

THE USE OF AVIRIS IMAGERY TO ASSESS CLAY MINERALOGY AND DEBRIS-FLOW POTENTIAL IN CATARACT CANYON, UTAH: A PRELIMINARY REPORT

Lawrence Rudd¹ and Erzsébet Merényi²

1.0 Introduction

Worldwide debris flows destroy property and take human lives every year (Costa, 1984). As a result of extensive property damage and loss of life there is a pressing need to go beyond just describing the nature and extent of debris flows as they occur. Most of the research into debris-flow initiation has centered on rainfall, slope angle, and existing debris-flow deposits (Costa and Wieczorek, 1987). The factor of source lithology has been recently addressed by studies in the sedimentary terranes of Grand Canyon (Webb et al., 1996; Griffiths et al., 1996) and on the Colorado Plateau as a whole.³ On the Colorado Plateau shales dominated by kaolinite and illite clays are significantly more likely to be recent producers of debris-flows than are shales in which smectite clays dominate.³

Establishing the location of shales and colluvial deposits containing kaolinite and illite clays in sedimentary terranes on the Colorado Plateau is essential to predicting where debris flows are likely to occur. AVIRIS imagery can be used to distinguish between types of clay minerals (Chabrilat et al., 2001), providing the basis for surface-materials maps. The ultimate product of this study will be a model that can be used to estimate the debris-flow hazard in Cataract Canyon, Utah. This model will be based on GIS overlay analysis of debris-flow initiation factor maps, including surface-materials maps derived from AVIRIS data.

2.0 Debris-Flow Initiation

The mobility and transport competence of debris flows depends on a source of fine-grained material, particularly silt and clay, that serves as debris-flow matrix. In Grand Canyon this material is provided by the Hermit Shale, a terrestrial shale containing mostly (95%) illite and kaolinite clays (Griffiths et al., 1996). Kaolinite and illite-rich shales that have been identified as debris-flow source areas on the Colorado Plateau also have relatively high concentrations of exchangeable K^+ and Mg^{++} cations and low amounts (<15%) of Na^+ cations.³ Smectite clays have the capacity to absorb large amounts of water. One possible mechanism by which smectite clays reduce the likelihood of debris-flow activity involves rapid absorption of water during initial wetting. Smectites that have absorbed water will swell and seal off underlying areas, effectively stabilizing colluvial deposits by preventing further water absorption.

When a debris flow occurs, sand and smaller-sized particles occupy interstitial spaces in the debris-flow slurry, increasing the density of the matrix and the buoyant forces that contribute to the suspension of larger particles (Beverage and Culbertson, 1964, Hampton, 1975, Rodine and Johnson, 1976). The clay constituents of Grand Canyon debris flows, which provide 2-5 % of the total particles, are 60-80 % illite and kaolinite by weight, reflecting the source materials of terrestrial shales and colluvial wedges (Griffiths et al., 1996). Debris flows are responsible for creating virtually all of the rapids in Grand Canyon (Webb et al., 1988). Debris flows that travel significant distances in Grand Canyon occur most often when the Hermit Shale, or its associated colluvial wedges, outcrop at a height of 100 m or more above the river (Griffiths et al., 1996). This association between the Hermit Shale and debris flows in Grand Canyon indicates that lithology is an important factor in identifying debris-flow source areas. Other factors identified by Griffiths et al. (1996) include drainage area, channel gradient, and aspect of drainages that produce debris flows.

The relationship between the presence of terrestrial shales and an increased probability of debris-flow occurrence that was established in Grand Canyon has been observed in several other canyons on the Colorado Plateau, notably Cataract Canyon (Fig. 1) and Desolation Canyon in Utah⁴. Conversely tributaries of the San Juan River generally do not produce debris flows because terrestrial shale units have been eroded from the top of the Monument Upwarp (Baars et al., 1991).

¹ Department of Geosciences, University of Arizona (lrudd@geo.arizona.edu)

² Electrical and Computer Engineering Department, Rice University (erzsebet@rice.edu)

³ Rudd et al. (unpublished data) describe debris-flow initiation factors on the Colorado Plateau.

⁴ Webb et al. (unpublished data) have studied debris-flow initiation factors in Colorado Plateau bedrock canyons.

3.0 Site Description

Ending more than two hundred miles north of the start of Grand Canyon, Cataract Canyon's rapids rival those of Grand Canyon in steepness and intensity (Belknap, 1996). Forming the sides of Cataract Canyon are late Paleozoic sedimentary rocks (Fig. 2). The oldest outcrops found in Cataract Canyon are evaporates of the Pennsylvanian Paradox formation. Gypsum outcrops of this formation appear initially at Spanish Bottom and become increasingly more visible along the Colorado River between Cross Canyon and Gypsum Canyon. As much as 400 feet of Paradox Formation gypsum is exposed in Cataract Canyon (Baars, 1987).

Approximately 1000 feet of interbedded limestone, shale, sandstone, and chert of the Honaker Trail Formation overlay the Paradox Formation at the start of Cataract Canyon (Belknap et al., 1996, Baars, 1987). The Pennsylvanian Honaker Trail Formation forms cliffs and steep slopes throughout Cataract Canyon (Fig. 3). These cliffs are often covered with aprons of colluvium, composed of debris from rocks closer to the canyon rim. These colluvial wedges provide source material for the short-runout debris-flows responsible for creating rapids throughout the Cataract Canyon.

The Permian system in Cataract Canyon starts with the complicated, interfingering Elephant Canyon Formation and Hailgaito Shale. These formations unconformably overlay the Honaker Trail Formation in Canyonlands and are composed of near-shore marine limestones, dolomite, shale and sandstone (Baars, 1987). Shales in both formations contain a high percentage of kaolinite and illite clays (Table 1) and are positioned at a sufficient elevation above the Colorado River to give debris-flows originating at this point sufficient gravitational potential energy to deliver large rapid-forming boulders to the river.

Table 1 Semi-quantitative mineralogy by weight percent of clays included in the clay-sized fraction of Cataract Canyon surface materials.

Sample Type	% Illite	% Kaolinite	% Montmorillonite	% Quartz	% Calcite	% Other
Shale - Honaker Trail Formation	14	15	55	2	3	11
Shale - Elephant Canyon Formation	51	10	0	20	12	7
Shale - Hailgaito Shale	35	50	0	7	2	6
Colluvium	24	48	0	6	1	21
Debris-flow matrix	21	30	5	9	16	19

The Cedar Mesa Sandstone of Permian age forms the capstone on the walls of Cataract Canyon. Cedar Mesa Sandstone is a generally light-colored, fine to very-fine grained quartz-rich sandstone generally believed to have been deposited in a near-shore marine environment (Baars, 2000). Outcrops of Cedar Mesa sandstone extend for five or more kilometers northwest and southeast of the Colorado River in the study area, creating an uneven surface of relatively uniform lithology. To the southeast of Cataract Canyon the Cedar Mesa Sandstone is fractured by northeast – southwest trending normal faults, creating the Grabens Fault Zone. The proximity of Cataract Canyon to a zone of fractured and slumping rocks such as the Grabens Fault Zone is believed to be instrumental in providing much of the rapid-forming debris (Baars, 1987) that has been transported to the river by debris flows.

Debris flows in Cataract Canyon reach the river in one of two ways. First is the occurrence of short-runout debris flows that develop in steep chutes cut into the Honaker Trail Formation and overlying Hailgaito Shale and Elephant Canyon Formation. Although these debris-flow chutes are relatively short and generally within the immediate confines of the canyon, they are nonetheless clearly caused by debris-flow activity and are the main source of the debris which is responsible for the formation of rapids in Cataract Canyon (Fig. 3). The role of debris flows in the creation of rapids in Cataract Canyon has been questioned (Baars, 1987). Direct observation of source regions for the material responsible for the creation of rapids in Cataract Canyon reveal that the majority of rapids in Cataract Canyon result from the transportation of debris relatively short distances from canyon walls to the Colorado River. Long runout debris-flows also occur in Cataract Canyon and are responsible for the formation of large debris fans and rapids at the mouths of larger tributaries (Fig 3), such as Range Canyon and Imperial Canyon.

4.0 Spectra of Surface Materials

AVIRIS data of Cataract Canyon was collected on November 9, 2001 (Fig. 1). This data consists of two approximately northeast-southwest trending flight lines composed of nine individual images. Samples of the major

clay-containing surface materials in Cataract Canyon were obtained in late-May of 2001. These samples were analyzed at Brown University's RELAB. Figure 4 shows the lab spectra plotted with spectra of montmorillonite, kaolinite, and illite from the U.S. Geological Survey's Spectral Library. An obvious feature on the spectra of the shale, colluvium and debris-flow matrix materials found in Cataract Canyon is the 1.9 μm water absorption band, which matches well in placement and depth with the water absorption band in the illite USGS Spectral Library sample. The characteristic double-absorption feature at 2.2 μm readily visible on the Spectral Library sample of kaolinite is difficult to see in the RELAB samples (Fig. 4).

The materials sampled in Cataract Canyon were dry and very friable. It was not possible to obtain these samples in one piece in order to maintain a surface that would accurately match the ground surface exposed during the AVIRIS flights. All shale, colluvium and debris-flow matrix samples obtained in Cataract Canyon and sent to RELAB were composed of clay, silt, fine sand, and a wide variety of sizes of clay aggregates. Handling and transporting these samples changed the nature of their surfaces considerably, which may also have had an effect on the usefulness of the lab spectra obtained from the samples.

The clay mineralogy of the surface materials samples taken in Cataract Canyon was determined by semi-quantitative x-ray diffraction at the U.S. Geological Survey in Denver, Colorado. The x-ray diffraction data (Table 1) shows that the samples' clay mineralogy is dominated by kaolinite and illite. Only the Honaker Trail Formation sample contains significant amounts of montmorillonite. Figure 4 shows that the sample spectra have some similarities with the spectra of illite and kaolinite at 1.9 and 2.2 μm . There is also a significant dip in the sample spectra between 2.3 and 2.4 μm , a possible indicator of chlorite. The dip in the 2.3 to 2.4 μm region is also shown in the kaolinite and illite spectra.

5.0 Atmospheric Correction

Atmospheric correction of the AVIRIS images both Cataract Canyon flightlines was performed using both ATREM and FLAASH. The results of the application of both atmospheric correction algorithms are shown for debris flows, colluvium and gypsum in Figure 5. The spectra produced by ATREM show extreme spikes and dips in the curves that make the spectra much more difficult to use and necessitate additional corrections. The FLAASH corrected data is much more readily used without additional manipulation and is easier to compare directly to lab spectra. The differences between the spectra of pixels analyzed using ATREM and those corrected using FLAASH were significant, making the choice of using the FLAASH corrected data obvious.

6.0 Spectral Classification

Classification of the AVIRIS images to map the various clays of interest, is in progress. The class map will be one of the GIS layers that constitute the decision-making model for the assessment of landslide hazard. Training sites were chosen in the second AVIRIS image of the first flight line flown over Cataract Canyon. The average spectra for training sites containing gypsum, debris flows and colluvium (with kaolinite content), [shale of the Honaker Trail Formation (for montmorillonite content), and shale of the Elephant Canyon Formation (for illite representation)] are shown in Figure 6. In this figure the spectra are compared directly to USGS library spectra of similar materials. Gypsum associated with the Paradox Formation in Cataract Canyon compares very favorably to the library spectrum of gypsum. Both spectra show features due to OH stretching modes or H-O-H bending modes near 1.0, 1.2, 1.45, 1.55, 1.9 and 2.2 μm (Hunt et al., 1971) that are characteristic to gypsum. Debris-flow deposits and colluvium in Cataract Canyon display the double-absorption feature characteristic of kaolinite at 2.2 μm in the AVIRIS spectra. This feature is more pronounced in colluvium than in debris-flow matrix, consistent with the measurements shown in Table 1, and with the observation that the total clay content of most debris-flows is smaller, and the particle size distribution of debris-flow deposits is even more heterogeneous than that found in a typical colluvial wedge found in Cataract Canyon. For clay contents, the debris-flow and colluvium spectra are very similar to each other, a fact that supports the cause and effect link between these two types of surface materials. The failure of colluvial wedges in Cataract Canyon provides the raw material, including clay minerals, necessary for debris-flow initiation.

Debris-flow deposits and colluvium in Cataract Canyon tend to display the double-absorption feature characteristic of kaolinite at 2.2 μm and a chlorite signature between 2.3 and 2.4 μm . The fact that the kaolinite absorption feature is pronounced in colluvium is consistent with the mineralogy data in Table 1. This absorption feature is more pronounced in colluvium, perhaps because the total clay content of most debris-flows is small and

the particle size distribution of debris-flow deposits is even more heterogeneous than that found in a typical colluvial wedge found in Cataract Canyon.

7.0 Conclusions

The occurrence of debris-flow activity in Cataract Canyon is believed to have the same cause as debris-flow activity at Grand Canyon and elsewhere on the Colorado Plateau. In this physiographic province an abundance of clays rich in kaolinite and illite and lacking in smectite, high relief between the Colorado River and a shale-containing unit, and a river-corridor aspect that is aligned with the dominant storm track have been shown to increase the likelihood of debris-flow activity (Griffiths, 1996). The purpose of this study is the application of hyperspectral remote sensing technology to the assessment of surface material clay content in Cataract Canyon. To this end AVIRIS imagery of Cataract Canyon has been obtained, atmospherically corrected and preliminarily analyzed for patterns in the clay content of the surface materials.

At this stage the results of the study are promising. The spectra of training sites chosen for the image classification procedure have been found to compare favorably to library spectra of the minerals in the training sites. A goal of this study is the production of a map showing the composition of surface materials in Cataract Canyon based on the classification of both AVIRIS flight lines of this area. Areas containing kaolinite and illite clays will be considered to be at increased risk for debris-flow activity. The combination of a surface materials map and maps showing the relief and tributary-stream aspect of Cataract Canyon will provide the basis for a model of the debris-flow potential in this area.

8.0 Acknowledgements

Collection and analysis of data used in this study has been supported by the United States Geological Survey (Robert Webb, Project Director), the University of Arizona, and the NASA-funded project "Remote sensing for debris flooding hazard assessment in arid regions" (Vic Baker, Principal Investigator), grant number NAG-9293.

9.0 References Cited

- Baars, D.L., 2000, The Colorado Plateau: A geologic history: Albuquerque, University of New Mexico Press, 254 p.
- Baars, D.L., Stevenson, G., and Chesser, W.L., 1991, San Juan canyons: A river runner's guide and natural history of San Juan River canyons: Lawrence, Kansas, Canon Publishers, Ltd. 64 p.
- Baars, D.L., 1987, Paleozoic rocks of Canyonlands country, *in* Campbell, J.A., ed., Geology of Cataract Canyon and Vicinity, A Field Symposium-Guidebook of the Four Corners Geological Society, Tenth Field Conference-May 14-17, 199 p.
- Belknap, B., Belknap, B. and Evans, L.B., 1996, Canyonlands river guide: Denver, Eastwood Printing, 79 p.
- Beverage, J.P., and Culbertson, J.K., 1964, Hyperconcentrations of suspended sediment: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 90, p. 117-126.
- Chabrilat, S., Goetz, A.F., Olsen, H.W. and Krosley, L., 2001, Field and imaging spectrometry for identification and mapping of expansive soils, *in* Van der Meer, F.D. and DeJong, S.M., eds., Imaging spectrometry: Basic principles and prospective applications: Dordrecht, Kluwer Academic Publishers, 403 p.
- Costa, J.E., 1984, Physical geomorphology of debris flows, *in* Costa, J.E. and Fleisher, P.J., eds., Developments and applications of geomorphology: Berlin, Springer-Verlag Publishing, p. 268-317.
- Costa, J.E., and Weiczorek, G.F., 1987, Debris flows/avalanches: Process, recognition and mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, 239 p.
- Griffiths, P.G., Webb, R.H., and Melis, T.S., 1996, Initiation and frequency of debris flows in Grand Canyon, Arizona: U.S. Geological Survey Open-File report 96-491.
- Hampton, M.A., 1975, Competence of fine-grained debris flows: Journal of Sedimentary Petrology, v. 45, no. 4, p. 834-844.
- Hintze, L.F., 1988, Geologic History of Utah: Provo, Brigham Young University, 202 p.
- Hunt, G.R., Salisbury, J.W., and Lenhoff, C.J., 1971, Visible and near-infrared spectra of minerals and rocks: IV, sulphides and sulphates, Modern geology, v. 3, p. 1-14.
- Rodine, J.D., and Johnson, A.M., 1976, The ability of debris, heavily freighted with coarse clastic materials, to flow on gentle slopes: Sedimentology, v. 23, p. 213-234.
- Webb, R.H., Pringle, P.T., Reneau, S.L., and Rink, G.R., 1988, Monument Creek debris flow, 1984 - Implications for formation of rapids on the Colorado River in Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p.

Webb, R.H., Melis, T.S., Wise, T.W., and Elliott, J.G., 1996, "The Great Cataract," The effects of late Holocene debris flows on Lava Falls Rapid, Grand Canyon National Park, Arizona: U.S. Geological Survey Open-file Report 96-4.

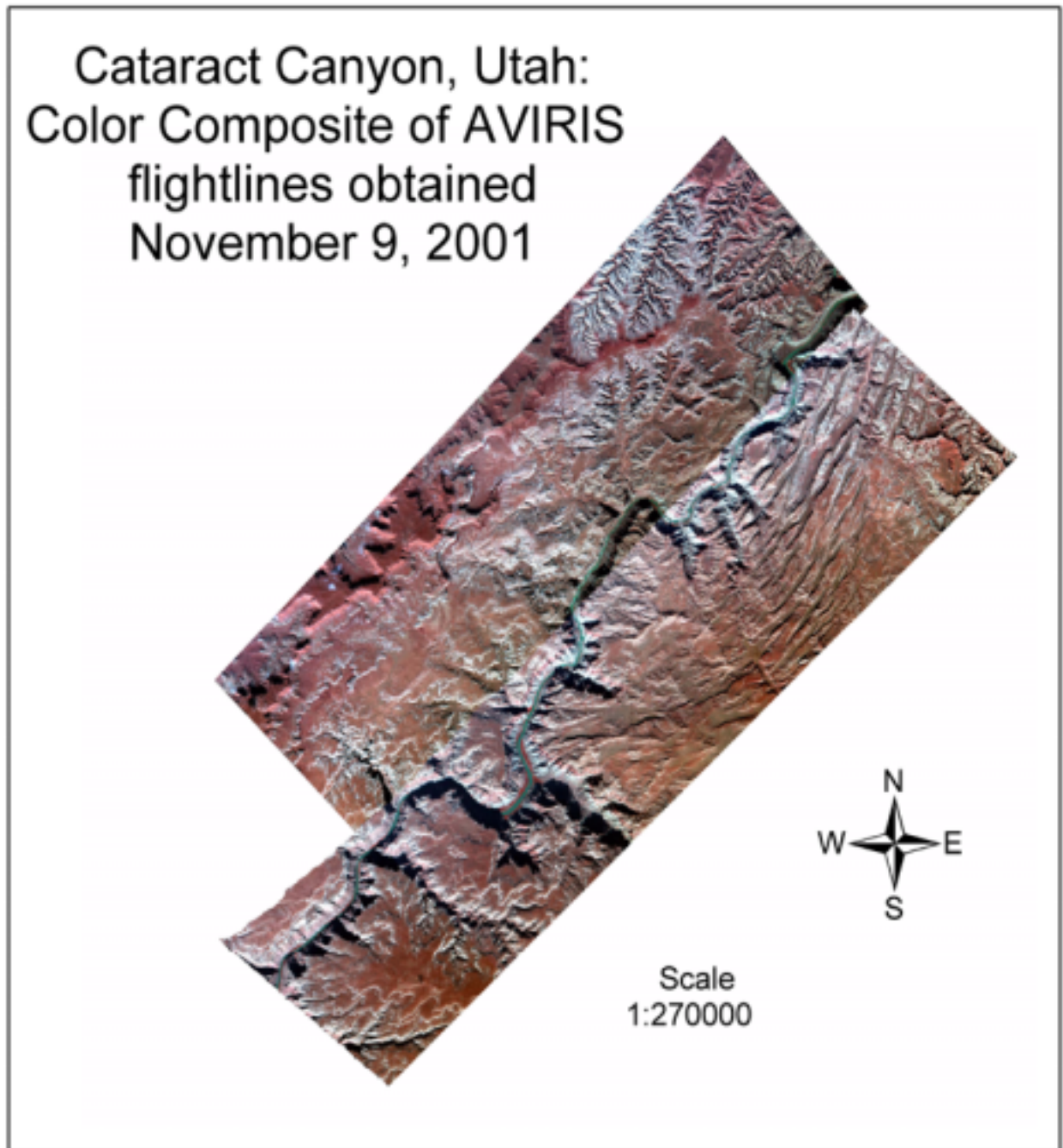


Figure 1 Color composite of the study area flight lines

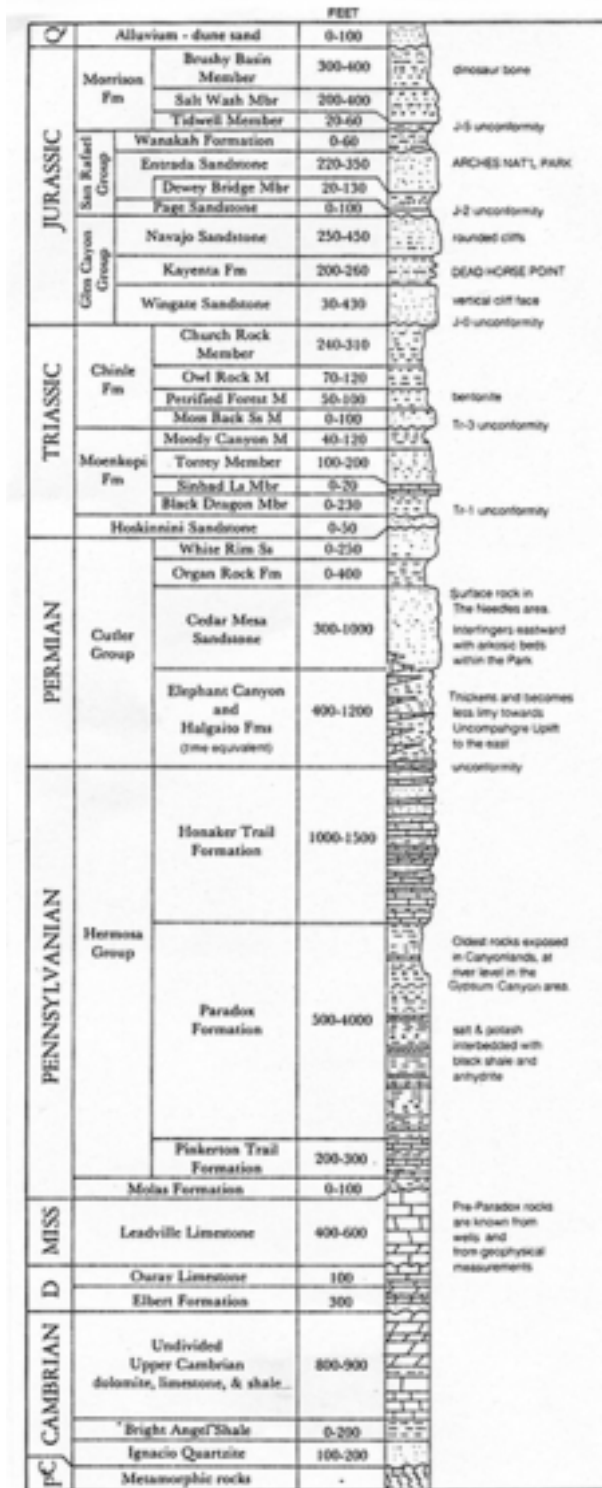


Figure 2 Stratigraphic section of the Canyonlands National Park area. Formations in Cataract Canyon extend from the Paradox Formation at river level to the Cedar Mesa Sandstone at the canyon rim (from Hintze, 1988).



Figure 3 View from the east across the Colorado River toward the mouth of Teapot (Calf) Canyon with Rapid 22 (Upper Big Drop) in the foreground. The Honaker Trail Formation is exposed at river level while the top one-third of the inner canyon consists of intertonguing Hailgaito Shale and Elephant Canyon Formation. Caprock is Cedar Mesa Sandstone. Note debris fan in Teapot Canyon and colluvial wedges at base of cliff downstream from rapid. (Photo Courtesy of Robert Webb)

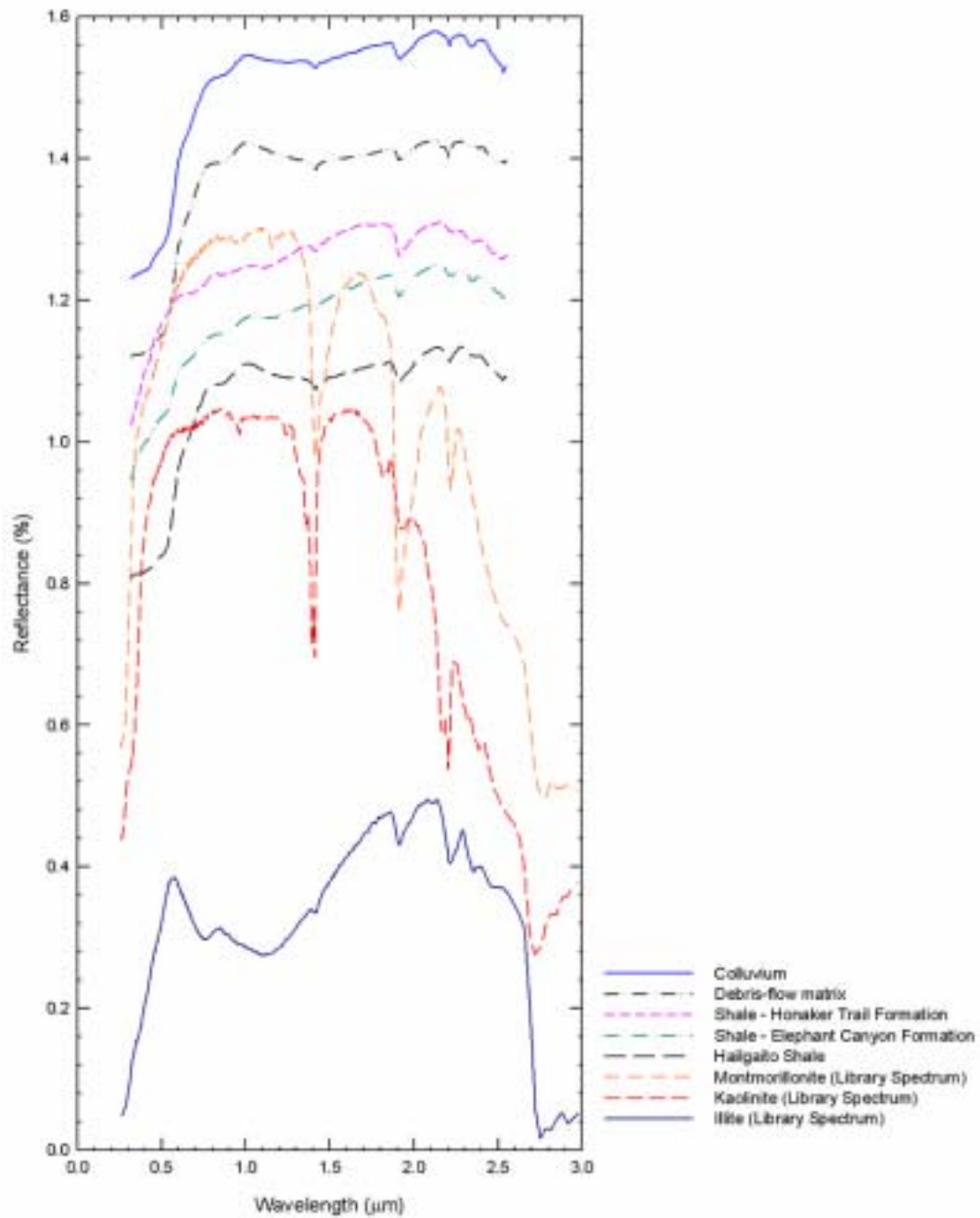


Figure 4 Comparison of Cataract Canyon surface material sample spectra as measured by RELAB and clay mineral spectra from the USGS spectral library. Spectra offset for clarity.

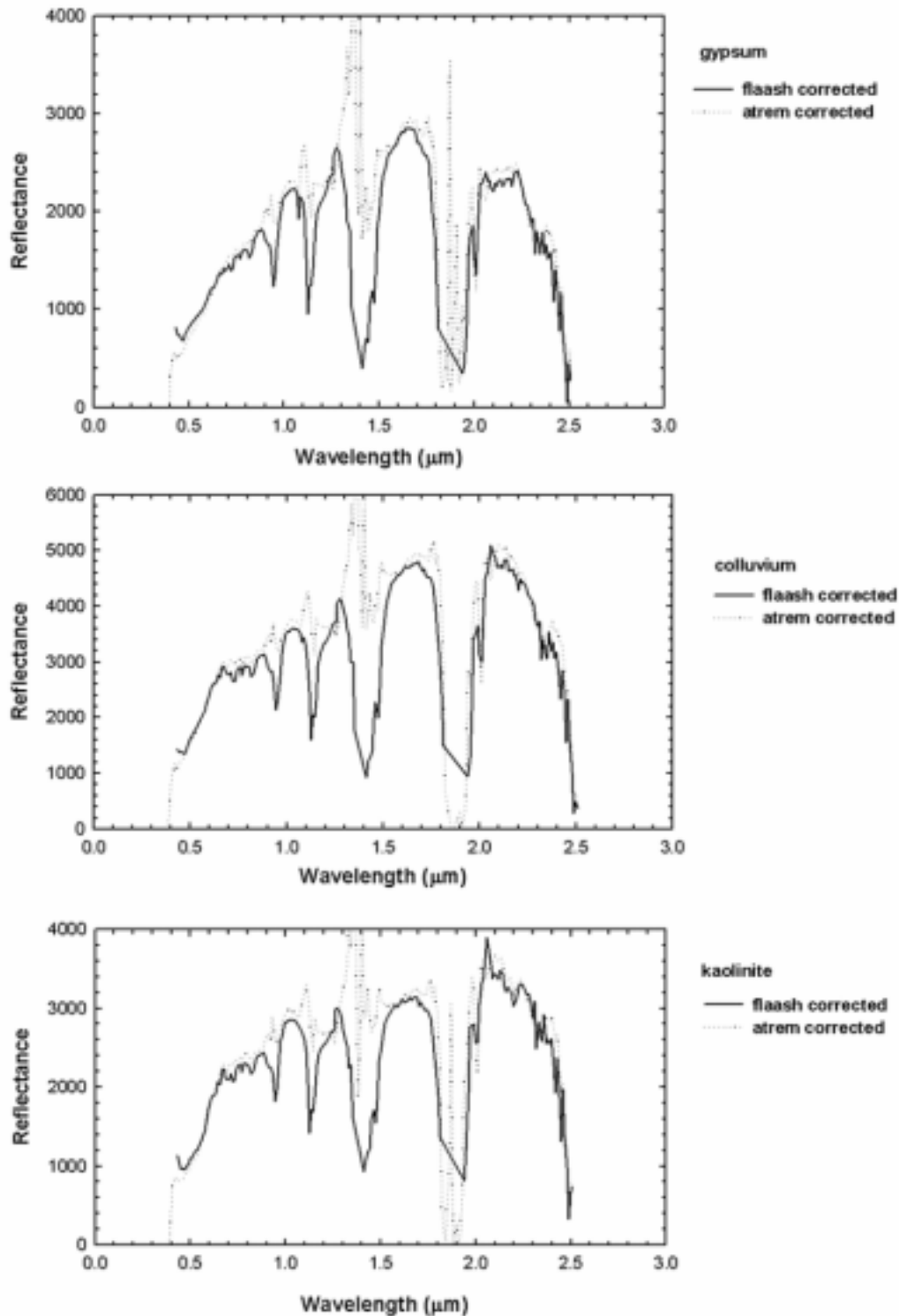


Figure 5 Representative AVIRIS spectra of classification training sites. Plots compare the results of FLAASH and ATREM atmospheric correction. The FLAASH correction is noticeably better.

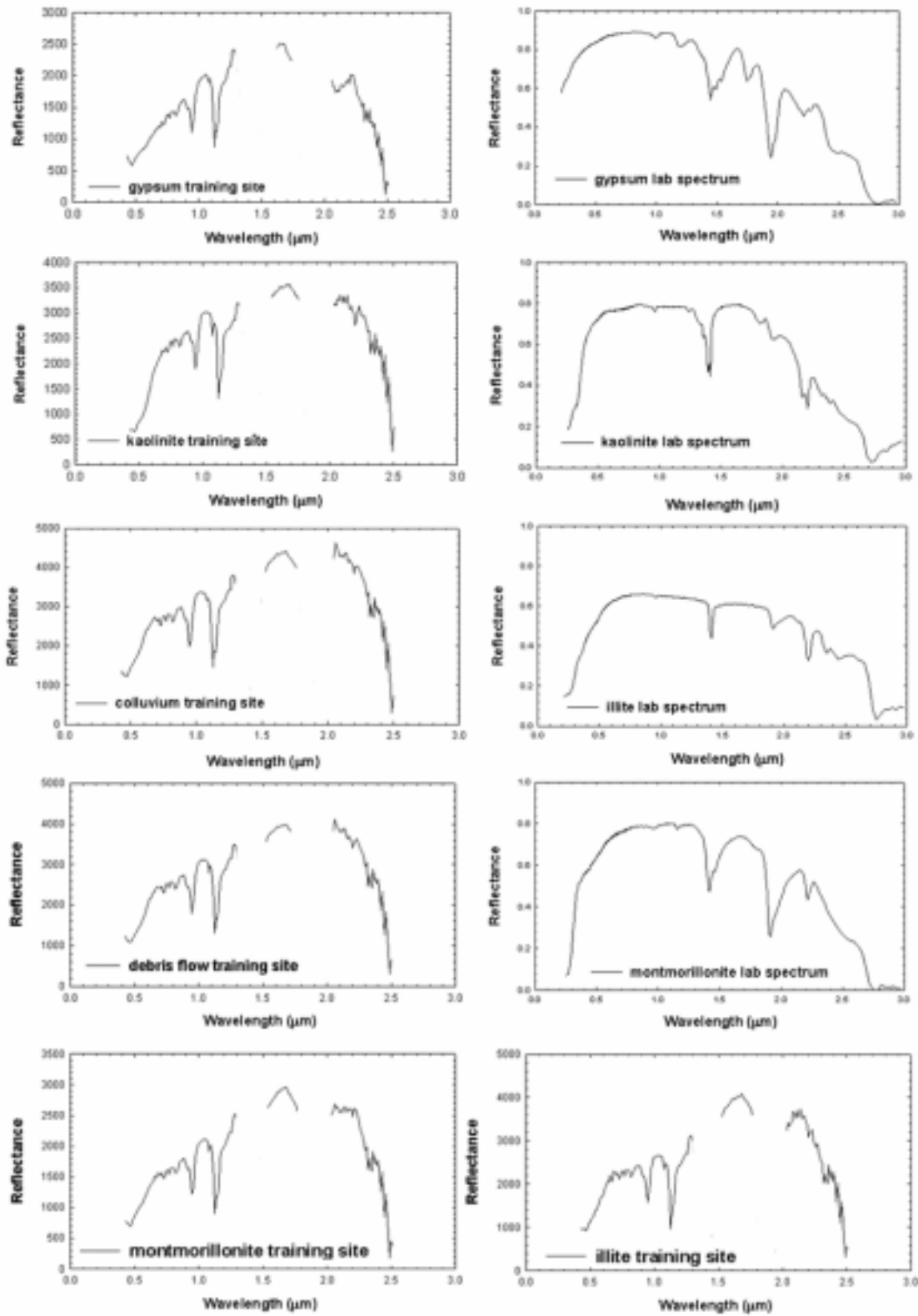


Figure 6 Spectra from preliminary classification training sites (AVIRIS data, shown in the first column and on the bottom of the second column) compared to USGS Spectral Library spectra (second column) for samples of gypsum, kaolinite, montmorillonite, illite, colluvium and debris-flow matrix.