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Quantitative mapping of arid alluvial fan surfaces using field spectrometer and hyperspectral remote sensing

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Abstract

Mapping and dating of arid and semi-arid alluvial fans are of great importance in many Quaternary studies. Yet the most common mapping method of these features is based on visual, qualitative interpretation of air-photos. In this study we examine the feasibility of mapping arid alluvial surfaces by using airborne hyperspectral reflective remote sensing methodology. This technique was tested on Late Pleistocene to Holocene alluvial fan surfaces located in the hyperarid southern Arava valley, Israel. Results of spectral field measurements showed that the surface reflectance is controlled by two main surficial processes, which are used as relative age criteria: the degree of desert pavement development (gravel coverage %) controls the absorption feature depths, while the rock coating development influences significantly the overall reflectance of the surface, but its effect on the absorption feature depths is limited. We show that as the percent of the surface covered by gravels increases, the absorption feature depth of the common gravels, in this case carbonate at 2.33 μm, increases as well; whereas the absorption features depth of the fine particle in-between the gravels, decrease (hydroxyl and ferric absorption features at 2.21 μm, and 0.87 μm, respectively), as the fines are removed from the surface. Using these correlations we were able to map the surface gravel coverage (%) on the entire alluvial fan, by calculating the gravel coverage (%) in each pixel of the hyperspectral image. The prediction of gravel coverage (%) is with accuracy of ±15% (e.g. gravel coverage of 50% can be predicted to be 35% to 65%). Using extensive accuracy assessment data, we show that the spectral based mapping maintained high accuracy degree (R^2=0.57 to 0.83). The quantitative methodology developed in this study for mapping alluvial surfaces can be adapted for other surfaces and piedmonts throughout the arid regions of the world.

Keywords: Quantitative hyperspectral remote sensing mapping; Alluvial fan surfaces; Reflectance spectra; Desert pavement; Rock coating

1. Introduction

Alluvial fans are a common feature in many arid and semi-arid regions and provide an important record of Quaternary tectonics and climate change (Birkeland, 1999; Bull, 1991). These deposits are often expressed as multiple surfaces that can be distinguished from one another by their relief and height above the active channel, soil characteristics, rock coating (varnish) development and degree of dissection (e.g. Bull, 1991; McFadden et al., 1989).

Several qualitative and semi-quantitative field techniques were developed in order to differentiate between adjacent alluvial surfaces based on the assumption that the changes in the degree of soil development and rock weathering are mostly time dependent for a given lithology and a geomorphic setting (e.g. Jenny, 1941; McFadden et al., 1989). One of the main methods in mapping chronosequences of alluvial surfaces is a combination between field characterization of a chronosequence and air photo mapping. Traditionally the latter is carried out by manual interpretation of the differences of the surface brightness as they are manifested in the color or black and white air photos (Bull, 1991; Christenson & Purcell, 1985). The alluvial surface brightness (in the visible region, 0.4–0.7 μm) is known to be controlled by two time-driven surficial processes: development

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of desert pavement and rock coating (Bull, 1991; Christenson & Purcell, 1985). Desert pavement is a continuous mantle of flat-lying, densely packed, partly overlapping gravels which developed mainly by dust accumulation and mechanical weathering (McFadden et al., 1987; Yaalon, 1970). The gravel coverage increases with exposure time, the gravel size decreases and the surface becomes smoother. Concurrently, with time the surficial gravels develop rock coating due to weathering, eolian accretion and biogenic activity (Bull, 1991; Potter & Rossman, 1977).

However, aerial photo mapping, which is based on visual estimation of the surface brightness, has several limitations. First, it is not objective since it is not based on explicitly defined procedure, but rather on personal, subjective, decision of visual gray scale levels. Secondly, in places, it is difficult to distinguish between age-adjacent surfaces due to subtle differences in their appearance (Beratan & Anderson, 1998; Kierein-Young, 1997; McFadden et al., 1989). Thirdly, mapping large areas is time consuming and requires numerous air photos. And fourthly, this method produces definite, categorical mapping units; thus continuous and gradual patterns cannot be mapped.

Herein, we suggest using an alternative, more quantitative and objective method for mapping alluvial surfaces, based on spectral analysis of hyperspectral reflectance data. Hyperspectral sensors possess high spectral and spatial resolution, which enable quantitative measurement of specific absorption features. The reflectance of alluvial fan surfaces was studied in the past mostly using multispectral sensors (Alwash et al., 1986; Beratan & Anderson, 1998; Farr & Chadwick, 1996; White, 1993;) which exhibit lower spectral resolution (and usually lower spatial resolution) than the hyperspectral ones. These studies differentiated between limited mapping units and could not explain the specific absorption features of the surfaces spectra in detail. Other remote sensing methods were also used to map alluvial fan surfaces: Gillespie et al. (1984) used the thermal region; Kierein-Young (1997) used radar to measure the surface roughness, combined with optical remote sensing; Hsu and Pelletier (2004) showed that the surface brightness of alluvial fan surfaces can be related to a scarp diffusion model, which in turn is correlated to absolute ages. Recently, Mushkin and Gillespie (2005) showed that the roughness of alluvial surfaces can be quantified by measuring the difference in surface reflectance in stereo bands.

This study was designed to evaluate the potential of spectral analysis of reflective hyperspectral data as an approach for mapping alluvial surfaces in arid regions. We examined the hyperspectral mapping results using an extensive ground truth survey. As part of the main target, we also examined the effects of the desert pavement and rock coating development on both field and airborne spectra of the alluvial surfaces. Thus, we were able to relate specific absorption features to ground-surveyed parameters, which can serve as criteria for field mapping and correlation. The technique was tested on an alluvial fan in the southern Negev desert, Israel. This fan exhibits various alluvial surfaces, which lack dramatic elevation differences between them; thus, traditional field mapping in this fan is more complicated.

2. Geology and geomorphology of the study area

The Wadi Raham alluvial fan (WRAF) is located in the Arava valley, southern Negev desert, along the Dead Sea Transform (DST) (Fig. 1). The DST is characterized by a series of elongated en-echelon tectonic basins bounded by sub-parallel left-stepped segments (Garfunkel et al., 1981). Two such basins, the Avrona and Yotvata playas, form the base level for the WRAF (Fig. 1). The fan is located on a structural saddle, and is a-symmetric: most of the fan drains from height of 170 m above sea level (asl) to the southeast, towards the Avrona playa (40 m asl), while in the northern part the fan drains together with Wadi Nimra, to the northeast into the Yotvata playa (60 m asl). The area of the WRAF is ~20 km^2 and it characterized by a low topographic gradient (~1°). The lithology of the Wadi Raham drainage basin (~130 km^2) is composed mainly of carbonate rocks of the Judea Group (Upper Cretaceous), and to a lesser extent of sandstone, chert, chalk (Cambrian to Senonian) and Precambrian rhyolites (Beyth et al., 1999). Most of the outcrops in Wadi Nimra drainage basin are of sandstone lithology (Fig. 1).

The present climate in the region is extremely arid, with mean annual precipitation of 25 mm. Rain events are sporadic. Mean annual temperature is 25 °C with a mean daily range of 14 °C (Bitan & Rubin, 1991).

3. Methodology

The methodology developed and used in this study included four main stages: (1) field characterization of the alluvial surfaces and air photo mapping of the alluvial fan; (2) spectral field measurements; (3) airborne hyperspectral data acquisition, preprocessing and analysis; and (4) accuracy assessment of the hyperspectral mapping.

3.1. Field and air photo mapping of the alluvial surfaces

The WRAF was mapped by visual interpretation of the surface brightness and hue in black and white and color air-photographs (scale 1:12,000) followed by field survey corrections. For the chronosequence determination and relative age estimation (Amit et al., 1996) we used the following: (1) the degree of surface dissection, determined by visual estimation (Amit et al., 1996); (2) the degree of desert pavement development determined by field evaluations of the surficial gravel size, sorting and coverage percentage (Amit & Gerson, 1986); (3) gravel coverage percentage, estimated on the basis of a 1*1 m metal net placed on each alluvial fan surface — the average coverage was determined based of ten measurements on each surface; (4) maximal gravel size and lithology, measured and noted at intervals of 10 cm of 20/30 m random transects located perpendicular to the general flow direction — the mean and median sizes and the kurtosis were calculated, as well as the lithology distribution; and (5) rock coating color determined using the Munsell color scheme. In this study we use the term ‘rock coating’ and not ‘rock varnish’ since rock varnish has specific chemical, mineralogical and textural definitions (Perry & Adams, 1978; Potter & Rossman, 1977).