AEOLIAN EROSION, TRANSPORT, AND DEPOSITION OF VOLCANICLASTIC SANDS AMONG THE SHIFTING SAND DUNES, CHRISTMAS LAKE VALLEY, OREGON: TIMS IMAGE ANALYSIS

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1. INTRODUCTION

Remote sensing is a tool that, in the context of aeolian studies, offers a synoptic view of a dune field, sand sea, or entire desert region. Blount *et al.* (1990) presented one of the first studies demonstrating the power of multispectral images for interpreting the dynamic history of an aeolian sand sea. Blount's work on the Gran Desierto of Mexico used a Landsat TM scene and a linear spectral mixing model to show where different sand populations occur and along what paths these sands may have traveled before becoming incorporated into dunes. Interpretation of sand transport paths and sources in the Gran Desierto led to an improved understanding of the origin and Holocene history of the dunes (Blount and Lancaster, 1990).

With the anticipated advent of the EOS-A platform and ASTER thermal infrared capability in 1998 (Kahle *et al.*, 1991), it will become possible to look at continental sand seas and map sand transport paths using 8-12 μm bands that are well-suited to tracking silicate sediments. A logical extension of Blount's work is to attempt a similar study using thermal infrared images (Edgett *et al.*, 1994). One such study has already begun by looking at feldspar, quartz, magnetite, and clay distributions in the Kelso Dunes of southern California (Ramsey *et al.*, 1993, 1994). This paper describes the geology and application of TIMS image analysis of a less-well known Holocene dune field in south central Oregon using TIMS data obtained in 1991.

2. THE SHIFTING SAND DUNES, OREGON

The Shifting Sand Dunes are located in Christmas Lake Valley, at the eastern end of what was once the Pleistocene Fort Rock Lake. The basin is surrounded by Pliocene to Holocene basalt flows and mafic hyaloclastic tuffs. The ancient lake bed consists mainly of fluvio-lacustrine and volcanic airfall deposits. The bulk of the lake sediments are sand and silt-sized volcanic glass and crystals deposited by airfall; other sediments include diatomaceous earth, fine volcanic ash, basalt, and andesitic epiclasts (Dole, 1942). Much of the airfall sediment is considered to have come from eruptions of Mt. Mazama (now Crater Lake; Dole, 1942; Allison, 1979). During the Holocene, the lake bed surface has been reworked and shaped by wind, fluctuations in the levels of smaller lakes and ponds, and the deposition of large quantities of sandy ash that resulted from the terminal explosions of Mt. Mazama 6,800 years ago (Allison, 1979).

The dune area is about 30 km long and 10 km wide and contains a wide variety of bedforms. The dune field consists of two northeast-trending, megaparabolic dunes, one of which is very active today, the other is covered by trees and sagebrush comprising the Lost Forest Research Natural Area. Active dunes superposed on the megaparabolic structure include barchan and transverse forms that have linear ridges on them indicating a weak bimodal wind regime. Linear dunes, dome dunes, and parabolic dunes are also present. The main deflation areas occur at the western end of the dune field. The main active dune area has a deflation zone bounded by dune ridges and contains Fossil Lake, an important Cenozoic fossil site. The dune field preserves a minimum of three major Holocene dune-building events (Edgett, 1994).

The main constituents of the Shifting Sand Dunes are volcanic glass and devitrified glass fragments, plagioclase crystals, basalt lithic fragments, aggregates of silt and clay-sized volcanic ash, pyroxenes, opaque minerals (mostly magnetite), and trace occurrences of fossil fragments and other minerals (Dole, 1942; Edgett, 1994). Most samples collected from the dunes in 1992 - 1994 contain nearly 50% plagioclase and 10 to 30% volcanic glass grains. The plagioclase is mostly andesine (Dole, 1942). The glass is mainly pumice shards, some of which have enclosed mineral crystals. Free crystals are mostly plagioclases and pyroxenes, and most of these have adhering glass and/or inclusions of glass, magnetite, or other minerals. The crystalline and glassy grains are generally angular to subangular, reflecting their original deposition as volcanic tephra. The volcanic ash aggregates are rounded to subrounded and are largely derived from erosion of a semilithified layer exposed in the deflation areas of the dune field. The volcanic lithic fragments are typically subrounded, probably indicating prior transportation by water. The Shifting Sand Dunes contain a mixture of sand deflated from the ancient lake bed plus sand-sized tephra deposited by the terminal eruptions of Mt. Mazama (Dole, 1942; Edgett, 1994).

3. TIMS IMAGE OF THE SHIFTING SAND DUNES

3.1 Data and Image Processing

The TIMS image of the Shifting Sand Dunes used in this study was acquired on September 21, 1991, by the NASA Ames Research Center C-130 Earth Resources Aircraft program. The C-130 had a mean altitude of 3657 m, resulting in an image with 9.1 m/pixel resolution at nadir. The raw image was converted to calibrated radiance, from which normalized emittance was computed for each of the six bands following the method of Realmuto (1990). Atmospheric attenuation effects along the margins of the image were reduced by subtracting a map of low frequency variation derived from a single-line low pass filter of 211 samples. Atmospheric effects were further removed by calibration transfer using laboratory spectra of material collected among the dunes (see Edgett and Anderson, 1995). The resulting 6-band image provides quantitative estimates of surface emissivity. The dune spectra in the image are consistent with spectra of samples from the same location as measured in the laboratory. The 6-band emissivity image was used in the two analyses which follow.

3.2 Surface 9.2 Micrometer Emissivity Image

Emissivity variations alone appear to be useful for distinguishing active and inactive dunes, interdunes, and deflation surfaces. TIMS band 3, in this case centered at 9.2 μm, provides the widest range in emissivities for the dune field (Figure 1). The entire range is only from 0.89 to 1.00, mostly concentrated between 0.90 and 0.95. Most of the emissivity variation results from the effects of surface composition, particle size, and vegetation. Vegetation has a high emissivity and relatively flat spectrum; most of the vegetation in the 9.2 μm image appears white (high emissivity). The lowest emissivities (0.89 to 0.91) correspond to the locations of active dune sand. Interdune areas have intermediate emissivities (0.90 to 0.95) which overlap on the low end with active sand and on the high end with vegetation. Interdune emissivities are a direct result of the material comprising the interdune surface, which in some places is sand and granules while in others is fine-grained ash and dry mud deposits. At the western end of the dune field in the vicinity of Fossil Lake, the large deflation area has low emissivities comparable to but generally a bit lower than the dunes (0.90 to 0.91). This deflation surface has a lag of granules and pebbles underlain by silt and sand. Further downwind (east), interdune emissivities rise; in some cases this is because the interdune is a dry pond with grasses and salts, in other areas, the interdune is a silty, semilithified lake bed layer from which ash aggregate grains are eroded and added to the dunes. Inactive dunes are distinguished from active dunes because they have higher emissivities; although some have patches of active sand. Vegetation on inactive dunes has a higher emissivity, and vegetation traps dust, which also raises the emissivity.

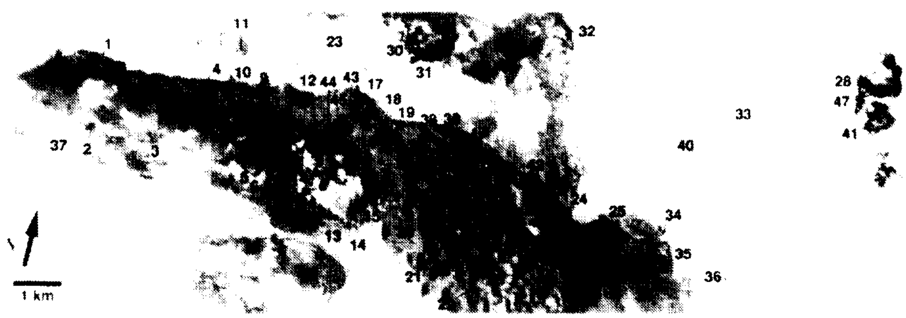

Figure 1. Emissivity image (9.2 μm) of main active portion of the Shifting Sand Dunes. Numbers indicate sample sites. Emissivities range from 1.0 (white) to 0.89 (dark gray).

3.3 Linear Unmixing Using Image Endmembers

Quantitative estimates of thermal infrared spectral emissivity are ideally suited for unmixing analysis. For grains larger than the wavelength (*i.e.*, dune sand), a linear unmixing approach can provide geologically useful results (Ramsey and Christensen, 1992*a*; Ramsey *et al.*, 1993, 1994). Such models are still in development and testing (Ramsey and Christensen, 1992*b*). Three types of endmembers can be selected: (1) spectra from pixels of different materials seen in the image, (2) laboratory spectra of materials collected from the field area in the TIMS scene, and (3) laboratory spectra of generic minerals in a spectral library. The present study follows the first approach, subsequent work will explore the latter two.

Five image endmembers were selected from the TIMS scene obtained in September 1991. Because there are no pure endmember materials in the scene, each selected here is a mixture of sub-endmembers. The first endmember is "regular sand," characterized by Dune 24 (Figure 1) with sub-endmembers: 48% plagioclase, 17% glass fragments, 9% ash aggregates, 12% volcanic lithic fragments, 9% pyroxene, and 5% opaques and others (from thin section analysis). "Regular sand" is the baseline against which other dune sands are compared. The second endmember consists of "mudchips," coarse aggregates of the silty volcanic ash derived from a capping layer among the lake sediments. The third endmember, "dark lithics," generally has abundant (> 25%) basalt grains and volcanic glass (> 30%). The fourth endmember consists of sagebrush and grass, which is distinct relative to the fifth endmember, "thick vegetation," which includes alfalfa crops and the pine trees of the Lost Forest.

The key result of this analysis is a map showing abundance of "regular sand" in the dune field relative to "mudchips" and "dark lithics." In the main active dune area, dark lithics are lags of granule-sized grains concentrated by wind, indicating areas of erosion near the base of dune ridges. The "mudchip" endmember represents surfaces with greater than 10% concentration of volcanic ash aggregate grains. Mudchips are most common in interdune areas at the middle of the main active dune area. Mudchips are eroded from the interdunes by the work of wind and off-road-vehicle usage and deposited locally on the dunes. Using the TIMS to identify and map mudchip (volcanic ash aggregate) contributions to the dunes represents a new approach to identifying local sources of sand in terrestrial dune fields. The unmixing analysis also has shown that the active dunes at the remote eastern end of Figure 1, within the Lost Forest, contain more basalt fragments than the main active dune area. The basalt in this case appears to be a local contribution from the erosion of mafic tuffs in the vicinity.

The distribution of mudchips and dark lithics in the mixing image follows a lineated pattern reflective of the ridges superposed on most of the dunes in the area. The dune ridges result from a season-dependent, weakly bimodal wind regime; the mixing pattern reflects the variation of erosion and deposition on dune surfaces among the dunes Future work will attempt to use grains collected from the dunes for unmixing analysis. Because of the abundance of glass and microcrystalline material in these sands, the Shifting Sand Dunes represent an intriguing and somewhat more complex problem for mixing studies than do the Kelso Dunes examined by Ramsey *et al.* (1993, 1994).

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