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SPECTRAL REMOTE SENSING OF INTRUSIVE AND VOLCANIC IGNEOUS ROCKS

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ABSTRACT. Results from a remote sensing study on the spectral reflectance of intermediate igneous rocks in the visible and near infrared spectral ranges of the electromagnetic spectrum are presented. The spectral data were obtained in laboratory by means of the multichannel spectrometer of high spectral and spatial resolution which was developed by scientists from STIL – BAS. Spectrometric measurements were carried out on characteristic intrusive and volcanic representatives of intermediate rocks that were generated in different depth facieses. Specimens of diorite and andesite, monzonite and latite, and syenite and trachyte were put side by side. To discriminate the rock specimens by spectral features a method based on statistical techniques such as Student's t-criterion, cluster analysis and discriminant analysis was developed and applied to their spectral reflectance characteristics. There were found statistically significant differences between the averaged spectral reflectance characteristics of the classification groups of intermediate basic rocks as well as between the spectral reflectance characteristics belonging to a classification group. By spectral features there were discriminated at a statistically significant level of confidence the main rock-forming minerals. The investigations were aimed as well to help in revealing the influence of texture peculiarity and variations of the chemical and mineral composition of rock specimens on their spectral features.

СПЕКТРАЛНИ ДИСТАНЦИОННИ ИЗСЛЕДВАНИЯ НА ИНТРУЗИВНИ И ВУЛКАНСКИ МАГМЕНИ СКАЛИ

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РЕЗЮМЕ. Проведени са експерименти за дистанционно изследване на отражателната способност на магмени скали, формирани в различни дълбочинни фациеси. Подбрани са образци на характерни интрузивни и вулкански представители на среднобазични магмени скали:с нормална и повишена алкалност: диорит - андезит; монцонит – латит и сиенит - трахит. Спектралните данни са получени в лабораторни условия с многоканален спектрометър с високи спекттрална и пространствена разделителни способности във видимата и близката инфрачервена области на електромагнитния спектър. За разграничаване на скалните подкласове по спектрални признаци е приложена разработена от нас методика. Върху данните за отражателната способност на скалите (спектрални отражателни характеристики) са приложени статистически методи (t-критерий на Стюдънт, клъстерен анализ, дискриминантен анализ и др.) за установяване на статистическата достоверност на разликите на осреднените спектрални отражателни характеристики в избрани дължини на вълните, равномерно разпределени в изследвания спектрален диапазон. Изследванията са насочени и към установяване на зависимостите на спектралните признаци от текстурните особености и вариациите в химичния и минерален състав на изследваните образци, както и за използване на спектралните признаци за разграничаванито им.

Introduction

The modern methods of remote sensing of Earth find an increasing field of applications for protection and rational use of earth resources and monitoring of environment (Clark, 1999; Rowan et al., 2003; Wu et al., 2004). They afford large scale research and continuous incoming of regional and global information for the ongoing processes on the Earth. By remote sensing data it could be determined the localization, character, variability and changeability of natural formations and natural resources as well as of anthropogenic objects (Avery and Berlin, 1992; Salisbury and D'Aria, 1994; Kruze, 1995; Clark et al., 1999; Berger et al., 2003)

Lithologic recognition and mapping is one of the primary tasks of oriented to geology remote sensing. Remote spectrometric measurements in the visible and near infrared (NIR) regions are an important method for mineralogical analyses of Earth surface (Kuung-Kuk Kang et al., 2001). Successful interpretation of such remote spectral analyses is relying on spectral reflectance studies in laboratory. Spectral reflectance is a consequence of the chemical composition and structure of the studied material which often become modified by environment, as well as the physical conditions. In the visible and NIR regions the gathered information is a consequence of variations of the reflectance due to electronic and vibrational processes.

The collection and analysis of reflectance spectra of different rock units is finalized with creation of a spectral library. Its purpose is to feed a system for analysis of remote sensing data to perform image calibration and to provide means for a reliable geologic interpretation (Salvi et al., 1997). Most often the spectral library is composed from reflectance data obtained in laboratory on mineral samples which yield very sound grounds for the application of both deterministic and statistic techniques of image analyses.

In our recent studies we presented spectral reflectance characteristics (SRC) of particular representatives of igneous, sediment and regional metamorphic rocks of different genesis, chemical and mineral composition (Krezhova et al., 2003a; Krezhova and Pristavova, 2003). Studies were conducted as well on the influence of structure-texture peculiarities of some rock specimens on their SRCs (Krezhova et al., 2003b; Krezhova et al, .2004) by applying statistical and deterministic methods for analysis.

The objective of this work is to present the efficiency of spectral remote sensing and the applied method based on statistical techniques for discrimination of rock types and their mineralogical diversity by spectral features.

Materials and methods

The object of investigation in the present work is intermediate igneous rocks with normal and raised alkalinity. Intrusive and volcanic representatives of this group of rocks were studied, namely diorite - andesite, monzonite - latite, and syenite - trachyte. The rocks possess a close chemical and mineral composition with differences expressed primarily in the percentage of main rock-forming mineral constituents owing to raised content of alkali (Na_2O, K_2O) in the group of monzonite and syenite. By structural characteristics there is a distinct discrimination of the intrusive from the volcanic representatives. The intrusive rocks diorite, monzonite and syenite are fully crystalline rocks of massive texture whereas their volcanic analogues are not completely crystallized and are built from a porphyry generation and a ground mass of volcanic glass.

Petrographic characteristic of the rock specimens under investigation

Diorite **-** very deep grey in color, fine-grained with massive to spotted in places structure. Very fine light greenish epidotic veinlets crosscut the sample. Texture - hypidiomorphic. Mineral composition - medium plagioclase (labradore - andesine), rhombic pyroxene, amphibole, biotite, quartz (single grains); accessories - sphene, apatite and zircon.

Andesite - dark green porphyry rock with massive structure. Texture - porphyritic on plagioclase and amphibole; ground mass - pilotaxitic. Mineral composition - porphyritic generation of plagioclase (labradore - andesine), rhombic pyroxene, amphibole and cryptocrystalline mass with microlites of plagioclase.

Monzonite - deep grey in color, medium to coarse grained rock with massive texture. Texture - hypidiomorphic, monzonitic. Mineral composition - medium plagioclase (andesine), K feldspar, amphibole, biotite, rhombic pyroxene, and quartz as single grains; accessories - sphene, apatite and zircon.

Latite - deep reddish in color, slight porous with porphyry character. Texture - porphyry on plagioclase (mainly) and amphibole, in the ground mass - trachytic. Mineral composition - porphyritic generation of plagioclase (andesine), rhombic pyroxene, amphibole and cryptocrystalline mass with microlites of plagioclase.

Syenite **-** grey, grey-pinkish in color, medium grained rock with massive structure. Texture - hypidiomorphic, poikilitic. Mineral composition - medium plagioclase (andesine), K feldspar, amphibole, biotite, quartz as single grains; accessories - apatite, sphene, and zircon.

Trachyte - deep grey in color with large in size whitish porphyry of K feldspar. Mineral composition - porphyritic generation of K feldspar (sanidine), single crystals of plagioclase (andesine), biotite and amphibole, and cryptocrystalline mass with microlites of K feldspar.

Data acquisition

Spectral data for the radiation reflected from the rock samples were obtained using a multichannel spectrometer of high spectral and spatial resolutions in the visible and NIR ranges of the electromagnetic spectrum. The spectrometer was developed by scientists and specialists from the Solar Terrestrial Influences Laboratory for carrying out spectral remote sensing investigations of natural formations, the atmosphere of Earth, and the World Ocean from the orbital space station "MIR" (Mishev et al., 1989; Mishev et al., 1990; Mishev et al., 1999; Krezhova, 2002; Krezhova, 2003). In the last years the multichannel spectrometer was used in research on natural objects (rocks, sands, vegetation, grunts) aimed to complement and to enrich the existing database of spectral characteristics for main classes of objects and to study the influence of different factors (natural and anthropogenic) on the reflective power of the objects (Yanev et al. 2000; Krezhova et al., 2004). The conditions for carrying out the spectrometric measurements were also analyzed with the intention to improve the techniques for measuring reflectance specific to the classes of objects under investigation and to help in better performance of future spectrometric systems.

The spectral measurements were performed in laboratory with the spectrometer operating in the mode of 128 spectral channels at a halfwidth of 2.6 nm each and spatial resolution of 2 mm^2 in the spectral range $480 \div 810$ nm. The rock samples are placed on a movable platform at a distance of 2.5 m from the spectrometer. The surface examined of each specimen is set perpendicular to the optical axis of the spectrometer. The time of registration of one spectrum is 25 ms at a spectrometry rate of 40 spectra per second. As a source of light three halogen lamps are used of 250 W of power each and the diffuse light scattering standard is a white screen covered with a layer of barium sulfate.

For each sample under investigation there were recorded data (spectra) for the reflected by on average 30 measured areas located in succession along a horizontal line. For each area there were collected on average 50 spectra. These data were accompanied with data for the dark current and the reflected by the standard screen radiation (100 spectra on average). For determination of the spectral reflectance coefficients at each channel which form the spectral reflectance characteristics the recorded data undergo a preliminary treatment. It involves averaging over the spectra of each pixel, taking into account of the dark current and referring the data to the reflected by the white screen radiation.

Methods

To assess the statistically significance of differences between the spectral reflectance characteristics of the rock specimens we applied the method developed in our previous work (Krezhova et al., 2005) which is based on statistical techniques. The algorithm implemented here for data analysis involves the following steps:

a) *Use of a priori* mineralogical information about the specimens examined;
b) Analysis of the SRC course in dependence on wavelength;
c) Formation of a SRC data set at selected wavelengths for further analysis;
d) t-criterion of Student;
e) Cluster analysis (CA);
f) Discriminant analysis (DA).

Steps in points a) and b) provide the possibility to select a set of wavelengths and to execute point c). The selected SRC data set is further used for performing of CA and obtaining at first approximation of a set of clusters of the pixels examined of each one of the specimens or the pixels belonging to one specimen (depending on mineral composition). The belongin of the pixels of the specimens to different clusters is used to design the grouping variables necessary to perform DA. Initially DA is performed only at a particular wavelength. In case that the number of incorrectly classified pixels is unacceptably large the DA is performed at combinations of two or more wavelengths. Finally, the DA assigns posterior probabilities to each of the pixels and determines the classification accuracy. Incorrectly classified pixels may be used for further updating.

Results and discussion

The average SRCs of the rock specimens examined are presented in Fig. 1. Two basic groups of spectral characteristics are distinctly differentiated. Among the curves of the first group fall the SRCs of rocks with normal alkalescency, diorite - andesite, and to the other group belong the SRCs of rocks with the raised alkalescency, monzonite - latite and syenite - trachyte. The differences between the average values of spectral reflectance coefficients of the rocks from the two groups at five wavelengths, which were selected to be distributed evenly in the working spectral range (550.2 nm, 599.6 nm, 649 nm 701 nm and 750.4 nm) are statistically significant at a level of confidence $p<0.05$ on the basis of the t-criterion of Student.

The intermediate rocks of normal alkalinity represented by diorite and andesite display the lowest reflective power. Their average spectral reflectance characteristics (curves 5 and 6 in Fig. 1) exhibit a similar course. The spectral reflectance coefficients of the average SRC of diorite are lower due to its darker color. For both specimens, no subclasses are discriminated by spectral features. This is reasoned by the fine-grained consistency of diorite and the fine porphyritic character of andesite. The grain size of the rock-forming minerals is lower than the spatial resolution of the multichannel spectrometer due to which their color characteristics merge.

For the group of intermediate rocks of raised alkalinity the pairs of monzonite - latite and syenite -trachyte, the average SRCs closely corresponded with their petrographic peculiarities. The intrusive rocks monzonite and syenite exhibit a similar course of the SRCs, curves 3 and 1 in Fig. 1, respectively, with the average SRC of syenite being of higher intensity of reflected radiation over the whole spectral range. This is due to the higher content of K feldspar (pale pinkish). The average SRC of the volcanic rock trachyte (curve 4 in Fig. 1) have a similar course with that of its intrusive analogue syenite and a lower reflective power because of the more satiated grey color of the ground mass. The course of the average SRC of latite (curve 2 in Fig. 1) differs from that one of the intrusive analogue - monzonite because the ground mass is strongly modified. The latter contains minerals and iron hydroxides bringing its color deep red-brown.

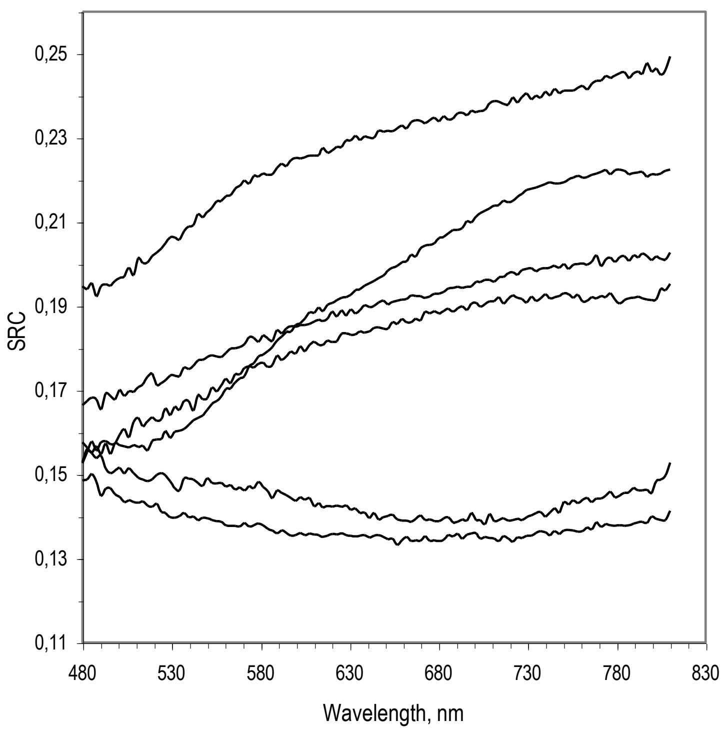

Fig. 1. Averaged SRC of the specimens: syenite (1), latite (2), monzonite (3), trachyte (4), andesite (5), diorite (6)

Among the SRCs of the examined areas of the specimen of monzonite there were discriminated two subclasses that correspond to macroscopically observed salic minerals (feldspars - light grey, subclass 1) and femic minerals (mainly amphibole - dark green, subclass 2). Fig. 2 shows the corresponding average spectral characteristics. In the SRCs of syenite there were separated three subclasses corresponding to the femic minerals (dark green, subclass 3), plagioclases (light grey, subclass 2) and K feldspar (pale pink, subclass 1). The average SRCs of the subclasses are displayed in Fig. 3.

Among the SRCs of the volcanic representatives of rocks, the group of latite and trachyte, in each one of the specimens there were clearly differentiated two subclasses that differ by both the SRC course and intensity, and correspond to the porphyric feldspar generation (subclasses 1) and the ground mass (subclasses 2). Fig. 4 and Fig. 5 show the average SRCs of the two subclasses in 2 and trachyte, respectively.

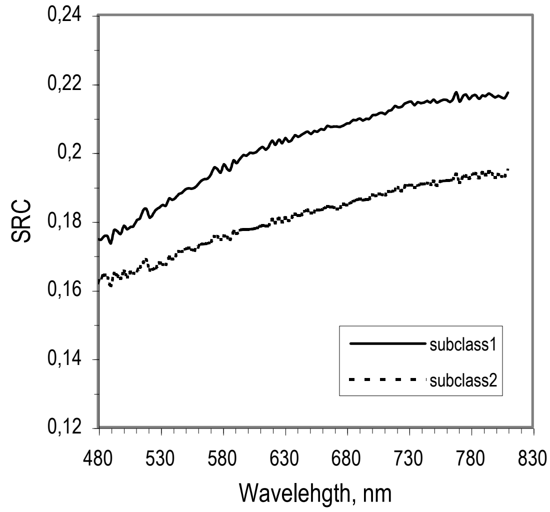

Fig. 2. Averaged SRC of the two subclasses in the monzonite

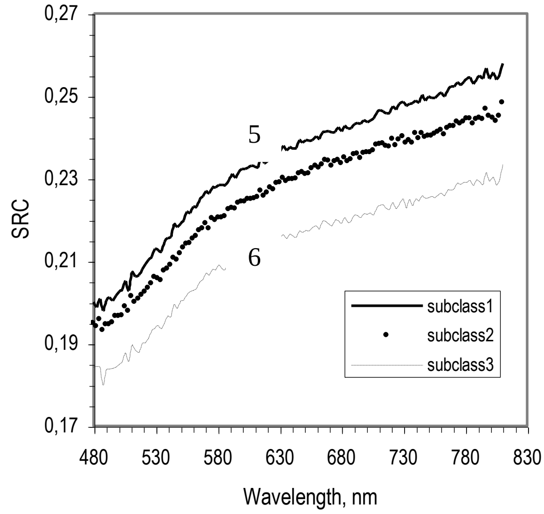

Fig. 3. Averaged SRC of the three subclasses in the syenite

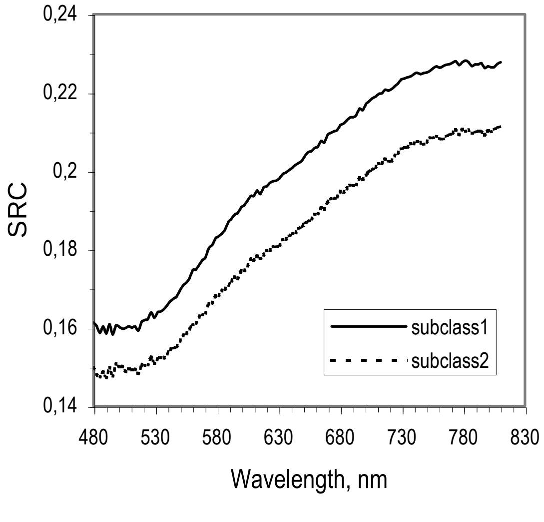

Fig. 4. Averaged SRC of the two subclasses in the latite

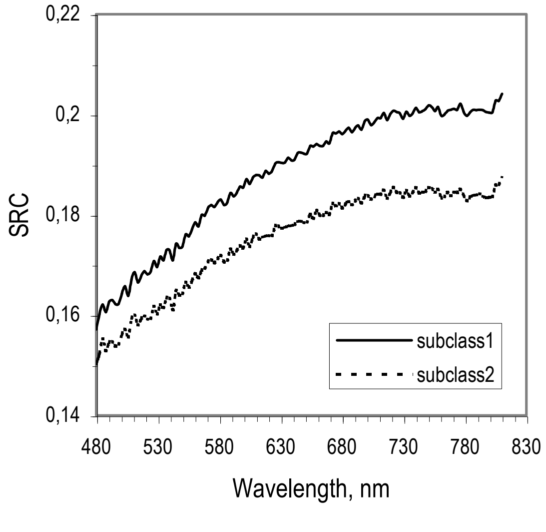

Fig. 5. Averaged SRC of the three subclasses in the trachyte

Table 1
Number of incorrectly classified pixels after performance of discriminant analysis of the SRCs of the rock specimens examined

Wavelength, nm	Specimen syenite 3 clusters (32 pixels)	Specimen monzonite 2 clusters (31 pixels)	Specimen trachyte 2 clusters (28 pixels)	Specimen latite 2 clusters(29 pixels)
550.2	4	1	3	3
599.6	6	0	0	1
649.0	6	1	0	0
750.4	6	2	0	3
All wavelengths	2	0	0	0

Making use of points a) and b) we have chosen four wavelengths at which the Student's t-criterion and CA were performed (Statistica package, 1995). As the SRC course was monotonous in the visible spectral range, the first three wavelengths were chosen to be equidistantly disposed (550.2, 599.6 nm, and 649.0 nm).The fourth wavelength was chosen to be approximately in the mid of the NIR range (750.4 nm) because most of SRCs within this range were almost parallel. The t-criterion indicated that at these wavelengths the average SRC of the specimens of different types differed statistically significant at $p<0.05$. The a priori information concerning the mineralogical diversity of the specimens examined and the results based on the SRCs have suggested the number of clusters which should be used as input for CA (usually 2 clusters). It turned out that only in the case of the syenite specimen more than 2 clusters (namely 3 clusters) were expected. DA was performed and the results are set out in Table 1. As it is seen if DA is performed at only one particular wavelength the best results are obtained at 599.6 nm and 649.0 nm.

Making use of all four wavelengths under consideration (a four dimensional space for classification) only for the specimen of syenite there remained two incorrectly classified pixels. In all other cases no incorrectly classified pixels were observed. Moreover posterior probabilities higher than 90% were assigned as a rule to the correctly classified pixels.

DA revealed that classification with less than two clusters and more than three clusters worsened the accuracy of DA classification, i. e. SRC of the specimens under consideration and the algorithm applied not only confirmed the expected mineralogical diversity but assigned posterior probabilities to the classification results. In addition the proper wavelengths for performing the classification were marked. Anyway, the last result should be checked over a larger amount of specimens in order to fill in a SRC database for assessment of the mineralogical diversity of different specimens in combination with the traditional mineralogical methods.

Conclusions

It was demonstrated that spectral remote sensing of natural objects by applying high resolution multichannel spectrometry and statistical techniques provides the reliable recognition of representatives of intermediate igneous rocks of normal and raised alkalinity by spectral features.

In addition, the SRCs of rock specimens and the statistical methods herein used provide the possibility the mineral diversity of different specimens to be assessed and classified at a satisfactory statistical significance. The results obtained may be used to design a database and to continuously improve it by adding to it results from new specimens.

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