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Exploring morphology, layering and formation history of linear terrestrial dunes from radar observations: Implications for Titan

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ABSTRACT

Understanding the morphology and internal layering of large aeolian dune fields through radar observations can provide unique insights into the climatic and geophysical conditions that led to their formation. In this study, we perform a large-scale characterization of the morphology and internal layering of linear dunes in hyper-arid areas on Earth, through utilizing multiple complementary radar datasets (SIR-C imaging, SRTM interferometry-derived elevations and radar sounding or Ground Penetrating Radar (GPR)). Linear dune fields in the Egyptian desert are of special interest, due to their significance as planetary analogs to dunes on Mars and Saturn's largest moon, Titan. Satellite radar imagery and elevation data of the region show significant variance in the geomorphology of different dune fields in Egypt. In addition, GPR probing of the first few meters suggests different inner settings in the layering of dunes of different ages in eastern and western Egypt, reflecting different paleoclimatic regimes that led to their formation. Furthermore, our radiometric analysis suggests that dunes with different inner layering arrangement also exhibit different radar backscatter returns as a function of their heights. For relatively younger dunes with a homogeneous inner structure, like the ones in eastern Egypt in the Qattaniya dune field, we observe that sigma0 does not change as a function of the dune height. For relatively older dunes in western Egypt like the Great Sand Sea (Northern (Siwa) and Southern dune fields), we observed a linear correlation between sigma0 and the dune height. Thus, surface properties of dunes like morphology and backscatter variation with height are related to inner characteristics like arrangement of internal layering, relative ages and can be used to infer their depositional history.

Linear dunes discovered in the equatorial regions of Titan by the Cassini-Huygens mission are morphologically very similar to these linear dune fields in the Egyptian Sahara. Hence, assessing the variability of morphology and radar backscatter properties of Titan's dunes as a function of their heights can help constrain the ambiguities associated with their internal structure and formation history and provide insights into Titan's paleowind regimes.

1. Introduction

The Egyptian Sahara occupies the north-eastern edge of the Sahara Desert in Africa. This desert occupies an area of almost 700,000 km^2, stretching from the Egyptian-Libyan border on the west to the Nile river on the east, from the Mediterranean Sea in the north to the border of Egypt-Sudan in the south (El-Baz, 1992; Bubenzer et al., 2007a, 2007b; Besler, 2008; Abouelmagd et al., 2012; Telfer and Hesse, 2013). Linear dune fields in the Egyptian desert are key elements in reconstructing recent paleo-climatic winds that steered moist Atlantic/Mediterranean air masses, north of the limit of tropical monsoonal rainfall at 20°N (Brookes, 2003), sustaining early Holocene lakes and playas in the region. The Egyptian Sahara has been extensively studied as an analog to planetary aeolian environments (El-Baz, 1981, 1992; El-Baz et al., 1979; Gaber et al., 2009; Kröpelin, 1993; Paillou et al., 2003). Both radar imaging and sounding data have been used for comparisons of terrestrial surface features in the Egyptian Sahara with Mars (Grandjean et al., 2006; Hugenholtz et al., 2012), including dunes (Breed et al., 1979; El-Baz et al., 1979), aeolian bright and dark-colored streaks (El-Baz and Maxwell, 1979), yardangs (El-Baz et al., 1979), dry channels (Breed et al., 1982), surface rock morphology (Garvin et al., 1981) and pits and flutes formed in rocks by wind erosion (McCauley et al., 1979). The Egyptian Sahara thus provides an excellent terrestrial analog for studying planetary aeolian processes and their roles in planetary paleoclimatic reconstruction. Radar characterization of these analogous terrestrial dunes provides crucial field comparisons for planetary dunes

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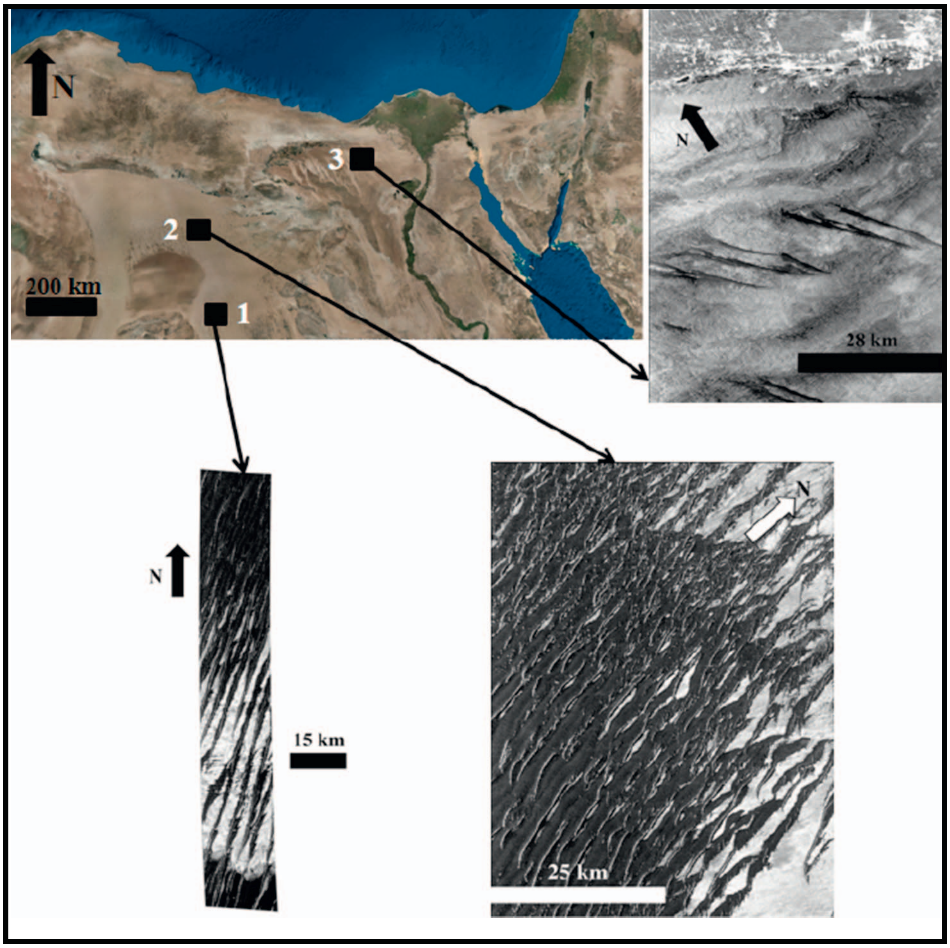

Fig. 1. Landsat visible imagery showing locations of three sites of analogous dune fields in Egypt. (1) Southern Great Sand Sea (central/south-western Egypt); (2) Northern Great Sand Sea (Siwa dunes in north-western Egypt) and (3) Qattaniya dunes (north-eastern Egypt; west of Cairo). Corresponding SIR-C radar backscatter scenes are also shown.

(mostly observed with radar), and can therefore provide unique insights into understanding their geomorphological characteristics, internal layering and formation history, in the absence of in-situ ground validation data for these planetary bodies.

We focus on three sites of dune fields in the Egyptian Sahara: 1) Southern Great Sand Sea in central/south-western Egypt, 2) Northern Great Sand Sea (Siwa) dunes in north-western Egypt and 3) Qattaniya dunes in north-eastern Egypt (~200 km west of Cairo). Fig. 1 shows the locations of these terrestrial analog dune fields. These large, linear dunes in the Egyptian Sahara have heights of tens of meters to ~100 m, widths of up to a few kilometers and lengths of up to hundreds of kilometers (Lancaster, 1995; Radebaugh et al., 2010). They are thus comparable in size and morphology to the linear dunes observed on Saturn's largest moon, Titan, with the Cassini radar instrument. Although linear dunes have also been observed on Mars, they are not as widespread, compared to other dune types, as on Titan (Edgett and Blumberg, 1994; Bourke et al., 2010). We will therefore only discuss the comparison of terrestrial linear dunes with those on Titan in this study.

OSL and radiocarbon dating indicate dunes in the Great Sand Sea to be older (~15,000–20,000 years as reported by Bubenzer et al., 2007a, 2007b; INQUA Dunes Atlas project, 2011) compared to the Qattaniya dunes (dune fields in the vicinity of the Nile valley, including the South-Rayan dune field and the neighboring Qattaniya dune field, date back to ~5000 years B.P., based on geomorphological evidence (Mohamed, 2012; Mohamed and Verstraeten, 2012; Verstraeten et al., 2014, 2017)). Although radiocarbon/OSL dating has not been done for the Qattaniya dunes, geomorphological and anthropogenic evidence can be used to prove that these dunes are relatively younger compared to the Great Sand Sea. The Nile river's discharge has reduced drastically several times in its history, but the last time that this occurred is estimated to be ~5000 years BP, and this provides an upper estimate on the age of the dunes in the Qattaniya dune field which lie to the west of the Nile river valley (Mohamed, 2012).

Terrestrial dune fields have been studied in the past with imaging radars (Blom and Elachi, 1981, 1987; Hugenholtz et al., 2012; Lancaster et al., 1992; McCauley et al., 1982). Along with radar images, Ground Penetrating Radar (GPR) or radar sounding data, which rely on the propagation of microwaves through the surface to deduce subsurface layering, have also been used extensively to study the layering and migration of terrestrial dunes (Bristow et al., 2000, 2005, 2007a, 2007b, 2010a, 2010b; Harari, 1996; Heggy et al., 2006a). Radar sounding instruments have also been used on planetary missions (Heggy et al., 2006b; Seu et al., 2007; Picardi et al., 2004; Ono et al., 2010) to examine the subsurface characteristics, especially subsurface water, on Mars and Earth's Moon.

2. Instruments and datasets

For our SAR characterization of the dunes in the Egyptian Sahara, we used C-band (5.8 cm wavelength) backscatter data from the Spaceborne Imaging Radar (SIR)-C, in Multi Look Complex (MLC) format in HH polarization, with a range resolution of 50 m and azimuth resolution of 50 m. A more detailed description of the SIR-C data can be found in Jordan et al. (1995) and Stofan et al. (1995). We have also utilized elevation data with a resolution of 1 arc-second (~30 m) from the Shuttle Radar Topography Mission (SRTM) (Blumberg, 2006; Farr et al., 2007). Table 1 shows details of the SIR-C scenes and the corresponding SRTM Digital Elevation Models (DEMs) used for this study.

We collected GPR/radar sounding data for the Qattaniya and Siwa dunes (Northern Great Sand Sea) in Egypt during a site visit in

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