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Image processing for ASTER remote sensing data to map hydrothermal alteration zones in East Kazakhstan

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Abstract. Porphyry copper deposits are accompanied by extensive aureoles of hydrothermally altered rocks which make it possible to detect them on satellite images in the absence of vegetation. The study is devoted to using the Earth's remote sensing data, particularly, satellite images from the Japanese sensor ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), which are used to identify areas that are promising for the discovery of porphyry copper deposits and ore occurrences within the copper belt of Kazakhstan. The analysis of numerous publications that offer various methods for processing ASTER images for the interpretation of hydrothermally altered rocks accompanying porphyry copper occurrences showed that the most effective method for this region is the Crosta technique. The Crosta technique, unlike other methods, does not use primary bands, but their combinations are obtained by the principal components analysis method. Thus, the combination of the results of the principal components analysis with the use of index images and analysis of the geological map made it possible to identify areas of hydrothermally altered rocks in the study area. The described technique helps to predict promising areas for porphyry copper mineralization of varying degrees of reliability, associated with their hydrothermal processing.

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Обработка данных дистанционного зондирования ASTER для картирования зон гидротермальных изменений в Восточном Казахстане

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космоснимки ASTER, метод главных компонент, гидротермально измененные породы, дешифрирование космоснимков

Аннотация. Медно-порфировые месторождения сопровождаются обширными ореолами гидротермально измененных пород, значительно превосходящих их по площади, которые позволяют обнаруживать их на космических снимках в условиях отсутствия растительности. Исследуется использование данных дистанционного зондирования Земли, в частности космических снимков японского сенсора ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), для выделения участков, перспективных на обнаружение медно-порфировых месторождений и рудопроявлений в пределах медного пояса Казахстана. Анализ многочисленных публикаций, в которых предлагаются различные методы обработки снимков ASTER для дешефрирования гидротермально измененных пород, сопровождающих медно-порфировые рудопроявления, показал, что наиболее эффективным из них для данного района является метод Crosta. В отличие от других методов он использует не первичные полосы (band), а их комбинации, полученные методом главных компонент. Таким образом, сочетание результатов метода главных компонент с применением индексных изображений и анализа геологической карты позволило выделить области гидротермально измененных пород в районе исследований. На основании описанной методики определены прогнозные участки, перспективные на медно-порфировое оруденение различной степени достоверности, связанные с их гидротермальной переработкой.

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Introduction

Remote sensing is a widely used tool in mineral exploration, as it has replaced the physical approach to discovering deposits. The physical approach required spending much time, effort, and money looking for geological studies.

Since 1920, the use of aerial photographic interpretation in the field of Earth sciences has become a fast and effective tool for the exploration of natural resources [1]. Therefore, the launch of Landsat-1 in 1972 and the continued development of new sensors have increased the spatial-temporal-spectral resolution of Earth observation data [2]. This made the digital imagery of the electromagnetic spectrum available for interpretation and use in mineral explorations in a short time.

Remote sensing is a comprehensive method that enables scientists to identify an object, by collecting all needed information about it. The interpretation of satellite images requires applying two basic paradigms, namely, data-driven, and knowledge-driven models. Both models are the dominant paradigms for spatio-temporal modeling and spatio-temporal decision-making [2].

The main idea behind this is that everything on Earth has its unique spectral signature, which provides the ability to identify features or abstract information about what is displayed on Earth's surface. Spectral signature is the energy reflected from features on earth and stored as bands. Mostly, bands will capture the visible, NIR, and SWIR regions which tend to contain more useful information about the earth's surface.

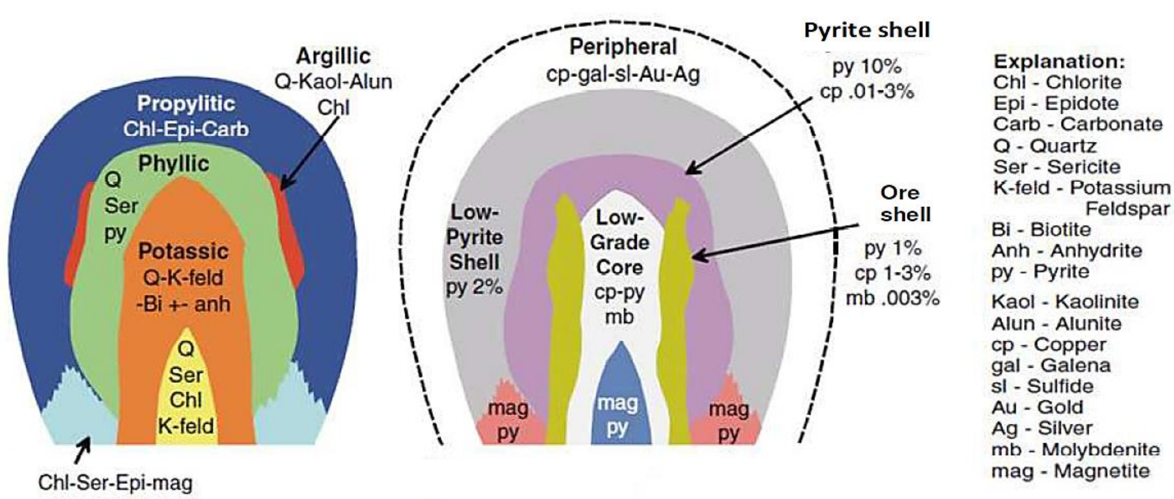
Minerals have distinctive spectral reflectance patterns at visible wavelengths and especially at reflected IR wavelengths [3]. Multispectral image data has been used for mapping hydrothermal alteration zones. Since 2000, and after the launch of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) in 1999, it has become more applicable for mineralogical and lithological studies to be run using the multispectral images provided by ASTER on a wide range of samples. ASTER covers a wide spectral region of the electromagnetic spectrum, from visible near-infrared (VNIR) to thermal infrared (TIR) [4].

The spectral range in ASTER consists of three main subsystems with different spatial resolutions and wavelengths. the subsystems are Visible near-infrared (VNIR), shortwave infrared (SWIR), and thermal infrared (TIR) [4].

SWIR spectral bands were designed to identify reflected radiation to distinguish Al-OH, Fe, Mg-OH, Si-O-H, and CO3 absorption features [5]. Therefore, scientists could identify specific hydrothermal alteration minerals like alunite, kaolinite, calcite, dolomite, chlorite, talc, and muscovite, as well as mineral groups. Hence, the SWIR properties make it suitable for mapping alteration zones in mineral exploration [6].

Applying statistical methods to the produced maps from remote sensing has been helping scientists with different approaches to analyzing point data but also filtering the data (removing missing pixels or filling the voids). Also, combining statistical methods with GIS layers obtained from remote sensing helps improve the generation of DEMs, simulate them, and optimize spatial sampling, the selection of spatial resolution for image data, and the selection of support size for ground data. Geostatistics is a subset of statistical methods used to analyze and interpret geographical data. Geostatistics enables mapping environmental variables using different techniques [7].

Advanced Spaceborne Thermal Emission and Reflection Radiometer give us the potential to map mineralogical alteration zones at low cost with high accuracy. Mapping these zones is important to distinguish high-potential areas of economical mineralization such as epithermal gold and hydrothermal porphyry copper deposits. Hydrothermal porphyry deposits consist of alteration mineral zones (Figure 1) [8]. These zones (phyllic, argillic, and propylitic) contain minerals that can be distinguished from each other using SWIR from ASTER data [9–11].



a *b*

Figure 1. Hydrothermal alteration zones are associated with porphyry copper deposits:
a – a schematic cross-section of hydrothermal alteration mineral zones, which consist of propylitic, phyllic, argillic, and potassic alteration zone;
b – a schematic cross-section of ores associated with each alteration zone

1. Geological settings

Hydrothermal deposits of porphyry copper are usually formed in areas of magmatic rock development. The deposits are usually associated with calc-alkaline plutons. Each hydrothermal copper-porphyry deposit is characterized by hydrothermal alteration mineral zones.

The area under consideration is characterized by low vegetation, which could mask part of the data, causing problems in image processing. It is located within the Zhilanda-Aygyz subzone of the Predchingiz zone. The study is in the Eastern Pribalkhash region and represents a fragment of the Kazakhstan Copper Belt.

To locate areas with copper, molybdenum, lead, and zinc anomalies, as well as to locate pink rhyolite porphyry in the central zone, where contact changes are apparent and suggest the presence of a copper-molybdenum porphyry mineralization process, Viktor V. Diakonov and Alexander E. Kotelnikov, 2016 conducted geological and geochemical analysis in the study area in 2016. They also linked these data to geophysical anomalies to further their understanding of the research area [12; 13].

2. Multispectral properties of hydrothermal alteration zone by ASTER data

The Advanced Spaceborne Thermal Emission and Reflection Radiometer is a multispectral remote sensing instrument that is a highly spatial, spectral, and radiometric instrument. ASTER is a cooperative effort between the Japanese Ministry of Economic Trade and Industry (METI) and the National Aeronautics and Space Administration (NASA). It was launched in December 1999.

ASTER consists of three main subsystems with a total of 14 bands that provide observation in these three different spectral regions of the electromagnetic spectrum: visible near-infrared (VNIR), shortwave infrared (SWIR), and thermal infrared (TIR), which contain 3, 6, and 5 bands, respectively, with different ranges of wavelength. In the VNIR subsystem, bands' ranges differ (from 0.52 to 0.86 μm) with a spatial resolution of 15 m. While the SWIR subsystem's bands' ranges differ (from 1.6 to 2.43 μm) with a spatial resolution of 30 m, TIR, the last subsystem, has bands' ranges (from 0.1.6 to 2.43 μm) with a spatial resolution of 90 m [6].

ASTER provides data that can be useful in a wide range of scientific investigations and applications, including (a) geology studies, (b) climatology studies, (c) volcano monitoring, (d) hydrothermal and water resource applications, and in other different fields of science [14]. It has significant properties widely applied in geology: (1) it allows the discrimination and identification of hydrothermal alteration minerals in the SWIR electromagnetic region; (2) it gives the ability to identify the vegetation and iron oxide minerals on the surface and map carbonates and silicates [15; 16]. ASTER generates two data products: Level-1A, which is raw image data, and Level-1B, which is a data product generated from Level-1A by applying radiometric and geometric correction coefficients [17].

3. Image analysis

Different image-processing techniques can be used on ASTER data, such as principal component analysis (PCA), band ratio, and minimum noise fraction (MNF) [18; 19]. The alteration zone as described previously is separated into three main parts; each of these zones is distinguished by specific minerals that work as indicators as they all have different spectra (Figure 2).

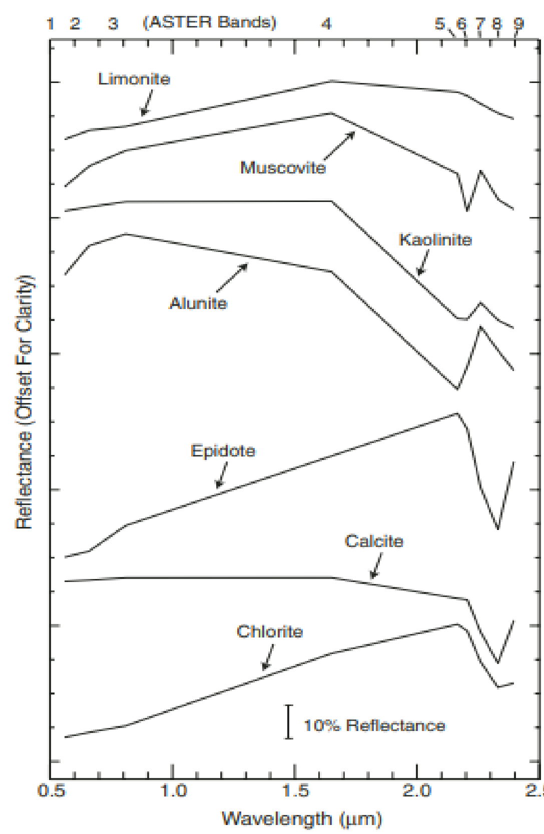


Figure 2. Laboratory spectra of common hydrothermal alteration minerals [18]

ASTER minerals' spectra are important indicators for different hydrothermal alteration zones, as summarized in Figure 2, and can indicate the zone as follows: (1) muscovite as an indicator for phyllic alteration zones with a 2.20 μm absorption feature shown in the 6th ASTER band; (2) kaolinite and alunite as indicators for argillic alteration zones with a 2.20 and 2.17 μm, respectively, absorption feature shown in the 5th ASTER band; (3) epidote, chlorite, and calcite are associated with propylitic alteration zones with 2.31–2.33 μm absorption features shown in the 8th ASTER band. Therefore, these unique absorption features for minerals led to many useful approaches for mapping and discriminating hydrothermal alteration zones [3].

4. Principal component analysis

PCA used the principal component transformation technique to reduce the dimensionality of the correlated multispectral data. The PCA method is widely used to map alteration zones [18]. The PCA technique aims to extract specific spectral responses, as in the case of hydrothermal alteration minerals. The likelihood of having a specific spectral contrast increases as the number of input channels decreases. In this study, the bands that have been used are those that have the potential to show more common spectral features of the alteration mineral.

To confirm the occurrence of minerals, a PCA technique was applied to find the relationship between the spectral responses of target minerals or rocks. The relationship is used to determine which of the PCs contain the spectral information due to the minerals and whether the pixels have high or low values related to the presence of the target mineral in that pixel or the absence of it [20].

Applying PCA to map hydrothermal alteration zones has been widely used as an advanced tool for statistical data reduction and satellite image processing. As it was recommended in the articles [21; 22] to map alteration minerals to indicate different alteration zones, for example, using a subset of ASTER bands (1, 4, 6, and 7) to map Kaolinite Also, band subsets (1, 3, 5, and 7) and (1, 3, 5, and 6) for mapping Alunite and Illite, respectively.

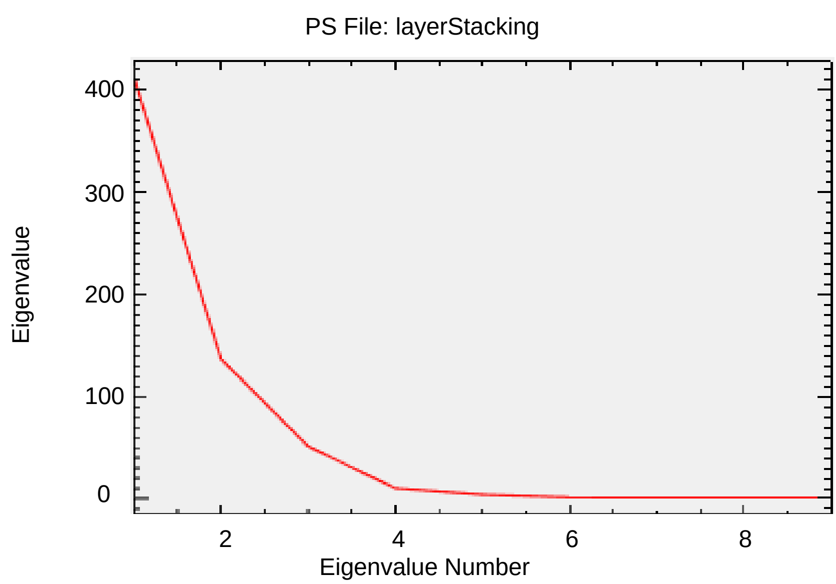


Figure 3. A curve showing that the first few bands contain most of the data, and the signal decreases with increasing noise towards the the curve tail (the graph is made using ENVI 5.3)

The eigenvalues of the 14 ASTER bands show that PC1, PC2, and PC3 have over 97% of the spectral information displayed in Figure 3; the rest of the low-order PCs have less than 3%; they usually contain low signal-to-noise ratios. PCs that contain more than 97% are widely used for lithological mapping [20].

5. Results and discussion

By applying the principal component analysis (PCA) to ASTER bands, we can highlight different areas of the hydrothermal alteration zones, as each zone has its rocks with specific minerals. Different minerals can be identified, like kaolinite and alunite, which show an absorption behavior in band 6 due to Al-OH; these two also show a reflection behavior that corresponds with the argillic zone [23].

Illite, smectite, and sericite minerals give an absorption behavior in band 6 and a reflection behavior in band 5, which correspond with the phyllic zone. The propylite zone is shown as a response to the reflecting of chlorite, epidote, and calcite, which shows absorption behavior in the 8th band and reflecting behavior in the 5th band [23].

PCA is a statistical tool used to extract specific spectral features. In 1989, Crosta and Moore developed a PCA technique using Landsat TM to map oxide/hydroxide iron minerals related to sulfide ore bodies in the granite-greenstone belt. PCA is calculated by forming a relationship between the spectral responses of minerals under consideration and values extracted from the eigenvector matrix.

Using a few selected bands to avoid mapping certain materials like vegetation and applying PCA to them helps extract information about targeted materials (hydrothermal alteration). This procedure is called the “Crosta technique” and has been widely used for mineral exploration due to its ease [24].

Choosing subsets of ASTER bands proposed by Loughlin (1991) according to spectral features related to hydrothermal alteration minerals in VNIR and SWIR and applying PCA to each chosen subset gives information about the target mineral. To identify which PC has the target information, we choose the PC that has the highest eigenvector value difference among bands. In the application of PCA to ASTER bands, subsets 1, 4, 6, and 7 were used to successfully map the argillic alteration zone as bright pixels into the PC-3 image shown in Figure 4, *a*. This is evident by the low negative contribution of band 7 and the high positive contribution of band 4 (Table 1).

To map the phyllic alteration zone, we used subsets 1, 3, 5, and 6. The phyllic zone shows a dark color pixel value in the PC-4 image (Figure 4, *b*), due to the high positive contribution of band 5 and the low negative contribution of band 6 (Table 2).

Implementation of PCA in ASTER bands 1, 3, 5, and 7 suggests information on the propylitic alteration zone. The spatial map shows the alteration zone as bright pixels in PC-3 (Figure 4, *c*), due to the high positive contribution of band 3 and the low negative contribution of band 5 (Table 3).

Table 1

Eigenvectors values for PC bands 1, 4, 6, and 7

Input layer	**Eigenvectors**			
	PC1	**PC2**	**PC3**	**PC4**
Band 1	0.69778	–0.7139	0.05644	0.01627
Band 4	0.35619	0.41171	0.83287	–0.09976
Band 6	0.44468	0.42624	–0.31436	0.72233
Band 7	0.43416	0.37303	–0.45202	–0.68413

Table 2

Eigenvectors values for PC bands 1, 3, 5, and 6

Input layer	**Eigenvectors**			
	PC1	**PC2**	**PC3**	**PC4**
Band 1	0.7678	–0.27059	–0.58071	–0.00636
Band 3	0.42198	–0.4684	0.77623	–0.00297
Band 5	0.3278	0.56166	0.16356	0.74184
Band 6	0.3535	0.62603	0.18303	–0.67054

Table 3

Eigenvectors values for PC bands 1, 3, 5 and 7

Input Layer	**Eigenvectors**			
	PC1	**PC2**	**PC3**	**PC4**
band 1	0.77196	–0.23351	–0.59107	0.01353
band 3	0.42365	–0.50435	0.7524	–0.00656
band 5	0.32243	0.57527	0.21036	0.7217
band 7	0.34732	0.60014	0.20068	–0.69204

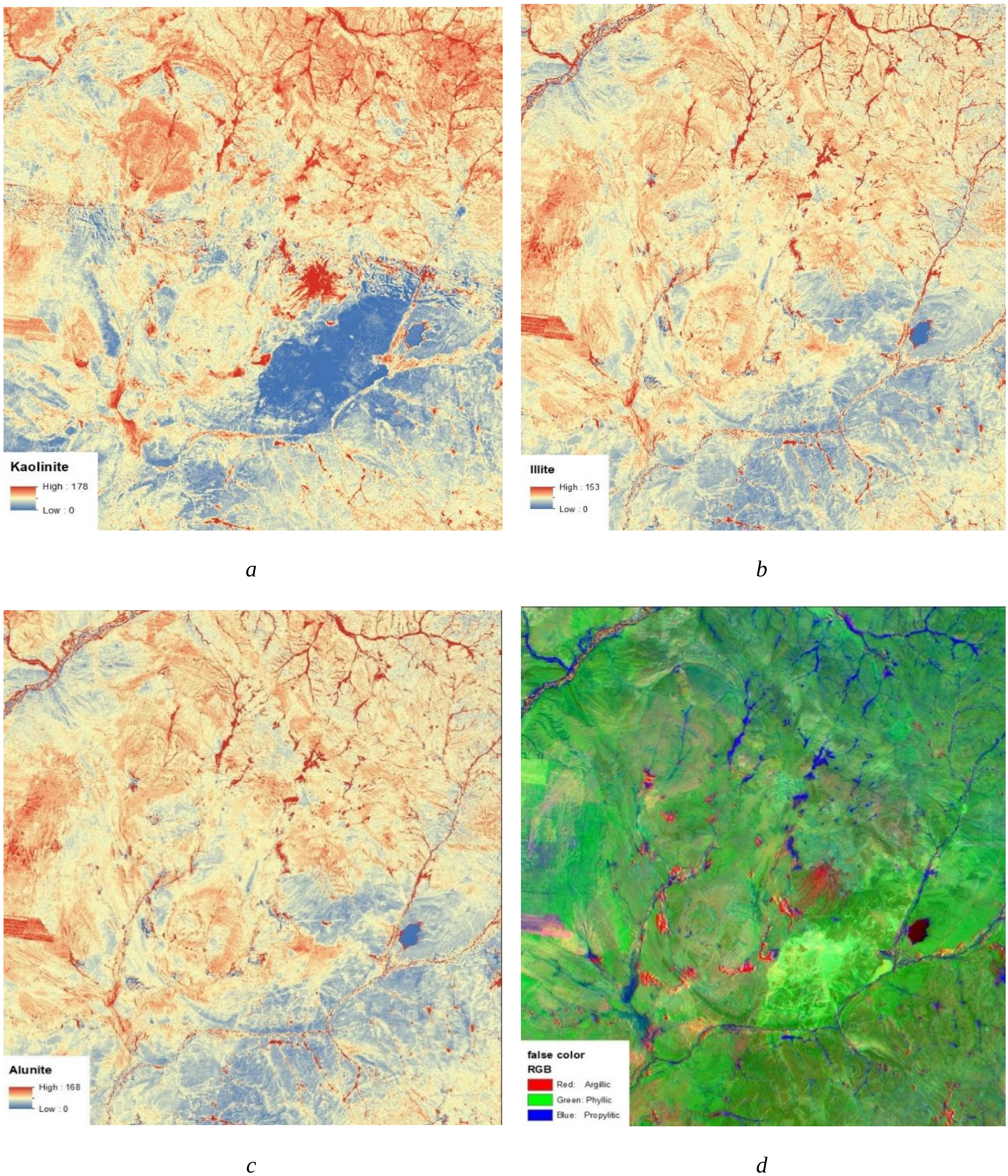


Figure 4. Applying the Crosta technique indicates places that show the presence or absence (the map is made using QGIS 3.18.3):
a – Kaolinite as an indicator of Argillic zone; *b* – Illite indicates Phyllic's zone;
c – Alunite indicates Propylitic's zone; *d* – false-color composite image of PC 3, PC 4, PC 3 image

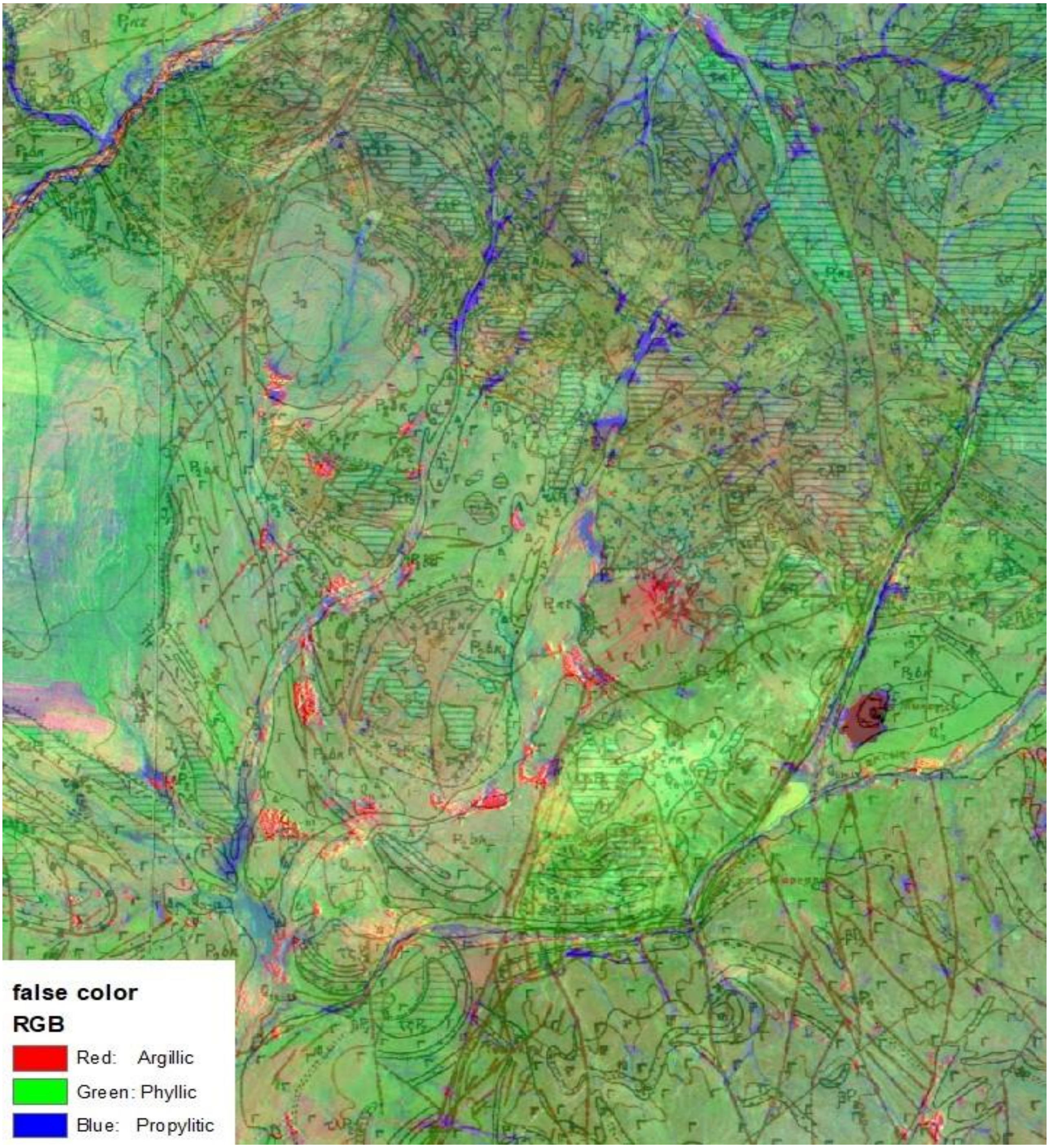


Figure 5. Predictions of hydrothermal alteration zones assigned as Argillic, Phyllic, and Propylitic on a geological base map [1; 2]

Conclusion

Analysis of ASTER satellite images using PCA and applying the Crosta technique gives promising findings and an understanding of the area under consideration. The satellite image interpretation and integration with the geological map of the area show that PCA is an applicable technique to be used in our study area to map hydrothermal alteration zones. Also, the result shows that our study area is suitable for this kind of image processing as it is characterized by a low vegetation mask.

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