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Evaluation of very high to medium resolution multispectral satellite imagery for geoarchaeology in arid regions, case study from Jabali, Yemen

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ABSTRACT

Archaeological research in the extent of the ancient Jabali silver mines (VIIth to XIVth centuries AD) in northern Yemen is a multidisciplinary project covering scientific disciplines traditionally related to archaeology, a geological approach, and also new technologies such as very high resolution remote sensing. Mining companies envisage the development of the Jabali deposit for zinc ore. Some of the planned facilities, particularly a large open pit will have a destructive impact on the old pits and processing heaps, already damaged by recent works. In the present study, remote sensing is used for a detailed study of the impact of preliminary mining works from the early 1980's, for situating the archaeological remains, for geological mapping and for prioritizing areas for future ground surveys. Results indicate that mapping using remote sensing in the visible to short wave infrared range has a great potential for the identification of gossans (iron caps) possibly related to archaeological remains. The phases of works in Jabali are clearly put into light by the study of a time series of Landsat data. Very high resolution QuickBird imagery appears particularly relevant for mapping most of the archaeological remnants, iron caps, and for the 3D visualization of the mining site when draped over a detailed digital elevation model.

1. Introduction

The first known aerial photograph was taken on an archaeological site on December 6, 1906 (Capper, 1907). Since this first attributed to Lt P.H.Shape over Salisbury Plain, directly above Stonehenge, remote sensing methods deeply developed during the 20th century. Basically, remote sensing is the discipline dealing with the electromagnetic signal reflected by the earth's surfaces and remotely sensed by airborne or spaceborne sensors. The main goal of remote sensing is to identify features on the earth's surface, which are difficult if not impossible to detect in the field. The main characteristics of the terrestrial surfaces include spectral, textural, and structural aspects. The spectral characteristics of the natural materials allow to discriminate different types of vegetation, water bodies, soils, and rocky surfaces. Remote sensing covers a wide range of application in archaeology from global to detail (at the meter scale).

Since 1972, the spatial resolution of the Earth observation satellites has considerably improved, either for multispectral or panchromatic sensors (**Figure 1**). Very high resolution could be defined for pixel size less or equal to 2m. Between 2 and 30m, the spatial resolution is simply high, corresponding to one major advance with the launch of Landsat 4 in 1982. Between 30 and 100m, the resolution is medium, including the first numerical images from Landsat 1 (1972) with 79m- pixel size. Between 100 and 1000m, the resolution is low or moderate, and very low beyond 1000m (geostationary satellites only). Whereas the spatial resolution is important, the spectral range plays also a key role in remote sensing (see also §3.2. Background).

Insert Figure 1 about here

In geoarchaeology, the most classical method is the identification of crop marks from aerial photographs, for example combined with field geophysical methods in Italy (Gallo et al., 2009) or England (Powlesland et al., 2006). Declassified CORONA satellite images from the 1960's were also used for crop mark identification in Southern England (Fowler and Fowler, 2005), and in combination with multispectral ASTER data to identify linear features (hollow ways or canals) and new archaeological sites in the former Mesopotamia (Altaweel, 2005). CORONA data were exploited in the Altai Mountains by Goosens et al. (2006) using the stereoscopic capability of the images. Landsat or SPOT data have been frequently used, particularly when large scales are concerned (Fowler, 2002; Barlindhaug et al., 2007). Other high resolution data such as the Russian Soyuz Kate-200 have been explored for studying ancient irrigated and cultivated areas in Yemen (Marcolongo and Morandi Bonacossi, 1997). Radar remote-sensing data are rarely applied to geoarchaeology and generally in combination with multispectral data (Vining and Wiseman, 2006).

As soon as the early 2000's archaeologists began using the new generation of very high resolution satellite imagery. Results were obtained with Ikonos imagery in different settings, for example in the American tropical forest (Garrison et al., 2008) or in Turkey (De Laet et al., 2007). Different archaeological places in Italy were investigated using QuickBird (Lasaponara and Mansini, 2005; 2006a; 2006b; Mansini and Lasaponara, 2007). The comparison of very high and more classical multispectral satellite imageries is relatively rare. Schmid et al. (2008) determined the spatial distribution of soil surface properties using very high (IKONOS) and high (ASTER) resolution imagery data, in order to identify environmental conditions resulting from anthropogenic influences at Aksum, Ethiopia. LiDAR (light detection and ranging) which is a recently developed airborne remote-sensing technique has been successfully applied to identify cultural features in a forested environment (Doneus et al., 2008; Gallagher and Josephs, 2008). Combined with hyperspectral data,

LiDAR data allow surface remains in Crete to be classified and mapped effectively (Rowlands and Sarris, 2007).

In the specific case of mining geoarchaeology, remote sensing could be applied to both the geological setting (medium to high resolution needed) and the archaeological survey (very high resolution needed), but until now few works have been published in that domain. The archaeological mining site of Jabali is concerned by an exploration licence and it is particularly important to evaluate the archaeological potential of this remote area before possible new works. Within this article a set of satellite remote sensing images with medium (Landsat MultiSpectral Scanner, 79m), high (Landsat Thematic Mapper, 30m) or very high (QuickBird, 0.67cm because of off-nadir data) ground resolution are examined.

2. Study area

2.1. Location

Jabali is located in the mountains of the southern Arabian peninsula, at the southern margin of the subsident Wadi Al Jawf basin, roughly 75km north-east of Sana'a, the capital city of the Republic of Yemen. Its geographical coordinates are 15°36'30" North and 44°46'30" East, at an elevation of about 1,960 m above sea level. Regional landscapes are characterized by volcanic trapps including the Jabal an Nabi Shu'ayb (3760 m) the highest point of the Arabian peninsula, deep valleys in the Proterozoic basement, karstic plateaus in the carbonate areas, some isolated Quaternary volcanoes, large endoreic basins such as the Wadi Al Jawf depression, and the southern border of the large Al Rub' Al Khali desert (**Figure 2**).

Insert Figure 2 about here

2.2. Mining geology

Initially, the Jabali deposit was contained in the uppermost unit of the Late Jurassic. The corresponding carbonate facies underwent emergence and pervasive dolomitization followed by karstification and vigorous erosion developed principally at the junction between regional faults. The sulphides then underwent almost total oxidation to zinc and lead carbonates in a vadose zone certainly helped by distension tectonics and dedolomitization (Al Ganad *et al.*, 1994). Now, the massive ore deposit has a surface expression in the form of a large iron-rich cap or gossan, and an associated zone of hydrothermal alteration. From a metallogenic point of view, Jabali is a Zn-Pb-Ag deposit currently explored only for zinc-ore. The mineral rights are held through an exploration licence which is led by ZincOx and Yemeni associates. The evaluation of the ore body shows that Jabali contains a geological resource of 8.7 million tonnes of oxide ore, grading about 9.2% zinc, 1.2% lead and 68g/t silver (<http://www.zincOx.com>). The mineralization comprises carbonates and oxides: smithsonite (ZnCO_3), hydrozincite ($\text{Zn}_5[(\text{OH})_3|\text{CO}_3]_2$), etc. Silver is mainly related to sulphides, which are represented, even less than oxides: sphalerite (relatively rare), galena, etc. (Al Ganad *et al.*, 1994). Mining will be from an open pit, with a 2:1 ratio of waste to ore, centered along the Wadi Jabali (**Figure 3**, site no 1). If the deposit is mainly composed of lead and zinc together with a few quantity of silver, the only one precious metal has attracted miner's attention. There was necessary a lead production in order to obtain silver by refining. Other smaller ore deposits have been identified at Majnah and Barran in the environs of Jabali to the East and the North-West, respectively.

Insert Figure 3 about here

2.3. Geoarchaeology

Since 2003, an archaeological research is led by a French team, joined by a German team in 2004. Field work is carried out with collaboration of Yemenis institutes as the Geological Survey. The area of Jabali was mined for silver as early as the pre-Islamic period. Basically, Jabali is known as one of the most important silver mines of the Abbasid world (Robin, 1988; Benoit et al., 2003; Peli, 2006; Peli and Téreygeol, 2007; Derooin et al., in press). Chronology of site is still in question. The first dates have been obtained in the 1980's. They are consistent with data derived from the treaty of famous geographer al-Hamdani. Currently the earliest date found is obtained with charcoals collected “at the base of the heaps” (Christmann *et al.*, 1983) (**Figure 3**, site 1). The results of counting of ^{14}C indicate a date around 613 ± 70 AD. Nevertheless, the data collected previously should be used with care because they ~~are not~~ georeferenced come out of a geological survey, not of an excavation. In the same area covered by mining activities, there are a lot of settlements with a wide chronological spectrum. On the site of Jabali, we observed occupations well before the Islamic period along the remains of modern camps. It is also possible that ore deposit has been previously exploited. However, description given by al-Hamdani is final. It refers to a very important mining activity which led to the installation of a village and the implementation of hundreds of furnaces. According to al-Hamdani, the mine was abandoned recently when he described Jabali site in the Xth century. No other recent text does mention any exploitation in that place. The new data obtained during our surveys show a strong contrast: the main phase of mining took place between the eleventh and fourteenth centuries. In the state of our knowledge, it is interesting to note that only al-Hamdani text highlights a mining activity at Jabali in the ninth century.

In view of this set of historical information, we can move forward as the most probable hypothesis that the major phase of activity took place between the eleventh and thirteenth centuries AD. Al-Hamdani would have perfectly described the first major phase of activity of the mine at a time when it would be victim of regional politic hazards. It is particularly

interesting to define the duration of this closure. The case of a raid on the mines is also known (for example in 847 AD at Melle, France). In general, the raids marked the collective consciousness but have no real impact on the continuation of operations in a macroeconomic for large trend. Jabali's case seems to be the same pattern. The political disorders from the nine century could lead to a temporary cessation of silver production. But deposit is not exhausted, the mining work has resumed and continued over several centuries.

The archaeological remains extent over more than 7 km from the wadi al-Khaniq to the Jabal Salab, including intermediary subsites: Plateau, Souq, and Shutaiba (**Figure 3**). At Jabali, the old workings cover up to 10 ha. Their irregular landforms follow the ore concentration morphology in a karstic setting. This latter is crossed by many shafts, drifts, low chambers and large tunnels, which sometimes exceed 100m in length (Robin, 1988).

The persistence of the site is now in question. Some of the planned facilities, particularly the large open pit located close to the major site will have a destructive impact on the old pits, the ore-dressing and ore-crushing areas, and also on the old canals coming from the Jabal Salab, already damaged by the preliminary mining works carried out since the 1980's. The other archaeological remains and slag heaps located far from the mine itself, especially on the small Plateau and in the wadi al-Khaniq (**Figure 3**, sites no. 2 and 3), will be unaffected.

3. Methods

3.1. Remote-sensing data and their processing.

Different sensors have been evaluated in the Jabali area, particularly Spot, ASTER, and ALOS multispectral and radar data in the framework of a PI project. But no long time series are available. Therefore, we emphasize here the interest of the Landsat chronicle and the uniqueness of the very high resolution QuickBird image.

3.1.1. Landsat

The Landsat system is a well known research/experimental enterprise. It is the longest running programme for acquisition of imagery of Earth from space. Landsat 1 was launched on July 1972; the most recent, Landsat 7, was launched on April 1999. The different instrument on board Landsat satellites have acquired millions of images, forming a unique archive. Since December 2008, the United States Geological Survey (USGS) offers all users the entire Landsat archive data at no charge (<http://edcsns17.cr.usgs.gov/EarthExplorer/>). The spectral range covered by the different Landsat sensor is indicated in **Table 1**.

Insert Table 1 about here

Some authors use only raw data (digital numbers) with standard colour composites. For a reliable study in time and space it is necessary to calibrate the data from the satellite's sensor and to know the potential of each spectral band. Basically, there are two ways for calibrating multispectral data: radiance or reflectance. Landsat calibration was used to convert Landsat MSS, TM or ETM+ digital numbers to exoatmospheric reflectance (reflectance above the atmosphere). In the present study we used the classical reflectance. This later is defined as the ratio of the radiant energy reflected by a body to that incident upon it. Reflectance is a function of the incident angle of the energy, viewing angle of the sensor, spectral wavelength and bandwidth, and the nature of the object. Changes in sun elevation angle cause variations in the illumination condition under which imagery is obtained. At Jabali the sun elevation at acquisition time ranges from 37 to 65° all along the year. Basically, higher the sun elevation, higher the reflectance. This is the reason why we used the Landsat ETM+ scene acquired on June 5, 2008 (the most recent in the database) with one of the most important sun elevation

(63.49°). Because no reliable climate data were available for the remote area of Jabali, no atmospheric correction was applied. Moreover, transmittance i.e. the ratio of the intensity at the sea surface of radiation that has passed through the atmosphere to the intensity of the radiation at the top of the atmosphere, is upper than 94% when sun elevation is upper than 30° (the latter is systematically verified for the site located at latitude 15° North). Only the clearest data were used, the ‘clearness’ being visually estimated using the blue range. All the Landsat data used are listed in **Table 2**.

Insert Table 2 about here

3.1.2. QuickBird

Launched in October 2001, QuickBird represents the new generation of very high resolution imageries (**Figure 1**), which are very useful for archaeological investigations (e.g. Lasaponara and Masini, 2006b). QuickBird data have been particularly used for detailed study of the sector of mines (Cierny et al., 2005; Derooin et al., 2006b). The Jabali area is covered by the QuickBird scenes 02MAR30073205-P2AS (panchromatic, 0.61 m ground resolution at nadir) and 02MAR30073205-M2AS (multispectral, 2.44 m ground resolution at nadir), both as standard imagery with a position accuracy of 23 m. The spectral range of the four multispectral bands (blue, green, red, and near infrared range) is identical to the ones of the Thematic Mapper (**Table 1**). The scenes were simultaneously acquired on March 30, 2002 and their local spatial resolution (off-nadir) is 0.67 and 2.68m, respectively. At first, the two QuickBird scenes were pan-sharpened. Some GPS ground control points carried out during a first visit in Spring 2004 by DBM showed differences between 30 and 50 m. Further GPS ground control measurements of obviously identifiable natural points and GPS-tracks along

roads in both directions were carried out during the campaign in Spring 2005 with 1-3 m accuracy by a registration time of two minutes per point (Kleibrink and Joemann, 2004).

3.1.3. Digital Elevation Model (DEM)

With an about 90m-accuracy, the Shuttle Radar Topography Mission (SRTM) DEM is worldwide available. Different DEMs have been also generated using ASTER and Spot 5 data in supermode. Unsatisfactory results yielded the transformation on the two SRTM and ASTER terrain models. The best adaptation of the scene to the area could be calculated by the transformation on a digital terrain model from digitized elevation lines of the topographic map (map sheet 1:50,000, Jabal Bahrah, Series YAR 50 (E), Sheet 1544 B4, Edition 1-OSD 1988). Maps at a larger scale or of a newer date are not available. An official topographic survey to standardise the coordinate reference of Yemen has taken place after Yemen's unification in 1990. Because of missing opportunities, Jabali could not be connected to this new grid, until now. A subset of 11 km x 10 km size within the borders of UTM 38 P 473000 m E to 484000 m E and of 1723000 m N to 1733000 m N was chosen to calculate the DEM, according to the size of the available QuickBird scene. After testing on reference points, GPS receivers delivers an accuracy of about 1 to 3 m for the ground coordinates and about 10 m for the elevation. The GPS points were chosen to serve as reference points to transform all available data to a unique datum. The subset of the "Jabal Bahrah" sheet was scanned. After some image enhancements, the scan could be digitised automatically. This process delivers lines and structures, that has to be edited and allocated carefully to appropriate elevations. Finally, the DEM was calculated by surface operators. To check the result, these recalculated contour lines were compared with their originals from the map sheet without relevant differences. Finally, this DEM could be used to rectify the satellite scenes and to generate 3D views, such as Figure 3.

3.2. Background

In such an arid area poorly covered by detailed topographic maps and aerial photographs, the use of remote sensing methods is particularly suitable. Preliminary results of remote sensing investigations based on multiscale data have already been presented. They referred to the geological (Deroin *et al.*, 2006a) and archaeological setting as well (Deroin *et al.* 2006b).

Physical and chemical changes produce by alteration can be detected using remote sensing techniques because many minerals in alteration assemblages have characteristic spectral features. These features are the result of electronic transitions and molecular vibrations. In the visible range, electronic processes in transition metals, such as iron, manganese, or nickel, produce broad absorption bands and are responsible for the sharp decay in the reflectance of the rocks at wavelengths shorter than 600nm (Vitorello and Galvão, 1996). Basically, two major spectral intervals are widely used in geological applications. Narrow absorption bands occur in the range from 2,000- to 2,500nm, the so-called short wave infrared range (SWIR), due to vibrational processes related to Al-OH, Mg-OH, Fe-OH and CO₃. Thus, several types of alteration clay products or carbonate-rich rocks could be identified. Ubiquitous Fe²⁺ and Fe³⁺ provide broad band absorptions in the 350- to 1,300nm range (visible and near infrared) (Torrent and Barrón, 2002). **Figure 4** presents the spectral curves of hematite and goethite, the main iron oxides encountered in the Jabali iron caps. Major absorption features of hematite and goethite are centered at 850nm and 930nm, respectively. The same figure provides also information on the spectral behaviour of two carbonate sedimentary rocks, limestone and dolomite, characterized by their key mineral, the calcite [CaCO₃] and the dolomite [CaMg(CO₃)₂], respectively.

Insert Figure 4 about here

In the natural environment, only mixture of minerals with different grain size is encountered. When laboratory measurements are concerned, it appears that the finer grains provide the higher reflectance. **Figure 5** illustrates this point using the smithsonite (ZnCO_3) as an example.

Insert Figure 5 about here.

Theoretically speaking, only hyperspectral methods allow the diagnostic narrow-band spectral features that are present in terrestrial materials. These spectral features are typically 20-40nm in width. Spectral imaging systems such as Airborne Imaging Spectrometer (AIS) or the more recent Airborne Visible and Near-Infrared Radiometer (AVIRIS) can produce data with sufficient resolution for the direct identification of those materials with diagnostic features (Vane and Goetz, 1988). For most of the minerals, the Landsat sensors which supply broad-band images cannot resolve these features because their spectral bandwidths are 100-200nm. Particularly, spaceborne Landsat TM cannot discriminate hematite and goethite because the Landsat TM near infrared band covers 760- to 900nm (there is a goethite absorption band centered on 930nm). Moreover, hematite (oxide) and goethite (hydroxide) are generally mixed to form 'limonite'. Variations in amount of limonite can be discerned using remote sensing data (e.g., Abrams et al., 1977). Thus, orbital multispectral scanners have been extensively employed in the discrimination of iron oxide-bearing surface materials (e.g., Demattê et al., 2004; White et al., 2007) and in the specific case of gossans in arid regions (Rowan et al., 1974; Abdelsalam et al., 2000; Volesky et al., 2003; Daneshfar et al., 2006). These authors demonstrated that gossans and associated alteration zones could have distinct spectral signatures because they are frequently large enough to be detected with orbital remote

sensing platforms. They are characterized by a high reflectance in the red range and a relatively low reflectance (with respect to other minerals) in the near infrared range (due to the absorption band). One simple method of spectrally identifying these iron oxides using Landsat-TM has been the ratio band 3 (red)/band 1 (blue) (Drury, 2001). This ratio has been used in the Landsat-TM colour composite: red=5/7; green=4/5; blue=3/1 to emphasize gossans in blue and alteration zones in magenta (a mixture of red and blue) (Abdelsalam et al., 2000).

3.3. Objectives

The interest of the multispectral remote sensing imagery is evaluated manyfold: (i) for the study of the geological context of the archaeological site, particularly iron caps; (ii) for the analysis of the impact of previous works realized in the last 30 years and to establish the chronology of the works; (iii) for the study of the archaeological remains and landscapes. The uniqueness of the present work is the combined use of very high to medium remote sensing imagery for mapping gossans and the geological setting of a mining archaeological site, which could be damaged by a new open pit. Jabali is a remote place and field work is frequently hampered by local bedouins. Therefore, the use of remote sensing is vital. With the recent opening of the Landsat archive, it is now possible to use large time series of multispectral data covering more than three decades.

4. Results

4.1. Geological context of the mine

Landsat imagery is particularly suitable for geological mapping at medium scale (about 1:200,000) in arid region (e.g. DEROIN *et al.*, 1998). The first large scale geological maps of Yemen have been produced using Landsat imagery (Grolier and Overstreet, 1978; Kruck and

Schäfer, 1991). In **Figure 6**, the mineralization of Jabali is put in light when using TM band no 3, *i.e.*, the red range of the electromagnetic spectrum. The preferred colour composite is: Red=band 7 (SWIR); Green=band 3 (red light); Blue=band 1 (blue light). The main gossan (**Figure 6**, no 1) appears light green. This is clearly explained by the alteration halo of iron oxides (red in natural light) concentrated around the deposit and linked with (de)dolomitization phenomena. Limestones and dolomites can be easily identified by their spectral response and their texture as well. The control of structural elements is probably more important than previously envisaged (Al Ganad et al., 1994). While the Jabali lineament (**Figure 6**, no 16) controlling dedolomitization is well known, cenozoic thermal events characterized by magmatic rocks (volcanites and granite intrusions) could significantly contribute to concentrate in Jabali elements initially present in the basement. The link between the Proterozoic basement (**Figure 6**, no 15) and the mineralization is clear. It seems that Jabali is situated just above a major Proterozoic shear zone separating two terranes, the Asir/Afif terrane to the north-west and the Abas Gneiss terrane to the south-east according to the terminology used in Whitehouse et al. (2001).

Insert Figure 6 about here.

Ten landscape units have been selected in the region covered by the Landsat subscene for a detailed analysis of their spectral properties (**Figure 7**). Only one unit corresponds to vegetation (a palm tree grove). Its spectral behaviour characterized vegetation with a poor visible reflectance (maximum is about 15%), a high reflectance in the near infrared range (about 32%) and a poor reflectance in the mid and short wave infrared. The other units correspond to mineral surfaces with a globally increasing reflectance from short (14 to 20%) to large wavelengths (22 to 45%). Basaltic flow is the less reflective surface (black in visible

light), while a white limestone appears as the more reflective (white in visible light). A doline to the South of Jabali offers the higher reflectance in the SWIR, probably due to its clay content. Phenomenon such as dedolomitization or contact metamorphism leads to identical value in both MIR and SWIR range, which is unusual for mineral surfaces. Gossan is characterized by a significantly lower reflectance in the short wave infrared than in the mid infrared. The iron oxides of the iron cap present a different spectral behaviour than hematite and goethite individually (**Figure 4**). In the natural environment (iron cap) the coarse grain size plays probably an important role and contributes to the decrease of the reflectance in the SWIR range (see also **Figure 5**). Dedolomitization constitutes a structural guide for the Zn-Pb-Ag mineralization, whereas gossan is the main guide for identifying old works (see also §4.3).

Insert Figure 7 about here.

4.2. Evolution of Jabali main site

Unfortunately, most of the references concerning mining activity at Jabali are confidential reports. Due to a great amount of companies working in that place since 1980, the memory of former works possibly disappears even at the Yemen Geological Survey. Moreover, access to some areas could be denied by the local Bedouins and field work especially close to the Jabali deposit is always difficult. Thus, some planned works have been never achieved. Remote sensing allows us to identify the different phases of work in the mining district with the detection of general infrastructure, geophysical field campaign, trenching, drilling, etc. Some of these phases had a destructive impact on the archaeological remains.

The first Landsat satellite data available on the Jabali area was acquired on September 6, 1972, 45 days after the launch of Landsat-1, the first Earth observation satellite. We have

selected seven Landsat MSS scenes covering an important period of time, from 1972 to 1986 (**Table 2**), i.e. before the first work (1980) and until the end of the first intensive phase of exploration. These data allow a large scale reconnaissance mapping. The following chronology can be proposed. No important road is visible in the images prior to the data acquired on 1979 (May 21). The main road linking Sana'a to Ma'rib is well expressed in the image taken in 1980 (**Figure 8**).

Insert Figure 8 about here.

In spite of medium spatial resolution (79m), the main tracks to Jabali and Majnah ore deposits are visible in the image from 1986. This is consistent with the considerable work that was carried out on the Jabali deposit by Yemeni Ministry of Oil and Mineral Resources and Bureau de Recherches Géologiques et Minières (BRGM, France) from rediscovery in 1980 through 1986. A large scale grid (**Figure 8**, c) appears in the MSS image from 1986. This pattern is well known in arid countries and characterized geophysical ground prospection (probably a seismic reflection campaign) for improving the knowledge of subsurface geology. The results of such an investigation are useful for mineral prospection and for oil prospection as well. Note that the use of the simultaneously acquired Landsat-TM image indicates that the geophysical prospection was also carried out in the left bank of the Wadi Al-Khaniq (with smaller grid lines). The comparison of two images acquired in 1984 and 1986, respectively but separated by only 14 months, emphasizes the development of the main track for the access to the Jabali ore deposit: enlargement of a previous narrow track, setting of a new camp (future MC2), new tracks in the ore deposit, etc. (**Figure 9**).

Insert Figure 9 about here.

A short phase of exploration began in July 1991 and principally samples were collected from bulldozer trenches for geochemical and economic studies. Reconnaissance and diligence studies were completed within a large prospecting permit area in 1996 and 1997. This area covered approximately 2,400km² to reassess the Jabali deposit and then to broaden the investigations. According to the Landsat images, these new investigations poorly impacted the landscape. However, the progressive extension of the track to Majnah is shown by analysis of Landsat TM images acquired in 1991, 1995, and 2000, respectively.

In the Jabali area, no remotely-sensed major work occurred within the last ten years, as proven by analysis of a Landsat-ETM+ chronicle (**Table 2**). Recently, a high voltage electricity line was built (checked during field campaign 2008) more or less along the main road. The tracks of pylon emplacement are detected because the digged soil presents a high reflectance. The decade is characterized by new mining operations carried out by ZincOx Resources plc. Mainly new drillholes and small trenches have been done with a relatively light impact on the landscape. Last results were used to reevaluate the ore-body (see also Section 2). Construction of the mine and associated facilities is now scheduled (but frequently postponed), such that production of a high quality zinc oxide should commence at the end of 2009... (<http://www.zincox.com>). A site camp sufficient for 300 people is under construction close to the military camp MC2 (**Figure 3**).

4.3. Characterization of gossans

It has been shown in section 4.1 that gossans present original spectral properties. The analysis is developed using a time series of multispectral data in order to find possible ‘anomalic’ response related to the work conducted at Jabali. Eleven dates have been selected for the

period from 1984 to 2008 (**Table 3**). The region of interest covers about 40ha (46 Landsat-TM pixels). The standard deviation of the mean reflectance value is always low. As an illustration, the standard deviation for the data acquired in 2008 is as follow (reflectance expressed in per cent): TM 1= 16.0 ± 0.4 ; TM 2= 20.0 ± 0.7 ; TM 3= 24.3 ± 0.9 ; TM 4= 29.2 ± 1.4 ; TM 5= 32.2 ± 2.1 ; TM 7= 29.1 ± 2.4 . The standard deviation is then slightly higher in the infrared radiation.

We remember that reflectance strongly depends on the sun elevation (**Table 2**). Only the general trend and the relative reflectance between the difference ranges should be considered. In the visible range (**Figure 10**) the spectral behaviour seems regular from 1995 onward (green line regularly positioned between blue and red lines). Between 1984 and 1991, this regularity is absent. In 1987 (and to a lesser degree in 1988), the red range presents a local peak, whereas the data were acquired in early February (sun elevation of only 40.6°). This is the evidence of work, which considerably modified the gossan surface. Infrared curves confirm the trend with high reflectance particularly in the MIR and SWIR range.

The time series is relatively simple to collect and easy to process. The method is relevant for identifying gossans and their temporal evolution. Other multispectral sensors have been evaluated. It appears that the ‘red range’ of ALOS (Advanced Land Observation Satellite) is less sensitive than the Landsat one for detecting iron oxides. (Deroin et al., 2009). This could be explained by the fact that iron oxides (mainly hematite) show increasing reflectance in the red range (**Figure 4**). Therefore, the reflectance value in the orange range (considered by ALOS AVNIR-2 because it covers 610-690nm) is necessary lower than the reflectance value in the “pure” red range considered by Landsat-TM (630-690nm).

In spite of the relatively low spectral resolution of the multispectral dataset, it is possible to identify spectral features related to iron oxides (probably hematite). New gossans have

already been identified in the environs of the main Jabali mine using the red range of the Landsat imagery, particularly near Shutayba (**Figure 3**, no 4).

Insert Table 3 about here.

Insert Figure 10 about here.

4.4. Archaeological mining remains at Jabali

The QuickBird image offers a spatial resolution of less than 1m. Thus, most of the archaeological remains can be mapped. Illustration on the Plateau (**Figure 3**, no 2) was already provided (Deroin et al., 2006b). We focus here on the Jabali main area (**Figure 3**, no 1 and **Figure 11**).

Insert Figure 11 about here.

At Jabali, different kinds of mining remains could be observed in the QuickBird image and checked in the field. They were either pits filled with fine-grained sediments featuring flat circular spoil heaps; adits of varying shapes which could be found on the mountain slopes; partially open round shafts with a diameter of 1 to 1.5 m clearly visible in the QuickBird image; and open cavities whose roofs had collapsed (**Figure 11**). To the extent that they were accessible the pits of the central plateau directly affected by the planned mining efforts were surveyed underground by the team from Bergbau-Museum (Cierny et al., 2005). It was found that underground extraction more or less followed the shape of the karst, whereby the impregnated karst filling was almost completely removed. Some of the pits south of Jabali, i.e. those on the northern slope of the Jabal Salab, had greater dimensions than those found on the central plateau. As this part of the deposit is not directly threatened by future mining

activities, it was decided for time-saving reasons to forego a survey. While exploring the pits large, labyrinth-like excavations were observed, including the largest known excavation in the entire complex. In addition to the old mining documents the ever-present processing heaps were mapped (tailing). They reached several metres high in parts and were eroded to a greater or lesser extent. Numerous strata packages were observed, consisting of fine-grained sediment. Most of these strata are separated from each other by coarse grained layers.

5. Discussion

While the geological setting of Jabali area has been well identified by the different Landsat sensors (MSS, TM, ETM+), the delineation of archaeological remains is only possible using very high resolution imagery (QuickBird in our case). The main advantage of opting for the very high resolution image is that data are acquired across the visible and near infrared range at a resolution close to the actual spatial patterns of the remains: a 1.5-m diameter shaft, a 2-m long wall, etc. Compared to aerial photographs the QuickBird imagery can be promptly geo-referenced (Lasaponara and Masini, 2006a). Moreover, it offers a world wide coverage. This makes them ideal for researches performed in areas where aerial photography and topographic map are restricted such as the Republic of Yemen. But the imagery provided by the commercial remote sensing satellites is only available for the last decade. Previous period of time should be explored using the Landsat chronicle. Due to the medium resolution of the first data (MSS=79m) only large scale elements could be characterized (as a large track for example). Since 1982, Landsat TM sensor allows to obtain high resolution data with a large spectral range. We would like to insist on the necessity to calibrate the data for a correct analysis. Without this preliminary and essential work, the particular spectral behaviour of the gossan can not be identified. Image processing such as classification, PCA (principal component analysis) transform, IHS (intensity-hue-saturation) analysis, should be conducted

using calibrated data. In the present work, visual analysis of colour composites has been the focus of our attention because specific processing is not needed in the arid environment of Jabali. For an optimal use of the spectral range for lithological investigations (geology and/or archaeology), the composite red=band 7 (SWIR), green=band 3 (red), blue=band 1 (blue) is probably the best. The near infrared range (band 4) could be also used for delineating the vegetation areas (rare at Jabali).

Figure 12 summarizes the main geological and archaeological features of the Jabali mine. Some scientific questions arise. One major issue concerns the climate of the past: Where grew the trees necessary for the melting of the ore and domestic uses ? Al-Hamdani mentioned 400 furnaces and the slag heaps cover more than 70ha (Benoit *et al.*, 2003). He mentioned too a mining village which has been rediscovered as the Plateau closely linked with metallurgical activities (**Figure 3**, no 2). Importance of water also arises in silver production. Although restricted, its use is necessary, particularly at the beginning of dressing process. The object of first washing is twofold: removal of earthy impurities and preliminary cleansing previous to hand-picking. To compensate for recurring lack of water, miners establish a system for collecting rainwater taking advantage of basin of receipt that represents Jabal Salab. Lack of storage and poor watertightness show that it is primarily an extra support system. Its primary function would be to first avoid that the water rushes into the mines during the heavy rainfall of the monsoon. The study of residues of ore dressing confirmed this hypothesis. Importance of washing ore is incidental compared to hand-picking. Therefore, the hydrological regime (precipitation, run-off, palaeocourses of the wadis) and the landscape as well were clearly different from the current one.

Insert Figure 12 about here.

6. Conclusion

The paper demonstrates the potential of satellite imagery in the frame of the Jabali multidisciplinary project, that covers scientific disciplines traditionally related to archaeology (field and underground survey, archaeometry, study of the historical sources, etc.), a detailed geological approach in an area only covered by large-scale maps, and also new technologies such as remote sensing. Now, spatial resolution as precise as 61cm with QuickBird used in the present approach is available. Nevertheless, it should be noticed that geological applications, and particularly geological mapping, do not necessary require the very high spatial resolution. On the contrary, geoarchaeology needs both very high and high resolution imagery. For the detailed archaeological interpretation, a high quality DEM has to be also used.

Landsat and QuickBird data have been demonstrated their interest for the geological mapping of the area. For a reliable study the satellite's sensor must be calibrated and each spectral range must be evaluated. We particularly recognized new gossans (iron caps) to the south-east of Jabali, near Shutayba archaeological site, partly checked in the field during the 2008 campaign. The survey of the archaeological site since it has been rediscovered in the early 1980's has been done using a Landsat data chronicle. Field data and the detailed analysis of multisource satellite images opens up promising perspectives. New places for future field prospections have been identified.

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CAPTIONS

List of figures

Figure 1. Evolution of spatial resolution of the remote sensing sensors since 1972.

Figure 2. Location of the Jabali test site in Yemen.

Figure 3. The Jabali archaeological mining site.

The QuickBird image acquired on March 30, 2002 draped over the digital elevation model extracted from the 1:50,000 scale topographic map of Yemen. Distance from Jabal Amrah to Jabal Salab: about 5km. The blue tones correspond to Jurassic carbonates affected by the thermal metamorphism due to the Jabal Amrah magmatic body's emplacement. The yellow to beige tones correspond to dolomite and dedolomitized carbonates (Jabal Salab). The yellow numbers refer to the archaeological places: 1. Jabali major site: Mines, ore dressing and crushing areas; 2. Plateau with building remains, close to the wadi; 3. Wadi al-Khaniq rich in slag heaps; 4. Shutayba: old mines and slag heaps; 5. Souq: old mines.

Figure 4. Reflectance of calcite, dolomite, hematite and goethite (raw data are from the JPL spectral library).

The spectral range of MSS- and TM/ETM+ sensors is indicated at the top of the figure.

Figure 5. Reflectance of smithsonite as a function of grain size (raw data are from the JPL spectral library).

Thin line corresponds to reflectance of 0-45 μ m- grain size; regular line corresponds to 45-125 μ m; thick line corresponds to 125-500 μ m.

Figure 6. Colour composite of the Landsat TM data acquired on June 5, 2008: Red=band 7 (SWIR); Green=band 3 (red light); Blue=band 1 (blue light). The white square defines the enlargement (A). Size: about 65km x 50km.

Numbers: 1. gossan (Jabali); 2. white limestone (Jabal Haylan); 3. platy limestone (Souq); 4. contact metamorphic limestone; 5. basaltic cone; 6. Palm tree grove (upstream part of Wadi al Khaniq); 7. doline in dolomite; 8. dedolomite; 9. basaltic lava flow; 10. sand of Al Rub' Al Khali desert; 11. alluvium (junction Wadi al Khaniq-Wadi al Jawf depression); 12. reg (stony desert) on marly limestone; 13. intrusive granite; 14. trachyte (Jabal Amrah); 15a to 15c. Different rocks of the Proterozoic basement (gneiss); 16. lineament (structural control of the Jabali deposit associated with dedolomitization).

Figure 7. Spectral behaviour of ten landscape units as seen on the Landsat TM data acquired on June 5, 2008 (calibrated reflectance).

Thematic Mapper bands: 1. blue; 2. green; 3. red; 4. near infrared; 5. mid infrared; 7. short wave infrared. The landscape units correspond to numbers 1 to 10, Figure 6.

Figure 8. Evolution of the prospection area during preliminary works using Landsat MSS data.

Landsat-1 MSS data acquired on September 6, 1972. Colour composite: red=band 7 (near infrared); green=band 5 (red); blue=band 4 (green). 1980. Landsat-3 MSS data acquired on January 10, 1980. Colour composite: red=band 7 (near infrared); green=band 5 (red); blue=band 4 (green). 1986. Landsat-5 MSS data acquired on February 1, 1986. Colour composite: red=band 4 (near infrared); green=band 2 (red); blue=band 1 (green). Explanation of the map: a. main road (Sana'a-Ma'rib). b. main tracks. c. linear features corresponding to geophysical prospection. d. Location of Figure 9.

Figure 9. Evolution of the Jabali area during preliminary works using Landsat TM data. .

The area (size 4.5 km x 3km) is indicated in Figure 8. Left: Landsat-5 TM data acquired on November 26, 1984. Colour composite: red=band 7 (SWIR); green=band 3 (red); blue=band 1 (blue). Right: Landsat-5 TM data acquired on February 1, 1986. Colour composite: red=band 7 (SWIR); green=band 3 (red); blue=band 1 (blue). Note the enlargement of the track (A), the new camp (B), and the development of prospection at Jabali (C).

Figure 10. Reflectance curves of the Jabali gossan at 11 dates.

Calibrated reflectance for each Landsat-TM band (numerical values in Table 3): blue line (blue range); green line (green range); red line (red range); dashed red line (near infrared range); broken red line (mid infrared range); black dotted line (short wave infrared range).

Figure 11. Map of the main mining archaeological remains at Jabali (from Cierny et al., 2005, modified).

The QuickBird colour composite is in true colors.

Dark blue dashed lines: limit of the mining complex; yellow lines: limit of tailing with slag heaps; light blue lines: limit of mining overburden collapsed; pink: canal track; red: stone wall ✕ (symbol to be changed) mine; ⊙: shaft; ○: cavity.

AB. Cross-section represented in Figure 12.

Figure 12. Cross-section of the Jabali area with geological and archaeological main features.

After Al Ganad et al. (1994), modified.