USE OF THE SENTINEL-2A MULTISPECTRAL IMAGE FOR LITHO-STRUCTURAL AND ALTERATION MAPPING IN AL GLO'A MAP SHEET (1/50,000) (BOU AZZER–EL GRAARA INLIER, CENTRAL ANTI-ATLAS, MOROCCO)

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ABSTRACT: The discovery of natural resources remains the main mission of Earth observation satellites, especially in geographical areas that have a very difficult accessibility as those of the Bou Azzer–El Graara inlier (Central Anti-Atlas, Morocco). This work investigates the use of different satellite data, such as Sentinel-2A's multispectral imagery, in order to direct the prospection program in an efficient manner, saving both time and cost. The image processing methods of Landsat 7, 8, and “Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)” (30 m/15 m) were used to create methods for Sentinel-2A images (10 m). The red, green, blue (RGB) image 12.8.2, 11/12.11/2.11/8, principal component (PC) 1,2,3(11.12.2), and other new images were the result of principal component analysis (PCA), and classification by the Iterative Self-Organizing Data Analysis Technique (ISODATA) and K-Means allowed realization of a lithological cartography as well as maps of lineaments through directional filters and the ratio of 11/12 for hydrothermal alteration zone mapping. The assembly of lithological, structural, and hydrothermal alteration data gave an idea of the mineralogy of the study area. Validity of the results was tested by comparison with the field data and the geological maps of the studied site (62% for the hydrothermal alteration zone, 81% for the lithological map, and 74% for the structural map).

Keywords: remote sensing, multispectral image, Sentinel-2A, mineral prospecting, Bou Azzer–El Graara inlier (Morocco).

1. INTRODUCTION

In the field of geology, Landsat and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) remain the most widely used Earth observation satellites. This work is part of the use of geomatics to direct prospectors to areas that may contain concentrations of ores. It will provide mining operators and exploration juniors with a decision-making tool that has the advantage of being economical, fast, and, above all, applicable in remote and inaccessible areas. The objective of this work is to evaluate the potential of Sentinel-2A multispectral imaging (MSI) for mineral resource mapping.

In Morocco, the new mining code, Law 33-13, has provided opportunities for exploration and research of large area of mineral resources through the introduction of the exploration license with a maximum perimeter of 2,400 km² and the merger of research permits. Through

the state of knowledge of the various aspects of the use of Landsat 7, 8, and ASTER geological multispectral satellite images, several treatment methods have been studied that are summarized in Table 1.

Table 1. (part one) Multispectral image processing methods for mineral prospecting

Image	Satellite	Resolution	Associated processing	Study zone	Author(s) and year	Result
543	L 7	30	F0°, F45°, F90°	Djelfa, Algeria	Amri et al., 2017	Lithology and lineaments map
751						
3/4 7/5 2/3						
2/1 3/2 7/5						
PC1, 2, 3(571)						
PC1, 2, 3(573)						
1 4 5 7 1 3 4 5	L 7	30	PCA	Gördes region (Turkey)	Vural et al., 2016	Exploring Gördes zeolite sites
6/5 7/6 4/7	L 8	30	SVM	Draa Bas, Maroc	Adiri et al., 2016	Lithological discrimination
(6 + 8)/4 9/4 5/3	ASTER	15				Clay
6/5	L 8	30				Alluvium
5/3	ASTER	15				Schist
5/4	L 8	30				Granite and biotite
3/2	ASTER	15				Rhyolite
4/7	L 8	30				
3/6	ASTER	15				
7/6	L 8	30				
(6 + 8)/4	ASTER	30				
9/4	ASTER	30				
B1, B4, B6, and B7 B1, B3, B4, and B8	ASTER	30	PCA	Arequipa province of South Peru	Wang et al., 2015	Mineral alteration
Band 5 of the level-1B and level-2 (AST2B05S) SWIR	ASTER	30	SAM	Sar Cheshmeh in Iran	Shahriari et al., 2015	Hydrothermal alteration mapping
573	L 7	30	PCA	Central region of Kenya	Mwaniki et al., 2015	Litho-structural map
674	L 8					
3/2 5/1 7/3	L 7					
4/3 6/2 7/4	L 8					
4/2 6/7 5/10	L 8	30	----	Iran	Pour and Hashim, 2014	Alteration zone

Table 1. (part two) Multispectral image processing methods for mineral prospecting

731	L 7	30	Normal and selective PCA	Hang, Algeria	Achek and Aidouni, 2014	Lithological discrimination
742						
5/7 4/5 1/3						
5/3 3/1 7/5						
432						Lithological discrimination, the vegetation appears in red
754						Lithological discrimination, the vegetation appears in blue
3/1						Good discrimination for rocks subjected to hydrothermal alteration and for iron oxides
1/2, 2/1						Good discrimination for rocks rich in iron oxides
5/7						Good discrimination for rocks rich in Al-OH
7/5						Good discrimination of clays
5/4						Good discrimination of iron oxides
5/7						
5/7	TM	30			Al Hakim and Sulistijo, 2013	Zone d'altération
Band ratio composites ([6/3–1/3–9/5] and [8/6–8/7–4/7] [RGB])	ASTER	30	FOPCA	Wadi Kid, southeastern Sinai peninsula, Egypt	Gad and Raef, 2012	Lithological mapping
752	L 7	30/15	Fusion with B8 (15 m) and F. D.	Ivory Coast	Ouattara et al., 2012	Litho-structural map
30 m strips	L 7	30 m	OIF		Imessaoudene, 2012	Lithology
Ratio 4/9 and RGB composite 148	ASTER	30	FOPCA	Ankara Bala	Öztan and Süzen, 2011	Mapping evaporate minerals (gypsum)
Four RGB combinations (3, 5, 6, and 8)	ASTER	30	SAM	Mainland Gujarat, India	Nair and Mathew, 2012	Lithological map

Table 1. (part three) Multispectral image processing methods for mineral prospecting

321	L 7	30	Directional filter 0°, 45°, 90°, and 135° Matrix 3*3 and 7*7	Central Hoggar, Algeria	Amri et al., 2009	Lithological discrimination lineaments map
742						
5/7 5/1 5/4						
5/3 4/2 3/1						
567	L 7	30	---	Northeast of Hajjah, Yemen	Qaid and Basavarajappa, 2008	Lithology
468	ASTER	30	----		Mike, 2005	
753	L 7	30		Sudan	Shaddad, 2005	Delineation of dry soil and distinct rock surfaces
7/visible	Landsat TM MSS	30	----	Tunisia	Escadafal and Peugeot, 1987	Mineralization (gypsum)
5/4 6/5 7/6						Alteration
3/2 3/1 5/7						Lithology
7/3						Snow and ice
3/5						

Key: ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; FOPCA, feature-oriented principal component analysis; PC, principal component; PCA, principal component analysis; RGB, red, green, blue; SAM, spectral angle mapper; TM, Thematic Mapper; MSS, Multispectral Scanner System; OIF, Optimum Index Factor ; SVM, support vector machine; SWIR, Short-Wave Infrared.

Our study area, red square in Figure 1, the area covered by Al Glo'a leaf, belongs to the domain of the central Moroccan Anti-Atlas that consists of a mountainous chain with polyphase deformation that runs along the northwestern edge of the West African Craton. Located about 100 km southwest of Ouarzazate, the Al Glo'a leaf forms part of a perimeter at the southern end of Bou Azzer–El Graara eastern inlier, along the major accident of the Anti-Atlas in its central part. This area constitutes a reference in the Moroccan geological literature for the understanding of Precambrian events of the Anti-Atlas. This interest is accentuated by the great metallogenic richness of this inlier (cobalt, copper, gold, barite, etc.) (Soulaimani et al., 2013b).

The area covered by the Al Glo'a (Figure 1) sheet is positioned on the eastern end of the Bou Azzer–El Graara inlier. This corresponds to two contiguous depressions (Bou Azzer and El Graara) extended WNW–ESE over a length of approximately 67 km and a maximum width of 15 km. Morphologically, by looking from a low position, the inlier is surrounded by Paleozoic sedimentary cover cliffs. The altitude of the inlier lands is mainly around 1,300 m, while the cuestas of the cover areas frequently reach 1,400–1,500 m and exceed 1,600 m on several occasions (Soulaimani et al., 2013b).

Fig. 1. Geological setting of the study area (red square) (Soulaimani et al., 2013b)

2. MATERIAL

The Sentinel-2A MSI instrument captures images of 13 spectral bands ranging from visible to mid-infrared over a width of 290 km (Table 2):

- The four spectral bands (blue [490 nm], green [560 nm], red [665 nm], and near infrared [842 nm]) having a resolution of 10 m;
- Three spectral bands (443, 945, and 1,375 nm) are provided with a resolution of 60 m; and
- Six bands are provided with 20 m (bands N°: 5 [705 nm], 6 [740 nm], 7 [783 nm], 8A [865 nm], 11 [1,610 nm], and 12 [2,190 nm]).

Table 2. Sentinel-2A MSI bands (GDAL)

Band name	Resolution (m)	Central wavelength (nm)	Bandwidth (nm)	Purpose
B01	60	443	20	Aerosol detection
B02	10	490	65	Blue
B03	10	560	35	Green
B04	10	665	30	Red
B05	20	705	15	Vegetation classification
B06	20	740	15	Vegetation classification
B07	20	783	20	Vegetation classification
B08	10	842	115	Near infrared
B08A	20	865	20	Vegetation classification
B09	60	945	20	Water vapor
B10	60	1,375	30	Cirrus
B11	20	1,610	90	Snow/ice/cloud discrimination
B12	20	2,190	180	Snow/ice/cloud discrimination

Key: MSI, multispectral imaging.

MSI database, a multispectral instrument, has made it possible to directly download images of the Sentinel already corrected for atmospheric effects via the website <https://scihub.copernicus.eu/dhus/#/home>. We have chosen an image, Figure 2c and d, with the product type S2MSI2Ap (Sentinel-2A; 2015) and the processing level 2Ap, picked up on 09 April 2017 at 10 h 56 min 51 s in Bou Azzer–El Graara area. It is characterized by 97% bare soil, 0.08% cloud cover, 0% snow ice, 1.01% vegetation, and 0.000013% water.

Fig. 2. Study area location: (a) Morocco's location in the world; (b) location of the sheet of Al Glo'a in Morocco; (c) location of the sheet of Al Glo'a in the initial Sentinel-2A image; (d) location of the initial Sentinel-2A image; and (e) the sheet of Al Glo'a (hydrogeological map)

In this work, we have studied only a part of the image (Figure 2), extracted by the technique of Imagine Erdas Area of Interest (AOI), relating to the Al Glo'a map sheet at scale 1/50,000 (Figure 3 and red squares in Figures 1 and 2). This study area is limited by the boundaries shown in Table 3.

The outcrops of Neoproterozoic rocks in the central part of Al Glo'a sheet (Figure 3) are covered by upper Ediacaran volcano-sedimentary rocks (Ouarzazate group) and a lower Paleozoic sedimentary cover (Soulaimani et al., 2013b).

3. METHOD

The approach adopted in this article is the use of remote sensing space techniques that can be deployed downstream of conventional exploration programs. This requires significant technical and financial resources and, especially, accessibility that remains very difficult in the field. The processing methods mentioned above (Table 1) will be the subject of an analogy based on the correspondence between the bands of the different satellites and Sentinel-2. The goal is to move to a high resolution of 10 m instead of 30 m to provide information on the lithology and geological structures, which are valuable for mineral prospecting and exploration activities. Figure 4 shows a comparison among the Landsat 7, 8, ASTER, MODIS, and Sentinel bands.

Fig. 4. Comparison of Landsat 7, 8, Sentinel-2, ASTER, and MODIS bands (USGS Landsat Program)

Through this comparison, one can make an analogy to create a method of treatment with Sentinel-2A. Table 4 presents several methods of treatment after deletion of those that do not correspond with the bands of the MSI (bands 8, 9, 10, 11, 12, 13, and 14 of ASTER; bands 10 and 11 of Landsat 8 and band 6 of Landsat 7).

Table 4. MSI Sentinel-2A image processing methods

Image	Satellite	Sentinel-2A image by analogy	Resolution (m)
543	L 7	11.8.4	10
751		12.11.2	10
3/4 7/5 2/3		4/8.12/11.3/4	10
2/1 3/2 7/5		3/2.4/3.12/11	10
PC1, 2, 3(571)		PC1, 2, 3(11.12.2)	10
PC1, 2, 3(573)		PC1, 2, 3(11.12.4)	10
6/5 7/6 4/7	L 8	11/(8 or 8A).12/11.4/12	10 or 20
6/5	L 8	11/(8 or 8A)	10 or 20
5/4	L 7		
5/3	ASTER	12/8	10
5/4	L 8	(8 or 8A)/4	10 or 20
3/2	ASTER		
4/7	L 8	4/12	10
3/6	ASTER	8/12	10
7/6	L 8	12/11	20
(6 + 8)/4	ASTER		
5/7	L 7		
5/7	TM		
573	L 7	11.12.4	10
674	L 8		
3/2 5/1 7/3	L 7	4/3.11/2.12/4	10
4/3 6/2 7/4	L 8		
731	L 7	12.4.2	10
5/7 4/5 1/3		11/12.8/11.2/4	10
5/3 3/1 7/5		11/4.4/2.12/11	10
432		8.4.3	10
754		12.11.8	10
3/1		4/2	10
1/2, 2/1		2/3.3/2	10
752	L 7	12.11.3	10
321	L 7	432	10
742		12.8.3	10
5/7 5/1 5/4		11/12.11/2.11/8	10
5/3 4/2 3/1		11/4.8/3.4/2	10
7/visible	L 5	12/visible (2, 3, and 4)	10
3/2 3/1 5/7		4/3.4/2.11/12	10
7/3		12/4	10
3/5		4/11	10

Key: ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; MSI, multispectral imaging; PC, principal component.

After visualizing the different ratios and normal red, green, blue images (RGBs) and the one that results from the principal component analysis (PCA), we chose the images that give

good results. These are the subject of treatments through the PCA and unsupervised classification to define lithology, other algorithms for structural mapping, and ratio 11/12 for hydrothermal alteration zones. The method is summarized in Figure 5.

Fig. 5. Treatment method used

Key: PCA, principal component analysis; RGB, red, green, blue.

4. RESULTS

In this article, we have presented all the resulting images of the different treatments of the methods used. All these images listed in this part have the same scale (1/50,000) and the same elements as the GLO'A map (Figure 3). They are oriented toward north with the same coordinates of the edges shown in Table 3.

4.1. Band reports

Fig. 6. Band reports (1/50,000): (a) 8/4, (b) 8/3, (c) 8/12, (d) 8/11, (d) 8/11, (e) 4/3, (f) 12/4, (g) 12/3, (h) 12/2, (i) 12/11, (j) 11/8, (k) 11/2, and (l) 11/12

4.2. Composites colored in RGB

Fig. 7. Composites colored in RGB (1/50,000): (a) 432, (b) 843, (c) 11.8.4, (d) 11.12.2, (e) 11.12.4, (f) 12.4.2, (g) 12.8.3, (h) 12.11.2, (i) 12.11.3, (j) 12.8.2, (k) 12.11.8

Key: RGB, red, green, blue.

4.3. Composites colored in RGB ratios

Figure 8. Composites colored in RGB ratios (1/50,000): (a) 3/2.4/3.12/11, (b) 4/3.4/2.11/12, (c) 4/3.11/2.12/4, (d) 4/8.12/11.3/4, (e) 11/4.4/2.12/11, (f) 11/4.8/3.4/2, (g) 11/8.12/11.4/12, (h) 11/12.8/11.2/4, (i) 11/12.11/2.11/8

Key: RGB, red, green, blue.

4.4. Principal component analysis

Fig. 9. PCA (1/50,000): (a) PCA RGB PC1,2,3 (11.12.2), (b) PCA RGB PC1,2,3 (11.12.4)

Key: PCA, principal component analysis; RGB, red, green, blue.

4.5. The neo-channels

Neo-channels are composites of the initial bands of a satellite image; they are the result of the arithmetic operations of the original bands.

Fig. 10. The neo-channels (1/50,000): (a) PC1_(11/12.11/2.11/8), (b) PC1_(12.8.2), (c) PC1_(11.12.2), (d) PC1_{(CP1 (11/12.11/2.11/8); CP1 (12.8.2); CP1 (11.12.2))}, (e) RGB (CP1 (11/12.11/2.11/8); CP1 (12.8.2); CP1 (11.12.2))

Key: PC, principal component; RGB, red, green, blue.

4.6. Unsupervised classification

Fig. 11. Unsupervised classification (1/50,000): (a) algorithm: ISODATA (10 classes), (b) algorithm: K-Means (10 classes)

Key: ISODATA, Iterative Self-Organizing Data Analysis Technique.

4.7. Linear chart

Table 5 shows the different criteria for the choice of type of lineaments.

Table 5. Criteria of linear chart

Criteria	Case				
	1	2	3	4	5
Filter radius (pixels)	10	10	7	7	10
Edge gradient threshold	100	100	100	100	100
Curve length threshold (pixels)	30	100	50	20	20
Line fitting error threshold (pixels)	3	3	3	3	3
Angular difference threshold (degrees)	30	30	30	30	30
Linking distance threshold (pixels)	20	20	5	5	20

Fig. 12. Case images of linear chart (1/50,000): (a) linear chart of case 1; (b) linear chart of case 2; (c) linear chart of case 3; (d) linear chart of case 4; (e) linear chart of case 5; and (f) linear chart of the five cases

5. DISCUSSION

5.1. Band reports (ratios)

We can visualize precise geological formations from the ratios. Table 6 presents the usefulness of the important ratios.

Table 6. The usefulness of Sentinel-2A image ratios

Sentinel-2A ratio	Utility
8/4 and 8A/4	Vegetation in white
4/3	Vegetation in black
8/3	Feces cones associated with medium-sized fluvial terraces, oblique megadid sandstone beds, and adoudou gray formation; vegetation in white
8/12	Sandstone oblique of megaripples, silty clay, and sandstone wrinkles
8/11	Pyroclastic tuffs
12/4	
12/3	Adoudou formation, microbialite dolomites, clayey interlites, basalts, indurated siltstones, fine sandstones, and alluvial fans associated with medium fluvial terraces
12/2	Adoudou formation and pyroclastic tuffs
12/11	Gray aphyric rhyolitic ignimbrites, sandstone, pelites, marble–schist alternations, pyroclastic rhyolitic breccias
11/8 and 11/8A	Alternation of stromatolitic dolomite layers, clay-silty heterolytic facies with wave lines, micro-gabbro and pyroclastic tuffs
11/2	Adoudou formation, silty clay, and sandstone wrinkles

Hydrothermal alteration is linked to the underground circulation, which can attract the surface of hot water, loaded with dissolved minerals (Ar, Copper, Barite, etc.). This circulation of hydrothermal fluids often occurs in the veins in volcanic zone, near a magma chamber, or in plutonic zone. It dissolves the minerals present in the rocks crossed. Figure 6i and l shows the hydrothermal alteration zone (Figure 6i, white color and Figure 6l, black color).

5.2. Composites colored in RGB

After a comparative study among the different composites (11.8.4, 12.11.2, 11.12.4, 12.11.4, 12.4.2, 8.4.3, 12.11.8, 12.8.2, 12.11.3, 4.3.2, 12.8.3, 11.12.2), we chose the 12.8.2 composite in RGB. The latter has a very good geological discrimination (Figure 7j).

5.3. Colored composites of RGB ratios

Comparison among color composites with ratios in RGB (4/8.12/11.3/4, 3/2.4/3.12/11, 11/4.4/2.12/11, 11/8.12/11.4/12, 11/8A.12/11.4/12, 11/12.11/2.11/8, 4/3.11/2.12/4, 11/12.8/11.2/4, 4/3.4/2.11/12, and 11/4.8/3.4/2) shows that the composite 11/12.11/2.11/8 has surface lithological discrimination (Figure 8i). In this image, the geological formations appear in several colors: the adoudou in gray, sandstone oblique of megaripples, argillites silty and purple sandstone wrinkles, alluvial fans associated with medium fluvial terraces in orange, pyroclastic tuffs in brown, and doleritic basalts and microgabbros in blue.

5.4. Principal component analysis

The PCA is part of the group of multidimensional descriptive methods called factorial methods. The PCA proposes, from a rectangular table of data containing the values of p quantitative variables for n units, geometric representations of these units. These variables make it possible to determine the main components (principal component [PC]) that represent the contribution of the original tapes involving the spectral response of relevant substances and the spectral information of minerals of particular interest. It is used to create new uncorrelated components by identifying the axes in the original data that account for the largest amount of variation. This method has always shown the effectiveness of the results

related to geological discrimination and mineral exploration. Minerals and substances are represented as dark or bright pixels in PC images, respectively, according to the sign of the charge of the proper vector (Corumluoglu et al., 2015; Vural et al., 2017). The satisfactory results obtained by this technique guide us to use this technique at different stages of this process (Figure 9). The PCA has developed a high precision with respect to the existing geological map, as illustrated in Figure 13. This figure is the result of a comparison between these two well-georeferenced images.

Fig. 13. Comparison between the PCA result and the geological map

Key: PCA, principal component analysis.

5.5. Neo-channels

Given the effectiveness of the PCA, RGB of the first major components (PC1 (11/12.11/2.11/8), PC1 (12.8.2), PC1 (11.12.2)) provide a good result (Figure 10a–c).

5.6. Unsupervised classification “UC”

The tests of "UC", according to the different algorithms ISODATA and K-Means, can achieve lithological cartographies (Figures 11 and 14). We have created several maps by changing the number of classes. Figure 14 presents a simple example of the results of 10 classes for the two algorithms. It also presents a similar result between the two cases (Table 7).

Fig. 14. Unsupervised classification of 10 classes of ISODATA and K-Means algorithms

Key: ISODATA, Iterative Self-Organizing Data Analysis Technique.

Table 7. Geological formations of 10 classes of the classification

Class	Geological formations
1	Basalts; alluvial fans associated with the middle terraces fluvialites; homogeneous basalts more or less doleritic; breccias and andesitic pyroclastic tuffs
2	Sandstone oblique bed of megaripples and conglomerates
3	Sedimentary layers (clay and sand)
4	Sandstone; siltstones and basic siltstones
5	Dark area (the shadow of the reliefs)
6	Silty argillites; sandstone with wrinkles; alternation of layers of stromatolitic dolomite and heterolithic clay-silty facies with wrinkles of waves and desiccation slits
7	Microbialite dolomites and clay interludes; sandstone with HCS (hummocky-cross stratification) then tigillites and pelites
8	Vegetation
9	Adoudou formation (microbialite dolomites and red clay-silty interludes; basal sedimentary breccia)
10	Igoudine formation (microbialite dolomites and clay interludes)

5.7. Linear charts

The first main component of RGB (PC1 (11/12.11/2.11/8), PC1 (12.8.2), PC1 (11.12.2)) has been processed to generate the lineaments (Figure 12). This case has given a satisfactory result (74%), especially after the deletion of the lines, which corresponds to objects other than those of the faults, like the roads, the borders, the limits between the geological formations, the summits of the ridges, and the shadow of the objects.

5.8. Validation of the results

The results of 100 sites in the images and the geological map of the study area were verified randomly. This validation revealed that the validation rate with the field reality is of the order of:

- 62% for the hydrothermal alteration zone;
- 81% for the lithological map, knowing that we tested only two images with 10 classes; so, this test does not take into account all the details of the geological map; and
- 74% for the structural map, if we take the geological map as a reference.

6. CONCLUSIONS AND PROSPECTS

This work aims to evaluate the image potential of MSI (13 spectral bands) for the mapping of mineral resources. The approach followed consists of several steps: 1) using satellite image processing methods of several satellites including Landsat 7, 8, and ASTER 30 m and the correspondence between their bands to create methods for Sentinel-2A images with a resolution of 10 m; 2) visualizing the different ratios, normal RGBs, and other results from the PCA, we chose the images (12.8.2; 11/12.11/2.11/8 and PC1,2,3(11.12.2)) that give good results in the field of geological discrimination; 3) the new images ((PC1 (11/12.11/2.11/8), PC1 (12.8.2), PC1 (11.12.2)) are the subject of treatments through the PCA and unsupervised classification with ISODATA and K-Means algorithms to define lithology; and 4) other directional algorithms are used for structural mapping and the ratio 11/12 for hydrothermal alteration zones. It is possible to summarize the data presented in Figure 14 and Table 7, which are shown in Figure 15 that presents a geological map of 10 classes of the study area by the ISODATA algorithm.

Fig. 15. Unsupervised classification with ISODATA algorithms (10 classes)

Key: ISODATA, Iterative Self-Organizing Data Analysis Technique.

These results allow us to identify the probable mining sites by interpretation of the lithological and structural data resulting from the image processing method, especially those related to the hydrothermal alteration zone. In our study area, Anti-Atlas, the overlaps

between the Adoudounien formation and hydrothermal alteration have a favorable surface area for the genesis of copper deposits, especially with the existence of a structural anomaly such as faults, while the overlaps between the latter two and the Ordovician formation favor the creation of gold mineralization. Validation of results revealed that the validation rate with the field reality is of the order of 62% for the hydrothermal alteration zone, 81% for the lithological map, and 74% for the structural map.

These results remain of great use in mining prospecting to reduce both cost and time, especially in sites with difficult access, and to guide conventional methods of mining research. Future work will also focus on 1) hyperspectral imaging, 2) radar imagery, 3) optical radar fusion, and 4) multispectral and hyperspectral fusion to assess their potential, particularly when combined with other geophysical and geochemical data, for subsurface exploration.

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Received: 2019-07-29,

Reviewed: 2019-09-30, and 2019-11-07, by J.R. Olędzki,

Accepted: 2019-12-04.