Ca, Al, and Si are given in % oxides, while Au, Ag, and Hg are in ppb; other elements are in ppm

	Xinlin1	Xinlin2	Gaxian1	Gaxian2	Moguqi	Fanbaotu1	Fanbaotu2	Manhakacha
Li	29.54	26.31	11.08	23.9	27.06	19.83	15.64	44.69
Na	3.67	3.91	4.02	2.44	2.08	2.44	3.42	2.66
K	2	1.69	3.26	2.53	2.92	2.26	2.35	2.83
Be	2.33	1.6	2.89	2.09	1.96	1.73	1.55	2.26
Mg	2.88	2.72	1.01	4.14	1.19	2.66	0.75	0.29
Ca	3.88	4.42	1.42	1.17	1.34	1.25	2.23	0.49
Sr	946.34	990.92	665.7	241.27	219.64	252.98	308.76	148.99
Ba	639.41	577	999.29	750.56	557.78	588.74	548.83	837.4
Y	18.95	18.74	14.4	17.4	16.21	12.72	23.09	16.44
La	37.72	37.31	41.57	27.41	21.12	20.15	21.48	29.07
Th	4.7	5.29	10.51	9.26	8.48	5.83	5.65	8.49
U	4.15	2.73	4.83	2.47	2	1.58	0.95	1.99
Ti	5444.61	5915.12	3282.58	4195.04	2865.27	2059.84	4098.63	1221.68
Zr	133.67	115.66	258.28	217.31	128.57	102.51	183.87	139.67
V	74.31	87.7	66.24	93.05	83.2	95.05	86.69	52.89
Nb	16.29	15.65	15.45	12.98	9.7	7.32	15.65	8.37
Cr	54.99	46.97	30.9	393.24	49.83	183.72	35.87	14.02
Mo	1.1	1.09	1.53	1.44	1.87	1.03	0.99	1.44
W	2.18	1.95	0.87	1.71	2.32	1.99	0.76	1.08
Mn	617.99	598.82	554.14	998.91	791.49	1455.6	495.83	1335.97
Fe	4.82	5.33	3.27	5.78	4.64	4.54	3.84	3.78
Co	17.75	19	10.02	23.92	13.86	26.87	9.75	11.82
Ni	32.7	30.97	15.87	204.83	21.83	138.52	18.56	28.87
Cu	19.63	17.42	25.7	12.53	18.26	16.96	9.26	12.57
Ag	58	94	33	48	97	105	86	65
Au	2.51	0.65	2.32	2.08	0.52	1.03	0.68	0.3
Zn	52.89	59.96	44.73	75.08	67.97	45.04	38.67	41.14
Cd	43.25	65.92	56.58	79.61	166.21	112.18	63.08	69.25
Hg	61.33	37	9.23	16.5	8.1	18.45	7.87	8.59
B	9.39	11.29	10.98	24.03	17.31	25.08	14.63	16.32
Al	15.9	17.1	15.07	14.44	12.13	11.74	13.42	10.55
Si	52.84	50.4	66.06	61.8	71.12	69.65	66.88	74.16
Sn	1.31	1.3	2.32	2.79	1.85	2.87	2.11	1.33
Pb	14.11	15.84	19.16	23.63	34.83	28.12	13.84	30.32
P	1928.17	2034.98	919.05	635.69	457.9	334.62	281.08	230.83
As	5.1	5.28	4.87	18.24	30.72	43.96	9.98	29.69
Sb	0.22	0.24	0.34	0.86	2.14	1.77	0.47	1.63
Bi	0.13	0.17	0.13	0.26	2.17	0.25	0.18	0.26
F	487.92	448.84	439.94	408.34	328.84	279.25	219	162.17

Ti, Cu, Ni, Al, and P (Fig. 3). Using the emulated spectra of the Gaxian deposit as the reference spectra, we subtracted the normalized data from “1,” and the elements with higher concentrations then fell into the absorption ranges of the emulated spectra. The weight of the factor assigned to Cu and Ni was 10, while that for Mg, Ca, Sr, Ti, Al, and P was 5, reflecting the effects of ore formation on these elements. Using these values, we generated a scale image with the MRSFF method (Fig. 5). A scale image and root mean square (RMS) image were output. The images were related

to material abundances, where brighter pixels indicated a better match to the Gaxian2 spectra, which represent the geochemical characteristics of the Gaxian deposit.

3.5 Prospective area classification

We classified prospective areas from among the Ni sulfide deposits based on three criteria: (1) possible location of identified ultramafic rocks classified by SAM, (2) a high

Fig. 3 Spectral ranges extracted from geochemical images

Table 2 Spectral angles and cumulative frequency percentages calculated from the SAM rule image for ultramafic rocks

	39 elements/oxides (original concentrations)		21 elements/oxides (original concentrations)		39 elements/oxides (normalized values)		21 elements/oxides (normalized values)	
	Spectral angle (radian)	Cumulative frequency percentage	Spectral angle (radian)	Cumulative frequency percentage	Spectral angle (radian)	Cumulative frequency percentage	Spectral angle (radian)	Cumulative frequency percentage
Xinlin1	0.0276	0.0017	0.0115	0.0150	0.2471	0.0093	0.1086	0.0053
Gaxian1	0.2188	22.9669	0.0690	3.3073	0.5396	16.8894	0.4855	11.4690
Gaxian2	0.2725	42.2877	0.1619	50.9528	0.5490	18.9513	0.5047	13.8571
Moguqi	0.2749	43.0746	0.1877	67.6854	0.5830	26.8787	0.5161	15.3464
Fanbaotu1	0.2759	43.4848	0.1915	69.9895	0.6943	48.8699	0.7289	48.2850
Fanbaotu2	0.5513	84.7185	0.2106	80.9429	0.6998	49.8062	0.7463	50.7137
Manhakacha	0.7809	93.2605	0.2738	96.0346	0.9201	80.8011	1.0254	81.2948

MRSFF scale value, and (3) distribution of prospective areas along a structural belt.

When applying the first of these criteria, the classification of ultramafic rocks was limited to just 15% of the region (i.e., the cumulative frequency percentage was less than 15%, and the spectral values were less than 0.70; Fig. 4) to limit the scope of the potential ultramafic rocks.

Prospective area classifications of MRSFF scale images for Ni sulfide deposits were performed using the density slice method, which is a thresholding technique used in image classifications to select data ranges and colors for highlighting areas in a greyscale image. In this study, prospective areas were classified according to cumulative frequency statistics. Cumulative frequency statistics were obtained by computing parameters from the histogram statistics of MRSFF scale images. The pixel values corresponding to the cumulative frequency statistics of 97.5%, 92%, and 85% in the scale image were taken as the threshold values, which is typical for the classification of geochemical exploration anomalies

[25]. Level A corresponded to scale values of > 0.85, level B corresponded to scale values of 0.71–0.85, and level C corresponded to scale values of 0.57–0.71 (Fig. 6). Different colors were then assigned to levels A, B, and C.

4 Results and discussion

4.1 Characteristics of prospective areas for Ni sulfide deposits

The scale image for MRSFF was classified using three levels. After the levels were limited according to the possible ultramafic rocks identified from the SAM method, seven prospective areas for Ni sulfide mineralization were grouped (Fig. 6) based on the concentrations of the levels. The characteristics of the predictive areas were assessed against known ultramafic rocks and mineralization (Table 3). The prospective areas included Gaxian, Dahongshan, Badaogoumen, Fangbaotukacha, Heremutu, and Wutonghua, the lithologies of which are komatiite,

Fig. 4 Spectral angle mapper (SAM) classification results for the normalized data of 21 elements and oxides

peridotite, pyroxene peridotite, gabbro, pyroxene, and lherzolite. In other prospective areas, spilite keratophyres and veins of gabbro occurred. Ni sulfide mineralization in Fangbaotukacha occurred in feather-like fractures.

We contrasted the prospective areas with the geochemical background and anomalies. We classified the geochemical anomalies according to the anomaly threshold: mean + 2*standard deviations. The results showed that the three classified levels of MRSFF scale values were

coincident with the anomalies. Figure 6 illustrates that in the Badaogoumen prospective area (No. 4), the levels of scale values coincided with Ni, Co, P, Ca, and Mg in most of the areas.

Geochemical element concentrations were extracted to contrast high-scale values created with the MRSFF method. We extracted the Z profiles of the central pixel in clustered pixels with high scale values and obtained the normalized values of different elements, where

Fig. 5 Enhanced scale image constructed using the multi-range spectral feature fitting (MRSFF) method. The reference emulated spectra are from Gaxian2

higher values corresponded to geochemical anomalies of the given element. Three types of element anomaly combinations were identified: (1) Fe, Co, Ni, Cu, V, and Cr, which were found in Dahongshan, Fangbaotukacha, Xinchengmuchang, Heremutu, and Wutonghua; (2) Fe, Co, Ni, Cu, V, Cr, Au, As, and Sb, which were found in the Gaxian, Wunuer, and Badaogoumen areas; and (3) Na, Mg, and Ba, which were identified in the Wuniuhe

prospective area. The first and second types were consistent with ultramafic rocks or ultramafic rock-related mineralization, although type 2 may have undergone later hydrothermal alteration. The genesis of the third combination type led to a high Na content, and rocks may contain minerals such as Na-rich plagioclase.

Fig. 6 The grouped prospective areas in Daxinganling and the contrast among geochemical anomalies and prospective areas. Levels A, B, and C represent threshold values of the scale image from the MRSFF method, which are equal to 97.5%, 92%, and 85% (i.e., Level A corresponds to scale values > 0.85 , level B corresponds to scale values from 0.71 to 0.85, and level C corresponds to scale values of 0.57–0.71). Prospective areas include 1. Gaxian; 2. Wunuer; 3. Dahongshan; 4. Badaogoumen; 5. Fangbaotukacha; 6. Heremutu; and 7. Wutonghua

4.2 Discussion

In the past, spectral data have been used with the SAM and MRSFF methods, and an attempt has been made to apply these methods to geochemical data. The rasterized geochemical images were treated as vectors in multidimensional space, where the number of elements was equal to the number of dimensions. We assigned the order of elements according to families in the periodic table in

this study. This arrangement was mainly combined with prior geological knowledge; that is, geochemical elements had the characteristics of enrichment or depletion. In fact, the results produced by the SAM and MRSFF methods are not affected by any element arrangement order.

One of the advantages of this study is that the linear quintic polynomial interpolation method can keep the geochemical values from sampling sites unchanged. We have made a comparison, if the chemical composition of

Table 3 Summary of lithologies, mineralization, and geochemical anomalies in prospective area

No	Prospective area	Favorable formations and lithologies	Mineralization related to ultramafic rocks	Element combination of geochemical anomaly
1	Gaxian	Middle Proterozoic komatiite from; olivine is 60%, and the other minerals include serpentine, talc and chlorite, tremolite and chrome spinel	Gaxian nickel deposit occurs	Mg, Cr, Fe, Co, Ni, Cu, Au, B, As, and Sb
2	Wunuer	Spillite keratophyre formations; The Daminshan Formation and Moergenhe Formation are spillite keratophyres interlayered with siliceous rocks, sandstone, limestone, and quartz crystal tuff		Mg, V, Fe, Co, Cu, and Au
3	Dahongshan	Plagioclase pyroxene peridotite, altered to serpentine and talc. Only olivine crystal residues remain. Accessory minerals: zircon, apatite, pyrite, and magnetite		Mg, Sr, V, Cr, Co, and Ni
4	Badaogoumen	Spillite keratophyre formation and gabbro veins		Mg, V, Mn, Co, Ni, As, and Sb
5	Fangbaotukacha	Peridotite and olivine (70–75%). Magnetite up to 30–40%. Accessory minerals: chrome spinel, pyrite, and zircon	Sharigetai chromite mineralization, composed of two ultramafic rocks. The first (180 m long and 40–60 m wide) contains dense disseminated chromite in feathery fractures, with alteration including carbonization and serpentinization. The second (250 m long and 10 m wide) contains 0.14–0.25% Ni	Mg, Ti, V, Cr, Fe, Co, Ni, and Cu
6	Heremutu	Dark green ultramafic rocks composed of peridotite, gabbro, pyroxene, and ilmenite		Mg, Ti, V, Fe, Ni, and Cu
7	Wutonghua	Ultramafic rocks, composed of diopside and websterite, with minor olivine pyroxenite, gabbro, and altered tremolite		Mg, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, and P

Geochemical element anomalies were determined by normalized values greater than 0.95

a sampling site has a maximum value, and the actual value of its adjacent sites is much smaller, if adopting Kriging method, which is commonly used in geochemical anomaly the value of the surrounding sites will also become very high after interpolation, which leads to a big difference with the original chemical composition value. If linear quintic polynomial interpolation is used, the values of the surrounding sites are the same as the original values and do not change. Another advantage is that according to the mineralization characteristics of the surrounding rock (ultramafic rock) and ore body, regional deposits can be predicted by pattern recognition. This approach was different from the traditional method of selecting prospecting targets according to geochemical anomalies (or multielement comprehensive anomalies). However, if based on only copper and nickel anomalies, it was preferable to include deposits related to nonultramafic rocks such as mafic rocks, skarn deposits or low-temperature hydrothermal deposits. Therefore, the most important issue was how to eliminate the influence of these anomalies. The SAM method could reveal the distribution of major elements in ultramafic rocks and reduce the influence of other factors. Considering the multielement geochemical characteristics of the ore-forming system, the MRSFF method was used to classify the ore-forming system; this method reflected not only the anomaly intensity but also the overall trend of the whole mineralization and alteration system.

Nine prospective areas for Ni sulfide deposits were obtained using the SAM and MRSFF methods. All areas showed high prospectivity for ultramafic rocks or Ni mineralization, providing guidelines for future exploration. In the traditional approach, prospectivity maps are created using a geochemical block method that predicts across thousands of km² [26]. In this study, the pixel size of the geochemical images is 1 km, which provides much better predictions than previous methods and has advantages in terms of accuracy and targeting locations [27].

5 Conclusions

This research represents the first attempt to use rasterized geochemical data for the selection of prospective areas, the SAM method to predict the locations of ultramafic rocks, and the MRSFF method to locate areas with geochemical characteristics similar to those of the reference Ni sulfide deposit. Then, prospective areas are classified according to these two methods. The classified MRSFF levels in the prospective areas have nearly the same positions as the geochemical anomalies, and ultramafic rocks and related mineralization also provide clues about the occurrence of Ni sulfide deposits.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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