Comparison of Airborne and Spaceborne Sensors for Remote Sensing Analysis of Potential Debris Flow Source Areas on Mount Shasta, California

James Crowley

Volcanic debris flows are extremely dangerous natural phenomena that begin as slope failures high on volcanoes and surge for many tens of kilometers down surrounding river valleys. Many such events are linked to the presence of hydrothermally altered rocks, which weaken volcanic edifices and produce clay-rich mudflows that can travel especially long distances. However, because such rocks and structures commonly are situated in rugged terrain that is difficult to access, information concerning potential altered-rock source areas for debris flows is sparse.

In this investigation, researchers explored the utility of airborne and spaceborne remote sensing systems and digital elevation data for mapping hydrothermally altered rocks and other volcanic features that may contribute to potential debris flow hazards. This investigation took place in a well-known volcanic study area at Mount Shasta, California. Investigators used data acquired from NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and from the EO-1 Hyperion, the first spaceborne imaging spectrometer.

There were two objectives for the investigations. The first was to compare alteration mapping results obtained with high radiometric quality AVIRIS data to results acquired from the somewhat poorer quality, but geographically agile, Hyperion sensor. The second objective was to develop analytical methods for using remote sensing observations to characterize altered rock zones that represent potential debris-flow source areas. In particular, the investigators compared volume estimates of altered rock masses at Mount Shasta with estimates made by using AVIRIS data of Mount Rainier, Washington, and Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) data of Mount Adams, Washington. For these estimates, investigators combined remotely sensed mineralogy with digital terrain information.

Researchers collected 48 rock and soil samples from the upper edifice of Mount Shasta to aid in evaluating the remote sensing data. Several dozen altered rock samples from Mount Adams and Mount Rainier were also obtained during this study. Each sample was measured on a visible to short-wave infrared (0.4-2.5 μm) laboratory spectrometer, and X-ray diffraction patterns were generated to determine the bulk sample mineralogy.

Airborne remote sensing data of Mount Shasta were acquired on September 29, 1996, by NASA's AVIRIS carried aboard the high-altitude ER-2 research aircraft. AVIRIS provides data in 224 narrow (~10 nm bandwidth) spectral channels spanning the 0.4-2.5 μm wavelength region. In the 2.0-2.5 μm wavelength region, where many alteration minerals display diagnostic spectral features, the signal-to-noise of this AVIRIS data set is approximately 300:1. At typical ER-2 flight altitudes of ~20 km, each AVIRIS pixel covers about 20 m^2 at sea level, and the images extend across an 11 km swath.

Hyperion data were acquired on October 2, 2001. Typical Hyperion image swaths are approximately 7.7 km wide and extend up to 185 km in length. Like AVIRIS, the Hyperion sensor provides data spanning the 0.4-2.5 μm wavelength range, but with 242 narrow (10-nm bandwidth) spectral channels. The data set used in this study was subset to 196 spectral channels to exclude overlapping and unused spectral bands. The signal-to-noise of the Hyperion data in the critical 2.0-2.5 µm wavelength region is approximately 40:1

The same general calibration and image-processing procedures were used on both the AVIRIS data set and the Hyperion scene. However, following the reflectance calibration, the Hyperion data were enhanced by applying statistically based transformations for reducing noise. Matched filtering and linear spectral unmixing were then executed on the noise-dampened data.

Figure 1 shows an AVIRIS image (left) of Mount Shasta and a Hyperion image (right) depicting various altered materials in different color patterns. Although there is good agreement between the AVIRIS and Hyperion altered rock distributions, the lower signal-to-noise of the Hyperion sensor imposed some limitations on the mapping results. Investigators could not reliably distinguish natroalunitic rocks from mainly kaolinitic rocks from the Hyperion data, and these two mineral categories were combined as a single class. On the other hand, reduced snow cover in the Hyperion image permitted detection of some areas of kaolinite + alunite alteration that were not visible in the AVIRIS data. Image spectra extracted from the same ground location in the Hyperion and the AVIRIS data sets are compared in Figure 2. It was concluded from these comparisons that Hyperion data were sufficient for observing key aspects of alteration mineralogy as determined by AVIRIS mapping and associated field studies.

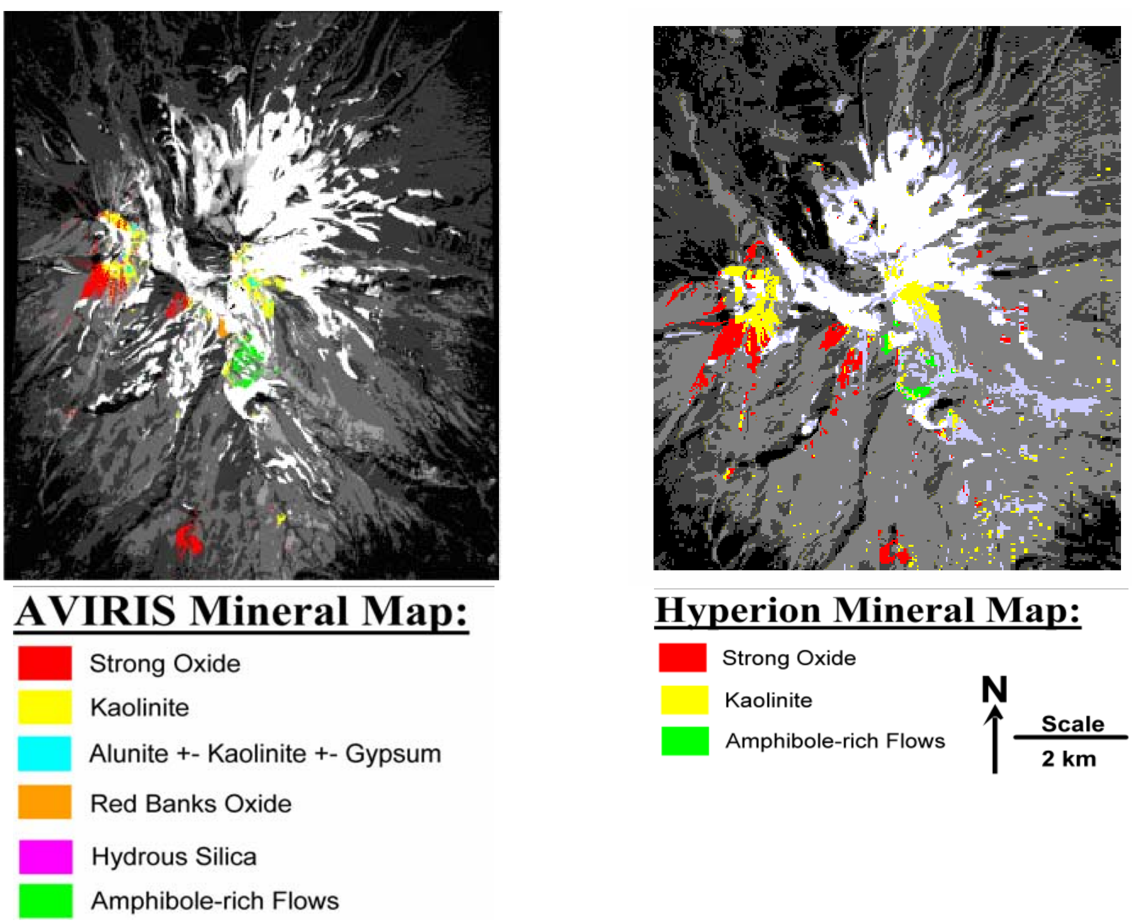

Figure 1. AVIRIS and Hyperion mineral maps.

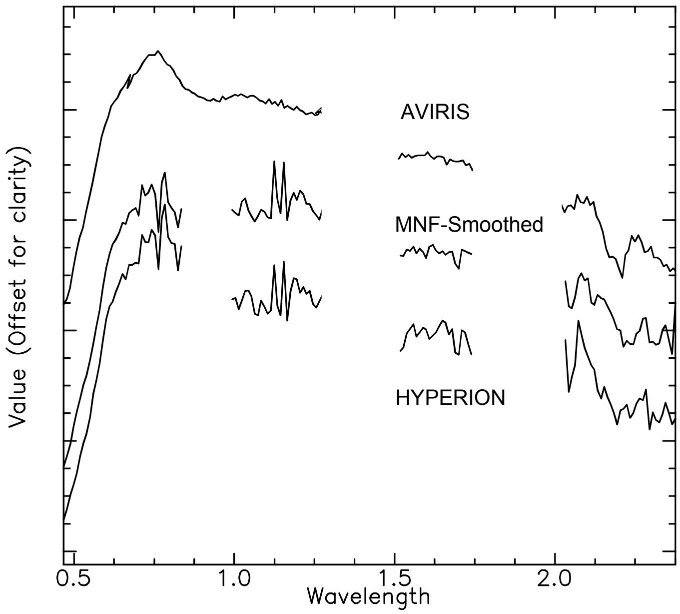

Figure 2. Image spectra from the same ground location.

AVIRIS and Hyperion pixels representing kaolintic and natroalunitic rocks were also used in a slope analysis to identify major areas of altered bedrock for each Mount Shasta watershed (Figure 3). The AVIRIS and Hyperion mineral maps were registered to the USGS 7.5 minute elevation model and to Shuttle Radar Topography Mission (SRTM) digital elevation data, respectively. In all but one area, Hyperion imagery (right) identified greater amounts of bedrock areas. This reflects the larger Hyperion pixel size as well as reduced snow cover at the time of data collection compared to the AVIRIS data set.

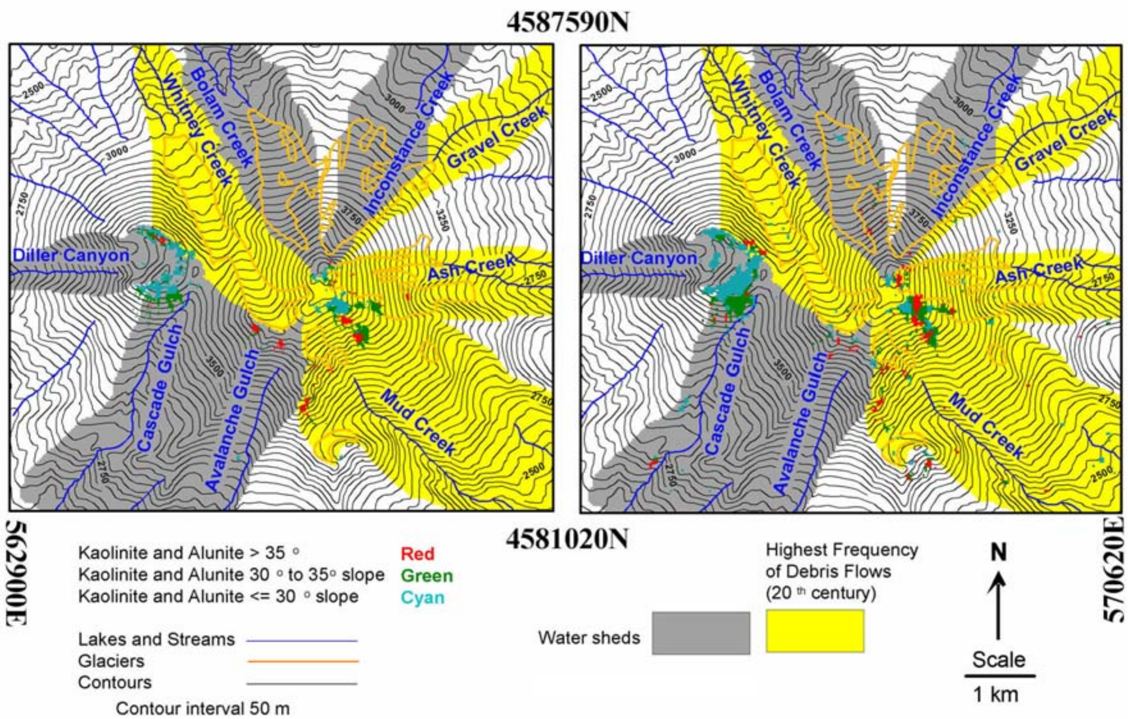

Figure 3. AVIRIS (left) and Hyperion identification of steep altered bedrock areas.

Volume estimates of selected altered rock masses were then made by using GIS (Geographical Information Systems) modeling techniques. To compare altered rock exposures and volumes at Mount Shasta to similar features at Mount Rainier, AVIRIS data of Mount Rainier acquired on July 19, 1994, were processed using the same methods as were used for Mount Shasta. No suitable AVIRIS data were available for Mount Adams. Thus, in order to analyze altered rock volumes at Mount Adams, investigators used reflectance imagery derived from level 1B ASTER data in conjunction with USGS/DEM (Digital Elevation Model) data. For all of the Cascade volcanoes examined to date, estimated altered rock volumes were generally consistent with the size of known Holocene debris flows.

The methods used in this study for mapping altered rocks on stratovolcanoes and associated debris-flow hazards, however, have important limitations. First, although remote sensing enables rapid data collection in areas that are difficult to map by traditional methods, altered rocks that are obscured by unaltered rocks or by snow and ice cover will not be discernable in remotely sensed images. Thus, any analysis of debris-flow hazards based solely on remote sensing of altered rocks may fail to recognize important altered rock masses. On the other hand, field observations in the Cascades and elsewhere suggest that large bodies of pervasively altered rock are extremely susceptible to mass-wasting processes and naturally tend to form steep cliff exposures. In the Cascades, most such exposures are periodically free of snow and ice and can be discerned with remotely sensed imagery.

The potential for catastrophic slope failures in unaltered rock masses is also significant. Recent work at Mount Rainier has shown that some large debris flows involved rocks that were mainly unaltered, particularly including flows triggered by pyroclastic eruptions and glacial melting. The use of remote sensing techniques to help identify unaltered rock masses that may represent debris flow source areas requires further investigation.

Conclusions

The successful use of spaceborne systems for mapping altered volcanic rocks has several implications for volcanic hazards studies. Remote sensing can provide basic information for making preliminary debris flow hazard assessments, including the locations of steep altered and unaltered rocks, estimated rock volumes, and the existence of glaciers or other water sources for debris flow mobilization. This capability will be useful for many areas of the Earth where traditional geologic data are lacking. Spaceborne systems also will facilitate comparative studies of altered volcanic rocks and debris flows in a variety of geologic and climatologic settings. This will help answer questions about the interplay between climate, edifice age and structure, alteration development, and mass wasting processes. Ultimately, remote-sensing observations of volcanoes should lead to a better predictive understanding of edifice failures and their associated hazards.