Final Technical Report

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Department of Earth and Planetary Sciences
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Title: Investigation into the Relationship between Heterogeneity and Heavy-Tailed Solute Transport

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Objective: The objective of this project was to characterize the influence that naturally complex geologic media has on anomalous dispersion and to determine if the nature of dispersion can be estimated from the underlying heterogeneous media. *The UNM portion of this project was to provide detailed representations of aquifer heterogeneity through producing highly-resolved models of outcrop analogs to aquifer materials.*

Project Description: This project combined outcrop-scale heterogeneity characterization (conducted at the University of New Mexico), laboratory experiments (conducted at Sandia National Laboratory), and numerical simulations (conducted at Sandia National Laboratory and Colorado School of Mines). The study was designed to test whether established dispersion theory accurately predicts the behavior of solute transport through heterogeneous media and to investigate the relationship between heterogeneity and the parameters that populate these models. The dispersion theory tested by this work was based upon the fractional advection-dispersion equation (fADE) model. Unlike most dispersion studies that develop a solute transport model by fitting the solute transport breakthrough curve, this project explored the nature of the heterogeneous media to better understand the connection between the model parameters and the aquifer heterogeneity. We also evaluated methods for simulating the heterogeneity to see whether these approaches (e.g., geostatistical) could reasonably replicate realistic heterogeneity. The UNM portion of this study focused on capturing realistic geologic heterogeneity of aquifer analogs using advanced outcrop mapping methods.

Results: During the course of this project, we used terrestrial lidar (LIght Detection and Ranging) to map and model the distribution of hydrofacies on several outcrop exposures. The results from this work were used to investigate the root causes of non-Fickian dispersion in natural groundwater systems. The UNM contribution to this study focused on providing realistic images of aquifer heterogeneity through application of interpreted lidar scans and digital photography of outcrop analogs for aquifers.

In total, we mapped facies on four outcrop study sites for this project in order to test our approach for delineating realistic heterogeneity – (1) an outcrop of braided river deposits located west of Albuquerque, New Mexico, (2) Ringold Formation exposures near Hanford, Washington, (3) alluvial fan deposits located north of Albuquerque, New Mexico, and (4) braided river deposits in an arroyo located west of Albuquerque.

Figure 1 shows the interpreted results from our first outcrop study area. This work focused on an approximately 3m x 1.5m outcrop exposure of braided river deposits near Albuquerque, New Mexico. This outcrop provides an analog for aquifer material in the Middle Rio Grande Basin, and was used for analysis of non-Fickian transport that was published in Klise et al. (2009). At this site, we were able to segment the lidar results to distinguish sand-dominated from gravel-dominated lithofacies, and assigned hydraulic conductivity (K) values to the different lithologic types for application in groundwater models. The segmentation was based on our observation that each of the different lithofacies (and thus hydrofacies) displayed the variable character of the laser return signal from 7 replicate scans of the outcrop. This approach is described in detail in Nichols et al. (2011), and the hydrofacies map developed from this project site was used for modeling comparisons reported in Klise et al. (2009), where strongly non-Fickian character was observed in our simulations through these deposits.

Figure 2 shows similar interpreted results from our second detailed study area, an outcrop of the Ringold Formation near Hanford, Washington. This outcrop is composed of mixed gravel-dominated beds and sand-dominated beds. We were able to successfully segment lithofacies from the lidar scans and run groundwater models through the interpreted segmented lidar map. By releasing particles at one end of the simulation and recording travel times to the other end of the simulation, we can see that this heterogeneity results in non-Fickian transport character (e.g., heavy-tailed breakthrough solution). The details of methods used to scan and map hydrofacies from this outcrop analog was also reported in Nichols et al. (2011).

The third outcrop area, a succession of alluvial fan deposits located north of Albuquerque, did not display sufficient contrasting character for facies segmentation from lidar scan results alone. When scanned, the gravelly deposits did not contrast with the sandy deposits in a manner similar to that seen at our first two study sites. This indicated that our approach was most-likely outcrop specific and that outcrop areas had to be selected carefully in order to successfully segment facies using just the lidar scan results. We have since implemented an approach that combines the lidar scans with high-resolution digital imagery.

At our fourth outcrop area, we attempted to produce a 3D map of heterogeneity in braided river deposits at the scale of an approximately 3m x 1m x 1.5m block using the terrestrial lidar approach. Because 2D representations of aquifer heterogeneity may result in unrealistic artifacts that could affect overall interpretation of transport results (e.g., effects of dead-end strata that probably extend laterally in the third dimension), we evaluated means to collect 3D analog data by scraping an outcrop at approximately 2cm intervals and collecting multiple scans of each exposed face. Because output from lidar produces a 3D point cloud, this sliced-outcrop approach utilized the full 3D capabilities of the terrestrial lidar equipment. Placement of known survey markers at scan corners allowed for compilation of the data into a 3D volume and we had hoped it would allow us to produce highly-resolved 3D models of heterogeneity.

Ultimately, we could not complete the 3D facies block during the course of this project. We are still working on this data set and still hope to be able to produce reliable results from this work. However, we face several challenges with this new 3D data set. First, we are creating a point cloud with over 100 million points. Ultimately, the 3D grid at a 2mm x 2mm x 2cm spacing has over 25 million nodes. This size is difficult to process with our current computer configuration. Second, we need to develop a 3D segmentation technique to delineate and identify the lithofacies from these maps. Third, the 25 million node grid is much too large for running standard groundwater models, however we recently have been collaborating with colleagues who are able to simulate groundwater at this and much higher resolutions. Therefore, if we are able to produce a 3D facies map from these data, we believe we will be able to simulate the dispersion character of these facies in 3D.

Overall results from the UNM portion of this project show that (1) terrestrial lidar can be used to produce detailed and quantified lithofacies and hydrofacies maps of aquifer sedimentary material; (2) not all outcrop exposures are suitable for lidar interpretation due to limited laser reflection intensity contrast; (3) multiple lidar scans of the same image area must be acquired in order to reasonably identify lithofacies type from reflection intensity mean and variance (the multiple scans generate a more accurate image by allowing us to average out random noise); and (4) non-Fickian dispersion character can be replicated at several outcrop analog study sites, where groundwater focusing occurs along coarser-grained laminae.

Resulting products from this research project:

Two publications were derived from this work:

Klise, K.A., Weissmann, G.S., McKenna, S.A., Nichols, E.M., Frechette, J.D., Wawrzyniec, T.F., and Tidwell, V.C., Exploring solute transport and streamline connectivity using lidar-based outcrop images and geostatistical representations of heterogeneity, Water Resources Research, v. 45, W05413, doi: 10.1029/2008WR007500, 2009

Nichols, E.M., Weissmann, G.S., Wawrzyniec, T.F., Frechette, J.D., and Klise, K.A., Processing of outcrop-based lidar imagery to characterize heterogeneity for groundwater models, *in* Outcrops Revitalized: Tools, Techniques and Applications: SEPM concepts in Sedimentology and Paleontology No. 10, p. 239-247, 2011.

Additionally, results of this work led to additional funding through the SERDP (DOD, DOE, and EPA joint program), where we mapped heterogeneity at the classic Borden Air Force Base site and other outcrops in New Mexico.

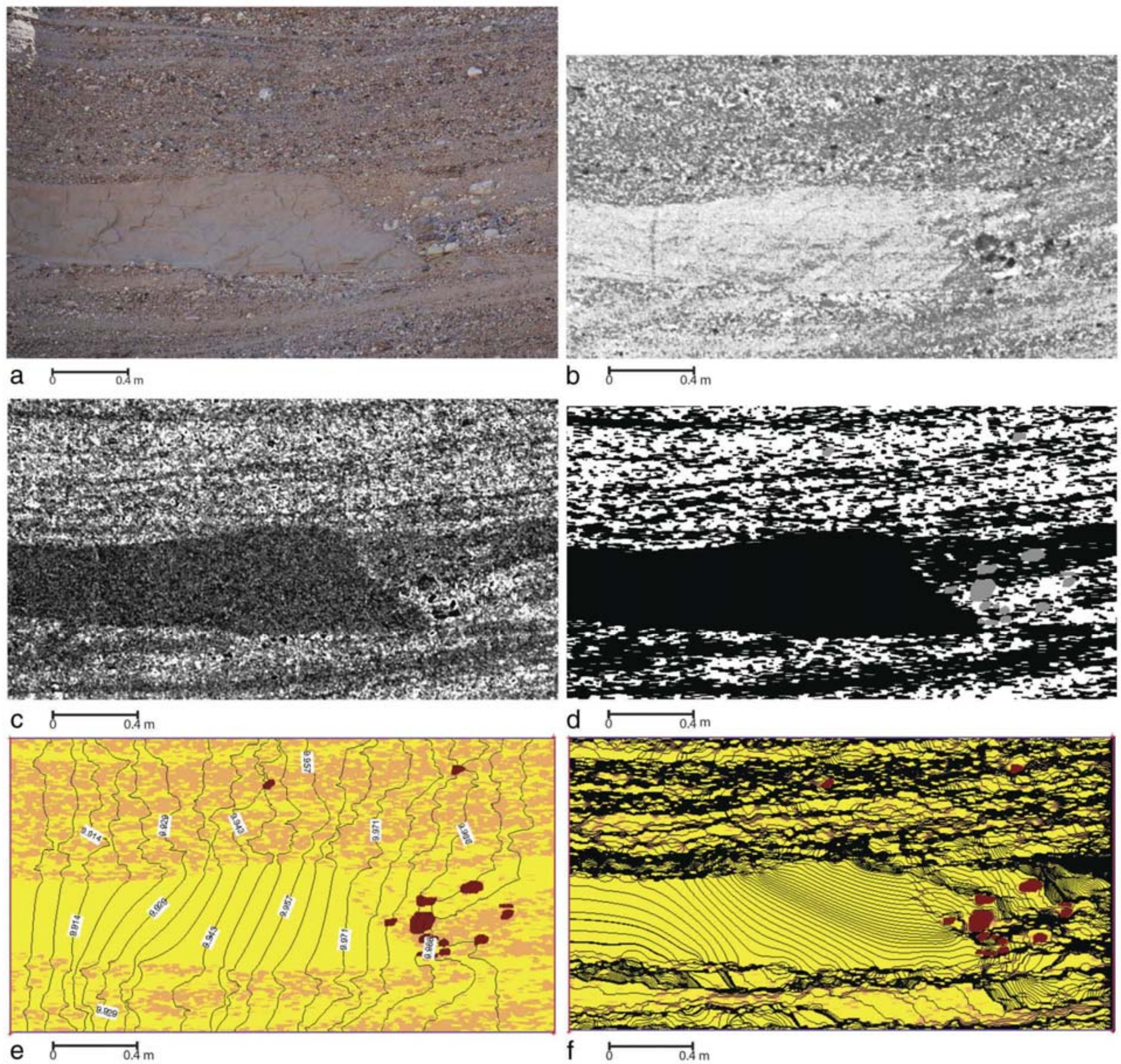

Figure 1: Images and interpreted lithofacies of the Ceja Formation, New Mexico. a) Photograph of the outcrop facies. b) 2D mean reflection intensity map. c) Standard deviation of reflection map. d) Segmented lithofacies map. e) Resulting groudwater model with contours of potentiometric head. f) Resulting groundwater model with MODPATH particle tracks. Notice extreme focusing of particles in the coarse-grained laminae. From Nichols et al., 2011.

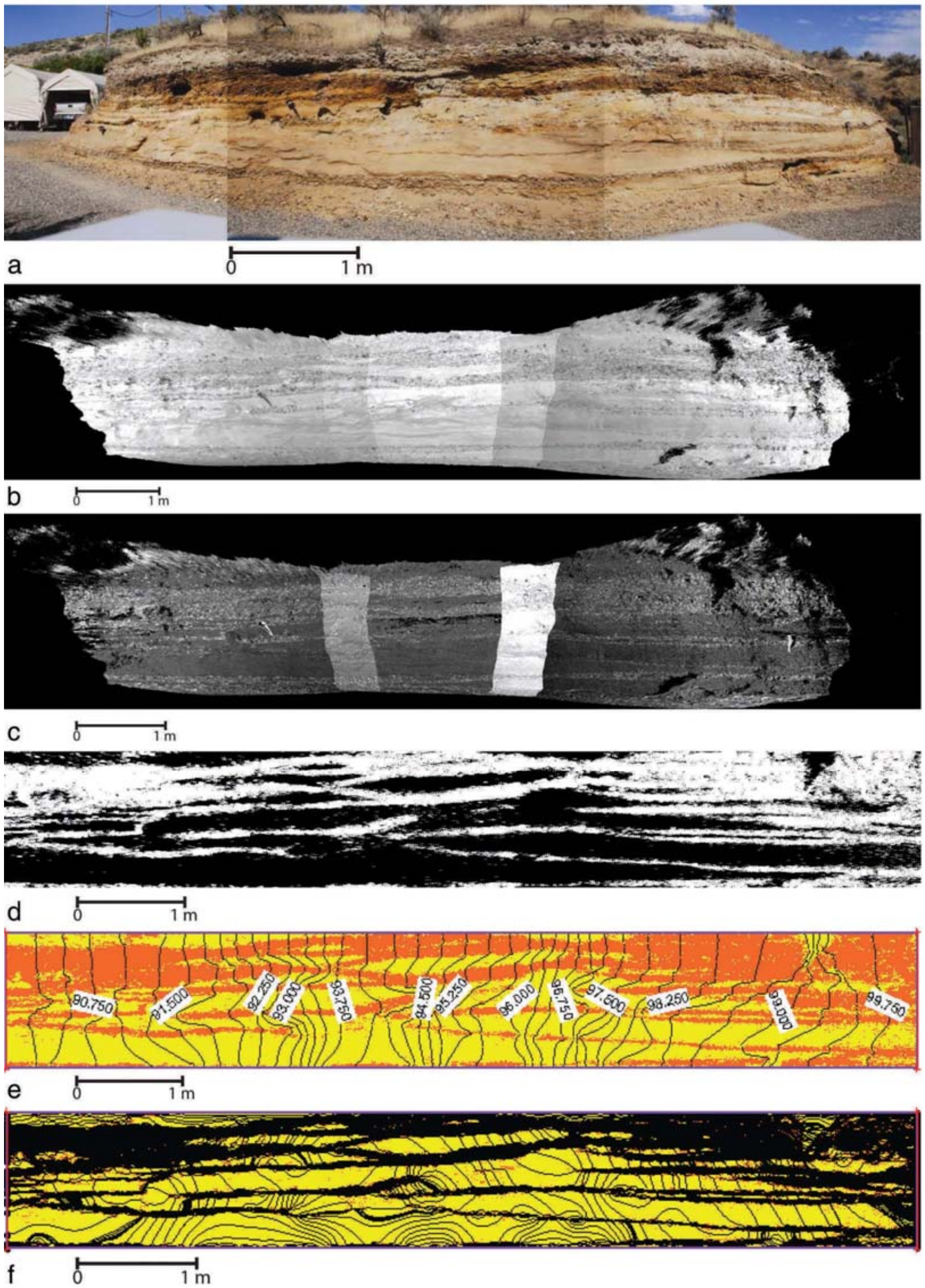

Figure 2: Images and interpreted lithofacies of the Upper Ringold Formation, Hanford, Washington. a) Photograph of the outcrop facies. b) 2D mean reflection intensity map. c) Standard deviation of reflection map. d) Segmented lithofacies map. e) Resulting groudwater model with contours of potentiometric head. f) Resulting groundwater model with MODPATH particle tracks. Notice extreme focusing of particles in the coarse-grained laminae. From Nichols et al., 2011.