Remote Sensing of Environment 184 (2016) 288–301

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Estimating the age of desert alluvial surfaces with spaceborne radar data

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ARTICLE INFO

Article history:
Received 14 January 2015
Received in revised form 2 June 2016
Accepted 6 July 2016
Available online xxxx

ABSTRACT

We present a new dating approach for desert alluvial surfaces that utilizes radar image data to obtain regional-scale correlations between dated surfaces and surfaces of unknown ages. The study was carried out along the Arava segment of the Dead Sea Transform north of the Gulf of Elat (Aqaba) using Advanced Land Observation Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) data with 6–12 m/pixel resolutions. Nineteen independently dated Quaternary morphostratigraphic alluvial units (5 to 1910 ka) from eight different sites with variable lithologies (carbonate/magmatic/chert) were examined in order to develop, test and validate the proposed approach. Expanding on previous studies that established the characteristic smoothing of desert alluvial surface through time and the capability of measuring such roughness variations with radar, we employed a pixel-aggregation approach that yielded a robust ($R^2 = 0.95$) power-law relation between the average radar backscatter value from the surface ('*AR*') and the abandonment age ('*T*') of the unit as measured with independent methods such as luminescence and/or cosmogenic radionuclide dating. We found that: 1) This *AR-T* correlation can be inverted to obtain calibrated radar-based *T* estimates as old as ~1.5 Ma with 35% uncertainty; 2) ALOS PALSAR 6 m/pixel images acquired at incidence angles of 34–38° yielded optimal results; 3) a sample of at least 70 contiguous radar pixels was required to capture the natural roughness variability of the surfaces examined, and 4) surface lithology did not exert a primary effect on *T* inversions. Validation experiments yielded radar-based ages of 3 ± 1, 91 ± 32, 484 ± 169 and 1604 ± 561 ka that compare to Holocene, 56 ± 14, 540 ± 60 and 1590 ± 250 ka ages previously determined for the same surfaces, respectively. We propose that with region-specific calibrations, spaceborne radar data can be used to quantitatively estimate the age of abandoned alluvial units across regional scales.

1. Introduction

1.1. Motivation

Abandoned alluvial landforms provide effective recorders of past tectonic activity, climatic variations and landscape evolution processes (e.g., Bull, 1977, 1991). Consequently, determining the surface age of morphostratigraphic alluvial units often comprises a pivotal component in quantitative studies of Earth's surface and its dynamics over recent geologic time-scales. Whereas in-situ radiometric dating approaches such as ^{14}C, luminescence and Cosmogenic Radionuclides (CRN) (hereafter "in-situ dating") are routinely applied in this context (e.g., Noller et al., 2000) the substantial resources required for application of these approaches, such as sample collection and laboratory analyses, typically restrict the number of surfaces that can be dated in a single study. Inherent analytical complexities as well as accessibility issues and lack of suitable dating material in desert environments can also limit the application of in-situ dating approaches in arid landscapes. As a result, efforts to determine the age of alluvial surfaces in desert environments are often restricted by the number of surfaces that can be effectively dated rather than by the number of surfaces of scientific interest identified. In this context, we present a new surface dating approach that utilizes spaceborne radar data to quantitatively estimate the age of abandoned alluvial surfaces that could not be otherwise dated using in-situ approaches.

1.2. Mapping desert alluvial landforms with remotely sensed data

Remotely sensed data provide an effective resource for mapping morphostratigraphic alluvial units in bare desert terrains: Farr and Chadwick (1996) demonstrated the use of panchromatic satellite images together with spaceborne radar data to distinguish between late Quaternary alluvial units in central Asia and Death Valley, USA. Others showed the benefits of combining visible - shortwave infrared (VIS-SWIR: 0.4–2.5 μm) data with radar images to map time-progressive compositional and roughness variations amongst abandoned alluvial

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http://dx.doi.org/10.1016/j.rse.2016.07.006
0034-4257/

units (Weeks et al., 1996, 1997; Kierein-Young, 1997). Satellite stereo imaging was also established as a complementary and effective measure for mapping surface roughness and relative age variations amongst morphostratigraphic alluvial units in Death Valley, USA and the Negev desert in southern Israel (Mushkin and Gillespie, 2005).

Airborne sensors provide additional effective tools for such mapping purposes. Multi-spectral thermal infrared images from Death Valley (Gillespie et al., 1984) and hyperspectral VIS-SWIR images from the Negev desert of Israel (Crouvi et al., 2006) were used to successfully map variations in composition and age-progressive varnish development on late Quaternary alluvial terraces. Airborne LiDAR data at 1 m/pixel resolution were also successfully applied to capture age-dependent roughness variations amongst late Quaternary alluvial terraces and to delineate and map morphostratigraphic alluvial units in Death Valley (Frankel and Dolan, 2007) and the Sonoran desert in SW USA (Regmi et al., 2013).

1.3. Post-abandonment evolution of desert alluvial surfaces

In-situ weathering of young and rough boulder-strewn deposits into smooth and persistent desert pavements presents a common post-abandonment evolution trajectory for alluvial surfaces in desert environments worldwide (e.g., Bull, 1977). Desert pavement development is typically driven by a suite of processes that include reg soil formation in the upper decimeters – meters of the deposits (e.g., Amit and Gerson, 1986), subaerial clast weathering (Wells et al., 1995), varnish development on surface clasts and accumulation of eolian dust as a clast-free Av horizon beneath the pavement rocks (e.g., McFadden et al., 1987). The initial roughness of desert alluvial surfaces primarily results from the wide range of boulder to pebble sized clasts found in such deposits and from larger-scale depositional elements such as boulder clusters, levees and bar and swale features. Gravity-driven diffusion of material from bars into swales and in-situ subaerial weathering of clasts typically reduce this initial roughness asymptotically over ~10^4 yr time scales until mature and smooth desert pavements are established (Amit et al., 1993; Matmon et al., 2006; Frankel and Dolan, 2007; Regmi et al., 2013; Mushkin et al., 2014). This predictable smoothing trajectory of desert alluvial surfaces has been widely recognized as an effective measure for relative age determination (e.g., McFadden et al., 1989; McDonald et al., 2003).

Typically, mature desert pavements, which consist of an Av silt horizon and an overlaying interlacing pavement of angular rock fragments, develop over time into an impermeable surface-armoring layer that promotes runoff accumulation during precipitation events. Such well-established (late-stage) desert pavements commonly display a dendritic network of erosional rills that drain the surface internally and incise into it over time (Christenson and Purcell, 1985; Wells et al., 1987; Farr, 1992) to the point where only remnants of the original pavement surface are preserved. In hyper-arid low-relief and tectonically stable settings, where such late-stage incision is minimal, extensive and smooth desert pavement surfaces can persist for 10^6 yr time-scales (e.g., Matmon et al., 2009; Guralnik et al., 2010).

1.4. Approach

1.4.1. Roughness as a remote measure for the age of desert alluvial surfaces

Recent studies demonstrated that airborne LiDAR can be used to measure the age-dependent smoothing of alluvial surfaces due to diminishing bar-swale relief at larger than meter ('supra-meter') length scales (Frankel and Dolan, 2007; Regmi et al., 2013). However, these studies also showed that late stage (greater than ~10^5 ka in the cases examined) incision rills can 'reverse' the age-progressive smoothing trajectory of undisturbed surfaces at supra-meter length scales and can therefore introduce ambiguities into straight-forward surface-age inversions from such roughness data.

1.4.2. Radar measurements of surface roughness

Radar backscatter, which primarily responds to sensor-surface phase angle, surface dielectric constant and sub-pixel surface roughness/structure (e.g., Ulaby et al., 1978), is a widely utilized tool for mapping spatial variability in soil roughness and moisture content (Ulaby et al., 1982). In the absence of significant soil moisture and vegetation, surface roughness integrated over all sub-pixel scales (down to ~the wavelength of the incident radar radiation) becomes the primary parameter modulating pixel-to-pixel variations in radar backscatter from low-lying desert surfaces (e.g., Evans et al., 1992; Farr, 1992; Weeks et al., 1996, 1997; Farr and Chadwick, 1996; Kierein-Young, 1997). Of the commonly used radar wavelengths, i.e., X (~3 cm), C (~5.6 cm), L (~24 cm) and P (~68 cm) bands, L-band appears to best capture the roughness variations between abandoned alluvial surfaces (e.g., Ulaby et al., 1978; Farr and Chadwick, 1996).

1.4.3. Radar backscatter as a calibrated proxy for surface age

Expanding on the characteristic smoothing of desert alluvial surface as a function of surface age (Section 1.4.1) and the capability of radar images to effectively quantify such roughness variability (Section 1.4.2) we examine the use of radar backscatter as a readily calibrated quantitative proxy for the age of morphostratigraphic alluvial units in arid environments (Fig. 1).

Four objectives were outlined to achieve this goal:

A) Determine the optimal radar backscatter metric that displays a systematic and predictive relation with surface age.
B) Evaluate the uncertainty of this radar vs. surface-age regression and its sensitivity to key variables such as measurement noise, natural roughness variability and surface composition.
C) Validate the performance of the proposed radar-based surface dating approach.
D) Demonstrate the use of radar backscatter to infer the age of morphostratigraphic alluvial units that could not be successfully dated with in-situ approaches.

2. Study sites

Our study area is located along the Arava valley segment of the Dead Sea Transform (DST) (Fig. 2), which separates the Arabian and African plates and accounts for ~105 km of left-lateral slip since the Miocene (Garfunkel et al., 1981). Asymmetric vertical tectonics along this segment of the DST (e.g., Garfunkel and Ben Avraham, 1996) have led to deeper exhumation of crustal lithologies along the eastern side of the Arava valley and together with the ~105 km of lateral offset result in

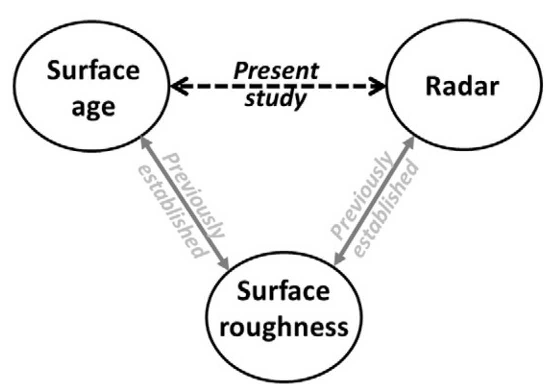

Fig. 1. The relation between radar, surface roughness and age of abandoned alluvial surfaces in desert environments. Previous studies demonstrated robust radar-roughness and roughness-age correlations for such landforms. In the present study we test the relation between radar and surface age.