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Alluvial fan surface ages recorded by Landsat-8 imagery in Owens Valley, California

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ABSTRACT

Alluvial fans are important depositional landforms that offer valuable records of terrestrial sedimentation history if their surfaces can be mapped and dated accurately. Unfortunately, as this often depends on detailed field mapping and intensive absolute dating techniques, it can be a challenging, expensive and time-consuming exercise. In this study, we demonstrate that quantitative information about the ages of alluvial fan surfaces in Owens Valley, California, is recorded by Landsat-8 multispectral satellite imagery. We show that systematic changes in the wavelength-dependent brightness of fan surfaces occur gradually over a timescale of ~100 kyr in this semi-arid setting, and are highly correlated with known deposit ages. Using spectro-radiometry and X-ray diffraction analysis of sediment samples collected in the field, we interpret that surface reflectance evolves primarily in response to the in-situ production of secondary illite and iron oxide by weathering in this landscape. Furthermore, we demonstrate that first-order predictions of absolute fan surface age can be derived from multispectral imagery when an initial age calibration is available. These findings suggest that multispectral imagery, such as Landsat data, can be used (i) for preliminary mapping of alluvial fans prior to detailed field work and before choosing sampling sites for conventional dating techniques, and (ii) to extend age models to undated neighbouring surfaces with equivalent physical properties, once an age-brightness calibration has been established.

1. Introduction

Alluvial fans are depositional landforms that occur in sedimentary basins worldwide and record useful information about landscape evolution and source-to-sink sedimentation (Armitage et al., 2011; Frankel et al., 2011; Hedrick et al., 2013; Owen et al., 2014; D'Arcy et al., 2017a). They typically comprise multiple superposed and juxtaposed surfaces that become abandoned and preserved as a result of incision, aggradation and/or avulsion (Harvey et al., 1999; D'Arcy et al., 2015). Dated alluvial fan surfaces therefore represent distinct time periods of deposition, and have been used as markers to infer fault slip rates and tectonics (e.g., Porat et al., 1997; Kirby et al., 2006; Frankel et al., 2007a, 2011), and examine how past climate changes have affected sedimentation (e.g., White et al., 1996; Owen et al., 2014; D'Arcy et al., 2017a, 2017b). In order to make use of alluvial fans as sedimentary archives of information, techniques for precisely mapping and dating their surfaces are essential.

Today, approaches available for the absolute dating of fan surfaces include cosmogenic radionuclide exposure dating (Dühnforth et al., 2007; Frankel et al., 2007a; Machette et al., 2008), luminescence techniques (Sohn et al., 2007), radiocarbon dating (Reheis et al., 1993), and U-series dating of pedogenic carbonates (Blisniuk et al., 2012; Oerter et al., 2016), among others (Noller et al., 2001). Inevitably, these techniques need to be used in combination with surface mapping for (i) selecting suitable sampling sites, and (ii) correlating and interpreting ages (Owen et al., 2011). In the field, fan surfaces can be mapped prior to absolute dating by using a variety of relative age indicators. These include soil development (Harden, 1987; Zehfuss et al., 2001), clast weathering (Bull, 1991; D'Arcy et al., 2015), surface roughness (Frankel and Dolan, 2007; Regmi et al., 2014), rock varnish and desert pavement maturity (Bull, 1991; Wells et al., 1995), soil carbonate content (Machette, 1985), fault scarp offsets (Le et al., 2007), sedimentological

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properties such as grain size (Al-Farraj and Harvey, 2000; D'Arcy et al., 2017a, 2017b), and surface morphology (Beratan and Anderson, 1998). These age indicators are most powerful when used in combination with each other and with absolute dating efforts (McFadden et al., 1989; D'Arcy et al., 2015).

Remote sensing is another valuable tool for mapping and correlating geomorphic features such as alluvial fan surfaces. It has long been recognised that fan surfaces of different age can be discriminated using multispectral imagery (Gillespie et al., 1984; Kahle et al., 1984; Gillespie, 1992). Differences in the reflectance properties of fan surfaces with different ages have been attributed to changes in chemistry, mineralogical composition and micro-relief as a result of sustained weathering (Gillespie et al., 1984; Kahle et al., 1984; Farr, 1985; Bull, 1991), and specific minerals can be identified within alluvial fan deposits from their reflectance spectra (Shipman and Adams, 1987; Ferrier and Pope, 2012). The gradual accumulation of brown-black rock varnish on clasts and red-brown clays in soils and desert pavements also darkens fan surfaces over time and reduces their albedo in many arid landscapes (Hunt and Mabey, 1966; Bull, 1991; Stock et al., 2007). More recently, it has been suggested that multispectral and hyperspectral imagery can be used to derive information about the types of sedimentary deposits present on alluvial fan surfaces (Milana, 2000; Crouvi et al., 2006; Hardgrove et al., 2010), and that the relationship between fan surface age and brightness is quantifiable (Dickerson et al., 2015). Ground-based studies have also shown that desert pavements act to polarize sunlight (Hibbitts and Gillespie, 2008), and average radar backscatter as a roughness proxy has been shown to correlate with the ages of alluvial surfaces in Israel and Jordan (Hetz et al., 2016). However, despite freely-available multispectral satellite imagery and a rapidly increasing number of published alluvial fan chronologies, the opportunity for mapping fan surfaces and predicting their ages using remotely-sensed data remains significantly under-explored. In this study, we use Landsat-8 imagery to characterise the visible to shortwave infrared (0.4–2.5 μm) spectral properties of 33 distinct alluvial fan surfaces in Owens Valley, California, which have depositional ages spanning the last ~125 kyr. Over this timespan we identify systematic changes in spectral character—i.e., brightness changes across the visible and near infra-red (VNIR) and short-wave infra-red (SWIR) spectral bands—that correlate with independently-obtained absolute fan surface ages. By comparing areas burned in wildfires with unburned parts of the fan surfaces, we show that age-related changes in surface brightness are largely insensitive to vegetation density. We then investigate the origins of these spectral patterns using both XRD and laboratory spectro-radiometry, and explore the opportunity presented for remote mapping of alluvial fans and developing preliminary surface age models. Building upon previous studies that distinguish relative fan surface ages using multispectral/thermal imagery (Gillespie et al., 1984; Kahle, 1987; Hardgrove et al., 2010) and radar (Farr and Chadwick, 1996), we demonstrate that it is also possible to distinguish between fan surfaces of different ages using Landsat-8 imagery, at least in Owens Valley. Finally, we perform a comparison between our target fan surfaces in Owens Valley and additional fan surfaces in neighbouring Death Valley, California.

2. Study area

We examine eight alluvial fan sequences in Owens Valley, California (Fig. 1). These fans comprise debris flow deposits exported by steep catchments along the eastern Sierra Nevada (cf. D'Arcy et al., 2015). The deposits are exclusively granitic in composition, owing to the constant bedrock lithology in the parent catchments; detailed lithological descriptions are provided by Bateman (1992). They have been mapped and dated by previous studies with a combined total of 89 ^{10}Be cosmogenic nuclide exposure dates spanning > 100 kyr (Zehfuss et al., 2001; Dühnforth et al., 2007; Le et al., 2007). D'Arcy et al. (2015, 2017b) subsequently combined and updated these ^{10}Be ages using a refined estimate of boulder surface lowering rate, consistent parameters for the age calculations, and information about the timing of past glaciation from the Birch Creek fan. D'Arcy et al. (2015) also extended the ^{10}Be age model to neighbouring fan surfaces by developing an empirical correlation technique based on the weathering rate of boulders. With 33 dated surfaces, these fans have an exceptional density of age constraints across time and space, and we refer the reader to D'Arcy et al. (2015, 2017b) for full mapping and dating information. Therefore, the Owens Valley fans present a particularly well-constrained opportunity to characterise how surface reflectance evolves over 10^4 to 10^5 year timescales in a semi-arid environment.

Owens Valley is a semi-arid basin occupying the rain shadow of the Sierra Nevada. Modern mean annual precipitation averages 50–200 mm yr^{-1} and annual temperatures average 14–18 °C (2004–2013 records from Independence; NOAA National Climatic Data Center, 2014). The climate was colder and wetter on average during the glacial period of the late Pleistocene; the Last Glacial Maximum (LGM) was 5–6 °C cooler and approximately twice as wet as modern conditions (e.g., Benson et al., 1996; Woolfenden, 2003; Yamamoto et al., 2007; Phillips, 2008).

Today, vegetation on the alluvial fans is limited to sparse cover of semi-arid shrub communities (Fig. 2; Ustin et al., 1986; Smith et al., 1990a, 1990b). After ~100 kyr of exposure the fan surfaces are discoloured and remain mantled by alluvial sediment (Fig. 2b). Detailed soil descriptions are provided by Zehfuss et al. (2001), which we supplement with XRD and spectro-radiometry analyses in this study. In places, wildfires have occurred on small patches of the fan surfaces, which appear brighter in imagery (Fig. 1) as a result of a reduction in vegetation density from 45 to 55% cover (mature, unburned surfaces) to 15–25% cover (recently burned surfaces). These measurements of vegetation coverage were obtained by thresholding high-resolution (< 1 m per pixel) aerial imagery of the fan surfaces, in which vegetation appears dark and sediment appears light, and counting the number of pixels that correspond to vegetation. Following several wildfires on these fan surfaces, it has been observed that the resulting charcoal is removed by wind (Bierman and Gillespie, 1991). We take advantage of these burned patches of fan surfaces to evaluate what effect a significant (~30%) reduction in vegetation cover has on the spectral characteristics of our target alluvial fan surfaces.

Even without the age constraints provided by previous studies, younger and older surfaces are easily discriminated in the field. Fig. 2 shows field photographs of two fan surfaces, one dating to ~5.5 ka and the other to > 100 ka. These pictures were taken in November 2013 with the same camera settings and constant white balance, in equivalent sunny lighting conditions and with no subsequent contrast enhancement; they therefore give a fair comparison of surface appearance. The younger surface (Fig. 2a) shows a debris flow snout with white-grey boulders surrounded by a pale grey gravel surface. The original depositional relief is intact and the clasts are bright, unweathered and unvarnished. By contrast, the older surface (Fig. 2b) exhibits weathered boulders with a moderate amount of dark grey varnishing on their top surfaces. The original depositional relief has degraded by diffusion, and the gravels and some of the boulder clasts have become orange as a result of oxidation. These post-depositional changes take place gradually. Fig. 2c shows photos of surface gravels (~10 mm) collected from surfaces spanning 4 to 62 ka. These images were also taken with constant lighting and camera settings/white balance, and no contrast enhancement was applied. They illustrate the intensity of the change in sediment colour over several 10s of kyr, which is apparent both in the field and in hand specimens.

3. Methods

We downloaded multispectral imagery for two cloud-free Landsat 8 scenes covering our target alluvial fans (path 41/row 35 and path 42/row 34), imaged on 12th May 2013. We selected Landsat 8 imagery for