U.S. Geological Survey Research in Handcart Gulch, Colorado: An Alpine Watershed with Natural Acid-Rock Drainage

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Abstract

Handcart Gulch is an alpine watershed along the Continental Divide in the Colorado Rocky Mountain Front Range. It contains an unmined mineral deposit typical of many hydrothermal mineral deposits in the intermountain west, composed primarily of pyrite with trace metals including copper and molybdenum. Springs and the trunk stream have a natural pH value of 3 to 4. The U.S. Geological Survey began integrated research activities at the site in 2003 with the objective of better understanding geologic, geochemical, and hydrologic controls on naturally occurring acid-rock drainage in alpine watersheds. Characterizing the role of groundwater was of particular interest because mountain watersheds containing metallic mineral deposits are often underlain by complexly deformed crystalline rocks in which groundwater flow is poorly understood. Site infrastructure currently includes 4 deep monitoring wells high in the watershed (300–1,200 ft deep), 4 bedrock (100–170 ft deep) and 5 shallow (10–30 ft deep) monitoring wells along the trunk stream, a stream gage, and a meteorological station. Work to date at the site includes: geologic mapping and structural analysis; surface sample and drill core mineralogic characterization; geophysical borehole logging; aquifer testing; monitoring of groundwater hydraulic heads and streamflows; a stream tracer dilution study; repeated sampling of surface and groundwater for geochemical analyses, including major and trace elements, several isotopes, and groundwater age dating; and construction of groundwater flow models. The unique dataset collected at Handcart Gulch has yielded several important findings about bedrock groundwater flow at the site. Most importantly, we find that bedrock bulk permeability is nontrivial and that bedrock groundwater apparently constitutes a substantial fraction of the hydrologic budget. This means that bedrock groundwater commonly may be an underappreciated component of the hydrologic system in studies of alpine watersheds. Additionally, despite the complexity of the fracture controlled aquifer system, it appears that it can be represented with a relatively simple conceptual model and can be treated as an equivalent porous medium at the watershed scale. Interpretation of existing data, collection of new monitoring data, and efforts to link geochemical and hydrologic processes through modeling are ongoing at the site.

Keywords: hydrologic observatory, watershed, alpine, mountain, groundwater, acid-rock drainage

Introduction

The Handcart Gulch research site was developed by the U.S. Geological Survey (USGS) in 2003 with the objective of better understanding geologic, geochemical, and hydrologic controls on naturally occurring acid-rock drainage in alpine watersheds. Characterizing the groundwater system was of particular interest because groundwater's role in the generation and transport of acid-rock drainage in mineralized mountain watersheds is poorly understood due to a lack of wells in these settings.

The 1.5-mi^2 site includes the upper portion of an alpine watershed in the Colorado Rocky Mountain Front Range and is at an elevation of 10,700–12,800 ft (Figure 1). The watershed is underlain by complexly folded and fractured Precambrian metamorphic rocks.

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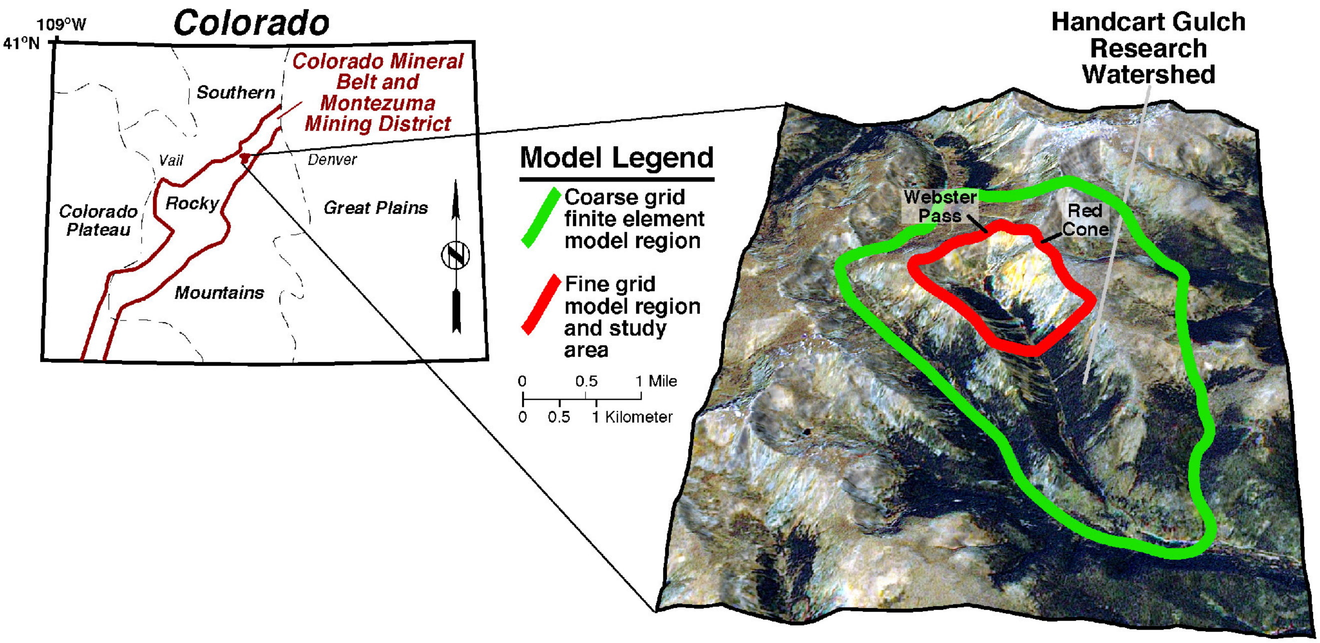

Figure 1. Location of Handcart Gulch in the Colorado Mineral Belt. The study area boundary (red) and numerical groundwater flow model domains (red and green) are also shown on a visible satellite image draped on a tilted digital elevation model.

It is located in the Montezuma Mining District, which lies within the Colorado Mineral Belt. The small perennial stream (flows of 0.1–4.5 ft^3/S) draining the site has a natural pH of 3 to 4, a result of the presence of an unmined mineral deposit composed primarily of pyrite with trace metals including copper and molybdenum.

The site's most unique feature is that it includes 13 groundwater monitoring wells ranging in depth from 10 to 1,200 ft. Mountain hydrologic research to date has focused on the surface water system, and monitoring wells extending to depths greater than a few feet are rare in alpine environments worldwide. Handcart Gulch thus provides the opportunity to address fundamental questions regarding mountain groundwater flow, such as: Is the bulk permeability of fractured crystalline bedrock sufficiently low (as is commonly assumed) to ignore bedrock-hosted groundwater in watershed hydrologic models? If not, what are typical bedrock groundwater flow rates and dissolved mass fluxes? What are typical water table elevations? To what degree do discrete geologic features, such as fracture networks and fault zones, localize groundwater flow paths, and at what scale might the bulk permeability structure be treated as a continuum? What geologic factors control the concentrations and fluxes of acid, metals, and other dissolved constituents in mountain groundwater flow systems? A better understanding of the role of groundwater in mountain watershed hydrology will allow us to better predict how changes in land use and climate will affect water quality and quantity in mountain watersheds.

This paper provides an overview of USGS research in Handcart Gulch and a brief synopsis of preliminary results from the site. More detailed information can be found in the following publications: Caine et al. (2006), Manning and Caine (2007), Kahn et al. (2007), Verplanck, Manning, et al. (2007), and Verplanck, Nordstrom, et al. (in press).

Site Instrumentation and Data

In the summers of 2001 and 2002 a private mineral exploration company (Mineral Systems, Inc.) drilled and cored four deep mineral exploration boreholes in Handcart Gulch (WP1–WP4; Figure 2). The wells are located in the upper part of the watershed, the highest one being on the Continental Divide at an altitude of 12,100 ft (WP1; Figure 2). Borehole depths range from 1,200 to 3,500 feet. Mineral Systems, Inc. donated the boreholes and drill core to the USGS, who reconditioned the boreholes for use as monitoring wells. The deep monitoring wells are screened continually or are open within the bedrock and have depths of 300 to 1,200 ft (borehole collapses prevented completing the wells to greater depths). The deep wells were supplemented with four new wells screened in the bedrock (100–170 ft deep) and five new wells screened in the overlying surficial material (10–30 ft deep). These nine new wells are located in five well nests adjacent to the trunk stream (HCBW1–HCBW4 and HCFW5; Figure 2). In addition to the wells, the site includes a stream gage and a meteorological station.

From 2003 to 2005, a variety of data were collected from the watershed: (1) basic geologic, fracture network, and fault data as well as alteration mineralogy and elemental geochemistry from both outcrop and drill-core rock samples; (2) geophysical borehole-logging data (Figure 3); (3) water level and single-well aquifer test data; (4) stream metal loading data from a tracer-dilution study in the trunk stream; (5) streamflow data from the trunk stream; and (6) a host of geochemical data from surface water and groundwater samples, including concentrations of major and trace elements, multiple stable isotopes (of strontium, sulfur, oxygen, and hydrogen), dissolved noble gases (including ^{3}He), and residence time indicators (tritium, chlorofluorocarbons, and carbon isotopes).

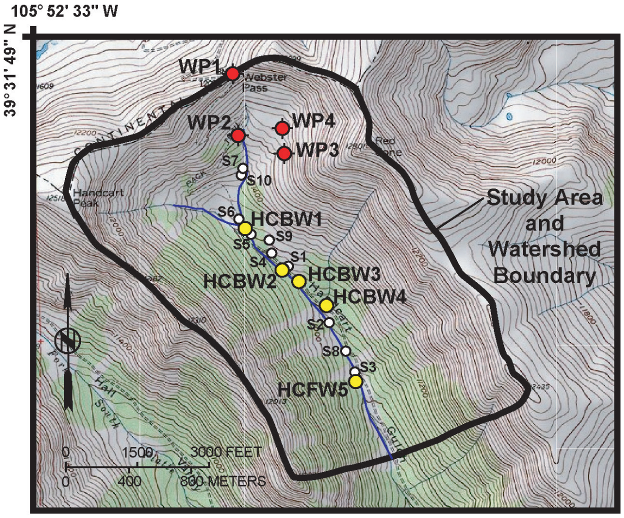

Figure 2. Topographic map of Handcart Gulch study area showing well locations. Deep wells (WP1–WP4) shown in red, shallow well clusters near trunk stream (HCBW1–HCBW4 and HCFW5) shown in yellow. Springs (S1–S10) are also shown in white. Base map from U.S. Geological Survey Montezuma Quadrangle, 1:24,000 (1958).

Monitoring activities at the site are ongoing. Water table elevations and ground temperatures are continuously monitored using dedicated pressure transducers and thermistors. Stream discharge and meteorological data will be continuously monitored starting in summer 2008. Stream and groundwater samples are collected annually for geochemical analyses. An important objective of these long-term monitoring activities is to identify and better understand watershed hydrologic and geochemical responses to climate change.

Preliminary Results

Outcrop and well-log data indicate that the bedrock is complexly deformed and primarily consists of tightly folded felsic and mafic Precambrian metamorphic rocks. Several types of geologic structures are present, but only the open-joint networks appear to be important in conducting groundwater flow. Down-hole televiewer data indicate pervasive, high-intensity open-joint networks at all depths logged. Flow metering performed in concert with the televiewer logging revealed few discrete inflows or outflows associated with individual structural features (Figure 3). The dominant hydrothermal alteration assemblage is quartz-sericite-pyrite (QSP), commonly found in felsic lithologies with an average concentration of about 8 weight-percent fine-grained, disseminated pyrite and quartz-pyrite veinlets. These are the primary source rocks for natural acid-rock drainage at the site. The intensity of hydrothermal alteration decreases away from Webster Pass and Red Cone and transitions outward from QSP to propylitic alteration to relatively unaltered rocks (Figure 1). The pervasive hydrothermal QSP alteration extends to as much as 3,000 ft below the ground surface.

Seasonal water-table fluctuations observed in wells in the upper part of the watershed are very large (up to about 150 ft). Dissolved gas data indicate unusually high excess air concentrations in bedrock groundwater along the stream, suggesting that the large water table fluctuations are ubiquitous throughout upper portions of the watershed (Manning and Caine 2007). Seasonal cycles of saturation and oxygenation in the thick unsaturated zone may be an important mechanism controlling pyrite oxidation and the liberation of acid and metals to ground and surface waters.

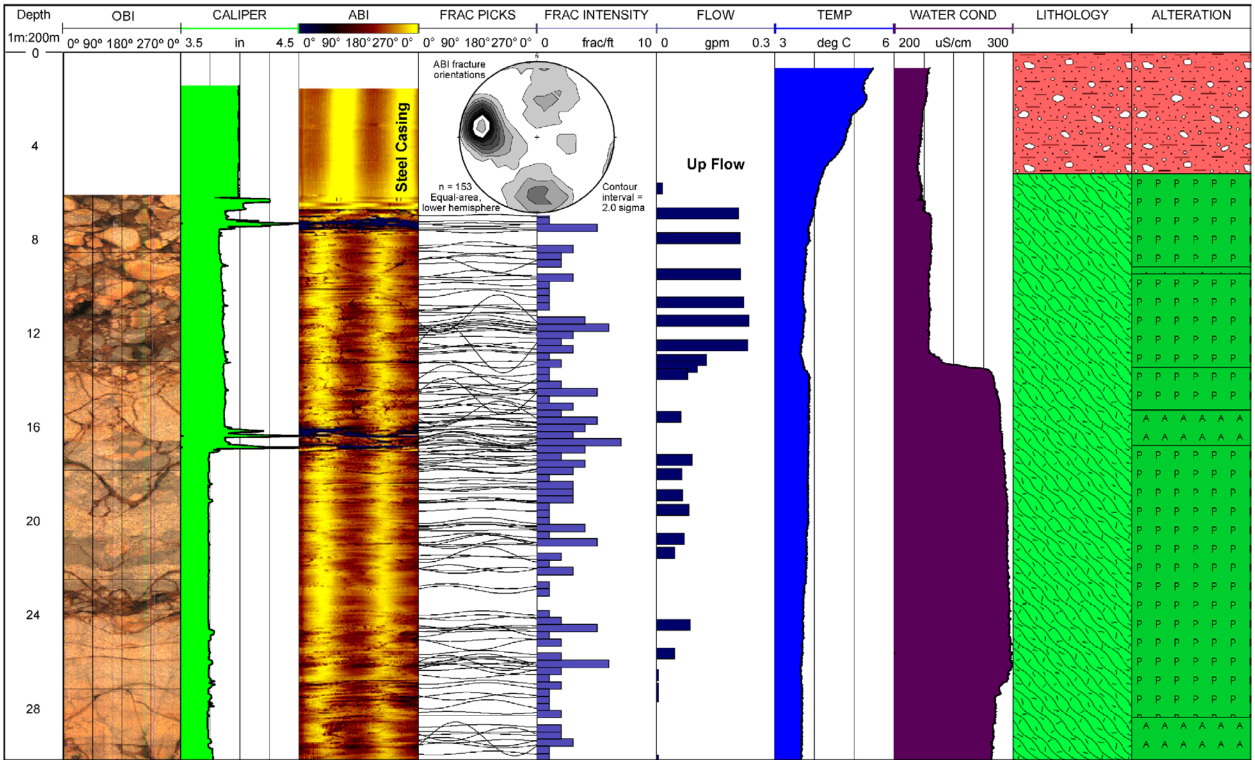

Figure 3. An example of composite geophysical and lithological logs from Handcart Gulch wells. Optical televiewer image (OBI) shows top of bedrock and sinusoidal traces of open fractures in WP4 (all other logs are from shallow well HCBW1 next to the trunk stream). Fracture orientations derived from the acoustic televiewer image (ABI) plotted on an equal area projection are consistent with outcrop and regional fracture orientations. Heat-pulse flow meter data (FLOW) indicates flow direction and magnitude in the well.

Artesian conditions exist in the bedrock near the trunk stream. Static water levels of up to 10 ft above ground surface and sustained or seasonal artesian flows of up to 20 gallons/min were observed in the bedrock wells along the trunk stream. The artesian conditions are probably caused at least in part by a thick layer (up to 40 ft) of well-indurated ferricrete (iron-oxide cement) present beneath the stream. The ferricrete apparently forms a confining unit that impedes groundwater discharge to the stream. As a result, much of the bedrock groundwater may flow down-drainage underneath the stream and discharge at an unknown location.

Single-well aquifer test data were used to estimate hydraulic conductivities (K) and specific storage values (S) for the surface deposits and bedrock. Derived K and S values for the surficial deposits were about 10^{-6} to 10^{-5} m/s and about 10^{-4} to 10^{-3} per meter, respectively, and values for the bedrock were about 10^{-9} to 10^{-6} m/s and about 10^{-5} to 10^{-4} per meter, respectively (Kahn et al. 2007). The bedrock K values are sufficiently high to allow substantial groundwater flow and suggest that bedrock-hosted groundwater may be an important component of the hydrologic budget.

Temperature-depth profiles from the deep wells become nearly linear at depths greater than about 300 ft below the water table (greater than about 600 ft below ground surface), suggesting that active groundwater circulation does not exceed these depths (Manning and Caine 2007).

A tracer-dilution study (Kimball et al. 2002) conducted in the upper 2 km of the trunk stream indicated that discharge, acidity, and loading of zinc and copper increase in the downstream direction, and zinc and copper concentrations exceed aquatic-life standards.

Groundwater samples from Handcart Gulch are Ca-SO_4 type and range in pH from 2.5 to 6.8. Most samples (75 percent) have pH values between 3.3 and 4.3 (Verplanck, Manning, et al. 2007). Surface water samples are also Ca-SO_4 type and have a narrower range in pH (2.7 to 4.0). Groundwater and surface water samples vary from relatively dilute (specific conductance of 68 µS/cm) to concentrated (2,000 µS/cm). Compared to other unmined, porphyry-mineralized areas in the Southern Rocky Mountains, dissolved copper concentrations in Handcart Gulch ground and surface waters are relatively high (10 to 1,000 µg/L) and dissolved zinc concentrations are relatively low (10 to 300 µg/L) (Verplanck, Nordstrom, et al., in press).

Tritium/helium (^{3}H/^{3}He) groundwater age results indicate increasing groundwater age with depth (Figure 4) (Manning and Caine 2007). Mean ages from integrated bedrock groundwater samples collected near the trunk stream are very similar. These data are consistent with a relatively simple conceptual model of the flow system in which recharge and aquifer thickness are constant throughout the drainage. They also suggest that the watershed aquifer system can be represented as an equivalent porous media using a numerical groundwater flow model in spite of the complexities in the geology and fracture networks.

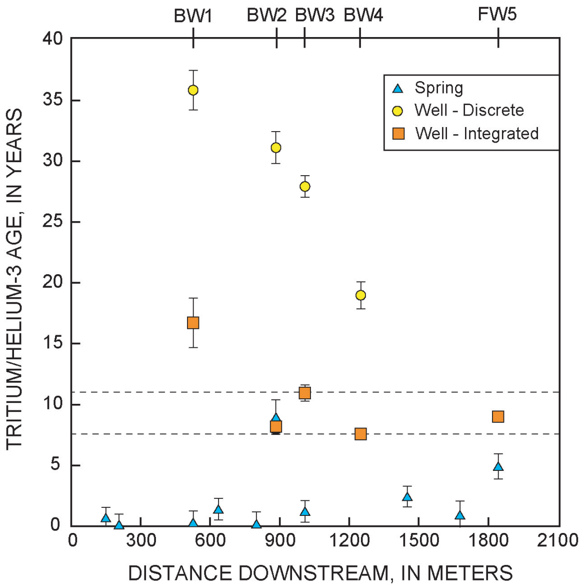

Figure 4. Distance downstream relative to ^{3}H/^{3}He age of groundwater samples from springs and bedrock wells located near the stream. BW1–BW4 and FW5 along top axis indicate well locations. Samples collected from springs are the youngest. Discrete well samples, collected from the bottom of the well screen, are the oldest. Integrated well samples, collected from the entire well screen, are of intermediate age. Dashed lines indicate the relatively narrow zone of variation of mean ages for integrated well samples (BW1 excepted).

Geologic, geophysical, hydrologic, and climatic data were used to construct two numerical groundwater flow models of the site. A finite-difference model of the watershed was constructed using MODFLOW-2000 (Harbaugh et al. 2000) to test the consistency of measured hydrologic data and available climatic information, and to develop a water budget (Figure 5) (Kahn et al. 2007). Modeled groundwater flow rates (based on measured hydraulic conductivities and heads) were consistent with measured stream discharge rates and precipitation. The derived water budget suggests that, under normal climatic conditions, 10–30 percent of precipitation leaves the site in the subsurface, either as underflow beneath the stream or as recharge to the deeper groundwater flow system. A preliminary version of a coupled heat, mass, and fluid-transport finite-element model of the watershed has been constructed using FEFLOW (Diersch 2002). Successful manual calibration to observed heads and temperatures was achieved by assigning hydraulic conductivities similar to those derived from aquifer-test data, decreasing permeability with depth, and applying a recharge rate of 10–20 cm/yr to the bedrock aquifer. The FEFLOW model is consistent with the MODFLOW-2000 model in that groundwater flow velocities under the stream are relatively high, with about 30 percent of bedrock recharge leaving the site as underflow.

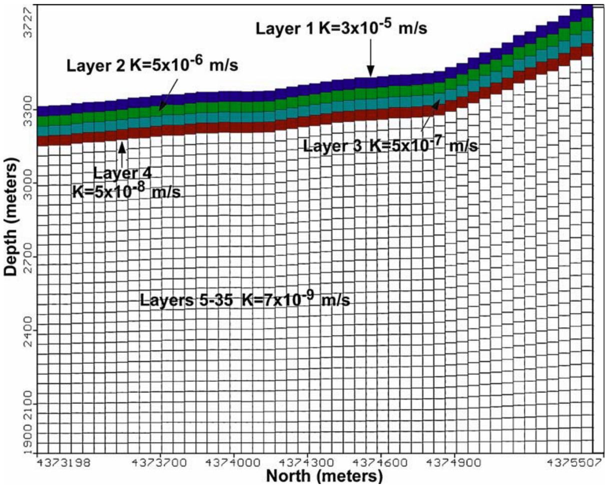

Figure 5. Cross section through three-dimensional MODFLOW groundwater flow model of site from Kahn et al. (2007). Section is roughly parallel to trunk stream. Section shows model mesh and layered hydraulic conductivity distribution, with hydraulic conductivity decreasing with depth.

Acknowledgments

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References

Caine, J.S., A.H. Manning, P.L. Verplanck, D.J. Bove, K.G. Kahn, and S. Ge. 2006. Well construction information, lithologic logs, water-level data, and overview of research in Handcart Gulch, Colorado: An alpine watershed affected by metalliferous hydrothermal alteration. U.S. Geological Survey Open-File Report 2006–1189.

Diersch, H.J.G. 2002. Interactive, Graphics-Based, Finite Element Simulation System FEFLOW for Modeling Groundwater Flow, Contaminant Mass and Heat Transport Processes. WASY, Berlin.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model: User guide to modularization concepts and the ground-water flow process. U.S. Geological Survey Open-File Report 2000–92.

Kahn, K.G., S. Ge, J.S. Caine, and A.H. Manning. 2007. Characterization of the shallow groundwater system in an alpine watershed: Handcart Gulch, Colorado. Hydrogeology Journal 16(1):103–121.

Kimball, B.A., R.L. Runkel, K. Walton-Day, and K.E. Bencala. 2002. Assessment of metal loads in watersheds affected by acid mine drainage by using tracer injection synoptic sampling: Cement Creek, Colorado, USA. Applied Geochemistry 17:1,183–1,207.

Manning, A.H., and J.S. Caine. 2007. Groundwater noble gas, age, and temperature signatures in an alpine watershed: Valuable tools in conceptual model development. Water Resources Research 43:W04404.

Verplanck, P.L., A.H. Manning, B.A. Kimball, R.B. McCleskey, R.L. Runkel, J.S. Caine, M. Adams, P.A. Gemery-Hill, and D.L. Fey. 2007. Ground- and surface-water chemistry of Handcart Gulch, Park County, Colorado, 2003–2006. U.S. Geological Survey Open-File Report 2007–1020.

Verplanck, P.L., D.K. Nordstrom, D.J. Bove, G.S. Plumlee, and R.L. Runkel. In press. Naturally acidic surface and ground waters draining porphyry-related mineralized areas of the southern Rocky Mountains, Colorado and New Mexico. Applied Geochemistry.