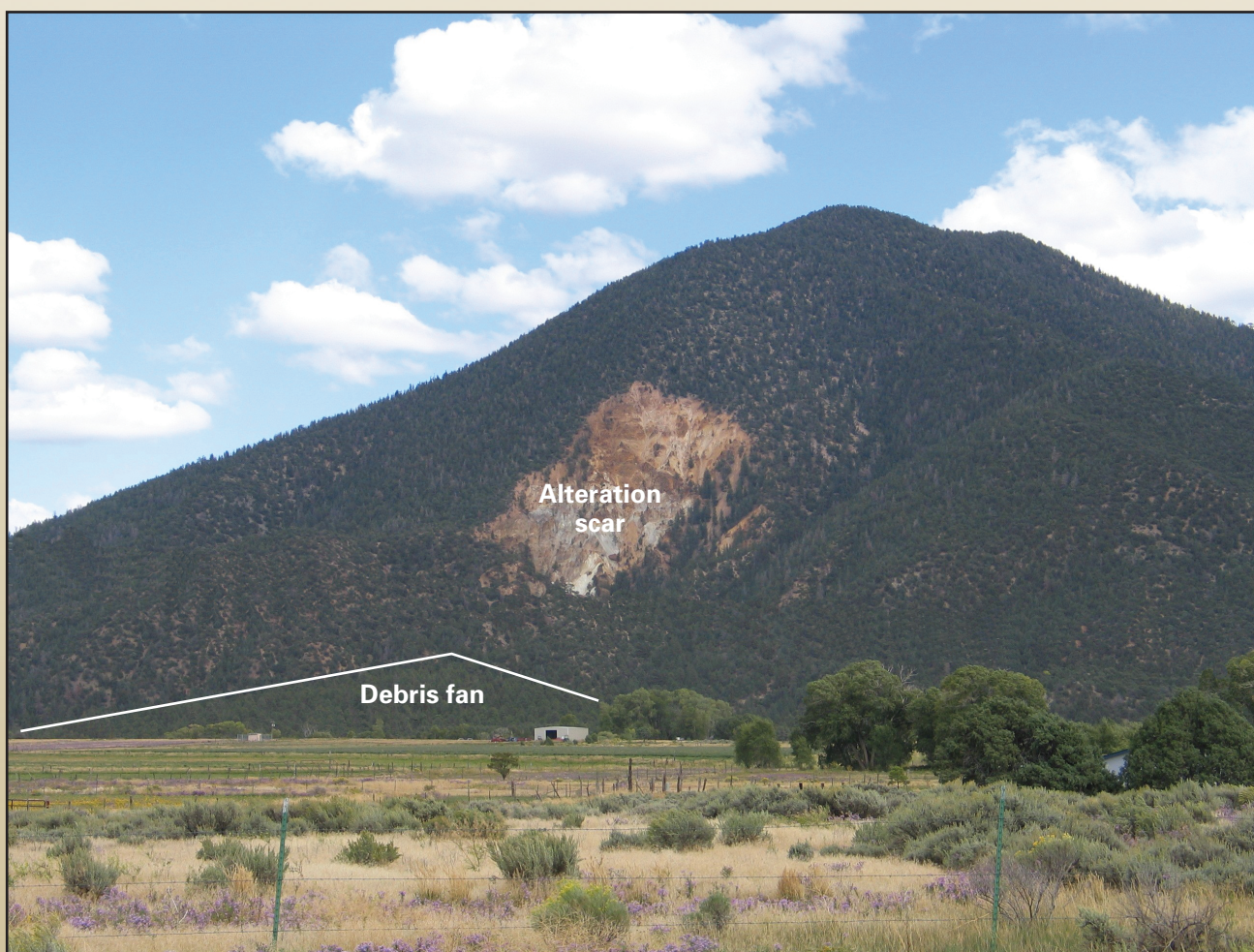


Prepared in cooperation with the New Mexico Environment Department

Questa Baseline and Pre-Mining Ground-Water Quality Investigation. 17. Geomorphology of the Red River Valley, Taos County, New Mexico, and Influence on Ground-Water Flow in the Shallow Alluvial Aquifer



Scientific Investigations Report 2006–5156

Front cover: View of the Taos Range near Questa, New Mexico, showing an alteration scar and large debris fan composed predominantly of sediment shed from that scar. Photograph by Kirk R. Vincent.

Questa Baseline and Pre-Mining Ground-Water Quality Investigation. 17. Geomorphology of the Red River Valley, Taos County, New Mexico, and Influence on Ground-Water Flow in the Shallow Alluvial Aquifer

By Kirk R. Vincent

Prepared in cooperation with the New Mexico Environment Department

Scientific Investigations Report 2006–5156

**U.S. Department of the Interior
U.S. Geological Survey**

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2008

For product and ordering information:

World Wide Web: <http://www.usgs.gov/pubprod>

Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:

World Wide Web: <http://www.usgs.gov>

Telephone: 1-888-ASK-USGS

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted materials contained within this report.

Suggested citation:

Vincent, K.R., 2008, Questa baseline and pre-mining ground-water quality investigation. 17. Geomorphology of the Red River Valley, Taos County, New Mexico, and influence on ground-water flow in the shallow alluvial aquifer:

U.S. Geological Survey Scientific Investigations Report 2006–5156, p. 50, 1 pl.

Contents

Abstract.....	1
Introduction.....	2
Purpose and Scope	2
Setting	3
Definition of Important Terms	3
Acknowledgments.....	4
Geomorphic History.....	4
Bedrock Geology.....	4
Base-Level Controls	4
Quaternary Landforms Near Questa	6
Quaternary Landforms in Red River Valley.....	7
Erosion Rates.....	10
Relative Rates of Erosion.....	11
Fan-Sediment Mixtures	14
Numerical Rates of Erosion	15
Erosion Averaged Over Millions of Years	16
Erosion Averaged Over the Past Millennia.....	16
Implications of Erosion Data	18
Disparity of Short- and Long-Term Rates.....	18
When Was the Bedrock Base of the Valley Last Carved?	18
Discussion of Classical Fan Area/Watershed Area Relations	19
Summary of Geomorphic History of Red River Valley.....	20
Ground-Water Flow in the Alluvial Aquifer.....	21
Geometry of Alluvial Aquifer	22
Longitudinal Profile Topography.....	22
Ground-Water Surface Profiles.....	22
Thickness of Alluvial Aquifer	24
Cross-Sectional Geometry of the Aquifer.....	25
Sedimentary Facies and Hydraulic Conductivity.....	26
Ground-Water Flow Model.....	29
Theory and Constraints.....	29
Flow Model Results	30
Hydrologic Observations near Cabin Springs.....	31
Water Budget for Alluvial Aquifer.....	32
Streambed Infiltration	32
Goat Hill Gulch Fan as a Source of Water	35
Ground-Water Pumping.....	35
Water Budget Results for Columbine Park.....	36
Influence of Geomorphology on Ground-Water Flow in the Shallow Alluvial Aquifer.....	38
Physical Condition of Alluvial Aquifer Prior to Mining	38
Why Does Ground Water Emerge Where It Does?	38
How Can the Water Table Persist Deep Beneath a Perennial Stream?	38
Along What Flow Path Did the Ground Water Travel?	38
Summary.....	39
References Cited.....	41
Appendixes	47

Plate

1. Surficial geologic map showing late Quaternary sediments deposited by the Red River and by tributary streams in the middle of Red River Valley, New Mexico. [click here](#)

Figures

1. Photograph of the Red River, looking downstream (west), near the town of Red River, New Mexico3
2. Graphs showing longitudinal profiles of the Red River (*A*) as it was approximately configured a million years ago, and (*B*) as it is presently (2006)5
3. Graph showing longitudinal profiles of the Red River streambed and terraces in the vicinity of Goat Hill Gulch.....8
4. Diagram showing the stratigraphy at four sites with radiocarbon age constraints (table 1), located along the Red River9
- 5–13. Graphs showing:
 5. Scaling relations for the areas of fans and their watersheds, (*A*) at various locations in the western United States including within the Red River Valley, and (*B*) near Questa12
 6. Scaling relations for the areas of fans and properties of their watersheds in the Red River Valley. *A*, Relation for fan area and total watershed area. *B*, Relation for fan area and a composite erosion amount estimated for their watersheds13
 7. Scaling relations for tributary fans within the Red River Valley, which (*A*) attempt to reconcile the nonlinear relation of fan area and fan volume, and (*B*) attempt to approximate the necessary conservation of the mass eroded from watersheds with the mass deposited in fans14
 8. Measured lead (*A*) and sulfur (*B*) concentrations in fan and hillslope sediments within the Red River Valley, and the correspondence of that data with the predictions based on geomorphologic evidence.....15
 9. Range in measured landscape erosion rates, expressed as the rate of vertical lowering of the substrate averaged over the watershed in question.....16
 10. Estimated mass balance of the volume of sediment eroded from Red River tributary watersheds and the volume of sediment stored in Red River tributary fans.20
 11. Model of the longitudinal geometry and sedimentary facies of the Red River shallow alluvial aquifer in the vicinity of the Molycorp, Inc. mine22
 12. Details of the water-table profile within and upstream from the mill reach (pl. 1), as it may have been during the August 2001 tracer23
 13. (*A*) Constraints on the deepest level of the bedrock/alluvium contact at the base of the Red River shallow alluvial aquifer, based on well logs; and (*B*) variation in top width of Red River alluvium.24

14.	Diagrams showing generalized models of the cross-sectional shape of alluvial aquifers in mountainous terrain where the width of the valley floor and depths to the water table and deepest alluvium/bedrock contact are known.....	25
15–17.	Graphs showing:	
15.	Model results for the flow of ground water during August 2001, in the sections of the alluvial aquifer composed of sediment deposited by the Red River.....	29
16.	Model results for the flow of ground water in the section of the alluvial aquifer composed of sediment deposited by the Red River during March 2002.....	31
17.	Discharge of the Red River through Columbine Park documented by the August 2001 tracer dilution study	32
18.	Map showing the shape of the water table during pumping test of Columbine Well 2, modified from GSi/water (1996).....	33
19.	Map showing the pH of the Red River and the change in pH of the alluvial ground water during pumping test of Columbine Well 2, modified from GSi/water (1996)	34
20.	Graphs showing the record of pumping from the Red River alluvial aquifer between January 2001 to April 2002.....	36
21.	Diagram showing the components of the water budget for the Red River alluvial aquifer in Columbine Park during the 2001 tracer dilution study.....	37

Tables

1.	Data for radiocarbon samples collected in the Red River Valley between the towns of Red River and Questa, Taos County, New Mexico	10
2.	Locations and descriptions of radiocarbon sample sites	17
3.	Alluvial aquifer hydraulic conductivity values based on tests at alluvial wells in the Red River Valley	27
4.	Long-term sources of water for mine use	35

Appendix Tables

1.	Map areas of tributary watersheds, alteration scars within watershed boundaries, and alluvial fans derived from the watersheds	48
2.	Concentration of total sulfur in debris-fan sediments	49
3.	Altitudes of bedrock/alluvium contacts interpreted from well logs	49
4.	Data for the model of ground-water flow within alluvium, deposited by the Red River, during the 2001 tracer study	50
5.	Data for the model of ground water flow within alluvium, deposited by the Red River, during the 2002 tracer study	50

Conversion Factors

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square kilometer (km ²)	0.3861	square mile (mi ²)
Volume		
liter (L)	0.2642	gallon (gal)
cubic meter (m ³)	1.308	cubic yard (yd ³)
cubic kilometer (km ³)	0.2399	cubic mile (mi ³)
Flow rate		
liter per second (L/s)	15.85	gallon per minute (gal/min)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
Mass		
metric ton	1.102	ton, short (2,000 lb)
Hydraulic conductivity		
meter per day (m/d)	3.281	foot per day (ft/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

Altitude, as used in this report, refers to distance above the National Geodetic Vertical Datum of 1929 (NGVD 29). Horizontal coordinate information is referenced to the American Datum of 1983 (NAD 27).

The timing of events in the geological past are given in this report as millions of years ago (Ma) and thousands of years ago (ka) whereas time periods are given as millions of years (my) and thousands of years (ky). Radiocarbon ages are given as years before present (B.P.), which specifically means radiocarbon years (not calendar years) before A.D. 1950 (¹⁴C yr B.P.). Certain radiocarbon ages were calibrated to calendar years before present (cal. yr B.P.).

Questa Baseline and Pre-Mining Ground-Water Quality Investigation. 17. Geomorphology of the Red River Valley, Taos County, New Mexico, and Influence on Ground-Water Flow in the Shallow Alluvial Aquifer

By Kirk R. Vincent

Abstract

Landforms, and the specific geomorphic processes that created them, influence the alluvial ground-water hydrology in the Red River Valley between the towns of Questa and Red River, New Mexico. These landforms, their history, and their influence on the alluvial ground water are the subject of this report.

The bedrock of the Taos Range surrounding the Red River is composed of Proterozoic rocks of various types, which are intruded and overlain by Oligocene volcanic rocks associated with the Questa caldera. Locally, these rocks were altered by hydrothermal activity. The alteration zones that contain sulfide minerals are particularly important because they constitute the commercial ore bodies of the region and, where exposed to weathering, form sites of rapid erosion referred to as alteration scars.

The valley of the Red River developed over the past 26 million years following cessation of volcanism, which had created a broad plateau. Subsequently, the Taos Range was created by tectonism associated with development of the Rio Grande rift. In direct response to the creation of relief, the Red River and its tributaries incised the Taos Range resulting in the rugged mountainous terrain visible today. Over the past 26 million years, hillslopes eroded at a modest rate of about 0.02 millimeter per year, on average. The rate of hillslope erosion likely increased through time because the area consisting of steep hillslopes increased through time, and the landscape had to erode through hundreds of meters of more resistant rock before the altered rock became exposed. A second process caused the Red River to incise the landscape in the late Quaternary. Prior to a million years ago, the Red River was essentially the headwater of the Rio Grande. In response to stream capture of the San Luis Basin, the Rio Grande downcut 260 meters (840 feet) over the past 600–700 thousand years, creating the Rio Grande gorge. The Red River was thus relegated to the status of a tributary, and downcutting of the master stream caused the Red River to downcut as well. The rate of this stream incision apparently decreased through time.

This episode of incision created the gorge at the mouth of the Red River and the valley at the site of Questa, but apparently had relatively little influence on the Red River Valley within the Taos Range upstream from Questa.

During the late Quaternary, erosion and deposition within the Red River watershed were variable in both time and space. The Red River incised the bedrock base of its valley during certain time periods, but the Red River also underwent episodes of sediment aggradation and episodes of reincision into that alluvium. Although the highest areas of the Taos Range were glaciated, glacial ice did not extend down into the study area between the towns of Questa and Red River. Nonetheless, aggradation of the Red River took place during periods of glaciation. The thickness of that accumulated sediment is not known, but it is likely less than 50 to 100 meters. The Red River evidently removed most of that sediment from the valley and resumed eroding the bedrock base of the valley immediately following the most recent period of glaciation. Then, the Red River and its tributary streams began to aggrade again about 14,000 years ago, just prior to the beginning of the Holocene. Thus, most deposits of alluvium in the valley are likely less than 10–20 thousand years old. Over the past thousand years, if not over the entire Holocene, erosion rates were spatially variable. Forested hillslopes eroded at about 0.04 millimeter per year, whereas alteration scars eroded at about 2.7 millimeters per year. The erosion rate of the alteration scars is unusually rapid for naturally occurring sites that have not been disturbed by humans. In addition, watersheds containing large alteration scars delivered more sediment to the Red River Valley than the Red River could remove. Consequently, large debris fans, as much as 80 meters thick, developed within the valley. The aggradation of those fans also caused the Red River to aggrade immediately upstream from them and created the characteristic segmentation of the longitudinal profile of the valley. Upstream from a large fan the alluvial valley bottom is not steep and is relatively wide. The alluvium is composed of gravel deposited by the Red River that is 30–50 m thick. Along the downstream half of a large fan, the Red River is steep, often consisting of a cascade of water flowing over boulders. The flood plain is

narrow or absent, sediment deposited by the Red River is thin, and these features are adjacent to the thick and wide debris fan deposits. Downstream from a large fan, Red River alluvium typically has intermediate gradient, width, and thickness. Thus, the alluvial aquifer in the axis of the Red River Valley consists of relatively long reaches of Red River gravel separated by shorter reaches dominated by debris-fan sediment.

The geomorphology of the Red River Valley has had several large influences on the hydrology of the shallow alluvial aquifer, and those influences were in effect before the onset of mining within the watershed. Several reaches where alluvial ground water emerges to become Red River streamflow were observed by a tracer dilution study conducted in 2001. Several potential factors could cause ground water to emerge from alluvium where it does. The emergence of ground water from alluvium at certain locations is partially caused by a narrowing of the aquifer. The aquifer narrows where erosion-resistant bedrock, which tends to form vertical cliffs, restricts the width of the valley bottom. Although the presence of a shallow bedrock sill, overlain by shallow alluvium, is a plausible cause of ground-water emergence, this cause was not demonstrated in the study area. The water-table gradient can locally decrease in the downstream direction because of changes in the hydraulic properties of the alluvium, and this may be a contributing cause of ground-water emergence. However, at one site (near Cabin Springs), ground-water emergence could not be explained by spatial changes in geometric or hydraulic properties of the aquifer. Furthermore, the available evidence demonstrates that ground water flowing through bedrock fractures or colluvium entered the north side of the alluvial aquifer, at a rate of about 20 liters per second, and is the cause of ground-water emergence. At that location the alluvial aquifer was already flowing full, causing the excess water to emerge into the stream.

An indirect consequence of altered rock in the tributary watersheds is the rapid erosion rate of alteration scars combined with the hydraulic properties of sediments shed from those scars. Those sediments have hydraulic conductivity values that are one to two orders of magnitude lower than the conductivity of the well-washed gravel deposited by the Red River. Where alteration scars are large the debris fans at the mouths of the tributary watersheds substantially encroach into the Red River Valley. At such locations debris-fan materials dominate the width and thickness of the alluvium in the valley and reduce the rate of flow of ground water within the Red River alluvial aquifer. Many hydrologists would refer to the debris-fan sediments as aquitards within an unconfined aquifer. Most sites of groundwater emergence are located immediately upstream from or along the margins of debris fans. A substantial fraction of the ground water approaching a debris fan can emerge to become streamflow. This last observation has three implications. First, very little water can flow the entire length of the study area entirely within the alluvial aquifer because the ground water repeatedly contacts debris-fan sediments over that length. Second, it follows that emerging water containing unique elemental constituents must

have entered the alluvial aquifer at a relatively short distance upstream. Third, a gravel aquifer downstream from a large debris fan can transmit more ground water than flows into it through the debris fan. This observation explains how the water table can be naturally, and permanently, located well beneath the level of the bed of a perennial stream.

Introduction

In the Red River Valley (pl. 1), the upwelling of ground water into the Red River is recognized as an important phenomenon that affects the solute concentrations and solute loading (Vail Engineering, 2000; McCleskey and others, 2003; LoVetere and others, 2004; Maest and others, 2004). However, the geologic and hydrologic properties that control the amount and location of emerging ground water are complex. In addition, some ground-water emergence occurs adjacent to the Questa mine, owned by Molycorp, Inc., and there has been speculation that some solute loading may be caused by mining. The investigations of baseline and pre-mining ground-water quality by the U.S. Geological Survey (USGS), conducted in cooperation with the New Mexico Environment Department (NMED), include a tracer injection and synoptic sampling study (Kimball and others, 2006) of the middle section of the Red River from the town of Red River to the USGS streamflow-gaging station at the Questa Ranger Station (pl. 1). The results from that study showed that stream discharges and solute loads in the river increase abruptly at specific locations, but the reasons for ground-water emergence at those locations were not obvious. Consequently, a study was conducted, as part of the larger USGS effort, to determine geomorphic factors that could cause ground water to flow from the shallow alluvial aquifer into the Red River.

Purpose and Scope

The purpose of this report is to describe the geomorphology of the Red River Valley and to determine the main geomorphologic factors that could cause ground water to flow from the shallow alluvial aquifer into the Red River. The approach is twofold: first, the general geomorphic history and processes were studied using standard field methods. Second, available data were used to define the hydraulic properties of Red River alluvium and tributary debris-fan sediments and to define the cross-sectional and longitudinal geometry of the alluvial aquifer for a reach of the Red River Valley. This information was combined to form a generalized conceptual model of the Red River aquifer, and specifically a mathematical formulation of ground-water flow. Darcy-based calculations of ground-water discharge were made for a sequence of cross sections of the alluvial aquifer, and the results were used to construct a water budget for the Red River aquifer in the vicinity of the Questa mine.

Setting

The study area (pl. 1) is located in Taos County, in the Taos Range of the Sangre de Cristo Mountains of north-central New Mexico, located generally between the towns of Red River and Questa. The Red River is a west-flowing tributary of the Rio Grande and drains about 290 square kilometers (km²) of the Carson National Forest upstream from the Questa Ranger Station. The area is rugged, with steep and largely forested hillslopes, but locally some hillslopes are unvegetated and erode rapidly (fig. 1). The altitudes of the Red River valley in the study area range from 2,280 meters (7,480 feet) near the mouth of the valley at the Questa Ranger Station to 2,646 m (8,680 feet) at the town of Red River, and the ridge crests on both the north and south sides of the river extend to more than 3,000 m. The climate is temperate and semiarid, but varies spatially. For example, at the town of Cerro (about 3 miles north of Questa) the mean annual temperature is 6.9° C (44.5° F) and mean annual precipitation is 321 millimeters (mm), whereas at the town of Red River those parameters are 4.0° C (39.3° F) and 521 mm (Western Regional Climate Center, 2003). Precipitation is dominated by snow at high altitudes and by rain at low altitudes. Vegetation in the Red River Valley generally corresponds to the following altitude zones: piñon-juniper woodland below 2,300 m, mixed conifer woodland between 2,300 and 2,700 m, and spruce-fir woodland above 2,700 m (Knight, 1990). Willows, cottonwoods, shrubs, and perennial grasses are common on the Red River flood plain. The following streamflow data, based on measurements obtained from 1930 to 1999, is for the USGS streamflow-gaging station 08265000 Red River near Questa, which is located at the Questa Ranger Station (pl. 1). The annual peak discharge ranged from 1,530 to 25,090 liters per second (L/s), or 54 to 886 cubic feet per second (ft³/s). Peak flows in the Red River and its largest tributaries generally result from spring snowmelt, whereas peak flows in the smaller tributaries generally result from summer thunderstorms. The annual mean streamflow ranged between 362 and 2,920 L/s (12.8 to 103 ft³/s). During the low-flow season, which is the focus of this report, streamflow in the Red River is typically 280–850 L/s (10–30 ft³/s) at the Red River near the Questa gaging station. During the low-flow season the source of streamflow along this gaining stream is primarily ground water.

There is a long history of mining in the area. Unless otherwise stated, the source of information in this paragraph is from McLemore and Mullen (2004). Within the Taos County region, mining for gold began as early as A.D. 1600, and the mining of a variety of precious metals increased in the late 1800s. In the section of the Red River Valley discussed in this report, ore bodies containing molybdenum were discovered around 1914, on the north side of the Red River in the vicinity of Sulphur Gulch (pl. 1). Underground mining was underway in 1919 by a company that would evolve into Molycorp, Inc. Traditional underground mining continued from 1919 through 1956 extracting an average of 430,000 metric tons (475,000 U.S. short tons) of ore per year. The company



Figure 1. The Red River, looking downstream (west), near the town of Red River, New Mexico, taken by Philip Verplanck in 2002. Visible in the background is a pale yellow alteration scar within the Hottentot tributary watershed.

shifted to open-pit mining and extracted an average of 4,000,000 metric tons of ore per year from 1965 to 1983. The style of mining changed again, this time to underground block caving, which produced about 900,000 metric tons of ore per year from 1996 through 2002. The block caving is now expressed at the surface as collapse structures and subsidence in an area within Goat Hill Gulch (pl. 1). The open pit, waste-rock piles, and the subsidence area are all prominent features of the landscape (Shaw and others, 2002), with locations shown on plate 1. Unlike some mining areas (for example see Vincent and Elliott, 2007), mill tailings are not obviously abundant in the landscape because after 1965 mill byproducts were transported downvalley as a slurry in a pipeline to a tailings pond located near Questa (McLemore and Wagner, 2004).

Definition of Important Terms

During the course of this study the author found that some previous reports used several terms in different ways. Most of these terms denote the origins of sedimentary deposits. For the sake of clarity, this section defines several terms as they are used in this report. The term “alluvium” is used in its general sense (Bates and Jackson, 1980) to indicate sediments deposited by streams, irrespective of the rheology (deformation properties) of the sediment transport medium (for example, debris flow or water flow). The term “colluvium” is used to indicate unconsolidated sediment mantling bedrock hillslopes, largely composed of fragments detached from the underlying bedrock and transported short distances downhill. The agent(s) of detachment and transport of colluvium is highly varied, but does not include transport by streams. The term “debris flow” indicates moving, viscous material consisting of water with high concentrations of entrained sediment, and the meaning of “debris-flow deposit” is, therefore,

self-evident. See Pierson and Costa (1987) for a rheologic classification of subaerial sediment-water flows. The terms “alluvial fan” and “debris fan” are used interchangeably to indicate landforms consisting of alluvium (irrespective of the rheology of the sediment transport medium) deposited by ephemeral streams tributary to the Red River. The landforms are generally lobate, in map view, where they encroach into the Red River Valley, but the debris-fan sediments also extend considerable distances upstream into the tributary watersheds.

Acknowledgments

The study described by this report was conducted with the support and cooperation of the project advisory committee whose members represent the New Mexico Environment Department, MolyCorp, Inc., and the Amigos Bravos stakeholders group. The author appreciates the many helpful technical discussions with Kirk Nordstrom, Robert Runkel, Briant Kimball, Jim Dungan Smith, and Bruce Walker. Comprehensive reviews by Steffen Mehl, Christoph Wels, Tim Cox, and Jordan Clayton greatly improved this report.

Geomorphic History

This section of the report draws relevant information from the literature and then develops new information on the geomorphic history of the Red River Valley.

Bedrock Geology

The types of rocks in the study area, and their degrees of alteration, control erosion rates and the geochemical nature of the erosion products. The bedrock geology is briefly summarized and is largely drawn from Meyer and Leonardson (1990) and Ludington and others (2005). They cite Schilling (1956), Lipman (1983), Lipman and Reed (1989), Czamanske and others (1990), and Meyer (1991) among others.

The oldest rocks in the study area are Proterozoic metamorphosed volcanic and sedimentary rocks that are intruded by granitoid plutons; these rocks are most extensively exposed on the south side of the Red River Valley. Elsewhere, these basement rocks are overlain by the late Oligocene Latir volcanic field, which is composed of andesitic volcanic and volcanoclastic rocks and rhyolite flows and ash-flow tuffs. Volcanism ended with the eruption of the rhyolitic Amalia Tuff and the formation, by volcanic collapse, of the Questa caldera about 26 Ma. The caldera generally lies on the north side of the Red River, and the Red River Valley generally follows the southern structural margin of the caldera. The caldera formation was synchronous with the early extensional formation of the Rio Grande rift, which is discussed in the next section.

After the formation of the caldera, two episodes of hydrothermal activity occurred. The first resulted in the regional alteration of the volcanic rocks of the Latir field, described as propylitic alteration. These altered rocks characteristically contain chlorite, epidote, albite, and calcite. From an environmental standpoint these rocks are important because they do not contain sulfide minerals in abundance, and the calcite should buffer any acid water present. The exact age and origin of the propylitic alteration is not clear. The second episode began when the volcanic rocks were locally intruded by a series of granites and porphyries in the form of dikes and small stocks that range in age from 25 to 18 Ma. These intrusions are thought to have been the source of the hydrothermal fluids that formed the molybdenite deposits in the area. The magmatic-hydrothermal fluids deposited quartz, molybdenite, pyrite, fluorite, carbonates, and associated minerals in veins, stockwork vein systems, and breccia ore bodies, which occur within a zone oriented N. 75° E. that is generally located on the north side of the Red River. Generally, around the intrusions there are shells (vertical and lateral zoning,) of various alteration assemblages. The largest is called “QSP” alteration assemblage and is characterized by quartz, sericite (fine-grained muscovite), and pyrite. The QSP alteration assemblage is important from an environmental standpoint because the presence of sulfide minerals results in acid waters upon weathering of the rock. All of the alteration assemblages are locally exposed in differing proportions. The QSP assemblage is the largest (Ludington and others, 2005) at sites that have been called “alteration scars” (Meyer and Leonardson, 1990; Shaw and others, 2003; McLemore and others, 2004). The alteration scars are conspicuous features of the landscape (fig. 1; pl. 1) because they are unvegetated, pale yellow in color, and erode rapidly. The alteration scars are discussed further in the section “Quaternary Landforms in Red River Valley.”

Base-Level Controls

The Red River has been incising into the Sangre de Cristo mountain block through geologic time in response to two processes: the creation of relief by tectonic forces over millions of years, and the incision of the Rio Grande less than a million years ago. This background information is particularly relevant to the section “Erosion Rates.”

The Rio Grande Valley (fig. 2) is a major structural rift in the North American plate (Chapin and Cather, 1994; Bauer and Kelson, 2004a) that started forming about 26 Ma in response to changes in the position of the tectonic plate subducting beneath the western margin of the North American plate (Lawton and McMillan, 1999). The study area of this investigation is located immediately east of the Rio Grande rift (fig. 2; pl. 1). From central Colorado, the Rio Grande rift extends south about 700 km where it merges with the Basin and Range province in southern New Mexico and northern Mexico, but the nature and history of the rift varies. Extension in the rift was left-oblique and the magnitude of the extension increases toward the south (Chapin and Cather, 1994). This caused the rift to be composed of a chain of basins that alternate between being east-tilted and west-tilted half-grabens, which are separated by structural accommodation zones. The northern part of the rift is called

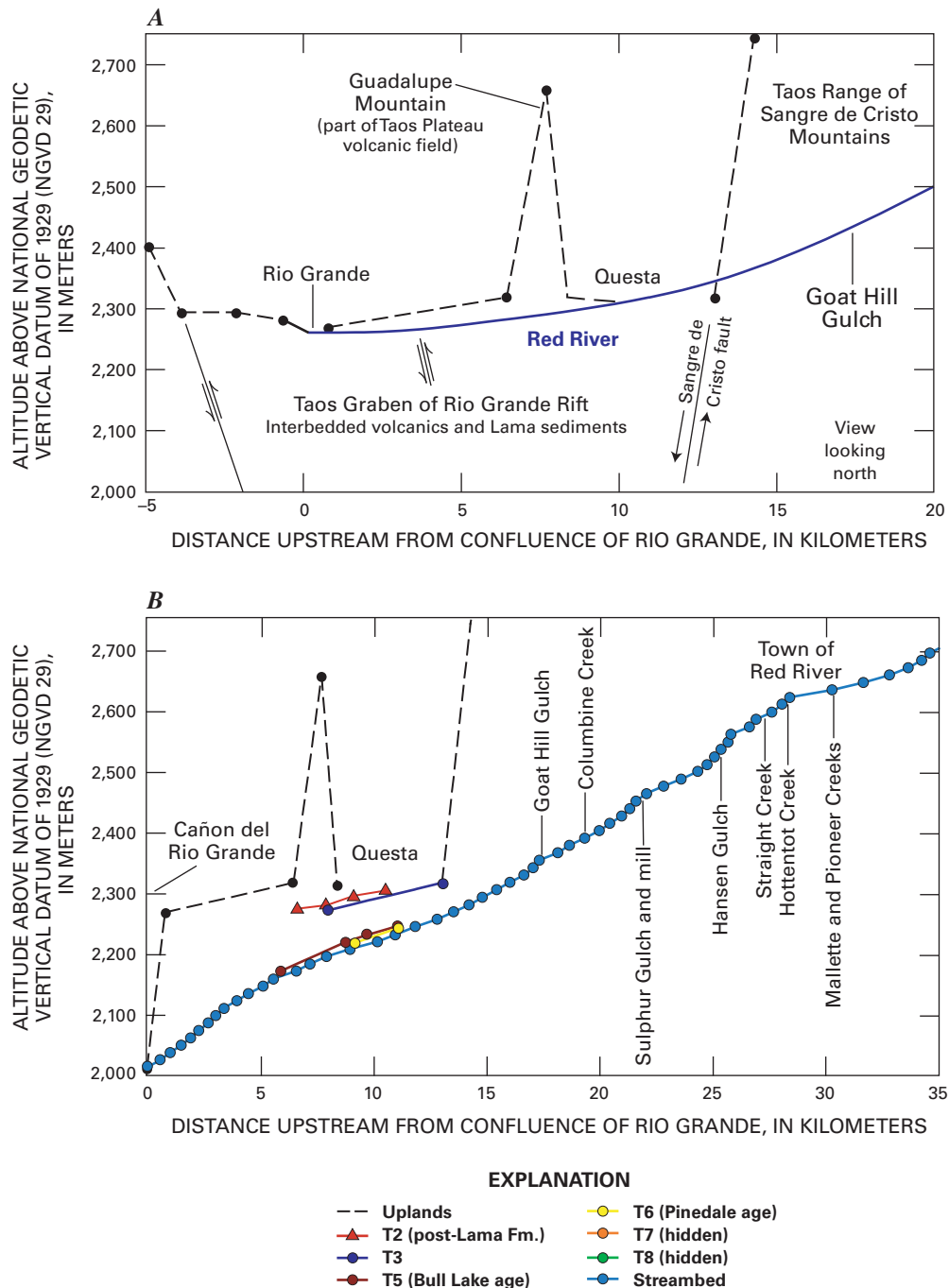


Figure 2. Longitudinal profiles of the Red River (*A*) as it was approximately configured a million years ago, and (*B*) as it is presently (2006). The scale ratios and lateral positions of the diagrams are not identical. The locations of faults bounding the Taos Graben were modified from Kelson and others (1998). The stream terraces (labeled with the letter T in the explanation box) in the vicinity of Questa, New Mexico, were mapped by Pazzaglia (1989).

the San Luis Basin, with Questa located near its southern end. The major structural feature is the Sangre de Cristo fault system, which consists of down-to-the-west normal faults located at the foot of the range front that constitute the eastern margin of the rift basin and across which there is as much as 7 km of structural relief (Kluth and Schaftenaar, 1994). The Sangre de Cristo fault is shown in figure 2A bounding the rift immediately

east of Questa. In general, the San Luis Basin is an east-tilted half-graben that is about 60 km wide, but there are three major internal complications (Grauch and Keller, 2004). In the central and western part of the San Luis Basin is a large intra-rift horst. In the central-southern part of the rift is the extensive Taos Plateau volcanic field, of which Guadalupe Mountain (fig. 2A) is a part. On the eastern side of the rift is the narrow (10 km)

and deep (3 km) Taos Graben, which is depicted in figure 2A. The Taos Graben contains basalt and andesite that intrude and interfinger with alluvial sediments. The volcanic rocks dominate the cliffs of the Red River gorge, which comprises the most downstream 5 km of the Red River Valley. Alluvial sediments dominate the basin fill in the vicinity of Questa (fig. 2A). In this region the most rapid phase of extension may have occurred in the middle to late Miocene (Chapin and Cather, 1994), and the creation of relief caused the Red River to incise into the mountain block. The Sangre de Cristo fault system remains active (Bauer and Kelson, 2004b). During major earthquakes, surface ruptures along the fault and associated deformation, should influence the Red River by creating local waterfalls or by tilting the streambed (Merriitts and Vincent, 1989; Vincent, 1995). The consequence of displacement along that fault system during the late Quaternary is not obvious as a steep reach in the profile of the Red River (fig. 2B), however, perhaps because a different base-level process overshadowed faulting.

Prior to a million years ago, the Red River was essentially the headwater of the Rio Grande and the Red River gorge did not exist. The Rio Grande Rift once consisted of a chain of closed basins, and through time the Rio Grande extended headward (north) capturing one basin after another (Newell and others, 2004; Connell and others, 2005). The last episode of that type was the capture of the San Luis Basin, which had been a closed basin and did not contribute surface water to the Rio Grande. The closed nature of the San Luis Basin may have been facilitated by the accumulation of erosion-resistant basalt flows of the Taos Plateau volcanic field and perhaps by tectonic complications caused by the Embudo fault accommodation zone that forms the structural margin at the south end of the San Luis Basin. In any case, the Red River was not incised into the basin-fill sediments but was flowing near the level of the top of those sediments (fig. 2A). In an exposure of basin-fill sediments near Questa, Wells and others (1987) discovered deposits of Tshirege volcanic ash, which had erupted from the Jemez Mountains about 1.1 Ma. Evidently, the deepest occurrence of the ash was 30 m beneath the surface of the basin-fill sediments; thus, incision occurred significantly after 1.1 Ma. Wells and others (1987) also discussed the occurrence of Bishop ash (740 ka) in the Hansen Bluffs lacustrine deposits of the San Luis Basin near Alamosa, Colo., and concluded the basin was still closed at that time. Pazzaglia (1989) noted that the soil characteristics of the oldest river terrace near Questa (labeled T2 in fig. 2B) are similar to those of a deposit in the San Luis Basin that contains reworked Bishop ash (McCalpin, 1983), which also suggests that the Red River was not incised at 740 ka. Wells and others (1987) concluded that the sill of the San Luis Basin was breached sometime between 700 and 300 ka, with the 600–700 ka timeframe being most probable. Newell and others (2004) and Connell and others (2005) have concurred with this hypothesis. The discharges in the Rio Grande increased substantially, in proportion to the newly acquired drainage area, and the increased shear stresses exerted on the bed caused the Rio Grande to incise 260 m (840 feet), forming the Rio Grande Gorge, also known

as Cañon del Rio Grande (fig. 2B). Assuming a duration of 600 ky, the average incision rate was about 0.4 m/ky, which is a rapid rate but not unprecedented (Stock and others, 2005).

The Red River was thus relegated to the status of a tributary and responded to that base-level fall (incision of the master stream) by incising. A base-level fall manifests as knick-points (waterfalls) or steep reaches, which migrate upstream (Leopold and Bull, 1979; Newell and others, 2004). These features do not migrate all the way to the drainage divide, however, because streams can accommodate a certain amount of steepening. Most of the middle Quaternary base-level fall was absorbed in the lowest 5 km of the Red River, as evidenced by the steep gradient in that reach (fig. 2B). Of the total base-level fall, only about 70 m (230 feet) of lowering has reached the range front. Although possible, it is not obvious that any of the base-level fall created over the past half-million years has reached the town of Red River (fig. 2B), in part because of the local base-level control exerted by certain tributary debris fans, as discussed in the section “Quaternary Landforms in Red River Valley.” This information indicates that the alluvial aquifer in the Red River Valley should be shallow, uncomplicated, and composed of young sediments, compared to the aquifer in the Rio Grande Rift (Benson, 2004).

Quaternary Landforms Near Questa

A flight of stream terraces is present along the sides and in the bottom of the Red River Valley adjacent to Questa (fig. 2B), and these alluvial landforms were mapped by Pazzaglia (1989). That investigation provided general insight and age constraints for the sediments in the Red River Valley study area upstream and demonstrated that there were periods of stream aggradation despite the net-incision over the past 700 ky. Frank Pazzaglia provided a copy of his thesis map (written commun., 2002), and the spatial positions of his mapped terraces were transferred onto the longitudinal profile of figure 2B. That profile was constructed using the USGS Guadalupe Mountain, Questa, and Red River topographic quadrangles, which have a scale of 1:24,000 and a contour interval of 40 feet (about 12 m). The transect of the profile follows the valley center rather than the present course of the meandering Red River stream.

Pazzaglia mapped 10 alluvial surfaces in addition to alluvial fans. The oldest surface is the top of the basin filling sediments, the youngest are the flood plain and the bed of the Red River. The other 7 surfaces are stream terraces, designated as T2 through T8. Those terraces preserved with considerable spatial extent are shown in figure 2B, except that terraces T7 and T8 are so low that they are hidden by the line depicting the streambed. The three oldest terraces (including T2 and T3 in fig. 2B) are elevated, occupying positions in the landscape greater than 50 m above the streambed, and they are strath terraces. Strath terraces are roughly planar erosional surfaces cut into bedrock or older sediment by streamflow processes and are generally covered by a veneer of alluvium. The strath terraces indicate that early in the formation of the valley near the town of Questa, the Red River repeatedly stopped incising

for fairly long periods, long enough for the river to migrate laterally and carve the erosion surfaces. The remaining terraces occupy low positions in the landscape, being less than 20 m above the current (2006) level of the streambed, and these are fill terraces. Fill terraces consist of relatively thick sections of alluvium, which cover erosional surfaces that are deep or are not visible in the exposures available. The fill terraces indicate that late in the formation of the valley near Questa, the Red River repeatedly stopped incising and aggraded before resuming incision. Pazzaglia (1989) compared the style and degree of soil development on the terraces with that of landforms clearly associated with glacial moraines in the San Luis valley, just north across the Colorado border (McCalpin, 1983), to determine the approximate age of the terraces. He concluded that terrace T5 was so-called Bull Lake in age (about 150 ka), and that terrace T6 was so-called Pinedale in age (20–15 ka). Note that the headwaters of the Red River were glaciated, but ice did not extend into the portion of the valley discussed in this report. The river apparently aggraded during periods of glaciation and incised during interglacial periods: dynamics that have been observed elsewhere (Bull, 1991; Vincent and others, 1994). In addition, the rate of incision by the Red River has slowed. At Questa, the amount of net incision during the past 150 ka was about 12 m (about 0.08 m/ky), whereas the total incision was greater than 90 m over the past 700 ky or so (greater than 0.13 m/ky).

Pazzaglia (1989) also mapped debris fans emanating from watersheds along the mountain front just north of Questa (see cover photograph). In that area the piedmont is not dissected, which provides an ideal setting for accumulation of all sediment eroded from the watersheds and for identification of phases of aggradation that caused the fans to prograde. Cross cutting relations suggested the fans were of three distinct ages, and fans in the same age-category had similar ground-surface characteristics and soil development. These fans represent three episodes of aggradation, separated by periods of erosion, at least locally. The oldest episode was not dated directly. Comparison of the style and degree of soil development on the fans with that of landforms clearly associated with glacial moraines in the San Luis valley (McCalpin, 1983) led Pazzaglia (1989) to conclude that this episode was synchronous with Bull Lake glaciation. The fans of intermediate age exhibit soil development similar to that of landforms deposited elsewhere during the Pinedale glaciation, and Pazzaglia (1989) discovered a sample of charcoal with a radiocarbon age of $8,590 \pm 150$ years before present (B.P.) in one of these fans. Pazzaglia (1989) concluded that these fans were aggrading in the late Pleistocene through the early Holocene, and that the youngest fans were deposited during the middle to late Holocene, based on charcoal samples with radiocarbon ages of $4,850 \pm 140$ and $3,500 \pm 240$ B.P. that were discovered in those deposits.

The above information from the Questa vicinity suggests the following for the Red River Valley between Questa and the town of Red River. Over the timeframe of millions of years the valley was dominated by erosion. Over the timeframe of hundreds of thousands of years the valley incision was greater

near Questa than near the town of Red River, and there were likely pauses in incision. Over the timeframe of the last one or two hundred thousand years, stream incision was likely interrupted by periods of aggradation. The alternating stream dynamics were driven by major fluctuations in global climate.

Quaternary Landforms in Red River Valley

In order to understand the geomorphology of the Red River Valley, between the towns of Questa and Red River, the landforms were mapped (pl. 1) as part of this study. Deposits and geomorphic surfaces were examined in the field, and the surfaces were mapped with the aid of aerial photographs using a stereoscope. The aerial photographs were taken September 23, 1969, and were made available by Molycorp, Inc. Soil properties that change through time can be used to map landforms by age (for examples see Vincent and others, 1994; Vincent and Chadwick, 1994; Vincent, 1995), but for the following reasons the landforms in the study area were not mapped based on soil development. Note that descriptions of argillic and calcic soil horizons can be found in Birkeland (1984). In the more arid area near Questa, Pazzaglia (1989) observed fairly well developed argillic and calcic soil horizons in the older landforms and moderately to weakly developed calcic horizons in the younger landforms. However, neither argillic nor calcic soil horizons were observed by the author in deposits between Questa and the town of Red River. In addition, sediment color is dominated by the color of the parent material rather than being the result of soil formation through time. Radiocarbon age constraints are limited in number. Consequently, geomorphic features were mapped by origin rather than by age. Three features were mapped and are discussed in the following order: alteration scars, alluvium deposited by the Red River, and tributary alluvial fan deposits (pl. 1).

Although the hillslopes in the Red River Valley are generally forested, there are sites of unvegetated alteration scars (Meyer and Leonardson, 1990; McLemore and others, 2004). Those hillslopes are steep and rugged, and are a conspicuous pale yellow (fig. 1). As used in this report, “pale yellow” refers to a specific color mix (Munsell Color, 2000) that is imparted by the mineral jarosite, which is a weathering product of pyrite. The material of the scars consists predominantly of rhyolite or andesite bedrock that had been hydrothermally altered, as discussed in the section “Bedrock Geology.” Where these altered rocks are at or close to the ground surface, they undergo chemical weathering (Plumlee and others, 2007). The secondary sulfide minerals in these altered rocks are easily weathered, producing acid that promotes further disintegration of the rock. The result is a soil profile (Birkeland, 1984), although the low pH, presence of minerals like jarosite, and other soil-horizon characteristics are uncommon. The soil of the alteration scars erodes rapidly, as demonstrated in the section “Numerical Rates of Erosion.” The alteration scar sediment is transported as debris flows, and much of the debris-flow sediment has come to rest at the mouths of tributary watersheds forming debris fans. The chemistry of such debris-fan sediment is discussed briefly in the section “Fan-Sediment Mixtures.”

The sediments deposited by the Red River are dominated by well-washed sandy pebble-gravel or sandy cobble-gravel, with stratification inclined in the downvalley direction. These deposits compose the streambed (fig. 1), flood plain, and as many as four low terraces. The term “flood plain” has many usages (Graf, 1988). As used in geomorphology, a flood plain is a landform adjacent to a stream that is actively being constructed and maintained by that stream. Terraces are former flood plains that were abandoned because the stream incised. Most of the landforms created by the Red River (as opposed to tributary debris fans) are terraces. The stream terraces along the Red River are discontinuous in two ways. First, debris fans locally interrupt the sediments deposited by the Red River, as illustrated in figure 3, and the implications of this are discussed later in this section. Second, between debris fans the Red River terraces are not continuous, at least not at present, as illustrated for three terraces in figure 3. This means that the implications of the terraces should be interpreted with caution (Merritts and others, 1994), because the terraces may have never been continuous, or they once were continuous and now are preserved only locally. The longitudinal profiles of the terraces, however, tend to parallel that of the streambed (fig. 3); the heights of the terrace surfaces are fairly consistent, being about 2, 3.5, 5.5 or 8–9 m above the streambed, suggesting that there were once four continuous terraces. Therefore, the terraces are interpreted to represent an episode of stream incision (interrupted by periods of lesser aggradation), which was likely regional in nature rather than being controlled by local base-level processes (Merritts and others, 1994). Although limited in number, the radiocarbon age constraints available suggest that this episode of net incision occurred during the middle and late Holocene. For example, the stratigraphic exposure at site RR–2 (fig. 4, table 1) contained charcoal with an age of 5.4 ka and is part of the second-oldest terrace, whose surface (at site RR–2) is 5.3 m above the bed of the Red River. In the study area, the Red River flood plain is typically narrow, indicating that the lateral movement of the channel has been

minimal during the late Holocene. The Red River is not particularly dynamic, compared to other streams the author has studied, and this observation is relevant to the discussion in the section “Streambed Infiltration.”

Sediment deposited by ephemeral streams that are tributary to the Red River generally form alluvial fans, also called debris fans. The nature of the landforms largely depends on whether or not an alteration scar is currently present within its tributary watershed. Alluvial fans shed from watersheds that do not contain alteration scars are small, forested, and typically are not active at present based on two lines of evidence. First, most of these fans have no active stream channel, and many have been truncated at their distal margins by the Red River without having been gullied by their tributary streams. Second, the surfaces of the fans usually consist of a thin layer of organic duff covering a soil A-horizon that is dark with decomposed organic material. In this setting, development of organic A-horizons probably requires an absence of sediment deposition for centuries to millennia (Birkeland, 1984). Other than containing buried A-horizons, these fan deposits resemble Red River gravel in that they consist of clast-supported, sandy pebble-gravel or sandy cobble-gravel (deposited by water flow rather than debris flows) and are not pale yellow. Exceptions to this characterization are discussed in the next paragraph. Typically the deposits of these fans contain a few to several buried A-horizons. The exposure of site RR–4 contains three buried A-horizons (fig. 4). In a separate example not shown, eight buried A-horizons were observed in a 3-m-high exposure. Thus, these fans aggraded episodically and, being small, have not affected the geometry of the Red River in significant ways.

Certain alluvial fans shed from watersheds that do not contain alteration scars, however, resemble fans that currently have scars in their watersheds except that they are not active at present. They have surficial duff and organic A-horizons and typically do not have stream channels. An example of one such fan is located at the site labeled RR–3 on plate 1 (fig. 4). The significance of these fans is drawn out in the section “Implications of Erosion Data.”

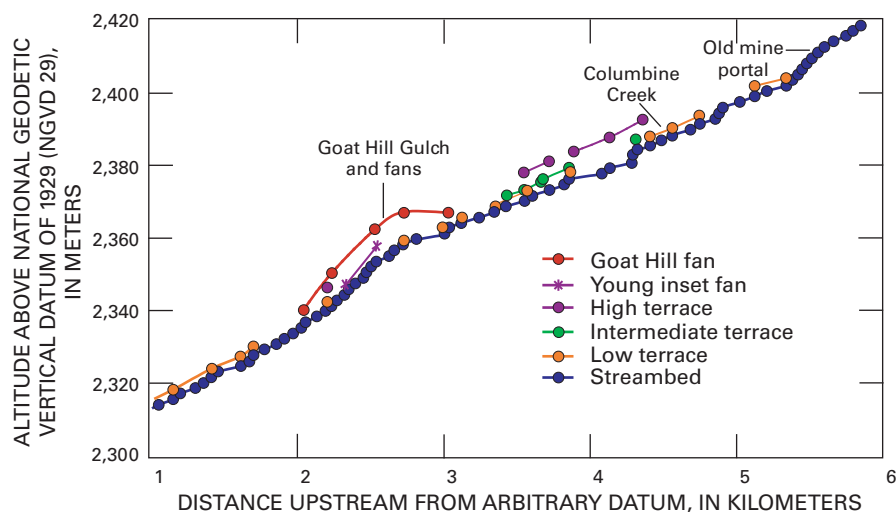
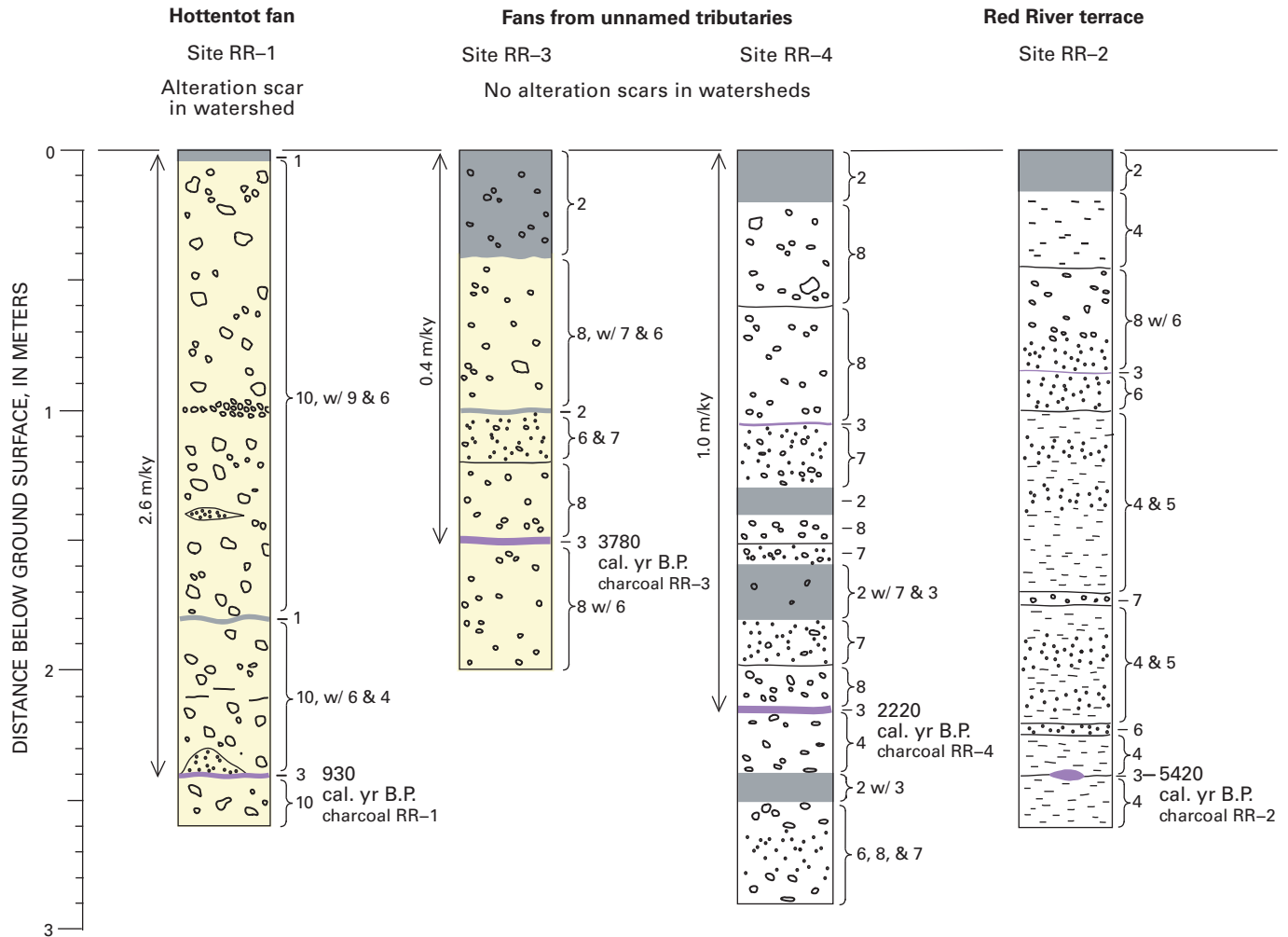


Figure 3. Longitudinal profiles of the Red River streambed and terraces in the vicinity of Goat Hill Gulch (pl. 1).



EXPLANATION OF STRATIGRAPHIC UNITS

- 1 Soil O-horizon; leaf litter and decomposed leaves, needles, and twigs
- 2 Soil A-horizon; predominantly silty sand, locally containing pebbles, and darkened by organic material locally including charcoal or ash
- 3 Charcoal layer or lens
- 4 Sandy silt lamina or thin beds of silt
- 5 Silty sand
- 6 Sand bed or lens
- 7 Pebbly sand
- 8 Sandy pebble-gravel
- 9 Open work pebbles
- 10 Sandy cobble-gravel

The first number indicates the dominant sediment type. Sediments present in relatively equal proportions are indicated by numbers separated by comas or ampersand. Sediments present in relatively small proportions are indicated by numbers preceded by the "with" (w/) symbol.

Figure 4. Stratigraphy at four sites with radiocarbon age constraints (table 1), located along the Red River (pl. 1).

Table 1. Data for radiocarbon samples collected in the Red River Valley between the towns of Red River and Questa, Taos County, New Mexico.

[Sampling sites are shown on plate 1, the sites are described in table 2, and the results are shown in figure 3; B.P., before present; m, meters]

Field number	Lab number	Material	$\delta^{13}\text{C}$ (per mil)	^{14}C Age ¹ (years B.P.)	Calibrated ages, in years B.P. ²			Depth below surface (m)
					Intercept(s) ³	1-sigma range ⁴	2-sigma range ⁴	
RR-1	GX 31211	Charcoal	-22.8	990±60	930	950–800	1,050–740	2.4
RR-2	GX 31212 AMS	Charcoal	-23.1	4,650±50	5,440; 5,420; 5,320	5,460–5,360 5,330–5,310	5,580–5,540 5,480–5,300	2.4
RR-3	GX 31213	Charcoal	-25.3	3,520±70	3,830; 3,790; 3,780; 3,730; 3,730	3,890–3,690	3,980–3,610	1.5
RR-4	GX 31214	Charcoal	-22.4	2,240±60	2,310; 2220; 2,210	2,340–2,150	2,350–2,070	2.15

¹Conventional radiocarbon age ($\delta^{13}\text{C}$ corrected), based on the Libby half-life (5,570 years) for ^{14}C , as reported by Geochron laboratories in years before A.D. 1950 (B.P.). The error is ± 1 sigma (δ) as judged by the analytical data alone. The sample was crushed if necessary and dispersed in water. The eluted clay/organic fraction was treated in hot dilute 1N HCl to remove any carbonates. It was then filtered, washed, dried, and combusted in oxygen to recover carbon dioxide for analysis.

²Ages calibrated (cal.) to calendar years B.P. using the CALIB4.3 program based on Stuiver and Reimer (1993) with data from Stuiver and Braziunas (1993) and Stuiver and others (1998). The 1998 atmospheric decadal data set and laboratory error multiplier $K=1$ were used in the calculations. All ages were rounded to the nearest decade.

³The intercept(s) of the radiocarbon age with the calibration curve.

⁴Calibrated age range(s) using the intercept method. 1 sigma = square root of (sample standard deviation² + curve standard deviation²); 2 sigma = $2 \times$ square root of (sample standard deviation² + curve standard deviation²).

Alluvial fans shed from watersheds that currently contain alteration scars typically consist of very poorly sorted, matrix-supported gravel that is pale yellow. The clasts are typically pebble and cobble in size, but boulders are occasionally present. The clasts are angular to subrounded. The matrix consists of sandy silt or silty sand. The deposits are somewhat cohesive and are able to hold a vertical face greater than 5 m high. The sedimentary beds tend to be discontinuous over length scales of 10 m, and stratification generally parallels the ground surface. Debris-flow levees are abundant. These fans are active. The dynamic nature of the stream channels on these fans has been observed since the onset of this project in 2001, and debris flows on these fans have proven hazardous in recent decades (Shaw and others, 2003; Plumlee and others, 2007). Evidence of partially buried living trees by debris-flow sediments is observed. The fans are forested, but duff is thin and discontinuous, and surficial organic soil A-horizons are not present or are thin (less than 5 cm). In addition, buried soil horizons are very few in number or are not present within the deposits, with site RR-1 serving as an example (fig. 4). The fans tend to have a single channel rather than multiple distributary channels typical of other types of fans (Vincent and others, 2004). Where the alteration scar in the watershed is particularly large, the fans are large and extend across the full width of the Red River Valley. The fan at the mouth of Goat Hill Gulch is a particularly good example (pl. 1). In those cases, the toe of the fan is partially breached by the Red River, and the tributary stream has incised into the distal portion of the fan.

These large fans forced the Red River to aggrade upstream from them, which is typical of sites where tributaries deliver more sediment, or larger sediment, than the main stream can transport away. The characteristic result is a segmented longitudinal

profile of the main stream (Miller and others, 2001; Vincent and others, 2007). Upstream from a fan, the main stream is not steep and is in a relatively wide alluvial valley bottom. At the downstream margin of a fan, the main stream is steep, often forming a bouldery cascade, the flood plain is narrow or absent, and terraces are absent and likely were never present in these locations. The segmented profile at the Goat Hill Gulch fan is particularly obvious (fig. 3), but segmentation also occurs at other fans or fan complexes along the Red River (fig. 2B). As is typical of the response to a base-level rise (Leopold, 1992), the aggradation upstream from the obstruction did not extend over long distances upstream. One implication of the recognition that the large debris fans caused aggradation is that the sediment at depth beneath the surfaces mapped as debris fans (pl. 1) should be dominated by debris-fan sediment rather than by Red River gravel, and this implication is used in the section “Sedimentary Facies and Hydraulic Conductivity.”

Although limited in number, the radiocarbon age constraints available suggest that the most recent episode of aggradation of the Red River upstream from the large fans began before the middle Holocene (fig. 4, table 1), which is consistent with the observations of Pazzaglia (1989). This episode of aggradation is discussed further in the section “Implications of Erosion Data.” The hydrologic consequences of the large debris fans are developed throughout the remainder of this report.

Erosion Rates

Watershed-scale erosion rates are calculated in this section in order to place the contemporary dynamics of the landscape into a long-term context. The relative rate of erosion of alteration scars and forested hillslopes is determined first and

is evaluated using fan-sediment chemistry. That relative erosion rate is then used to partition a numerical rate of erosion of the Hottentot watershed into the numerical rates of erosion of alteration scars and forested hillslopes.

Relative Rates of Erosion

The relative rate of erosion of alteration scars and forested hillslopes can be determined using the geometric properties of the landscape. Geomorphologists have long recognized that there are scaling relations between the areas of alluvial fans and the areas of their watersheds, and that these relations differ from one mountain range to another. Such relations are illustrated in figure 5A; where lines 1 and 2 are from Bull (1964), lines 3 and 4 are from Hooke (1972), line 5 is from Hooke and Roher (1977), line 6 is from Denny (1965), line 7 is from Rockwell and others (1984), and line 8 is from Pazzaglia (1989). The relation from Pazzaglia (1989) is reproduced in figure 5B in order to illustrate the scatter typical in these data. The scaling relation for the data presented in this report, for south-facing watersheds and their fans along the Red River, is presented in figure 6A, and a portion of that relation is reproduced as line 9 in figure 5A. This relation has unusually low values for both the exponent and coefficient, and these observations will be addressed after some background discussion.

Why do the scaling relations shown in figure 5 occur, and why do they differ from site to site? The relations occur because they approximate a mass balance. Watershed area is a proxy for the volume of sediment produced in a given time, which is the product of the area being eroded and the mean erosion rate. Fan area is a proxy for the volume of sediment stored in the fan over the same timeframe. If the mass-balance approximation was perfect, the exponent of the relations would be 1. Typically, however, the exponents are close to 0.9 (0.87 in fig. 5B), and they rarely fall outside the range of 1.0 to 0.8. Several explanations have been offered as to why the exponents are usually slightly less than unity (Cooke and others, 1993), but these issues are not a major concern of this report. The major differences among scaling relations are the values of the coefficient (0.995 in fig. 5B). Technically the value of the coefficient is the area of a fan with a drainage area of 1 km². The value of the coefficient typically ranges from 2.0 to 0.15 and controls the vertical position of the lines on diagrams such as figure 5A. Previous workers have suggested that the coefficients differ from site to site largely because the rates of erosion, which are controlled by climate and rock lithology, differ from site to site. Rapid erosion rates should result in a large value of the coefficient (Bull, 1968). For example, lines 1 and 2 in figure 5A are for nearby sites (that have a similar climate), but line 1 represents a site where the bedrock is composed of erodible shale, whereas line 2 is for a site where the bedrock is composed of more resistant sandstone (Bull, 1964). Certain tectonic conditions can also influence the coefficient (Denny, 1965; Rockwell and others, 1984). Along a given range front, the climate, lithology, and tectonics (and thus erosion rates) are often relatively uniform, and the data

from such sites have modest scatter (for example, fig. 5B). The data presented in this report for watersheds and fans along the Red River, in contrast, have large scatter (fig. 6A). The large scatter in the Red River data (fig. 6A) may be caused mostly by the large contrast in the rates of erosion of alteration scars compared to the rates of erosion of forested hillslopes. In other words, erosion rates are not spatially uniform and this concept is put to use in the next paragraph.

A numerical value of a relative erosion term (E) can be determined by manipulating the data documented in Appendix 1 and shown in figure 6A. The relative erosion term expresses how much faster the scars erode compared to forested areas, and it was derived in the following way: The volume of sediment eroded (V_c) is equivalent to the volumetric rate of erosion for the whole watershed (Rt) multiplied by the appropriate time period (T).

$$V_c = Rt \times T \quad (1)$$

For watersheds in the Red River Valley, the volumetric rate of erosion must account for the vertical erosion rate for forested hillslopes (R_n) over the map area of those hillslopes (A_n) as well as the vertical erosion rate for alteration scars (R_s) over the map area of those scars (A_s).

$$Rt = (A_n \times R_n) + (A_s \times R_s) \quad (2)$$

A factor expressing the composite erosion amount (C) was developed by dividing equation 2 by the erosion rate for forested hillslopes,

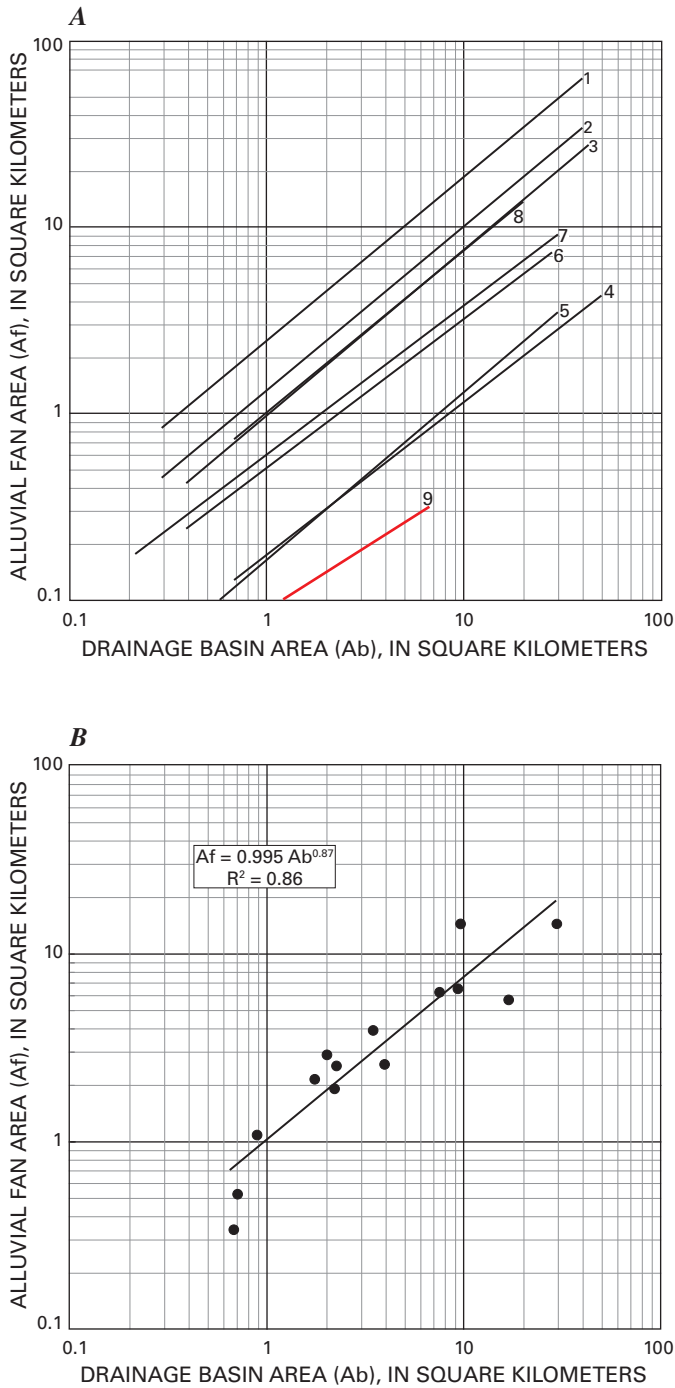
$$C = Rt / R_n = A_n + (A_s \times E) \quad (3)$$

where E equals the ratio of the erosion rate of scars and non-scarred areas

$$E = R_s / R_n. \quad (4)$$

Data for the Red River tributary watersheds were applied to equation 3, and the relative erosion term was changed in an iterative manner in order to maximize the correlation coefficient of the regression equation. The correlation coefficient is close to that maximum when the relative erosion term is between 50 and 100 and is at that maximum when the relative erosion term is 70. Figure 6B illustrates the result of using a relative erosion term of 70 in equation 3. The relative erosion value of 70, which indicates that scars erode 70 times faster than forested areas, is used later to partition the short-term erosion rate for the Hottentot watershed in the section "Numerical Rates of Erosion."

The procedure used to develop figure 6B accounts for the two distinct areas of erosion, but, although substantially improved, the correlation coefficient remains low. In addition, the relation's exponent is quite low compared to the relations for other sites (fig. 5) and compared to a precise mass balance where the exponent should be 1. The low exponent of the curve in figure 6B could have several possible explanations. The conditions at present may not accurately represent conditions over the longer term. Certain alteration scars may have enlarged through time while other scars may have healed and vegetated. More important, it is likely that the scaling factor for fan area and fan



EXPLANATION

Number	Source
1	Bull, 1964
2	Bull, 1964
3	Hooke, 1972
4	Hooke, 1972
5	Hooke and Rohrer, 1977
6	Denny, 1965
7	Rockwell and others, 1984
8	Pizzaglia, 1989
9	This study

Figure 5. Scaling relations for the areas of fans and their watersheds, (A) at various locations in the western United States (sources are given in the text) including within the Red River Valley (line 9, in red), and (B) near Questa (after Pazzaglia, 1989). The data set for graph (B) consists of watersheds that face west, are located along the range front of the Taos Range north of Questa, and do not contain alteration scars.

volume is not a one-to-one relation. At the sites used to develop the relations shown in figure 5A, the fans reside on broad desert piedmonts where there is comparatively unrestricted space available for deposition of fan sediments. The Red River Valley, in contrast, is narrow, and large fans have restricted areas for deposition and thus thicken through time. In other words, fans with large map areas likely have disproportionately large volumes compared to fans with small areas, which would act to lower the exponent of the correlation line shown in figure 6B. This concept is evaluated in the remainder of this section with the intent of improving the relation in figure 6B.

The concept that fans with large map areas have disproportionately large volumes compared to small fans can be demonstrated using the geometry of simple objects. For example, the volume of a cube can be calculated as the area (of any side of the cube) with exponent of 1.5. Doubling the area of the sides increases the volume by a disproportionate amount, by about 2.8 times. A cube is also a useful example because the dimensions of volume result entirely from the exponent of the equation. Area (for example, square meters) raised to the 1.5 power results in the dimensions of volume (cubic meters). It follows that the volume of a horizontal cone, as a second example, can be calculated as the map area raised to the 1.5 power, multiplied by some dimensionless coefficient. The value of the coefficient depends on the proportionality of the cone's height and basal radius. Unfortunately, the area/volume scaling relation for debris fans in the Red River Valley cannot be established using the geometry of one single solid object, such as a section of a cone. Yet, the map area of fans, with exponent of 1.5, should yield a reasonable prediction of the shape of the relation if the coefficient can be estimated using site-specific information. For that reason, the volume of the debris fan at the mouth of Goat Hill Gulch was estimated, as explained in the next paragraph. This fan-volume information is used to improve the scaling relation of figure 6B and also is used in the section "Implications of Erosion Data" to evaluate the time period over which the debris fans developed.

The fan at the mouth of Goat Hill Gulch (pl. 1) is used because information about the base and sides of the deposit is available. The fan sediments rest on a bedrock erosion surface, and estimation of the geometry of the erosion surface is guided by two observations. First, the deepest level of the bedrock erosion surface in the Red River Valley adjacent to the mine is known. The depths used here to determine sediment thickness are based on the analysis of well logs made in the section "Thickness of Alluvial Aquifer." Second, the shape of the bedrock erosion

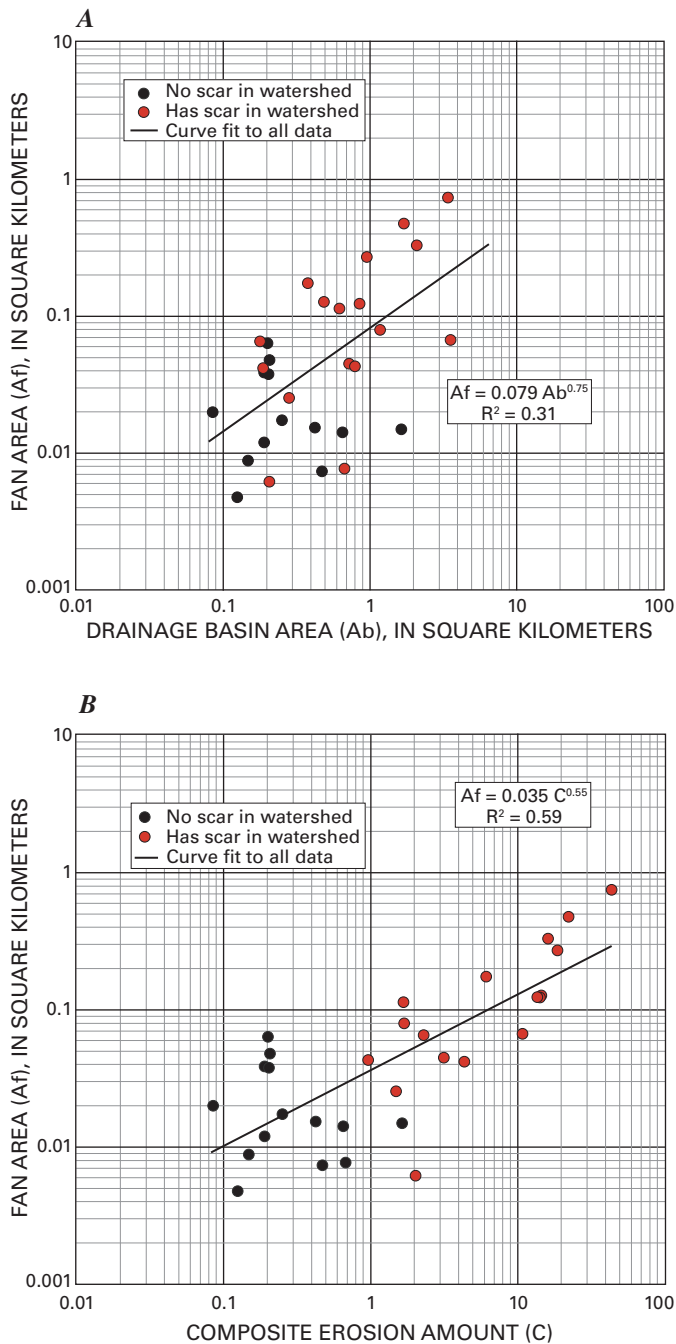


Figure 6. Scaling relations for the areas of fans and properties of their watersheds in the Red River Valley. All watersheds are tributary to the Red River, face south, and are numbered on plate 1. The area data are in Appendix 1. Graph (A) illustrates the relation for fan area and total watershed area. Graph (B) illustrates the relation for fan area and a composite erosion amount estimated for their watersheds. That composite is discussed in the text, and the relation shown embodies the assumption that alteration scars erode 70 times faster than forested hillslopes.

Hill Gulch (watershed 7A) but also from what is informally referred to as “little Goat Hill Gulch” (watershed 7B). The bulk of this fan is contained within the Red River Valley, as opposed to within the tributary valleys, and in map view that portion has the shape of a segment of a circle with radius of 1,230 m and cord length of 1,600 m. That cord roughly follows the 7,880-ft contour on plate 1. This portion of the fan is idealized as having two parts. One part is beneath the surface and is shaped approximately like an upright cylinder 50 m tall, cut by a plane that passes through the cord and dips approximately south at 35 degrees. The dipping plane accounts for the inclination of buried hillslopes on the north side of the valley. That solid object has a volume of about 13.4 million cubic meters (m^3). The second part is near the surface and is shaped approximately like a truncated cone with maximum thickness of 12 m at the cord and zero thickness along the arc. This solid object has a volume of about 4.5 million m^3 . The sediment volume within Goat Hill Gulch proper was calculated assuming the sediment thickness decreases linearly from 60 m at the mouth (at the cord used in the previous calculations) to zero meters at the upstream end. A series of trapezoidal cross sections were constructed for the main valley for integration of volume, and the four small tributary fans were modeled as well. The volume of sediment within Goat Hill Gulch was about 8.9 million m^3 . The sediment cross section at the mouth of “little Goat Hill Gulch” (at the cord used in the previous calculations) resembles a trapezoid with top width of about 230 m and maximum thickness of about 60 m. Moving upstream, the cross-sectional area decreases to zero over 1,000 m. This tapered object has a volume of about 4.6 million m^3 . The total volume of tributary sediment, within the simple objects previously discussed above is about 31.5 million m^3 . A porosity of 25 percent was assumed in order to remove the pore-volume from the bulk-volume of the sediment, resulting in a solid volume of about 24 million m^3 .

In order to more closely approximate an erosion/deposition mass balance, fan volume was assumed to equal fan area raised to the 1.5 power, multiplied by a coefficient determined by fitting the curve to the data calculated for the fan at the mouth of Goat Hill Gulch (fig. 7A). Data for the Red River tributary fans were then applied to the resulting equation shown in figure 7A, and the relative erosion term again was changed in an iterative manner in order to maximize the correlation coefficient of the regression equation. Once again,

surface in cross section is best idealized as a trapezoid with a horizontal base and with sides (which are buried hillslopes) inclined 35 degrees. The use of this shape is justified by the analyses made in the two sections “Thickness of Alluvial Aquifer” and “Cross-Sectional Geometry of the Aquifer.”

In order to estimate the volume of the fan at the mouth of Goat Hill Gulch (pl. 1) it was broken into parts, each of which can be idealized using the geometries of simple solid objects. The geometric relations used are basic; for example, they can be found in Appendix III of Beakley and Leach (1972). Note that this sedimentary deposit was derived in large part from Goat

the correlation coefficient is close to that maximum when the relative erosion term is between 50 and 100, and is at that maximum when the relative erosion term is 70. Figure 7B illustrates the result for a relative erosion term of 70, and the value of 70 is used to partition the short-term erosion rate for the Hottentot watershed developed in the section “Numerical Rates of Erosion.” The procedure described in this paragraph and used to develop figure 7B accounts for the nonlinear relation of fan area and fan volume in a rational but approximate way. Compared to the relation in figure 6B, the exponent of the relations in figure 7B is substantially improved, which is befitting a relation whose underpinnings are a mass balance where the exponent should be 1. This mass balance is discussed further in the section “Implications of Erosion Data.”

Fan-Sediment Mixtures

Fan-sediment chemistry is used here in an attempt to evaluate the relative erosion value of 70, developed in the preceding section. The mineralogy of hydrothermally altered rock is distinct compared to rock that was not altered. Presumably, most forested hillslopes are for the most part underlain by rock that was not altered. Therefore, the chemistry of fan sediments should reflect the mixture of sediment that was derived from alteration scars and sediment that was derived from forested hillslopes (fig. 8).

The sediments of 10 tributary fans (pl. 1) were sampled by USGS staff (Stan Church, David Fey, and the author). At each fan, a sample was obtained from the largest exposure of sediment available and within the interval of 1 to 4 m beneath the ground surface. Subsamples were collected from approximately 20 randomly selected points in the exposure. The subsamples were combined to form a composite sample, and this material was passed through a 2-mm stainless steel sieve. The fine fraction was then analyzed in the laboratory. The sediment was analyzed using inductively coupled plasma-atomic emission spectrometry (ICP–AES) as documented by Briggs (2002). The ICP–AES data for major, minor, and trace elements in the fan sediments are presented in Church and others (2005). The sample labels used in this report and the labels used by Church and others (2005) for those samples are given in Appendix 2. The sediment also was analyzed for total sulfur by combustion by Zoe Ann Brown (U.S. Geological Survey, written commun., 2005). The method of analyzing total sulfur by combustion is described by Brown and Curry (2002), and the data for total sulfur in the fan sediments are presented in Appendix 2.

Using chemistry to verify the mix of sediment derived from alteration scars and sediment derived from forested hillslopes is complicated because the bedrock in watersheds consists of rhyolite and andesite in proportions that are not readily available. Rhyolite and andesite have large differences in silica and iron, for example. For that reason this report used two elements enriched during hydrothermal alteration, namely lead and sulfur. Lead is enriched in scar sediment (Briggs and others, 2003) and should have remained immobile during weathering and transport. Leaching studies of scar material

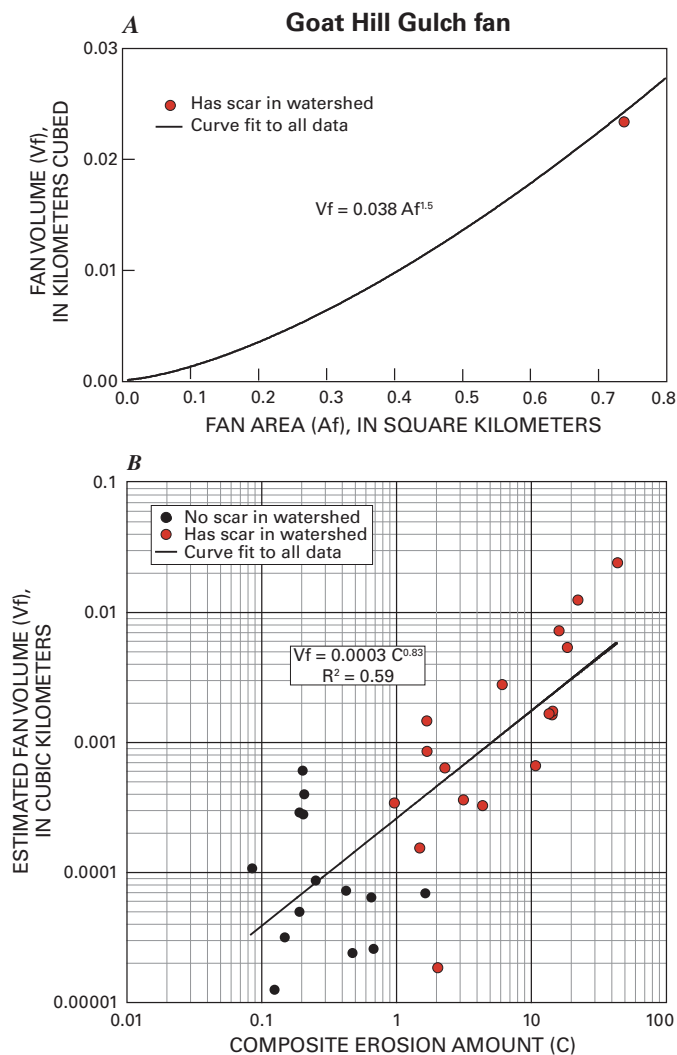


Figure 7. Scaling relations for tributary fans within the Red River Valley, which (A) attempt to reconcile the nonlinear relation of fan area and fan volume, and (B) attempt to approximate the necessary conservation of the mass eroded from watersheds with the mass deposited in fans. Terms and methods are defined in the text.

(Smith and others, 2007) observed that the concentration of lead in the leachates was very low compared to that for zinc, copper, and other metals. In addition, the concentration of lead was very low and usually less than detectable in ground-water samples from wells (LoVetere and others, 2004), in samples from seeps and springs (Sara LoVetere, U.S. Geological Survey, oral commun., 2005), and in stream-water samples (McCleskey and others, 2003; Maest and others, 2004) from within the study area. Sulfur is abundant in scar sediment (Briggs and others, 2003), but some sulfur may have been transported past the fans in stream water. Leaching studies of scar material (Smith and others, 2007) indicated that the concentration of sulfate in the leachates was large. In addition, sulfur, in the form of sulfate, was the dominant anion in samples of ground water (LoVetere and others, 2004) and in stream-water samples (McCleskey and others, 2003; Maest and others, 2004) from within the study

area. Thus, the concentration of sulfur should be high in fan sediments dominated by scar material but not quite as high as in the original scar material.

The relative amounts of sediment in a fan that was derived from alteration scars were predicted using the areas of scars, the areas of forested hillslopes in the watershed, and the relative erosion value of 70 (fig. 8). For example, if a watershed were half forested and half scar, the fans should contain 70-parts scar sediment for every 1-part sediment derived from forested areas. Concentrations of elements in fan sediments should fall proportionally between that of the two end-member source materials. The concentrations of elements in those two end-member sources were taken as the median of the values for the appropriate samples that are available. The concentrations of lead and sulfur in alteration-scar materials were measured by Briggs and others (2003), and their values are plotted in figure 8 by using a horizontal-axis value of 100. The concentrations of elements in rock underlying forested hillslopes were estimated using the fan-sediment data presented in this report for watersheds that have no alteration scars, and the results for one sample of “unaltered composited colluvium” analyzed by Briggs and others (2003), which are plotted in figure 8 by using a horizontal-axis value of zero.

The observed lead (fig. 8A) and sulfur (fig. 8B) concentrations in fan sediments generally correspond with the predicted mixing lines. The concentrations of sulfur in fan sediments tend to fall slightly below the predicted mixing line (fig. 8B), as expected, because sulfur is mobile and some of it leaves the sites of clastic deposition in water. The concentrations of lead in fan sediments tend to fall slightly above the predicted mixing line, which, if anything, suggests that the rapid erosion rate for alteration scars calculated in the section titled “Erosion Averaged Over the Past Millennia” could be too low.

Numerical Rates of Erosion

Two numerical erosion rates are calculated in this section for the Hottentot Creek tributary watershed (pl. 1), which is largely unaffected by human activities and currently (2006) contains a large alteration scar. The Hottentot watershed was chosen because a radiocarbon-age constraint is available for the fan at the mouth of that tributary. The erosion rates are cast as the vertical lowering of the landscape averaged over the area of the watershed, which is often referred to as a denudation rate. The results are given in millimeters per year. For reference, one millimeter per year is equivalent to one meter per thousand years and also one kilometer per million years.

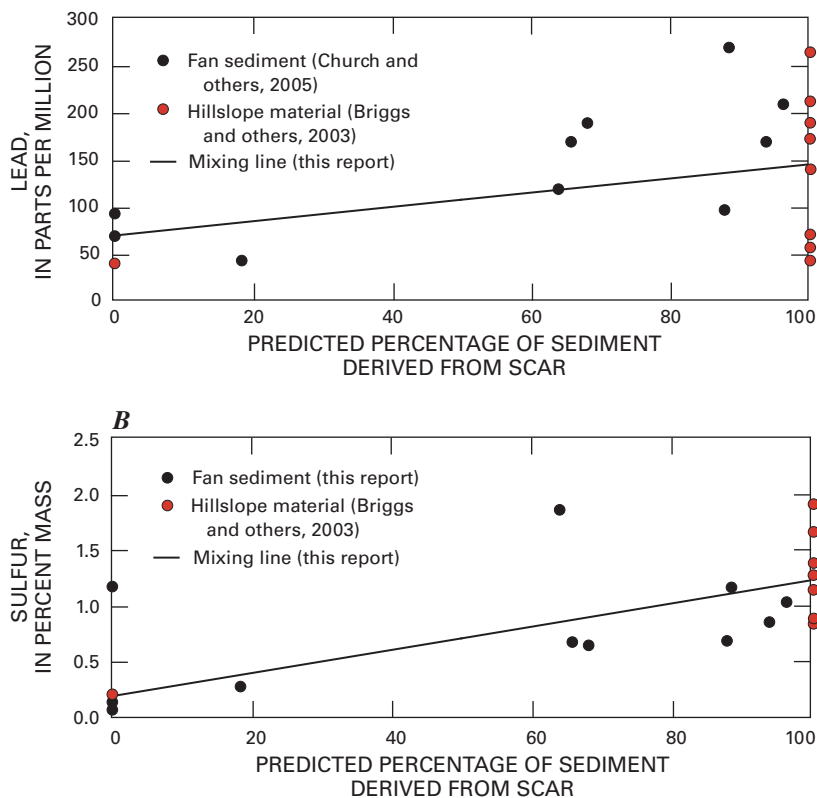


Figure 8. Measured lead (A) and sulfur (B) concentrations in fan and hillslope sediments within the Red River Valley, and the correspondence of that data with the predictions of the proportional source (forested hillslopes and alteration scars) of the sediment from this report. For the fan deposits, the lead data is from Church and others (2005) and the total sulfur data is from Appendix 2. For the hillslope end-members (shown in red), the sulfur and lead data are from Briggs and others (2003).

Erosion Averaged Over Millions of Years

In order to calculate a long-term erosion rate, the topography of the landscape must be known with some certainty for some specific time in the geologic past. Comparison of that ancient topography with the current topography mapped on plate 1 allows the volume of missing rock to be calculated. The nature of Questa caldera volcanism allows estimation of an ancient topography. After eruption of the Amalia Tuff 26 Ma, the landscape of the study area was a broad and low-relief plateau. Ash-flow sheets have nearly planar top surfaces that dip gently, typically less than a few degrees, because they are the result of gaseous ignimbrites (Peter Lipman, U.S. Geological Survey, written commun., 2005). The Bishop Tuff in California (Gilbert, 1938) provides an example of the planar surface of an ash flow that has undergone little erosion. Estimating the altitude of the top surface of the Amalia Tuff is complicated by the fact that its top surface is largely eroded away and by the fact that the tuff has locally been displaced and tilted by faulting. Fortunately, the tuff is present in the Hottentot watershed, which means that the present topological reference frame can be used without concern for the regional uplift that likely occurred over the past 26 million years. Based on the mapping of Lipman and Reed (1989), the highest exposure of the Amalia Tuff in the Hottentot watershed is at an altitude of 3,341 m (10,962 feet). Toward the north, near the northern margin of the caldera, exposures of the tuff occur as high as 3,658 m (12,000 feet); yet, in that same area the top surface of the tuff is also in contact with younger volcanic rocks at 3,353 m (11,000 feet). If the top surface of the Amalia Tuff were still present at the site of the Hottentot watershed,

it would have an altitude of at least 3,353 m and might be as high as 3,658 m. These two constraints on the altitude of the ancient surface, in comparison with the current topography of the watershed, allow the amount of missing rock to be estimated and denudation rates calculated. Assuming 3,353 m for the top of the tuff, the denudation rate is 0.015 mm/yr. Assuming 3,658 m for the top of the tuff, the denudation rate is 0.027 mm/yr. Given the uncertainties in the calculation, a conservative expression of the result is 0.02 ± 0.01 mm/yr. This rate is similar to that determined for many landscapes (fig. 9).

Erosion Averaged Over the Past Millennia

The late-Holocene erosion rate for the Hottentot watershed presented in this section is unusually rapid. For that reason, special attention is given to factors that could result in an artificially rapid rate, namely an underestimate of the time over which erosion occurred or an overestimate of the sediment eroded.

In order to calculate a short-term erosion rate, an estimate is made for the volume of sediment deposited in the Hottentot fan over a specific period of the recent past. The time period is based on the age of radiocarbon sample RR-1 (tables 1–2; fig. 4). The calibrated age (Stuiver and Reimer, 1993) of the sample is 930 cal. yr B.P. (before 1950). The sample was analyzed in 2004; thus, 54 years was added to the standardized radiocarbon expression of age so as to avoid underestimating the period of sediment deposition. In the following calculation 984 years was used for the period of sediment erosion and accumulation, but in the text this is rounded to “one thousand years” for the sake of simplicity. There are two types of errors

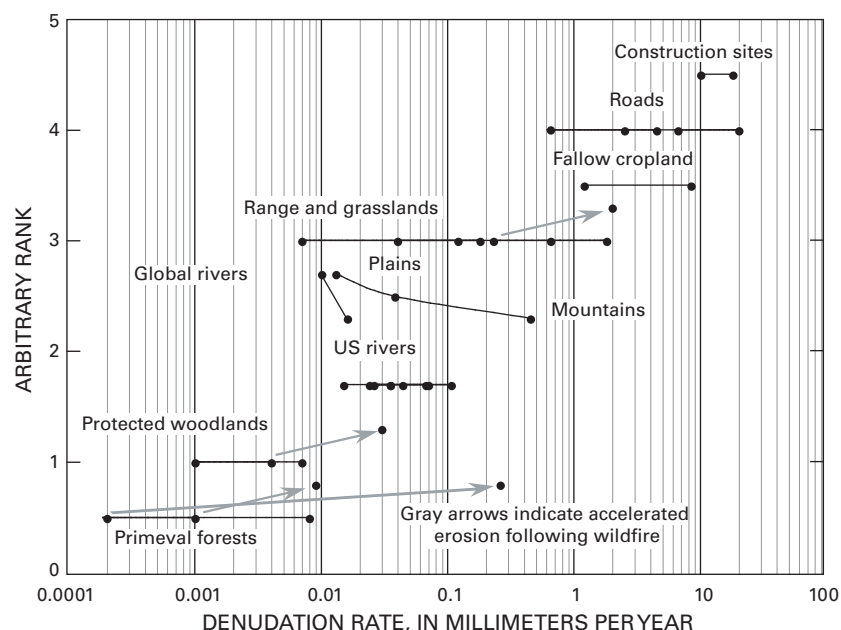


Figure 9. Range in measured landscape erosion rates, expressed as the rate of vertical lowering of the substrate averaged over the watershed in question. The gray arrows indicate accelerated erosion following a wildfire. Data are from Dunne and Leopold (1978) and Milliman and Meade (1983).

Table 2. Locations and descriptions of radiocarbon sample sites.

[Location coordinates are latitude and longitude in decimal degrees; m, meter; cm, centimeter]

Field number	Location coordinates	Material	Notes on sample and location
RR-1	36.707950°N –105.431494°E	Charcoal	Sample from Hottentot alluvial fan in exposure cut by Hottentot Creek about 20 m upstream from State Highway 38. Charcoal from an 8-m-long contact defined by thin, discontinuous lenses of charcoal and partially burned wood judged to be the result of an in-place burn. The sample was 2.4 m beneath the surface of the fan.
RR-2	36.680601°N –105.510316°E	Charcoal	Sample from high terrace of Red River, located on the south side of the Red River about 350 m upstream from the confluence of Columbine Creek, in exposure cut by the Red River. Sample from lens of charcoal on a 5-m-long stratigraphic contact containing other lenses of charcoal and ash. Sample judged to have burned in place. The terrace surface is 5.3 m above, and the sample was 2.9 m above, the low-flow water level of Red River. The sample was 2.4 m beneath the terrace surface.
RR-3	36.705522°N –105.404911°E	Charcoal	Sample from fan of unnamed tributary entering valley from south; within the town of Red River, beneath the most easterly ski lift, directly across from the mouth of Mallette Creek, and in an exposure cut by the Red River. Charcoal was part of a 4-m-long A-horizon, locally baked at the base, and judged to have burned in place. The sample was 1.5 m beneath the surface of the fan.
RR-4	36.694781°N –105.487308°E	Charcoal	Sample from fan of unnamed tributary entering valley from the south, directly south of the intersection of State Highway 38 with the entrance road to the MolyCorp, Inc. mill complex, in exposure cut by the Red River. Charcoal part of a 7-m-long, 2-cm thick, ash-rich A-horizon judged to have burned in place. The sample was 2.15 m beneath the surface of the fan.

associated with this age constraint. The age of the sample has an uncertainty of plus 12 percent and minus 20 percent, using the 2-sigma age range based on the laboratory uncertainty (table 1). Dating sediment using most radiocarbon ages also involves a systematic error. Radiocarbon samples (excluding roots and translocated particles) are older than the sediments that contain them, by at least one growing season, and in some cases are centuries older (Friedman and others, 2005; K.R. Vincent, U.S. Geological Survey, unpublished data, 2002). If the period of erosion is erroneously too long, the resulting rate will be too low. Thus, if the denudation rates calculated in this section are substantially in error because of the age constraint, they are too low.

Estimating the volume of sediment deposited on the fan over the past 1,000 years also involves uncertainties. Sample RR-1 was extracted from a depth of 2.4 m beneath the surface of the fan (table 2). The simplest approach is to assume that over the past thousand years every point on the fan aggraded 2.4 m; this is referred to as the uniform thickness model. There are no geomorphological reasons to think the bed of thousand-year-old sediment systematically thickens or thins away from the fan centroid. This is true in the transverse directions as well as the longitudinal directions. In the exposures available in the study area, the most extensive being where the highway is cut into the Goat Hill Gulch fan, bedding planes generally parallel the ground surface of the fans. Elsewhere, it has been shown that alluvial fans develop over thousands of years without changing gradient (Vincent and others, 2004). For these reasons, the uniform thickness model probably gives the most realistic estimate of fan volume, which is 2.4 m times fan area. A minimum estimate of sediment volume can be made by assuming the sediments are

thickest at the site of sample RR-1 and thin to zero thickness at the perimeter of the fan. This is referred to as the tapered thickness model. Using the geometry of an inverted, upright and symmetrical cone as a guide (Beakley and Leach, 1972), the volume of the tapered thickness model is approximately one-third of the volume of the uniform thickness model. Neither model accounts for sediment eroded from the watershed that did not come to rest on the fan. A portion of the sediment detached from alteration scars during thunderstorms, and transported as debris flows, passes across the fans and enters the Red River (Plumlee and others, in press). Therefore, denudation rates based on the tapered thickness model are unrealistically low, and denudation rates based on the uniform-thickness model, although more realistic, may also be too low.

The final steps in the denudation calculation involve mathematically compacting the sediment back into rock and determining the mean thickness of the material over the watershed of interest. A porosity of 25 percent was assumed in order to remove the pore volume from the bulk volume of the sediment (Vincent and Chadwick, 1994). The denudation calculations were first done by assuming the sediment was uniformly derived from the entire Hottentot watershed. Then the calculations were done a second time assuming the sediment was derived solely from the alteration scars present in the Hottentot watershed. It is likely that most of the sediment was shed from the alteration scars rather than from adjacent forested hillslopes.

The results indicate that over the past thousand years the Hottentot watershed has eroded rapidly. The tapered-thickness model indicates the following: If the sediment was derived uniformly over the whole watershed, the denudation rate exceeded 0.2 mm/yr; but if the sediment was derived solely

from the alteration scars, the scar denudation rate exceeded 1.0 mm/yr. The uniform-thickness model indicates the following: If the sediment was derived evenly over the whole watershed, the denudation rate was (or may have exceeded) 0.5 mm/yr; but if the sediment was derived solely from the alteration scars, the scar denudation rate was (or may have exceeded) 2.9 mm/yr. Few natural landscapes erode at these rates (fig. 9), particularly for periods as long as a thousand years, and these rates are usually exceeded only at sites of intense disturbance by humans.

The relative erosion value of 70, developed in the section “Relative Rates of Erosion” is now used to partition the late-Holocene erosion rate for the Hottentot watershed. The uniform thickness model indicated that if the sediment was derived uniformly over the whole watershed the denudation rate was (or may have exceeded) 0.5 mm/yr, on average over the past thousand years. The portion of the Hottentot watershed that is not scarred is 4.7 times larger than the area composed of alteration scars. To achieve a watershed composite rate of 0.5 mm/yr, it follows that the forested areas eroded at 0.04 mm/yr and the scars eroded at 2.7 mm/yr.

Both of these rates are larger than the long-term rate of 0.02 mm/yr calculated for the past 26 million years, which is to be expected. Over the long term, the rate of erosion likely increased through time for two reasons; first, starting from a low-relief plateau, the area consisting of steep hillslopes, which are more prone to erosion, must have increased through time. Second, the landscape had to erode (lower) hundreds of meters (Steve Ludington, U.S. Geological Survey, written commun., 2005) through more resistant rock before large areas of altered rock became exposed to the processes of weathering and erosion. The erosion rate for forested hillslopes compares favorably with historical measurements of erosion (fig. 9). The 0.04 mm/yr rate is for the late Holocene during which there were occasional forest fires, as demonstrated by the presence of charcoal in the sedimentary deposits (fig. 4), followed by periods of forest recovery. Immediately after wildfires, erosion rates increased substantially. For example, compare the erosion rates for forests and woodlands where fires did not occur in the measurement period (solid circles at the tails of gray arrows in fig. 9) with rates measured after fires (solid circles at the heads of gray arrows in fig. 9). The alteration-scar erosion rate of 2.7 mm/yr, in contrast, is unusually rapid compared to erosion rates determined for undisturbed sites in general (fig. 9). The reason the alteration scars erode so rapidly is that the alteration mineralogy is such that the geochemical processes involved with near-surface chemical weathering cause the rock to decompose rapidly.

Implications of Erosion Data

In addition to the inherent value of the erosion rates presented in the preceding sections, three broader implications can be drawn from these results.

Disparity of Short- and Long-Term Rates

Over the past thousand years the Hottentot watershed has eroded about 25 times more rapidly than the average erosion rate for that watershed over the past 26 million years. This disparity between the short-term and long-term denudation rates is one line of evidence suggesting that the alteration scars may not have been persistent in the landscape through geologic time. As mentioned in the preceding section, it took considerable time for the landscape to erode (lower) to the level of the altered rock. Even after that occurred, however, it seems that the surficial expression of each zone of altered rock may not have resembled what we refer to as alteration scars in all places at all times. There is stratigraphic evidence germane to this issue, as discussed in the section “Quaternary Landforms in Red River Valley.” Namely, certain debris fans contain sediment that was clearly shed from alteration scars despite the fact that scars are not currently present in the watersheds of those fans. Together, these two lines of evidence demonstrate that alteration scars healed (became vegetated) and reformed through geologic time, confirming the hypothesis of Meyer and Leonardson (1990). At present, thunderstorms are particularly effective at eroding alteration scars (Plumlee and others, in press). It is tempting to speculate that changes in the frequency of intense thunderstorms during the Holocene (for example, Knox, 2000) influenced the healing or rejuvenation of alteration scars, but the exact mechanisms are not known.

When was the Bedrock Base of the Valley Last Carved?

The erosion rates presented in this report also allow a rare opportunity to estimate when the Red River last eroded to its deepest level before partially filling the valley with the sediment that hosts the shallow alluvial aquifer. This estimate is preceded by some background discussion. The bottom of most mountain valleys, including the Red River Valley, is composed of alluvium resting on an erosion surface carved into bedrock. The deepest parts of these erosion surfaces were carved by streamflow processes (rather than hillslope processes) that collectively have been called “corrasion” (Powell, 1875; Gilbert, 1877; Wohl, 1998). In certain mountain valleys, and usually only along relatively short reaches, the streambed is composed of exposed bedrock (Tinkler and Wohl, 1998). Thus, globally, corrasion is occurring only locally at present. To the author’s knowledge, the issue of when in the past corrasion was occurring in the more typical mountain valleys, the ones partially filled with alluvium, has received little attention.

The timing of periods of corrasion in the Red River Valley is partially constrained by what is known about periods of aggradation. In many areas throughout the Western United States, aggradation of alluvium occurred during glacial or pluvial episodes (Bull, 1991; Vincent and others, 1994), and this includes the Red River at least near Questa (Pazzaglia, 1989). In addition, stream incision into alluvium occurred during interglacial periods such as the Holocene. The sequence of terraces illustrated in figure 3 demonstrates that aggradation of the Red River (prior to the middle Holocene) was followed

by incision of lesser magnitude, and at least part of that incision occurred in the late Holocene. The Holocene has been a relatively long interglacial episode (Chappell and Shackleton, 1986). Yet, like most mountain streams, the Red River is not at its deepest level of incision, as demonstrated in the section “Thickness of Alluvial Aquifer,” and therein lies something of a paradox. The conditions that caused streams to transport away all of the sediment delivered to them, which allowed the erosion surface in the valley bottoms to be carved, are not clear. A major problem is that the timing of the corrasion episode(s) is not known. For example, consider the rivers in and near New Mexico discussed by Love and Connell (2005). Rivers where glaciation occurred in the headwaters typically flow on alluvium that is thin, and the timing of the last period of bedrock corrasion in these valleys occurred in the late Pleistocene, but the precise timing is not known. Rivers on the Colorado Plateau of New Mexico, where glaciation did not occur in the headwaters, had different histories. These rivers flow on thick sequences of alluvium, and the last period of corrasion of bedrock occurred prior to the late Pleistocene, evidently before, and perhaps long before, 80,000 years ago (Love and Connell, 2005). Establishing the timing of the most recent episode of corrasion by the Red River is the objective of the following paragraph.

The procedure involves estimating the volume of sediment contained in a fan and then using the denudation rates to estimate the timeframe over which the sediment accumulated. The fan at the mouth of Goat Hill Gulch (pl. 1) is used because its geometry is fairly simple and fairly well constrained, and most of the sediment beneath the mapped area of the fan likely consists of sediment delivered from the tributary watersheds rather than sediment delivered by the Red River. The justification for this statement is developed in the section “Sedimentary Facies and Hydraulic Conductivity.” The volume (minus porosity) of that debris fan is about 24 million m^3 , as estimated in the section “Relative Rates of Erosion.” The denudation rates of 0.04 mm/yr for forested areas and 2.7 mm/yr for alteration scars, developed in the section “Numerical Rates of Erosion,” were applied to the appropriate areas of the Goat Hill watersheds (Appendix 1). The resulting period of sediment accumulation is about 14,000 years. Alternative estimates of 11,000 years and almost 16,000 years come from applying the 2-sigma age range (table 1) resulting from the uncertainty reported by the laboratory for the radiocarbon age of sample RR-1. There is additional, but unknown, uncertainty resulting from the estimate of fan volume.

This evidence that the Red River began to aggrade about 14 ka suggests that the preceding episode of bedrock corrasion occurred during the period of transition from full glacial conditions to the conditions of the Holocene. Technically, this age of 14,000 has units of calendar years before A.D. 2004. According to Stuiver and Reimer (1993), that is equivalent to 11,900 “radiocarbon years before A.D. 1950” (^{14}C yr B.P.), which is the standard way radiocarbon laboratories, and many authors, report ages. In the mountains of Colorado, as summarized by Vincent and others (2007), glaciers began to retreat at about 14,000 ^{14}C yr B.P., and the last remaining ice

may have disappeared during the anomalously warm interval between 12,500 and 10,700 ^{14}C yr B.P. Thus, the available evidence suggests that the Red River incised and evacuated most sediment from the valley during deglaciation only to begin to aggrade again just prior to the Holocene. Aggradation occurred through most of the Holocene. Between 9,600 and 5,400 ^{14}C yr B.P. the treeline in the San Juan Mountains of Colorado was considerably higher than the present-day treeline, suggesting that the summer temperatures were higher than present during that time period (Carrara and others, 1991). In the late Holocene the Red River incised again, by a modest amount (fig. 3), which also has been documented for streams in the San Juan Mountains (Vincent and others, 2007). Unfortunately, the exact conditions that caused incision and aggradation are not known. In any case, it is likely that most of the alluvium in the Red River Valley is less than 10,000 or 20,000 calendar years in age.

Discussion of Classical Fan Area/Watershed Area Relations

The initial recognition of the scaling relations for the areas of fans and their watersheds (Bull, 1964; Denny, 1965) is something of a cornerstone in the science of geomorphology (Cooke and others, 1993). Perhaps for that reason, geomorphology students have often felt compelled to determine the scaling relations for the fans in their study areas (for example, Pazzaglia, 1989). Yet these scaling relations have not been put to practical use, and several implications of these relations have not been recognized. The results of this report are now discussed in that context.

This report demonstrates that these classical scaling relations can be useful in practical ways by using a scaling relation (fig. 6B) to partition numerical rates of erosion for the two distinct sites of erosion found in the Red River watersheds. This report demonstrates that nonuniform erosion can contribute to the scatter in data and that a nonlinear relation of fan area and fan volume can result in a low exponent for classical (area/area) scaling relations.

This report also demonstrates that the scaling relation for areas (fig. 6A) can be recast in the form of a mass balance. The first step was accomplished in the preparation of figure 7B, where data for the Red River tributary fans were applied to the equation shown in figure 7A. This procedure accounts for the nonlinear relation of fan area and fan volume in a rational but approximate way. In the second step, data for the Red River tributary watersheds were applied to equation 1 using the following values for the variables. The vertical erosion rate for forested hillslopes of $R_n = 0.04$ mm/yr was used. The vertical erosion rate for alteration scars of $R_s = 2.7$ mm/yr was used, and a time-frame of $T = 14,000$ years was used. This procedure accounts for the two distinct sites of erosion within the watersheds and converts watershed area into the volume of sediment produced in a given time. The resulting mass-balance scaling relation is shown in figure 10, where the data successfully plot close to the one-to-one line. Compare this result to the low position of the Red River relation (line 9) in figure 5A.

This comparison supports the suggestion that field settings where the space available for fan deposition is limited should result in classical relations with low coefficient values (Bull, 1968; Cooke and others, 1993). This consequence of the available space can be large, as demonstrated by the comparison of the vertical position of line 9 (Red River) with that of line 8 in figure 5A. Recall that the fans used to develop line 8 are located on the rather unrestricted piedmont of the Rio Grande Valley, immediately north of Questa (Pazzaglia, 1989).

It has long been recognized that sediment delivered to a fan may not be deposited on the fan or later may be eroded from the fan (Denny, 1965; Vincent and others, 2004), and this is certainly the case for the fans in the Red River Valley. One may be tempted to use this argument to explain the fact that the Red River data tend to fall slightly below the one-to-one line in figure 10 (fan volumes tend to be slightly less than erosion volumes), but that would be an incorrect interpretation. Recall that the amount of fan sediment accumulated over the past thousand years formed the basis of the erosion rates. The estimated mass balance shown in figure 10 explicitly accounts for only the sediment that came to rest on the fans. In other words, the actual volumes of sediment eroded from the watersheds (including the sediment that was transported off the fans and down the Red River Valley) are larger than shown in figure 10.

The author suggests that the vertical position (the coefficient) of classical scaling relations can in part be controlled by the time over which the fans developed. There has been a tendency to view the fan/watershed area relations as representing a steady state of erosion and deposition (Hooke, 1968; Hooke and Rohrer, 1977), and this may well be the case for

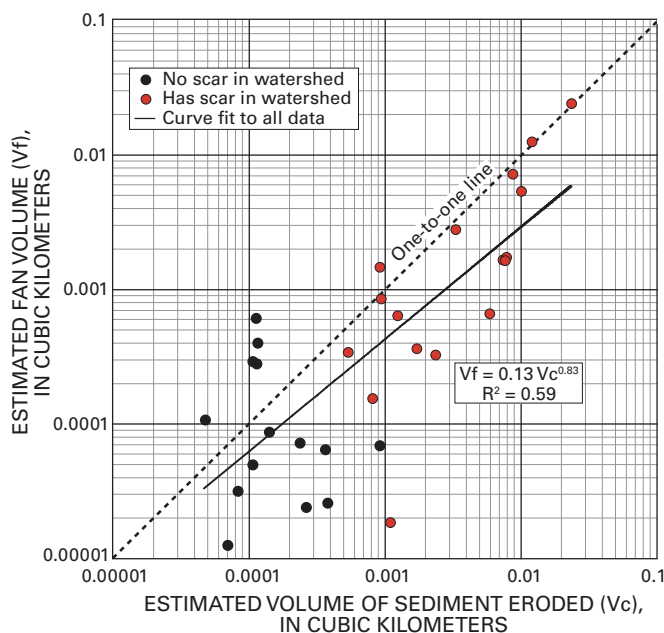


Figure 10. Estimated mass balance of the volume of sediment eroded from Red River tributary watersheds and the volume of sediment stored in Red River tributary fans.

certain examples. In other examples, it is important to recognize two things. First, watershed area is a factor that is usually fairly insensitive to time. For mountainous terrain that is mature (fully developed drainage networks) and over periods of less than a million years, for example, the map areas of most watersheds change very little through time. Fan areas, in contrast, may change substantially through time. Where the space available for the accumulation of fan sediment is expansive, the fans may enlarge through time. Elsewhere, geomorphic processes can reset the clock. Where fan deposits are entirely eroded away (such as in the Red River Valley), where the locus of fan deposition progrades, or where fans are buried, the map area of the extant fans is dependent on the sequence of events. In support of the notion that the vertical position (the coefficient) of classical scaling relations can in part be controlled by the time over which the fans developed, observe the following. In figure 5A, lines 1 and 2 have the highest vertical positions, and the fans in these two data sets accumulated over the past 600,000 years or so (William Bull, University of Arizona, oral commun., 2006). Line 8 has a middle position in figure 5A, and the fans in that data set are thought to have developed over the past 150,000 years or so (Pazzaglia, 1989). Line 9 (from this report) occupies the lowest position in figure 5A, and the fans in that data set (in addition to having restricted space) accumulated over the past 14,000 years or so.

Summary of Geomorphic History of Red River Valley

Landforms, and the specific geomorphic processes that created them, influence the alluvial ground-water hydrology in the Red River Valley between the towns of Questa and Red River, New Mexico. Among the geological features in the study area, the localized zones of hydrothermally altered rock are particularly important. Where this altered rock is near the surface, it weathers and erodes rapidly, creating the sites referred to as alteration scars (cover photograph; fig. 1). Large quantities of the material eroded from alteration scars have been deposited at the mouths of tributary watersheds as debris fans (pl. 1). These sediments contain high concentrations of certain elements that potentially could be of environmental concern, and restrict the flow of ground water as discussed in the subsequent sections of this report.

The Red River Valley developed over the past 26 million years following cessation of volcanism associated with the Questa caldera, which had created a broad plateau. Subsequently, the Red River and its tributaries incised in direct response to the creation of relief, at the western front of the Taos Range, by faulting associated with development of the Rio Grande rift. The result is the rugged, mountainous terrain visible today. Over the past 26 million years, hillslopes eroded at a modest rate of about 0.02 mm/yr, on average, but the rate of erosion likely increased over that timeframe. A second process caused the Red River to incise during the late

Quaternary. Before a million years ago, the Red River was essentially the headwater of the Rio Grande. In response to stream capture of the San Luis Basin, the Rio Grande incised 260 m (840 feet) over the past 600–700 thousand years, creating the Rio Grande gorge. The Red River was thus relegated to the status of a tributary, and downcutting of the master stream caused the Red River to downcut as well. The rate of incision apparently decreased through time. This episode of incision created the gorge at the mouth of the Red River and the valley at the site of Questa but apparently had relatively little influence on Red River Valley within the Taos Range upstream from Questa.

During the late Quaternary, erosion and deposition within the Red River watershed were variable in both time and space. In addition to eroding the bedrock base of the valley during certain time periods, the Red River also underwent episodes of sediment aggradation and episodes of reincision into that alluvium. Although the highest areas of the Taos Range were glaciated, glacial ice did not extend down into the study area. Nonetheless, factors related to the climate during periods of glaciation caused the Red River to aggrade. This is evidenced by the presence of terraces near Questa, which have ages coincident with the last two ice ages (fig. 2B). Unfortunately, the thickness of that accumulated sediment is not known, but the exposed thickness of the youngest ice-age terrace is 12 m (Pazzaglia, 1989). Within the Red River Valley upstream from Questa, no terrace has been demonstrated to have an age coincident with the last period of glaciation. By analogy with the terrace mapped by Pazzaglia (1989), during the last glaciation the Red River likely aggraded more, and perhaps much more, than 12 m. During or immediately following deglaciation, the Red River incised, evidently evacuating most sediment from the valley and allowing the river to resume eroding the bedrock base of the valley. Subsequently, the Red River and its tributary streams began to aggrade again, just prior to the beginning of the Holocene. Thus, most deposits of alluvium in the valley are likely less than 10 to 20 thousand years old.

Over the past thousand years, if not over the entire Holocene, erosion rates were spatially variable. Forested hillslopes eroded at an average rate of about 0.04 mm/yr, whereas alteration scars eroded at about 2.7 mm/yr. The erosion rate of the alteration scars is unusually rapid for naturally occurring sites that have not been disturbed by humans (fig. 9) and is the result of the unique geochemical properties of the hydrothermally altered rock. In addition, watersheds containing large alteration scars delivered more sediment to the Red River Valley than the Red River could remove. Consequently, large debris fans, as much as 80 m thick, developed within the Red River Valley at the mouths of tributary watersheds. The aggradation from those fans also caused the Red River to aggrade immediately upstream from them and created a characteristic segmentation of the longitudinal profile of the valley (fig. 3). The amount of aggradation of the Red River ranged from 30 to 50 m, and the period of aggradation persisted until at least the middle Holocene (fig. 4). During the late Holocene the Red River

incised about 8 m. Although these recent episodes of aggradation and incision were clearly driven by climate, the exact climatic conditions and geomorphic mechanisms are not known. In any case, the current configuration of alluvial deposits within the landscape has important influences on the ground-water hydrology of the study area.

Ground-Water Flow in the Alluvial Aquifer

It has been documented that water locally emerges from alluvium and enters the Red River (Vail Engineering, 2000; LoVetere and others, 2004). The most detailed observations were made by the USGS synoptic tracer-dilution studies in August 2001 and March 2002 (Kimball and others, 2006), which provide detailed documentation of the ground-water emergence rates and the associated changes in solute loading in the Red River. The emerging water was associated with visible seeps or springs or emerged through the streambed in a diffuse manner without being visually obvious. Ground water emerging in the area known as Columbine Park (pl. 1) is particularly noteworthy because that inflow is large and causes a substantial increase in Red River solute loading and because that area is adjacent to the Questa mine. With regard to that emerging water, Vail Engineering (2000) hypothesized that it (and its undesirable constituents) originated far upstream. They suggested that a portion of that water may have originated in the Bitter Creek watershed where it entered the alluvial aquifer and then flowed 12 km downstream in the aquifer until it emerged in Columbine Park. In other words, the undesirable water did not enter the alluvial aquifer from bedrock or colluvium adjacent to the mine (Vail Engineering, 2000).

This report attempts to answer two questions with regard to the observations made by the tracer-dilution study. First, why does the ground water emerge where it does? Second, along what flow path did the water travel, and specifically did it travel long distances in the alluvial aquifer as suggested by Vail Engineering (2000)? This part of the report focuses on the reach of the Red River in the vicinity of the MolyCorp mine (pl. 1, fig. 11) because that is where high-resolution topographic data and the logs of numerous wells are available.

The remainder of this report starts by describing how the geometry of the top, sides, and base of the Red River shallow alluvial aquifer were determined. The sedimentary facies within the aquifer are discussed, along with the influence the facies have on spatial variation in hydraulic conductivity. A ground-water flow model is then presented to explain why ground water emerges where it does. A water budget is constructed for the aquifer in the Columbine Park reach to answer whether or not all emerging water could have flowed into the reach by passing through the alluvial aquifer from reaches farther upstream in the Red River Valley.

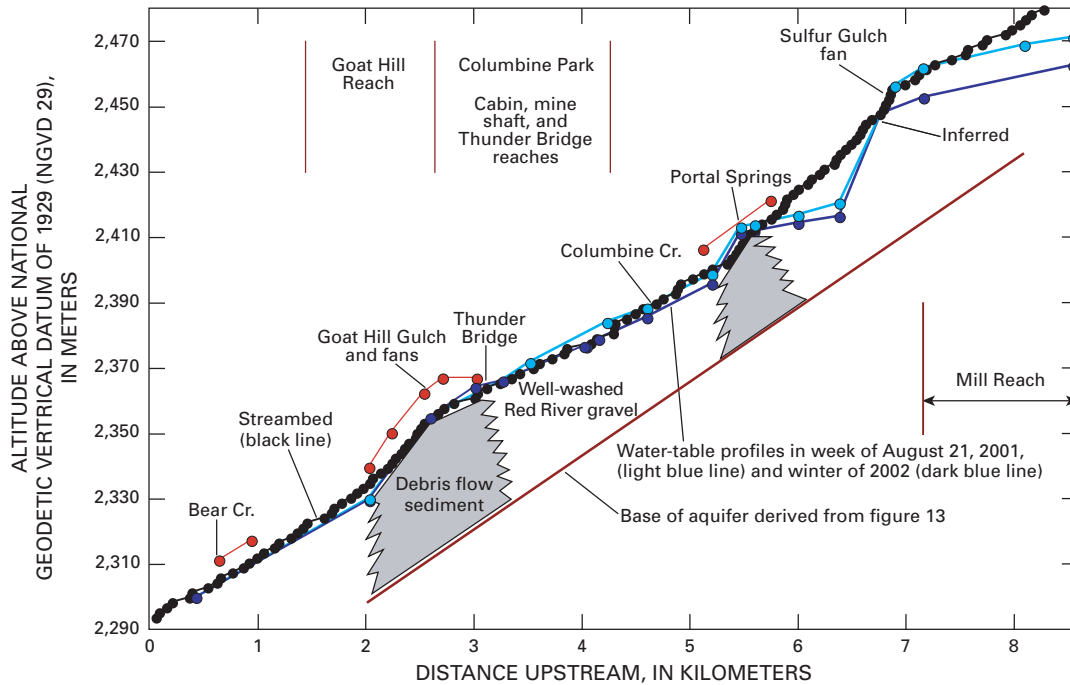


Figure 11. Model of the longitudinal geometry and sedimentary facies of the Red River shallow alluvial aquifer in the vicinity of the MolyCorp, Inc. mine. The light blue line depicts the water-table profile in the week of August 21, 2001, and the dark blue line is the ground-water profile based on measurements made in January and February 2002. The base of the aquifer is derived from figure 13. The named reaches are those used by Kimball and others (2006).

Geometry of Alluvial Aquifer

Longitudinal Profile Topography

Figure 11 is a longitudinal section of the Red River Valley bottom at streambed level and the shallow alluvial aquifer in the vicinity of the Questa mine. The positions of several points on the profile are indicated on plate 1. The profile is oriented parallel to the valley axis with the view looking north, and was constructed using a high-resolution topographic map made available by MolyCorp, Inc. That map has a contour interval of 5 feet (about 1.5 m) and encompasses the area from the mill site downstream to the confluence of Capulin Creek (pl. 1). The longitudinal locations of wells and the locations where topographic contours cross the streambed were projected perpendicularly to a common transect. That transect follows the center of the valley bottom in order to depict the gradient of the ground-water surface without distortion. The profile of the streambed is distorted as a consequence, however, and what appear as steps in the streambed occur where the meandering channel is oriented oblique to the valley axis and then turns directly downvalley. That distortion does not affect the interpretations drawn in this report. The distance scale is not the same as that used by the tracer team (Kimball and others, 2006) because they necessarily followed the meandering channel. For that reason the reaches defined by Kimball and others (2006) are included in figure 11 to aid comparison of this work with theirs.

Ground-Water Surface Profiles

To determine the rate of ground-water flow, the level of the water table must be documented because the water table constitutes the top of the unconfined aquifer and the gradient of the water table drives the flow. Figure 11 contains profiles of the water table of the shallow alluvial aquifer for two periods of time. These water-table profiles were constructed using levels of ground water measured in wells that penetrate the alluvial aquifer and are intended to depict the top of the aquifer at (or close to) the time of the two geochemical tracer-dilution studies of the Red River (Kimball and others, 2006).

The August 2001 profile (shown in light blue) is largely based on water-level measurements made by the USGS on August 21, 2001, in the middle of the week of the 2001 tracer dilution study (P.L. Verplanck, written commun., 2003). That same week, MolyCorp obtained two of the water-level values used here (MolyCorp, Inc., written commun., 2003). Three measurements were made by MolyCorp at other times: November 2002 at the wells at distances of 2.6 and 3.5 km, and winter 2003 for the well at 0.4 km. The water levels in those three wells do not fluctuate much through the seasons, and although they help define the shape of the lower end of the profile, they are not critical to the interpretations made herein.

The winter 2002 profile (shown in dark blue) is largely based on measurements made by MolyCorp in January and February 2002 (Bruce Walker, written commun., 2003). The two

measurements at Goat Hill fan were measured in December 2002, and the value near Bear Creek was measured in February 2003. One water level was inferred (and is labeled accordingly) near Sulphur Gulch fan (fig. 11). The nearby well was dry during the winter of 2002, but seeps were observed next to the stream during the March 2002 tracer, so it is assumed here that the ground water was at the level of the streambed at what is known as Sulphur Gulch Seep (pl. 1). This profile approximates the ground-water condition during the March 2002 tracer dilution study.

During both seasons, there were long reaches where the ground water was 3 to 17 m below the streambed. That observation does not depend on data from any single well and is not an artifact of measurement errors. The vertical resolution of the level of the streambed and water table, for example, is on the order of 1 m. In those same reaches the water table was deeper in the winter of 2002 than it was in the summer of 2001. During both seasons, there were several short reaches and one long reach where the ground water was at the level of the streambed. The reasons for the locally depressed water table and its implications are developed in the section "Water Budget for Alluvial Aquifer."

In the mill reach (fig. 11; mill area on pl. 1), the water-table profiles are based on limited data and, during the tracer studies, were likely more complex than shown in figure 11 for two reasons. First, water is pumped from the alluvial aquifer in that reach; thus, the water table fluctuates through time. Any cone of depression present during the August 2001 tracer cannot be evaluated accurately. Second, there are likely changes in the water-table gradient over long distances because the Red River streambed and the ground-water surface are steep upstream from the area depicted in figure 11. To evaluate

this, figure 12 was constructed. The mine's detailed map (1:6,000 scale) does not extend farther upstream than shown (red line), so profiles were extracted from USGS topographic maps. A profile from the USGS 7.5-minute Questa quadrangle (1:24,000 scale) was constructed to illustrate the resolution of data from that source in comparison to that from the mine's map. Data from the adjacent Red River quadrangle were used to define the streambed profile upstream from the mill. The longitudinal profiles of the Red River from both sources are shown in figure 12. The horizontal scales were registered using the position of the road entering the mill complex, which is visible on both maps. The two profiles match as well as could be expected given their differing resolution, and the data from the USGS map sufficiently illustrates the steep reach between the mill area and Hansen Creek. The Hansen Creek fan caused the exceptionally steep segment in the profile at 11 km. The USGS installed piezometers, and a well called La Bobita, and survey data from those installations (Cheryl Naus, written commun., 2004) are included in figure 12. The altitudes of the stream surface were surveyed close to the piezometers and those data match the topographic profile as well as can be expected. These wells were established after the August 2001 tracer study so the water levels at that time could not be measured. In early June 2004, the water table was essentially at the level of the streambed at piezometers P-2, P-3, and P-4. In the vicinity of piezometer P-1 and La Bobita, however, the water table was 2 to 3 m beneath the streambed. Between December 2002 and May 2004 the water level in the La Bobita well fluctuated through a 1.6-m range, with the water table lowest in late winter, highest in May, and in the middle of the range in August. Given that small range, the water level shown in figure 12 upstream from the mill should approximate the

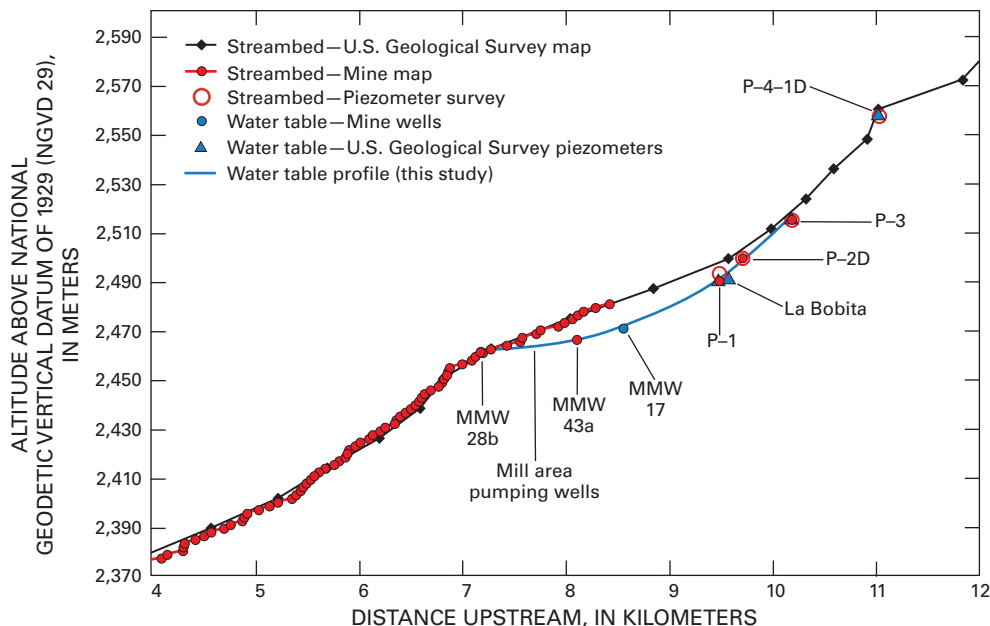


Figure 12. Details of the water-table profile within and upstream from the mill reach (pl. 1), as it may have been during the August 2001 tracer. Mine wells are labeled "MMW" and USGS installed piezometers are abbreviated using the letter "P."

water levels as they were during the August 2001 tracer study. At that time, the water-table profile must have been curved such that the gradient decreased in the downstream direction through the mill reach. Water-surface gradients were taken from the water-table profile line in figure 12 for modeling ground-water flow in this report through the mill reach during the 2001 tracer study; however, there is considerable uncertainty in the gradient values. Ground-water flow through the mill reach during the 2002 tracer study was not modeled for this report because the water table at that time was constrained by only two points.

In summary, the water-table profiles are tightly constrained over long reaches, downstream from the mill. Both water-table levels and gradients are essential constraints for calculating the rate of flow of ground water in the shallow aquifer, but first the base and sides of the aquifer are defined in general terms.

Thickness of Alluvial Aquifer

The deepest level of the bedrock/alluvium contact at the base of the alluvial aquifer is a key parameter in controlling the cross-sectional area of the aquifer and, consequently, the ground-water flow. The Red River alluvial aquifer is bounded at its base by bedrock, which is largely impermeable compared

to the gravel alluvium of the aquifer. The deepest level of bedrock at the base of the aquifer is inferred here by using the lithologic descriptions in the well logs for numerous ground-water wells (Appendix 3). The well logs used herein are documented in Souder, Miller and Associates (March 2000, May 2000, June 2000, and January 2003), and a few well logs were provided by Molycorp in written communication (2003). The data are shown in figure 13, and are grouped into three types, with one modifier. Several wells terminated in alluvium and the elevations of the bottom of those wells (black diamonds) are labeled “above bedrock.” Other wells passed through alluvium and terminated in bedrock and the altitudes of alluvium/bedrock contacts are shown on the figure by using two symbols. Wells located along the valley margin likely contacted bedrock at the sides of the aquifer (small red dots) rather than at the deepest base of the aquifer. Wells located in the middle of the valley provide the best indication of the deepest level of the bedrock contact at the base of the aquifer (large red dots). The precise level of bedrock contacts was difficult to decipher from certain well logs largely because cuttings of weathered bedrock can resemble alluvium, and large red circles are used to identify where that problem was encountered. Data from 32 well logs (Appendix 3) are shown in figure 13, although many of these wells terminate in alluvium or are located close to the valley sides. Data from the 15 wells with the deepest bedrock contacts indicate that the

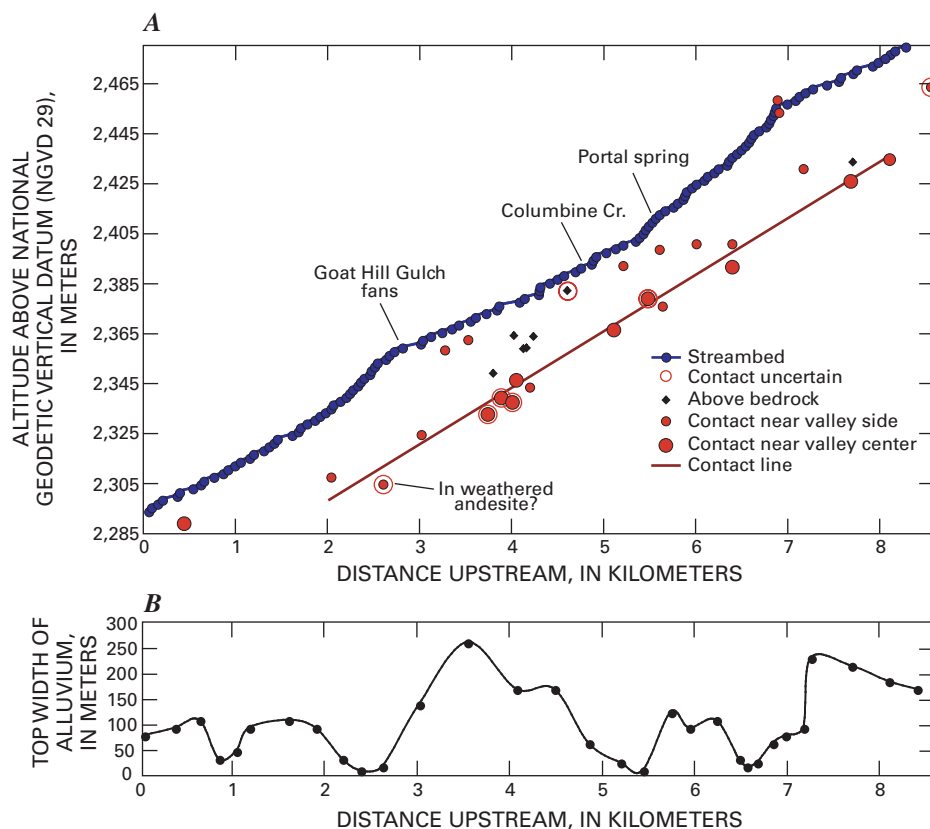


Figure 13. (A) Constraints on the deepest level of the bedrock/alluvium contact at the base of the Red River shallow alluvial aquifer, based on well logs (Appendix 3); and (B) variation in top width of Red River alluvium.

bedrock base of the shallow alluvial aquifer is linear in longitudinal profile, to a first approximation, over a length scale of at least 6 km (fig. 13). The bedrock surface no doubt has local relief, and the data indicate that relief is on the order of 3 m. The data defining the line are scattered about the middle of the valley rather than being oriented, in map view, along a specific transect. Therefore, the tight clustering of the data about the line in figure 13 indicates that the deepest portion of the bedrock valley resembles an inclined plane that is horizontal in cross section. This evidence is used in the section “Cross-Sectional Geometry of the Aquifer.”

In the study reach (fig. 13) the maximum thickness of the alluvium beneath the Red River streambed is rather uniform, ranging between 30 and 45 m. There is no evidence of particularly shallow, or particularly deep, bedrock at any location in the reach. This includes the area just upstream from Sulphur Gulch (at 7 km) where the top of the valley alluvium is narrow (75 m) and where the valley sides consist of bedrock cliffs. This also includes the downstream end (at 3.6 km) of Columbine Park where the valley is particularly wide (260 m) and the valley sides consist of hillslopes that are not cliffs. The tracer study documented the emergence of ground water at both of those locations where, instead of being thin, the aquifer is slightly thicker compared to elsewhere in the study reach. This evidence demonstrates that alluvial ground water does not emerge because of a particularly shallow bedrock sill, at least between distances 2 and 8 km in figures 11 and 13. The data also illustrate that the top width of the alluvial aquifer is a poor predictor of the maximum thickness of the alluvial aquifer. The line depicting the deepest level of the base of the aquifer derived in figure 13 is reproduced in figure 11 and is used to constrain the cross-sectional geometry of the aquifer, discussed next.

Cross-Sectional Geometry of the Aquifer

To determine the rate of ground-water flow, the generalized shape of the bedrock/alluvium contact at the sides and bottom of the alluvial aquifer must be estimated. It is likely that each individual cross section of the alluvial aquifer has some unique aspect to its shape and that no two cross sections are identical (Powers and Burton, 2004), but simple geometric shapes (fig. 14) are used in this study because detailed information is not available. Generalizing the cross-section shape introduces uncertainty into the ground-water flow calculations, which will be evaluated; but it turns out that the largest uncertainty is in the value of hydraulic conductivity.

The sides and bottom of the aquifer rest on an erosion surface carved in bedrock that predates the partial filling of the valley with alluvium. It is essential to recognize that because the bedrock surface is erosional, its shape is independent of the subsequent processes of deposition of alluvium and, therefore, is independent of the local thickness of alluvium. Hence, the top width of the alluvium is a poor predictor of the maximum thickness of the alluvium, as demonstrated in figure 13 where the top width of the alluvium in the valley is variable and the maximum thickness of the alluvium is largely uniform. The sides and bottom of the aquifer need

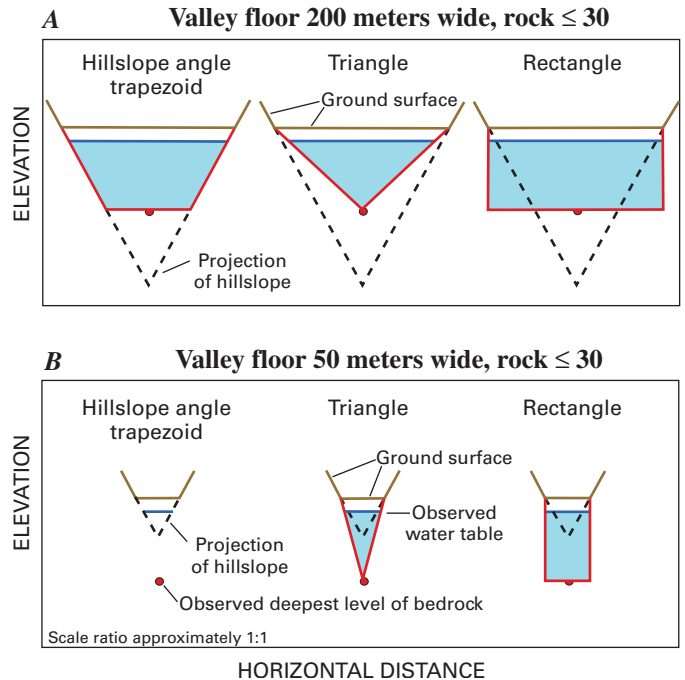


Figure 14. Generalized models of the cross-sectional shape of alluvial aquifers in mountainous terrain where the width of the valley floor and depths to the water table and deepest alluvium/bedrock contact are known.

to be discussed separately. At the sides of the aquifer, the bedrock surfaces are former hillslopes now buried by alluvium. Therefore, the best predictor of the angle of inclination of a buried hillslope is the angle of inclination of the extant hillslope above it. Most hillslopes adjacent to the bottom of the Red River Valley are inclined about 30 degrees, although near-vertical cliffs are present locally. Low-gradient hillslopes, inclined 10 or 20 degrees for example, are not present in this landscape. Thus, the sides of the aquifer are likely inclined about 30 degrees, may be near vertical locally, and should not be inclined substantially less than 30 degrees.

Generalizing the cross-sectional shape of the base of the aquifer near the valley center is more problematic. This is discussed using figure 14, which illustrates three generalized models for the cross-sectional shape of the Red River shallow alluvial aquifer, and also demonstrates that the appropriate choice depends on valley width. Figure 14A shows the situation where the valley bottom is 200 m wide, and the observed maximum depth to the bedrock contact in the center of the valley (red dot) is 30 m. Figure 14B shows the situation where the valley bottom is 50 m wide, and the maximum depth to the bedrock contact is again 30 m. In each case, a dashed black line depicts the projection into the subsurface of a hillslope inclined 30 degrees, and the red line is the model aquifer boundary. For each shape model, the cross-sectional area of the aquifer is a simple function of the observed top-width of valley-filling alluvium, the observed level of the ground-water surface (fig. 11), the observed deepest level of bedrock (fig. 13), the assumed angle of the sides of the aquifer, and the assumed shape of the base of the aquifer.

Hypothetically, one approach to estimating cross-section shape would be to project the opposing hillslopes into the subsurface to the point where they intersect, thus forming a V-shaped cross section, as shown using dashed lines in figure 14. Along the Red River, however, that procedure results in an inaccurate estimate, and usually an overestimate, of the maximum thickness of the aquifer. For example, where the valley bottom is 200 m wide, that approach predicts a maximum alluvial thickness of about 60 m, whereas the observed maximum thickness is 30 or 45 m (fig. 14A). There is no process-based reason to think the erosion surface bounding the aquifer is entirely buried hillslopes and thus V-shaped because it was streams, not hillslope processes, that carved the now-buried bedrock floor in the center of the valley. As an alternative, geomorphologists working in other study areas have tried extending the valley sides into the subsurface by using parabolic functions, but that procedure also overestimated the maximum depth to bedrock (Schrott and Adams, 2002). The floors of many bedrock valleys are remarkably horizontal in cross section (for example, Myers, 2000; Stock and others, 2005), and this is also true along the Red River near Straight Creek (Powers and Burton, 2004, 2007). Otherwise, if the cross sections were V-shaped, the observed deepest level of bedrock would not be the tightly constrained line shown in figure 13. That line is defined using data from wells that are near, but not precisely at, the valley center and some wells located near the valley side. A horizontal base for the center of the cross section is used in two of the shape models discussed next.

A trapezoid model assumes the bedrock floor at the base of alluvium is horizontal (in cross section) and at the level defined using well logs (fig. 13) and that the adjacent hillslopes project at 30 degrees into the subsurface and intersect the bedrock floor. Where the valley is wide (fig. 14A) this produces a realistic shape, as it best describes the categorical shape of the bedrock boundary observed in seismic cross sections of alluvial fill elsewhere in the Red River Valley (Powers and Burton, 2004, 2007). In addition, compared to the other models, the trapezoid model neither systematically underestimates nor overestimates cross-sectional area. Where the valley is narrow (fig. 14B), however, this model is inappropriate because the projected sides of the aquifer intersect above the observed maximum depth of bedrock. Where the top-width of the alluvium is 100 m, this model reproduces the observed 30-m depth to bedrock in the center of the valley. Hence, the trapezoid model is inappropriate for use in the study reach where the valley bottom is less than 100 m wide.

A triangle model assumes that there is no flat-bedrock floor at the base of the alluvium and that the sides of the aquifer extend as straight lines from the edges of the valley bottom to the observed deepest level of bedrock in the center of the valley. The triangle model produces a V-shaped cross section (fig. 14) and is thus unrealistic for reasons discussed in the beginning of this section. The triangle model implies that the inclination of the sides of the aquifer is proportional to the maximum thickness of alluvium and inversely proportional to the top-width of the alluvial fill. Those proportionalities may

be true by happenstance at some particular location but cannot be true universally. Where the valley is wide, that model represents the buried hillslopes inclined at angles lower than is observed elsewhere in the landscape. The triangle model produces a cross-sectional area that is too small, particularly where the valley is wide, and for that reason it is used only to illustrate the influence that assumptions of cross-sectional shape have on calculated rates of ground-water flow.

A rectangle model assumes that there is a flat-bedrock floor at the base of the alluvium, and that the sides of the aquifer are vertical contacts extending from the mapped edges of the valley alluvium down to the observed deepest level of bedrock. Applied universally, the rectangle model is unrealistic because the sides of the aquifer are assumed everywhere to be vertical and that these buried cliffs are coincidentally located at the edges of the present alluvial fill. In general, that model produces a cross-sectional area that is too large, and for that reason it is used to illustrate the influence that assumptions of cross-sectional shape have on calculated rates of ground-water flow. Where the valley bottom is narrow and cliffs are present on both sides, however, the rectangle model is probably most realistic.

In summary, estimates of the cross-sectional area of the alluvial aquifer are highly inaccurate without some knowledge of depth to bedrock. If the deepest level of bedrock is known, the appropriate model of cross-sectional shape depends on valley width. Where the valley is wide the trapezoid model produces the most realistic shape. Where the valley is narrow (less than 100 m along the Red River), however, the trapezoid model is inappropriate and the other two models must be used to bound the cross-sectional area of the aquifer and thus the rate of ground-water flow. The triangle model should systematically underestimate cross-sectional area. The rectangle model should overestimate cross-sectional area where the valley is wide; but where the valley is narrow and bounded by cliffs, it is likely the most realistic shape. An inappropriate choice of cross-sectional shape can have a large influence on calculations of ground-water discharge, as discussed in the section "Ground-Water Flow Model."

Sedimentary Facies and Hydraulic Conductivity

The alluvium in the Red River Valley consists of two major facies, and the contrast in their hydraulic properties greatly influences the flow of alluvial ground water. Facies is a geological term used to describe sediments that may be the same age but differ in texture, structure, or mineralogy because of differences in the sources of sediment and (or) differences in the processes of transport and deposition.

Alluvial deposits in the Red River Valley are derived from two sources. First, much of the alluvium in the study area consists of sandy gravel derived from the entire watershed and deposited by the Red River. These sediments compose the terraces, flood plain, and streambed of the Red River. Second, debris fans are present at the mouths of most tributary watersheds and are composed of sediment derived exclusively from the rocks of their watersheds. Where alteration scars are not

present in tributary watersheds, the fans are small and are generally composed of sediment resembling that deposited by the Red River. For these reasons the small fans likely do not have a substantial influence on the flow of alluvial ground water, and these small fans are not discussed further. Large debris fans that extend across all or most of the width of the Red River Valley, in contrast, are found at the mouths of tributary watersheds that contain large alteration scars. The Goat Hill Gulch fan is a good example (pl. 1). These fans are large because they have received massive amounts of sediment, which is the direct result of the rapid erosion rates of alteration scars. In general, the alluvium in the Red River Valley is composed of long reaches of gravel deposited by the Red River that are interrupted by shorter reaches consisting of large debris fans shed from tributary watersheds that contain alteration scars. These are the two primary facies of the alluvium in the study area, and the debris-fan sediments reduce the flow rate of alluvial ground water in Red River gravel, as discussed next.

Alluvium deposited by the Red River has distinctly different properties compared to the debris-fan sediments. The Red River alluvium is dominated by well-washed, sandy gravel with stratification inclined in the downvalley direction. The tributary debris-fan sediments, in contrast, consist of very

poorly sorted, silty sandy-gravel with stratification that is oblique to the axis of the Red River Valley. The fan sediments are weakly cemented and appear less porous than Red River alluvium in field exposures. These observations suggest that fan sediments should be less permeable than Red River gravel but belie the quantitative differences.

In order to evaluate the hydraulic properties of the sediments, all available measurements of aquifer hydraulic conductivity for Red River gravel and debris-fan sediment were assembled on table 3. The locations of wells are shown on plate 1. Technically, the conductivity values are the result of aquifer tests, but the methods used are informally referred to as “pumping tests” and “slug tests.” All hydraulic conductivity values were rounded to one significant digit. The table was constructed by first organizing the data by the type of surficial material penetrated by the wells. The data was then rank-ordered by the magnitude of hydraulic conductivity determined by pumping tests. Where pumping tests were not conducted, the data were then rank-ordered by the magnitude of hydraulic conductivity determined by slug tests. There is considerable scatter in the data, particularly for debris-fan sediment for several reasons. First is the uncertainty inherent in aquifer tests. The results of pumping tests and slug tests

Table 3. Alluvial aquifer hydraulic conductivity values based on tests at alluvial wells in the Red River Valley.

[Well locations are shown on plate 1; data from source USGS is the midpoint of the range in conductivity given by Blanchard and others (2006); SMA, Souder, Miller, and Associates; cm/s, centimeters per second; na, not available]

Well name	Hydraulic conductivity, cm/s			Data source
	Pumping test	Recovery test	Slug test	
Wells in Red River gravel				
Old Mill Well	0.3	0.3	na	SMA, June 2000
Mill Well 1A	0.2	0.3	na	SMA, June 2000
Columbine No. 2	0.07	na	na	Gsi/water (1996)
GW-3	0.07	0.04	na	SMA, June 2000
Wells in Red River gravel and close to the interfingering distal margins of debris fans				
GW-2	0.04	0.08	na	SMA, Jan. 2003
GW-1	0.04	0.007	na	SMA, Jan. 2003
Wells in debris fans containing alteration scar sediment.				
SC-8A ¹	na	na	0.5	USGS
SC-7A ¹	0.1	na	0.03	USGS
AWWT-1	0.1	na	na	USGS
SC-5A ¹	0.08	na	0.02	USGS,
SC-4A ²	na	na	0.01	USGS
MMW-19A ²	na	na	0.002	SMA, May 2000
SC-6A ²	na	na	0.008	USGS
SC-1A ³	na	na	0.0003	USGS
MMW-11A ²	na	na	0.0003	SMA, May 2000
MMW-27A ²	na	na	0.0002	SMA, May 2000
SC-3A ²	na	na	0.0001	USGS
MMW-21 ³	0.002	0.0006	0.00002	SMA, May 2000
MMW-22 ³	0.0006	0.0004	0.00001	SMA, May 2000
MMW-2 ^{2,4}	0.00001	0.00001	na	SMA, March 2000

¹Well is in a distal (downstream) position on the debris fan.

²Well is in a medial position on the debris fan.

³Well is in a proximal (upstream) position on the debris fan.

⁴Well is located near the lateral margin of the debris fan near a colluvial hillslope.

at the same well often differ, as illustrated by the data for wells MMW-21 and MMW-22. The results of slug tests are generally considered less reliable than the results of pumping tests because smaller volumes of the aquifer are tested. Second is the natural inhomogeneity of sediment properties, which occurs at various spatial scales. One or both of these reasons explain the scatter in the data for wells MMW-11A, MMW-19A, and MMW-27A, which are located close together (pl. 1). Similarly, there is considerable scatter in the data for wells SC-3A, SC-4A, and SC-6A, which are also located close together. There is some hint in the data that the hydraulic conductivity of debris-fan sediment increases in the downstream direction, and this is only partially explained by the fact that debris-fan sediments likely interfinger with Red River gravel at the distal margins of the fans. The logs of wells SC-5A, SC-7A, and SC-8A, for example, indicate the wells penetrated debris-fan sediment interfingered with Red River gravel in the subsurface (Naus and others, 2005; Blanchard and others, 2006). Aquifer tests at these wells resulted in hydraulic conductivity values substantially higher than that for other wells drilled into debris-fan sediment. Those other wells are located at proximal or medial positions on the fans, where for geometric reasons it is unlikely or impossible for Red River gravel to be present in the subsurface. In summary, the hydraulic conductivity values for “pure” debris-fan sediment are generally substantially lower than that of Red River alluvium (table 3). This is despite the fact that the sedimentary textures of the two deposit types, although noticeable in the field, are not profoundly different. Comparatively low hydraulic conductivity, however, is not the only requirement that would cause debris fan sediments to substantially reduce the flow rate of ground water down the Red River Valley.

The second requirement for reducing flow rate is that the spatial occurrence of the material, in cross section, must be extensive. The logs of wells drilled into tributary fans confirm that debris-flow sediments compose the entire thickness of the aquifer beneath the surface expression of the fans, at least locally. The observations involve sediment color. The exposed sediment of all fans shed from watersheds containing alteration scars, and the alteration scars as well, are pale yellow. As mentioned previously in this report, “pale yellow” refers to the specific Munsell (2000) color name that has the color code of 2.5Y 8.3 (dry). That color is imparted by the presence of the mineral jarosite, which is a weathering product of pyrite and is derived from alteration scars. In the author’s experience, pale yellow is a very rare color for alluvial sediment. In any case, exposures of sediment deposited by the Red River are only locally pale yellow (where beds of debris-flow sediment are present). The logs of wells drilled into Red River gravel rarely describe the sediment as yellow. Yet, logs of wells drilled into debris fans do mention yellow sediment, if any color is mentioned. The log of well MMW-44B is particularly illustrative because the sediment was described as being yellow from the surface of the Goat Hill fan all the way down to the bedrock contact. Unfortunately, most wells drilled into debris fans

are located on the margin of the Red River Valley; thus, well logs cannot confirm that debris-fan sediment is present in the subsurface over the full width of the shallow alluvial aquifer, but there are geomorphological reasons to believe this is the case.

There is geomorphological evidence suggesting that the type of alluvium observed at the present ground surface should be a reliable indicator of the sediment in the subsurface. In other words, where debris fans are mapped extending across the width of the Red River Valley (pl. 1), fan sediments should dominate the entire thickness and width of the underlying aquifer. The key word in that sentence is *dominate*. The opposite alternative would be that fan sediments are young and thin deposits overlying thick sections of permeable Red River gravel, in which case the fan sediments would not effectively reduce the overall hydraulic conductivity of the aquifer. That configuration would have required a long period of aggradation by the Red River with minimal fan aggradation, followed by an episode of rapid deposition of a sheet of sediments out into the Red River Valley. That sequence of events conflicts with available geomorphological evidence, however. In the Columbine Park reach the longitudinal profiles of the river terraces are parallel to the profile of the modern streambed (fig. 3). If the Goat Hill Gulch fan had enlarged during the late Holocene it would have covered older Red River terraces, and the modern streambed would be less steep than the terrace remnants. A better historical scenario is that tributaries delivered more sediment and coarser sediment than could be swept downstream by the Red River during the entire period of aggradation of aquifer alluvium. The debris fans aggraded, forcing the Red River to aggrade upstream from the fans. This scenario is consistent with the observed segmented longitudinal profile of the Red River, with the reaches on the downstream sides of the debris fans being steeper and the reaches upstream from the fans being less steep (fig. 3). The segmented profile is typical of mountain streams where tributaries supply excessive sediment (Miller and others, 2001; Vincent and others, 2007). In order for aggrading fans to constitute obstructions that forced the Red River to aggrade upstream from them, the fans must have extended across the full width of the valley during the period of aggradation just as they do at present. That is not to say there is no Red River gravel beneath the areas mapped as debris fans, which has been demonstrated at the margin of the Straight Creek fan. The concept is that debris-fan sediment should dominate the subsurface alluvium at the locations of the debris fans that caused inflections in the longitudinal profile. The available evidence suggests this concept is true. Given the observation that debris-fan sediments have comparatively low hydraulic conductivity (table 3), it is reasonable to hypothesize that the large debris fans should substantially reduce the rate of flow of ground water in alluvium of the Red River Valley. Where ground water flowing down valley in Red River gravel encounters an extensive body of low hydraulic conductivity sediment, excess ground water should emerge at the surface. Proof of that hypothesis requires a spatial coincidence of the sites of ground-water emergence with the margins of the large fans.

To that end, the mapped surficial extent of debris fans was used to estimate, in figure 11, the spatial extent of debris-fan sediments in the subsurface, as justified by the reasons discussed in this section. The depicted longitudinal lengths of the fan deposits are for the fans as they occur on the north side of the valley, the side of the source tributaries. The debris fans dominate shorter longitudinal sections on the south side of the valley (pl. 1). The jagged edges of the debris-fan deposits shown in figure 11 are meant to convey that the fan sediments likely interfinger with Red River alluvium to some degree. The available evidence suggests that debris-fan sediments should reduce the flow rate of ground water in the shallow alluvial aquifer beneath the Red River and cause ground water to emerge at the surface. The ground-water flow model, developed next, in combination with the results of the tracer study confirm that hypothesis.

Ground-Water Flow Model

A mathematical formulation of ground-water flow in the Red River's shallow alluvial aquifer was developed to evaluate the exchanges of alluvial water and stream water. Darcy-based calculations of ground-water discharge were made for a sequence of cross sections of the alluvial aquifer. Flow in four reaches composed of well-washed alluvium deposited by the Red River was estimated, and these reaches are labeled 1 through 4 in figure 15. Reach 1 is the mill reach and reach 3 encompasses Columbine Park (pl. 1). These reaches are separated by debris-fan sediments, and ground-water flow in the debris-fan sediments was not estimated for two reasons. The water-table gradients within the fans are not well constrained

(fig. 11), and the hydraulic conductivity of debris-fan sediments spans a large range (table 3). The locations, at the northern valley margin, of debris fans shed from watersheds containing alteration scars are shown in figure 15 by using horizontal, thick black lines. Only one cross section was modeled in reach 4, well downstream from the Goat Hill fan, because the constraints on the depth to bedrock are lacking downstream from 2 km in figure 15.

Theory and Constraints

Ground-water flow in the unconfined aquifer was calculated using Darcy's law

$$Q = -K \times dh/dl \times A \quad (5)$$

(for example, Freeze and Cherry, 1979) where Q is volumetric rate of ground-water flow (calculated), K is hydraulic conductivity (based on aquifer tests), dh/dl is water-table gradient (measured), and A is aquifer cross-sectional area (constrained by measurements). Equation 5 was used to calculate volumetric flow rate at four cross sections in reach 1, two in reach 2, six in reach 3, and one in reach 4. Data for the calculations are shown in Appendixes 4 and 5.

Where the valley bottom was wider than 100 m (fig. 14A), the trapezoid model was used as the best estimate of cross-sectional area. The two unrealistic cross-sectional shape models were used to evaluate the uncertainty (minimum and maximum) imposed on predicted ground-water discharge by assuming a generalized cross-sectional shape. The results (fig. 15) indicate that the value predicted using the trapezoid model should

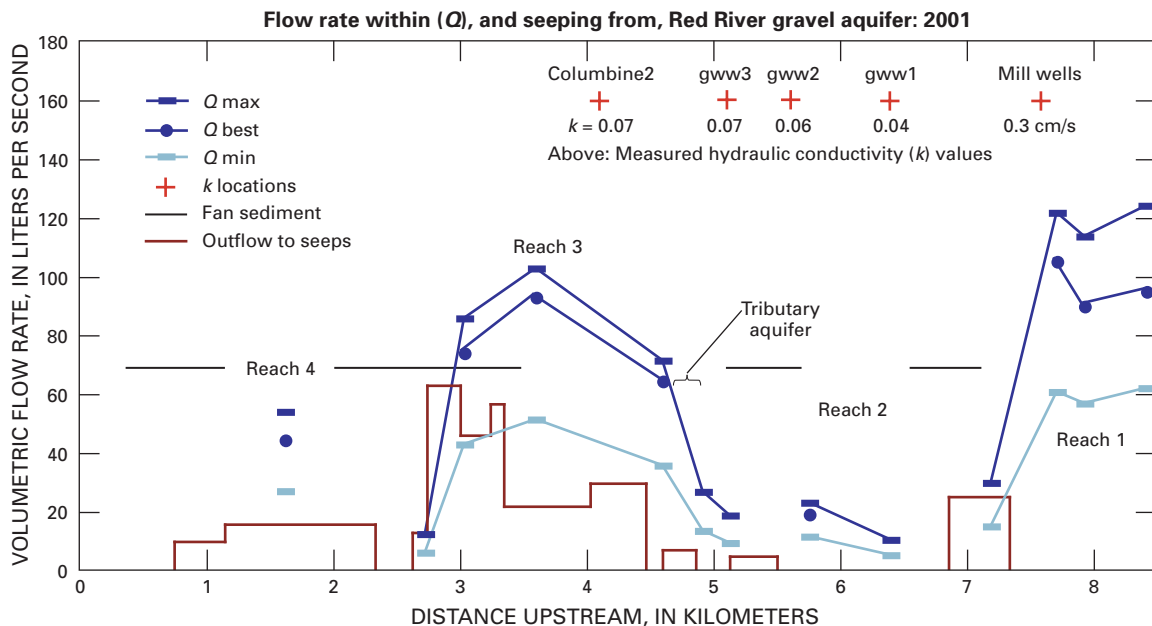


Figure 15. Model results for the flow of ground water during August 2001, in the sections of the alluvial aquifer composed of sediment deposited by the Red River. Gaps in the data are where debris-fan sediments are located. Flow in the fan deposits were not modeled, nor that in the reach downstream from 1.5 km.

not overestimate the actual value by more than 40 percent and should not underestimate the actual value by more than 30 percent. Where the valley bottom was narrower than 100 m (fig. 14B), the trapezoid shape is inappropriate, as discussed in the sections “Cross-Sectional Geometry of the Aquifer,” and the triangle and rectangle cross-sectional shape models were used to bound the magnitude of ground-water discharge.

Hydraulic properties have been determined from aquifer tests for three of the four model reaches. A hydraulic conductivity of 0.3 cm/s was assumed for the mill reach (fig. 11) based on the combined results of aquifer tests at the Old Mill Well and Mill Well 1A (table 3). A hydraulic conductivity of 0.06 cm/s was assumed for reach 2 based on the results of aquifer tests at well GWW-2. The hydraulic conductivity of 0.04 cm/s for well GWW-1 was not used because it is likely influenced by nearby debris-fan sediments. A hydraulic conductivity of 0.07 cm/s was assumed for the Columbine Park reach (fig. 11) based on aquifer tests at wells Columbine No. 2 and GWW-3 (table 3). No aquifer tests have been conducted in reach 4, and a hydraulic conductivity of 0.07 cm/s was tentatively assigned to that reach. The hydraulic conductivity of well-washed gravel is obviously spatially variable in the study area (table 3). There is no obvious geomorphological process that would cause sediment texture or structure (and thus hydraulic properties) to vary substantially in some systematic way within individual model reaches, however, except where Red River gravel interfingers with debris-fan sediments near fan margins. Therefore, the hydraulic conductivity was assumed to be uniform within each of the model reaches.

Flow Model Results

The estimates of ground-water flow through various cross sections during the August 2001 synoptic tracer study are shown in figure 15 along with the outflow to seeps, which are the gains in stream discharge measured by Kimball and others (2006) resulting from emerging ground water. The depiction of stream gains resembles a histogram and should be interpreted carefully. The height of a bar denotes the volumetric rate of the inflow, and the width of a bar denotes the subreach within which the gain occurred, so the area of a bar is meaningless.

The major result of the estimates of ground-water flow is that the volumetric flow rate within the gravel aquifer repeatedly increases and decreases in the downstream direction. Flow within reaches composed of Red River gravel is discussed first, followed by analysis of decreases in aquifer discharge between gravel reaches.

Within reaches 2 and 3, the calculated flow rate increases in the downstream direction because, in both cases, the aquifer both widens (pl. 1) and thickens (fig. 11) downstream from the head of the reaches. The downstream increase in flow within reach 2 is small and is not a compelling result given the uncertainties in the model parameters. In other words, that reach may or may not have received modest recharge. The downstream gain in aquifer flow rate within reach 3 is large,

in contrast, and is substantial with respect to the model uncertainties. An abrupt increase in calculated discharge of about 38 L/s occurred between 4.9 and 4.6 km, and that subreach corresponds with where the tributary alluvial aquifer under Columbine Creek joins the Red River aquifer. The aquifer under Columbine Creek also is composed of well-washed gravel, as opposed to debris-fan sediment. Notice on plate 1, that the width of the alluvium in the Columbine Creek Valley is about the same as the width of the Red River Valley just upstream from the confluence, and that the top of the Red River aquifer essentially doubles in width as it passes the mouth of Columbine Creek. The Red River aquifer essentially doubles in size, and the calculation indicates that the aquifer flow rate essentially doubles where it was joined by the major tributary aquifer under Columbine Creek. Therefore, the merging of two gravel aquifers is the simplest explanation for the abrupt gain in aquifer flow rate between 4.9 and 4.6 km. Downstream from 4.6 km, the model indicates that the aquifer continued to gain flow at the time of the 2001 tracer, and this apparent gain is discussed further in the section “Water Budget for Alluvial Aquifer.”

In the mill reach, reach 1, the ground-water flow rate was basically uniform, according to the calculations. There are three major uncertainties, however, in the calculation of flow within the mill reach. The precision of aquifer top-width values is low because the presence of the mill works made mapping difficult, but the aquifer does widen in the downstream direction (pl. 1). The deepest level of bedrock (fig. 13) is not well constrained upstream from 8 km. In addition, as discussed in the section “Ground-Water Surface Profiles,” the water-table gradients at the time of the 2001 tracer are not well constrained (fig. 12). For those reasons, the calculated magnitude and spatial variability of aquifer flow rate within the mill reach should be considered unreliable.

At the downstream ends of reaches 1 and 3, the rate of flow in Red River gravel decreases substantially. In reach 1, the discharge must decrease because the aquifer narrows upon entering the canyon bound by bedrock cliffs, upstream from Sulphur Gulch (pl. 1). In Columbine Park, the Red River gravel aquifer also narrows as it becomes increasingly pinched by the Goat Hill Gulch fan (pl. 1). In that subreach, some unknown amount of ground water also passes through the fan sediments. At the downstream end of reach 2, the gravel aquifer also is pinched by fan sediments.

Between model reaches, which are physically separated by debris-fan sediments, the flow rate of ground water in the gravel aquifer decreased substantially, and that was coincident with ground water emerging to become streamflow. Between reaches 2 and 3, the ground-water flow decreased by 4.2 L/s (fig. 15), assuming the rectangle model (fig. 14) best depicts the shape of the aquifer at 5.76 and 5.13 km, and the stream gained 4.0 L/s (Kimball and others, 2006). Theoretically, the change in aquifer discharge should match the aquifer outflow to the stream, for reasons of conservation of mass. Practically speaking, however, this exact match is surprising given the uncertainties in the calculations. Between reaches 1 and 2, in contrast, ground-water flow rate ostensibly decreased by about

90 L/s (using the “best” estimate at the downstream end of reach 1 in fig. 15), whereas the stream gained only 24.5 L/s (Kimball and others, 2006). This discrepancy is probably the result of the relatively poor constraints on ground-water flow within the mill reach. Between reaches 3 and 4, the ground-water flow rate decreased by 50 L/s, whereas the stream gained 226 L/s throughout the subreach where the Goat Hill fan constricted reach 3. The constraints on the flow model are excellent for the Columbine Park reach, and the large excess of emerging water will be discussed at length in the section “Water Budget Results for Columbine Park.”

The model results for ground-water flow during the March 2002 synoptic tracer study are shown in figure 16, along with the gains in streamflow measured by Kimball and others (2006), resulting from emerging ground water. Note that the 2002 tracer study extended only between 0.75 and 6.5 km in figure 16; thus any gains in streamflow between reaches 1 and 2, and between reaches 2 and 3, were not documented. The spatial patterns of ground-water flow were similar, although the magnitudes of flow were smaller, in 2002 compared to those in 2001. In reaches 1, 2, and 3, the magnitudes of flow must have been smaller in 2002 because the water table was both at a lower level and less steeply inclined (fig. 11). The 2002 tracer study occurred after a dry winter and 10 months after the snowmelt and regional recharge season. Depleted ground-water reservoirs might be expected just prior to the season of regional recharge driven by snowmelt; but in addition, considerable ground water was pumped from the shallow aquifer of reaches 1 and 3 during the period between the two tracer studies. Water withdrawal is discussed in the section “Ground-Water Pumping.” Changes in

the water table and the diminished rates of ground-water flow explain why the ground-water emergence rates were small at the downstream ends of reaches 3 and 4 in 2002 compared to those in 2001.

In summary, downstream changes in the hydraulic properties, and to a lesser degree the geometry, of the aquifer explain why most sites of ground-water emergence occur where they do. Ground water emerges to become streamflow where the gravel aquifer is narrowed or terminated by debris-fan sediment, and where the gravel aquifer is narrowed in canyons composed of resistant bedrock. Thinning of the aquifer at a shallow bedrock sill could cause ground water to emerge, but that is not the cause in the study reach, at least upstream from 2.5 km (fig. 13). Ground water was not observed to emerge where the water table was at a lower elevation than the streambed (fig. 11), as expected. Ground-water recharge from a source such as a bedrock fracture zone is not necessary to explain why ground water emerges where it does, except at Cabin Springs as discussed in the next section.

Hydrologic Observations near Cabin Springs

Cabin Springs is located on the north side of the Red River Valley in Columbine Park (pl. 1). This zone of emerging ground water is important because that is the site of the largest solute loading observed along the Red River during the 2001 tracer injection and synoptic sampling study (Kimball and others, 2006). In addition, as the data in this section illustrate, a bedrock/colluvium source of water is required to explain certain hydrologic observations.

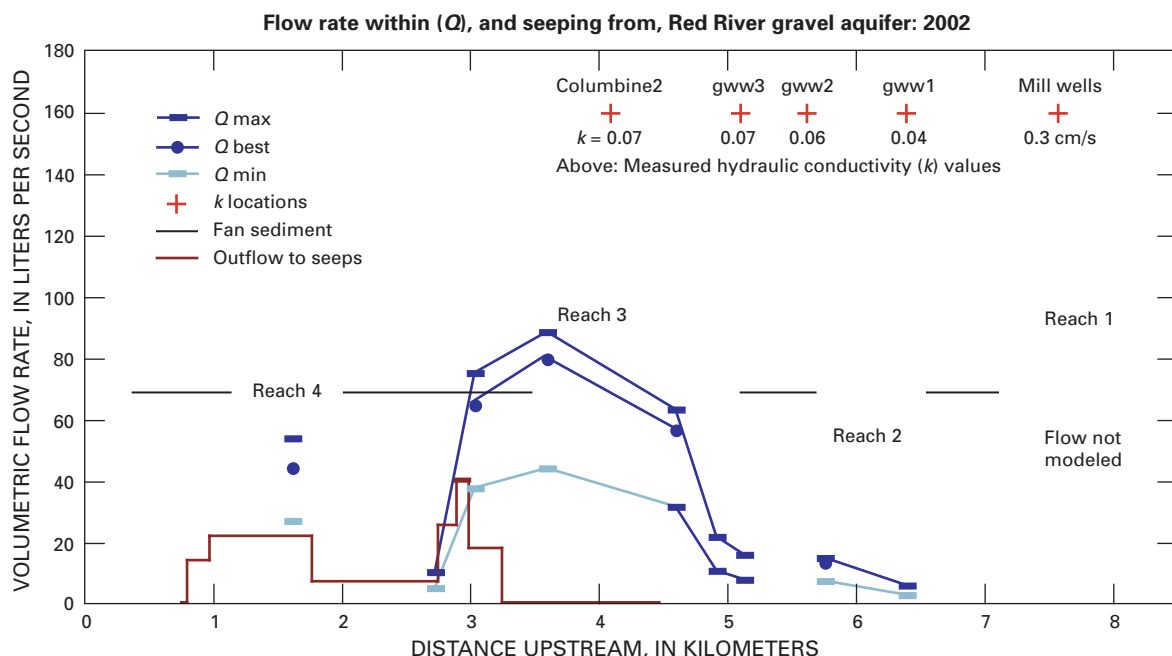


Figure 17 illustrates the rate of flow of the Red River through Columbine Park documented by the 2001 tracer study. In the vicinity of the Goat Hill Gulch tributary fan, the Red River gained discharge because the transmissivity of the alluvial aquifer decreased, in the downstream direction, as a result of the presence of debris-fan sediment. That gain in streamflow occurred over a long reach, in contrast to the point source where Columbine Creek enters the Red River. The gain in streamflow at Cabin Springs (23 L/s) also resembles a point source in that the gain occurred over a short reach and no gain was observed in the next reach downstream. There is no debris-fan sediment at Cabin Springs. In addition, the alluvial aquifer increases in width and thickness moving downstream past Cabin Springs (fig. 13). Because the transmissivity of the aquifer increases, moving downstream past Cabin Springs, the logical conclusion is that there is an external source of water.

The hypothesis that water enters the alluvial aquifer from an external source near Cabin Springs is confirmed by observations made during an aquifer test conducted during October 1996 (GSI/water, 1996). The solid lines in figure 18 shows the shape of the water-table surface of the alluvial aquifer after 15 days of steady pumping of Columbine Well No. 2. The locations of the pumping and observation wells are shown on plate 1 and fig. 18. If no recharge occurred during the aquifer test the water-table contours would be generally oriented north-south, perpendicular to the downvalley flow direction. Yet, the contours curve to become parallel to the bedrock hillslope and to the Red River streambed, on the north side of the valley. This led GSI/water (1996) to conclude that the alluvial aquifer was being recharged from a source located on the north side of the valley. Hypothetically, that source may have been from bedrock or from Red River streambed infiltration, but the latter source must be discounted. Figure 19 shows the pH of the Red River and the change in pH of the alluvial

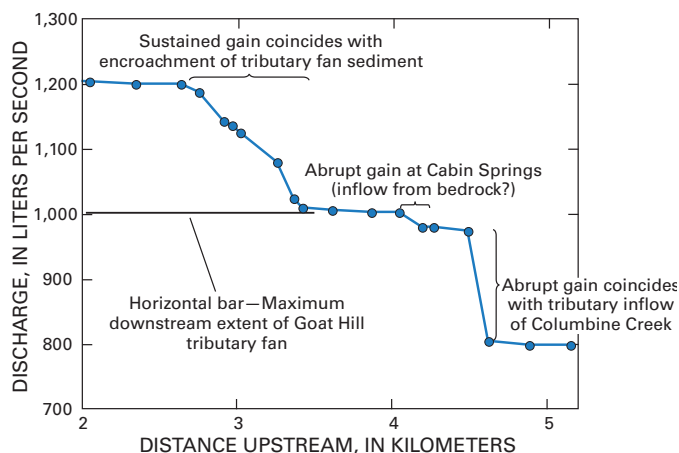


Figure 17. Discharge of the Red River through Columbine Park documented by the August 2001 tracer dilution study (Kimball and others, 2006). Data supplied by Robert Runkel (U.S. Geological Survey, written commun., 2004). The horizontal distance scale is the same as used in figures 11, 13, 15, and 16.

ground water during the pumping test of Columbine Well No. 2. The pH of the Red River was near neutral (GSI/water, 1996). In contrast, the ground water pH was slightly acidic before the pumping test and became more acidic during that test. This could not be the result of infiltration of near-neutral stream water. Thus, acidic ground water must enter the alluvial aquifer from bedrock/colluvium on the north side of the valley in the vicinity of Cabin Springs (GSI/water, 1996). The external water entered an alluvial aquifer that was flowing full and, thus, the excess water emerged from the alluvial aquifer to become streamflow. Based on the observed gain in streamflow during the 2001 tracer study, the rate of recharge from the bedrock/colluvium source was 23 L/s at a minimum. The rate of recharge from the bedrock/colluvium source was likely larger than 23 L/s because the transmissivity of the alluvial aquifer increased downstream from Cabin Springs (fig. 15) and the aquifer continued to flow full through that reach. The results of the ground-water flow model (fig. 15) suggest the aquifer gained 28 L/s between 4.6 and 3.6 km. Thus, taking the model results at face value, the rate of recharge from the bedrock/colluvium source may have been about (23 plus 28) 51 L/s.

The conservative conclusion is that the rate of recharge from the bedrock/colluvium source near Cabin Springs was larger than 20 L/s. After studying the bedrock of the area, Caine (2006) constructed a ground-water flow model and concluded that it is both physically possible and realistic for 20 L/s of ground water to be delivered to Columbine Park through bedrock fractures.

Water Budget for Alluvial Aquifer

A water budget of the alluvial aquifer in Columbine Park was constructed to evaluate whether or not the rate of recharge of the alluvial aquifer from the bedrock/colluvium source could be further constrained. The reference frame is that of the gravel aquifer, so a gain in streamflow is considered ground-water loss. The budget takes the familiar form of inflow minus outflow equals the change in storage. This is a synoptic water budget, however, and the flow is considered in a steady state, so inflows and outflows are expressed as rates not volumes. The water table also is considered steady, so the “change in storage” term is zero.

Streambed Infiltration

Any ground-water budget should consider streambed infiltration as a potential source of ground-water recharge, and this is particularly true for the Red River study area because there are reaches where the water table is seasonally or permanently below the level of the streambed (fig. 11). It is challenging to evaluate infiltration, however, because there is little empirical information available for perennial, gravel-bedded streams during base-flow conditions, and there is insufficient data to evaluate infiltration processes from a theoretical standpoint. For

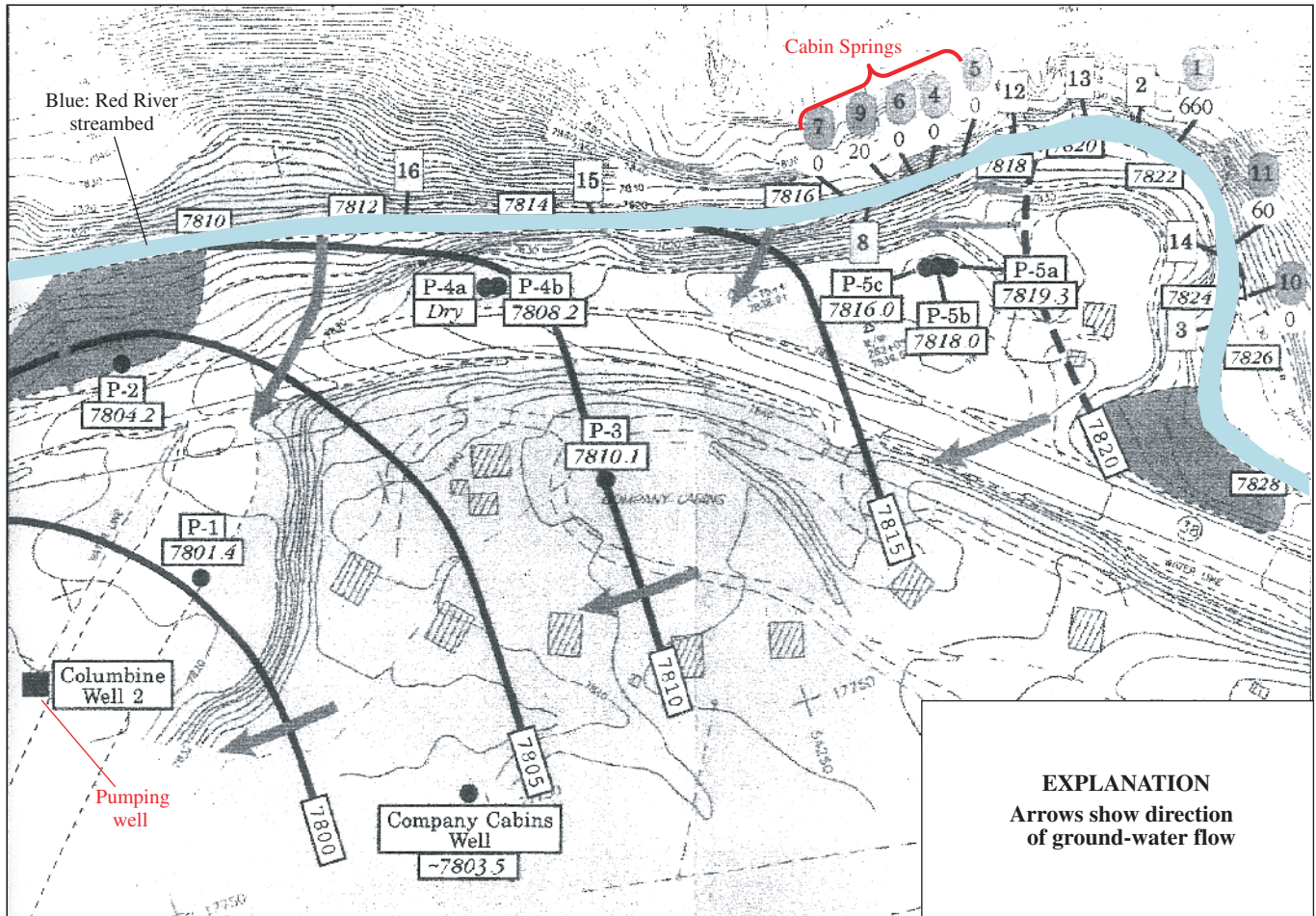


Figure 18. Shape of the water table during pumping test of Columbine Well 2, modified from GSi/water (1996). Water level contours are in feet, 5 foot contour interval, north is toward top of page.

that reason, select data are presented to illustrate the range in magnitude of infiltration, and the flow model is used to make some estimates for the Red River.

Ephemeral, sand-bedded streams are known for high rates of infiltration, which also is called transmission loss. Renard and Keppel (1966) documented a flash flood on a southern Arizona stream, which had duration of 2 hours and wave speed of about 1.5 m/s. About one-half of the volume of runoff was lost over a distance of 10.9 km, at a reach-averaged loss rate of 665 L/s/km. Assuming a wetted perimeter of 10 m, that equates to an infiltration rate of 24 cm/hr and includes the extremely high infiltration that typically occurs when the substrate is first wetted. Compared to ephemeral streams, infiltration along perennial sand-bedded streams is lower. Infiltration measurements have been made along Medano Creek, a perennial stream in Great Sand Dunes National Park in Colorado (Lachmar and others, 1999; McCalpin, 1999). During low-flow conditions, the sand-bedded reach lost runoff at 65 L/s/km, which equates to an infiltration rate of several centimeters per hour. Thomas and others (2000) documented daily average infiltration rates (excluding evaporative losses) ranging from 1.0 to 0.3 cm/hr along the Santa Fe River in New Mexico, which once

was an ephemeral stream that now receives perennial municipal effluent. Although the data are complicated by several factors, the infiltration rates appear to have decreased over the several-month period of the study. Decreasing infiltration through time is to be expected where a stream carries organic compounds in suspension, which will enter the streambed with the infiltrating water and clog the pores (Thomas and others, 2000). Along ephemeral streams the sealing can be reversed, when floods deeply scour the bed (Vincent and others, 2004) replacing the clogged sediment with fresh sand.

Measurements of infiltration have been made along the perennial, gravel-bedded reach of Medano Creek, upstream from where it flows past the sand dunes. These measurements also are notable because discharge entering and leaving a 4.3-km-long reach was measured using calibrated flumes; thus, the results should be accurate. During low-flow conditions, loss rates of 6 L/s/km (McCalpin, 1999) and 7 L/s/km (Lachmar and others, 1999) were measured. Assuming an average bed width of 3 m, which is based on the author's casual observations of that stream, these loss rates equate to infiltration rates of 0.7 and 0.8 cm/hr, respectively. Medano Creek is remarkable for its clear water. The Red River, in contrast, is often milky and is opaque with

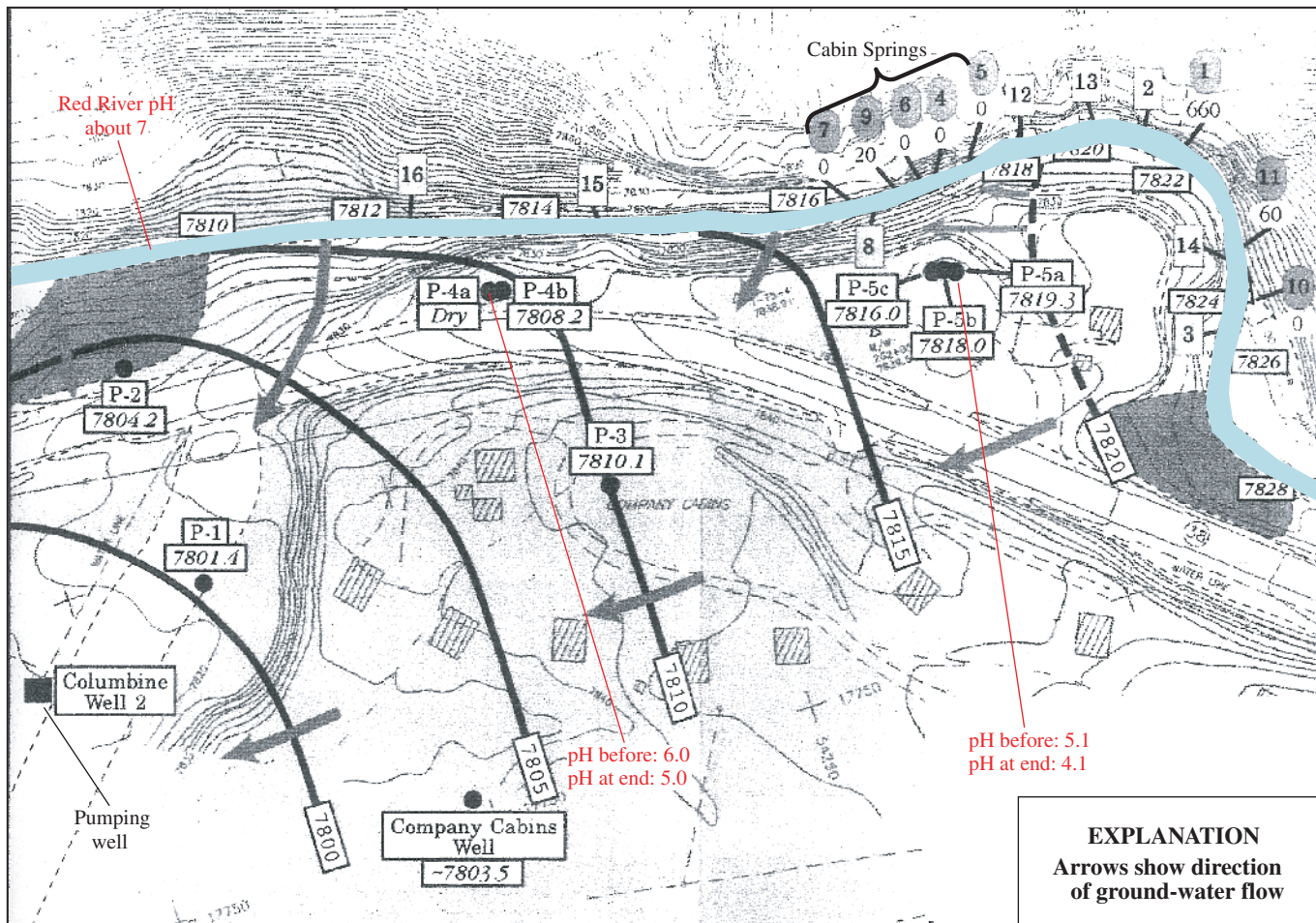


Figure 19. pH of the Red River and the change in pH of the alluvial ground water during pumping test of Columbine Well 2, modified from GSi/water (1996).

suspended sediment when thunderstorms generate runoff from alteration scars (Plumlee and others, 2007). Like suspended organics, suspended sediment enters the bed with infiltrating water and is filtered out of suspension near the bed surface. That process can only increasingly seal the streambed through time. Unlike ephemeral streams, gravel-bed streams, such as the Red River, rarely scour deeply over long reaches; thus, the bed seal is rarely broken up. For that reason, infiltration rates along the Red River are probably low, and likely insignificant (Vail Engineering, 2000). This can be illustrated with a simple calculation. Herein, 5 m is used for the average width of the Red River channel, which is based on width measurements made during the 2001 tracer study (Robert Runkel, written commun., 2004). An infiltration rate of 0.1 cm/hr, for example, equates to a reach-averaged streamflow loss rate of 1.4 L/s/km. The next two paragraphs evaluate whether or not infiltration of that magnitude is detectable in the available measurements and calculations.

During the 2001 tracer study, measurements of the volumetric rate of streamflow were made using a current meter at numerous locations. Those data were provided by Robert Runkel (written commun., 2004). Note that the base flow of the Red

River was on the order of 700 L/s. The author's analysis of the current-meter data suggests that the uncertainty in a streamflow measurement is on the order of plus or minus 7 percent, which means that a change in discharge of 50 L/s would be detectable. No downstream decrease in streamflow of that magnitude was observed in any reach, including those where the water table was well below the level of the streambed.

The flow model results (figs. 15 and 16) are now explored to see if the apparent downstream increases in aquifer discharge could be explained by streambed infiltration. In reach 2 (fig. 15) the aquifer flow rate apparently increased about 10 L/s in the downstream direction at a rate of about 16 L/s/km. If that is not the result of model errors and was the result of infiltration, a rate of 1.0 cm/hr is required. That rate of streambed infiltration is physically possible but likely too large based on the data presented in the preceding paragraphs. During the 2002 tracer study, the aquifer in the Columbine Park sub-reach from 4.6 to 3.6 km apparently gained discharge at a rate of 23 L/s/km. If that apparent recharge were by infiltration, a rate of 1.7 cm/hr is required. Again, that rate of streambed infiltration is physically possible but unlikely.

In summary, along the Red River during low-flow conditions the streambed infiltration rate is likely low and probably is less than 1 cm/hr if not negligible. In reaches where the water table was at the level of the streambed, such as the Columbine Park reach during the 2001 tracer, it is presumed that during low-flow conditions infiltration would not recharge an aquifer that is already flowing full.

Goat Hill Gulch Fan as a Source of Water

Ground water from tributary watersheds passes through tributary debris fans to recharge the Red River alluvial aquifer. The flow rate is probably low, however, in debris fans shed from watersheds containing alteration scars because they have low hydraulic conductivities (table 3). In addition to having a low hydraulic conductivity, the main part of the Goat Hill Gulch fan is hydraulically detached from its watershed. Underground mining has resulted in a collapse structure that has reached the ground surface in the Goat Hill Gulch valley (pl. 1). Thus, streamflow and shallow alluvial ground water in that tributary valley enter the mine before it reaches the Red River Valley. For that reason, it is assumed that ground water in the Goat Hill Gulch valley no longer recharges the Red River aquifer.

Ground-Water Pumping

Ground water is pumped from the shallow alluvial aquifer, causing the level of the ground-water table to fluctuate in certain reaches (Vail Engineering, 2000). This section illustrates why pumping must be included as an outflow in the water budget for the aquifer. The Questa mine has an extensive waterworks and pumps or diverts water for operations. In 2001, for example, the mine pumped and diverted more than 3 million cubic meters (820 million gallons) of water (table 4). For perspective, however, on average the Red River watershed yields 41 million cubic meters (11 billion gallons) a year of surface water, according to statistics for the local USGS streamflow-gaging station (Red River near Questa, station number 08265000). That gage is located about 4 km downstream from Columbine

Park. Thus, in 2001, the mine extracted the equivalent of about 7 percent of the annual volume of runoff passing the mine in the Red River. Water also passes the mine as ground water in the shallow alluvial aquifer. The ground-water flow model developed herein suggests that a flow rate on the order of 80 L/s for the alluvial aquifer in Columbine Park might be a reasonable average. Flow in nearby alluvial reaches is less (fig. 15). At face value, about 2.5 million cubic meters of water per year (or less) passes the mine as shallow ground water, which is equivalent to 6 percent (or less) of the annual runoff in the Red River. In 2001, the mine pumped about 2 million cubic meters (550 million gallons) of water directly from the shallow alluvial aquifer (see Mill Well 1, Mill Well 1A, and Columbine No. 2 well in table 4). On an annual basis, the mine pumps a volume of water from the aquifer that is the same order of magnitude as the volume of ground water that passes the mine in the Red River's shallow alluvial aquifer.

Since the inception of the current mining operation, the company has extracted water from various sources at various times (Vail Engineering, 2000). The volumes of water involved have been variable on daily, monthly, and annual timeframes. Water has long been pumped from the mine itself in order to keep it dry. In this study, it is assumed that appreciable ground water does not exit the shallow alluvial aquifer by passing through bedrock and ending up at the mine sump. Water extracted from all sources is used in the milling operation and then is exported downstream by pipeline to the tailings ponds close to the town of Questa. In the winter the mine uses considerable water to keep the tailings pipeline from freezing. Thus, water pumped from the aquifer is a permanent outflow and does not reenter the aquifer at some other location of concern in this study. For the period of interest, the history of pumping is illustrated in figure 20.

During the period between the two tracers, considerable ground water was pumped from the alluvial aquifer. In the mill reach, 970,000 m³ of water was pumped at an average rate of 58.6 L/s. That withdrawal seems sufficient to explain the decline in the water table observed between the times of the two tracer studies. The observed water table decline is about 9 m (fig. 11). This translates into a volumetric loss of 270,000 m³ of water, assuming the aquifer is rectangular, 120 m wide, 1 km long, and has porosity of 25 percent. This simple calculation ignores the dynamics of the ground-water system. Pumping drawdown can cause water loss from storage in the area surrounding the reach (Theis, 1940), which in this location likely involved storage loss in the gravel reach upstream from the mill site (fig. 12). In addition, there is the possibility that the alluvial aquifer receives long-term recharge from the surrounding bedrock aquifer. In any case, the calculation illustrates that pumping of water from the shallow aquifer is probably largely responsible for the observed water-table decline in the mill reach. In the Columbine Park reach, pumping during aquifer tests is known to cause a temporary cone of depression (fig. 18) and likely caused the longer term decline shown in figure 11. In that reach, 638,000 m³ of water was pumped at an average rate of 38.5 L/s during the period between the two tracers when the

Table 4. Long-term sources of water for mine use.

[km, kilometers; m³, cubic meters; a.k.a., also known as]

Name	Location on profile (km)	Total yield in 2001 (m ³) ¹
Mine sump		476,000
Columbine No. 1 well	3.80	0
Columbine No. 2 well	4.01	673,000
Mill 1A (a.k.a. Yard 1A) well	7.58	635,000
Mill 1 (a.k.a. Yard 1) well	7.68	722,000
River diversion at mill	7.71	600,000
Total		3,106,000

¹Based on data provided by Molycorp, Inc. (written commun., 2003), which is also on file with the New Mexico State Engineer's Office.

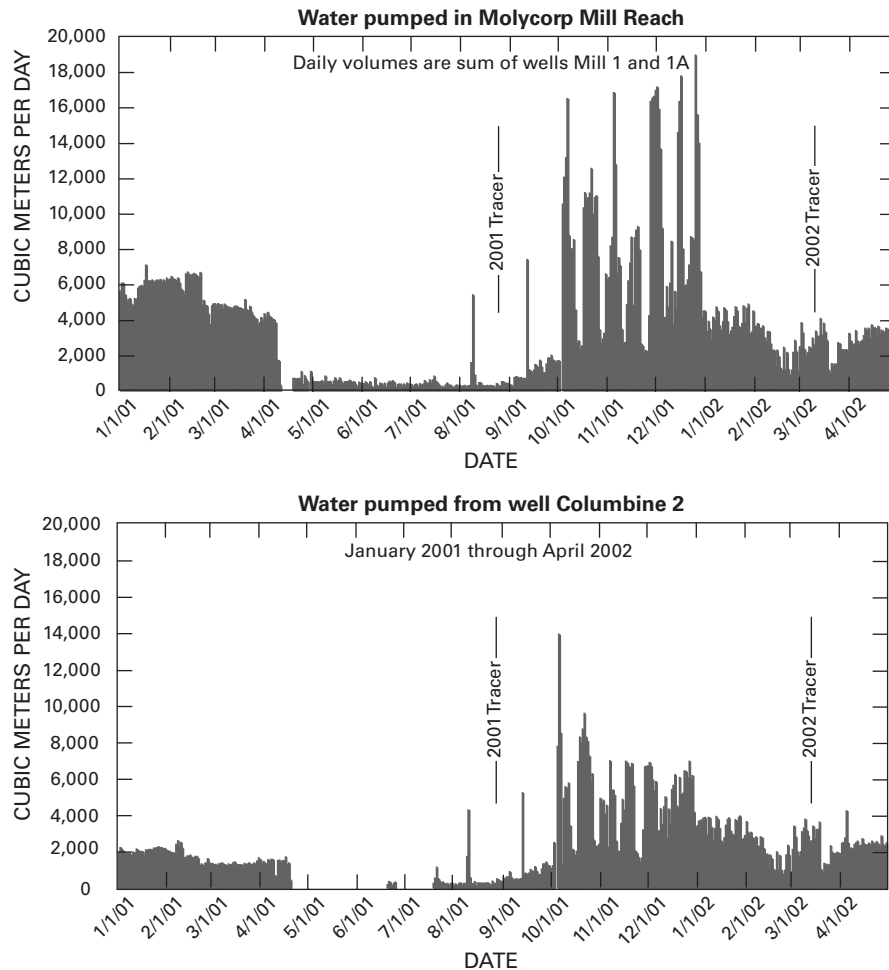


Figure 20. Record of pumping from the Red River alluvial aquifer between January 2001 to April 2002. Data supplied by Molycorp, Inc. (written commun., 2003).

water table declined less than 3 m. In reach 2, in contrast, the observed water-table decline cannot be explained by pumping for two reasons. First, there was no pumping of ground water in that reach before an extraction well went online in 2003 (Bruce Walker, written commun., 2004). Second, the water-table decline shown in figure 11 increased in the upstream direction from 2 to 4 m, making it unreasonable to explain this decline as the result of upstream propagation of the drawdown caused by pumping in Columbine Park.

To include pumping as an outflow in the aquifer water budgets, which of necessity assume steady-state conditions, the steady-state pumping outflows just prior to the two tracer studies must be approximated. The question involves what timeframe (days, months, or years) should be used to average pumping rates, and ground-water traveltime is used as an index. The average linear velocity of ground-water flow can be calculated as the product of hydraulic conductivity and water-surface gradient, divided by porosity (Freeze and Cherry, 1979). Porosity is assumed to be 25 percent. When the data for Columbine Park are used, the linear velocity is approximately 4 m/d and, thus, a water particle would require about 100 days to travel 400 m, which is about twice the width

of the aquifer. With that as a guide, the pumping rates (fig. 20) were averaged over the 3 months prior to the tracer studies. Ground-water pumping in Columbine Park, over the 3 months prior to the 2001 tracer, averaged 176 m³/d, or 2.0 L/s. There was no pumping in June and most of July (fig. 20), however, and the pumping rate averaged over the 35 days prior to the August 2001 tracer was 432 m³/d, or 5.0 L/s. In the water budget, 5.0 L/s was used as the best estimate. Ground-water pumping in Columbine Park, over the 3 months prior to the 2002 tracer, averaged 3,169 m³/d, or 36.7 L/s.

Water Budget Results for Columbine Park

The ground-water flow model for Columbine Park (fig. 15) seems to indicate that more water emerges to become streamflow than enters the aquifer from upstream. An additional source of recharge would be required, and a water budget is used to constrain the magnitude of that inflow. This water budget considers the reach through Columbine Park to just downstream from the Goat Hill Gulch fan (4.6 to about 2 km), and is depicted in figure 21.

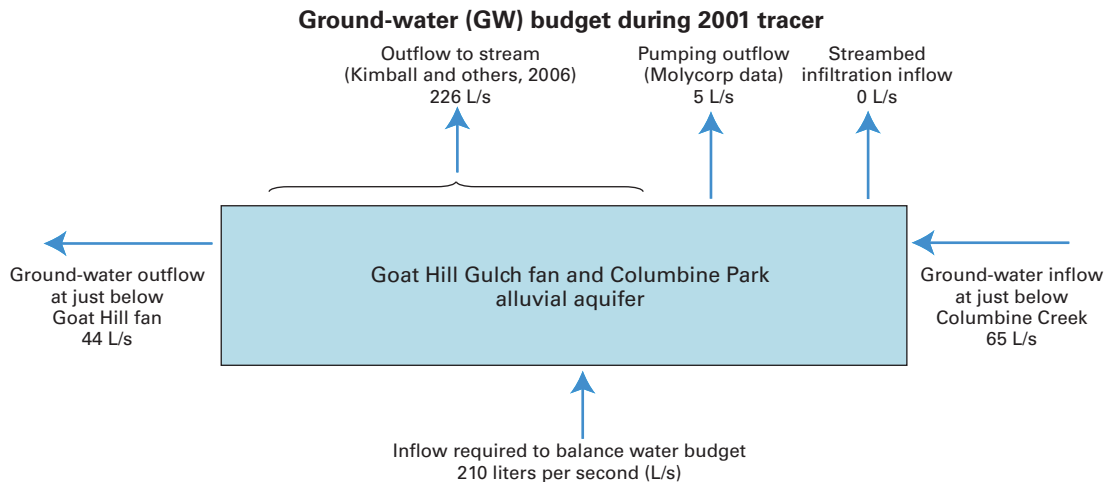


Figure 21. Components of the water budget for the Red River alluvial aquifer in Columbine Park during the 2001 tracer dilution study.

At the time of the 2001 tracer, about 65 L/s entered the reach at 4.6 km (fig. 15) as ground water derived from both the Red River alluvial aquifer and the Columbine Creek alluvial aquifer. Streambed infiltration is assumed to have been zero. There were three distinct outflows within the reach. Pumping extracted water at a rate of about 5 L/s. Ground water emerged to become streamflow at a rate of 226 L/s (Kimball and others, 2006). About 44 L/s exited the reach as ground water that passed through the Goat Hill Gulch fan. Assuming that the flow was steady state, inflows must be balanced by outflows, and an additional inflow of 210 L/s is required by the calculation. That inflow is shown entering the base of the alluvial aquifer in figure 18 but may have entered through the side of the aquifer. Conceptually, this water passed through bedrock or colluvium before entering the gravel aquifer. Subsurface recharge of 210 L/s is very large, however, and it is important not to overestimate the rate. A sensitivity analysis of the various factors (excluding hydraulic conductivity) was conducted with the result that the subsurface recharge had a rate as low as 180 L/s.

The budget procedure is now repeated for the time of the 2002 tracer (fig. 18). About 57 L/s entered the reach at 4.6 km (fig. 16) as ground water derived from both the Red River alluvial aquifer and the Columbine Creek alluvial aquifer. Streambed infiltration is assumed to have been zero. Pumping extracted water at a rate of about 37 L/s. Ground water emerged to become streamflow at a rate of 90 L/s (Kimball and others, 2006). About 44 L/s exited the reach as ground water that passed through the Goat Hill Gulch fan. Thus, an additional inflow of 114 L/s is required by the calculation. A sensitivity analysis of the various factors (excluding hydraulic conductivity) was conducted with the result that the subsurface recharge had a rate as low as 99 L/s.

Before reaching any conclusions the uncertainty in hydraulic conductivity must be addressed. It is tempting to have confidence in the hydraulic conductivity of 0.07 cm/s used to model flow within the gravel of reach 3 (including

Columbine Park) because that value was the result of aquifer tests at two wells located within the reach. There are two reasons, however, to suspect the value of 0.07 cm/s is less than the composite hydraulic conductivity of the reach as a whole. First, in the vicinity of Cabin Springs, the alluvium is coated and partially cemented with iron and manganese compounds, which may act to reduce hydraulic conductivity on that side of the valley. Those compounds have not been observed in alluvium on the south side of the valley. The monitoring wells used during the Columbine No. 2 well aquifer test are exclusively located on the north side of the valley (fig. 18), and for that reason the results of the aquifer test may be biased by the least conductive alluvium. Second, the flow model results for the 2001 time period (fig. 15) suggest that ground water passes the cross section at 3.6 km at a rate of 93 L/s, yet immediately downstream, about 203 L/s of ground water emerged to become streamflow. It seems unlikely that ground water would enter the alluvial aquifer at substantial rates in a reach dominated by debris-fan sediment that has comparatively low hydraulic conductivity. A more reasonable explanation is that ground water passes the cross section at 3.6 km at a rate substantially greater than 93 L/s. This means the hydraulic conductivity used in the flow model was too low, perhaps by a factor greater than 2. Therefore, the 100- to 200-L/s estimates of the rate of recharge from a bedrock or colluvium source are too large.

In summary, the Red River alluvial aquifer must receive subsurface recharge in the Columbine Park reach. This ground water passes through bedrock or colluvium before entering the alluvium along the north side or bottom of the gravel aquifer. The rate of recharge is at least 20 L/s, as demonstrated in the section "Hydrologic Observations near Cabin Springs." The water budget developed in this section failed to further constrain the rate of this inflow. The major uncertainty in the ground-water flow calculations was hydraulic conductivity rather than the boundary conditions of the aquifer.

Influence of Geomorphology on Ground-Water Flow in the Shallow Alluvial Aquifer

Physical Condition of Alluvial Aquifer Prior to Mining

This study is part of a larger investigation of the pre-mining ground-water quality in the Red River Valley. How well the current alluvial aquifer reflects the physical conditions prior to mining is discussed for that reason. Both the Red River and its tributary fans had episodes of aggradation and incision during the late Quaternary, but the most recent episode of incision was modest in magnitude and apparently occurred several thousand years ago. The rapid rate of erosion of alteration scars at present and the evidence that some scars have healed during the Holocene suggest that the sizes and locations of scars have changed through geological time. The current size and shape of the Red River alluvial aquifer, however, likely reflect the general geometry of the aquifer during the late Holocene. The debris-fan sediment that currently influence ground-water flow also exerted those same influences on ground-water flow a century ago, before mining began in the Red River Valley.

Why Does Ground Water Emerge Where It Does?

The five factors that potentially cause ground water to emerge from alluvium can be deduced by inspecting the Darcy equation for unconfined ground-water flow (equation 5). A downstream decrease in the cross-sectional area of an aquifer reduces the transmissivity of the aquifer and, thus, can cause ground water to emerge at springs or seeps. Decreases in aquifer width and thickness are considered separate factors of decreasing cross-sectional area, however, because different measurements are needed to document widths and thicknesses. Downstream decreases in water-table gradient and aquifer hydraulic conductivity are additional factors, as is the occurrence of a tributary aquifer merging with an aquifer that is already full.

Downstream changes in the hydraulic properties or geometry of alluvium explain why ground water emerges where it does at most sites in the Red River study area. At many locations ground water emerges to become streamflow where the gravel aquifer is narrowed or terminated by debris-fan sediment, and where the gravel aquifer is narrowed in canyons composed of resistant bedrock. Thinning of the aquifer at a shallow bedrock sill could cause ground water to emerge, but that is not the cause of emergence in the study reach adjacent to the mine, at least upstream from 2.5 km (fig. 13). A decrease in water-table gradient, which is evident at three locations in figure 11, may be a contributing cause of ground-water emergence in reach 4 and at the upstream end of reach 1 (fig. 15). Ground-water recharge from a source

such as a bedrock fracture zone is not necessary to explain why ground water emerges where it does, with one notable exception. In the vicinity of Cabin Springs, water passes from bedrock or colluvium into the alluvial aquifer. The rate of recharge from that source is at least 20 L/s, as discussed in the section “Hydrologic Observations near Cabin Springs.”

How Can the Water Table Persist Deep Beneath a Perennial Stream?

At several locations in the study area the water table was observed to be located deep beneath the level of the Red River (fig. 11). Ground-water pumping explains why the water table was at a lower elevation than the streambed seasonally in Columbine Park and commonly (apparently) in the mill reach. The water table being at a lower elevation than the streambed can be a naturally occurring phenomenon, however, as illustrated in reach 2 (6.5 km in fig. 11) where there was no pumping. Such a natural occurrence is confirmed by the observation that the water table was 5 m beneath the streambed at USGS well SC-9A (pl. 1) in May and March 2004 (Cheryl Naus, written commun., 2004). At that location the water table is likely beneath the level of the streambed on a permanent basis, based on water-table fluctuations in nearby well SC-8A (high in May and June and low in the winter) documented between December 2002 and May 2004. At that location, there is no pumping, and the site is downstream from a complex of debris fans that likely act to substantially reduce the hydraulic conductivity of the aquifer. Debris-fan sediments force ground water to emerge at the surface and transmit so little water that the next gravel reach downstream can receive less water than it can potentially transmit. Streambed infiltration is evidently insufficient to fully recharge the gravel aquifer. Thus, low hydraulic conductivity debris-fan sediments not only explain why ground water emerges where it does, but also how a gravel aquifer can naturally flow only partially full even though it underlies a perennial stream.

Along What Flow Path Did the Ground Water Travel?

In the Red River Valley emerging ground water either flowed a considerable distance within an alluvial aquifer or a short distance in alluvium after entering the aquifer from a bedrock fracture zone or colluvium. It has long been recognized that ground water emerging in Columbine Park has undesirable chemistry, and people have speculated about the source and flow path of those undesirable constituents. As mentioned previously, Vail Engineering (2000) suggested that the undesirable water was derived from a considerable distance upstream. Ostensibly, some of that water came from Bitter Creek (pl. 1), where it entered the alluvial aquifer in the vicinity of the town of Red River and flowed within the shallow aquifer as a “plume” a distance of 12 km to where

it emerged in Columbine Park. Their study used a correlation of streamflow with watershed characteristics rather than site-specific calculations of ground-water flow as was done in this report. They modified the regional-runoff relation of Hearne and Dewey (1988), which showed that average annual streamflow, measured at USGS streamflow-gaging stations in the region, correlated well with watershed area and winter precipitation. Vail Engineering (2000) recast the relation for each month of the year. They used their correlation curve to predict the water yield (average for October) at numerous locations along the Red River, and streamflow was measured (on October 13, 1999) at most of these locations by using a current meter. Where the observed stream discharge was less than the predicted yield, they assumed the “missing” water was flowing in the alluvial aquifer beneath the site. The estimates of ground-water flow ranged from 1 to 30 percent of the predicted yield. They assumed that yield represents local streamflow plus local ground-water flow even though the measurements used to calibrate their relation are only streamflow at gages. The ground-water flow in alluvium beneath those gages is not known. They rightly accounted for the dependence of precipitation on watershed altitude. However, in what they call their “verification” (see their figure 3, bottom pane) a watershed with “elevation” of about 10,000 feet is predicted to yield about 5 inches (12.7 cm), but the gaging-station data on their figure clearly show that such watersheds actually yield between 4 and 6 inches (10.2–15.2 cm). Thus, their predicted yields (of streamflow only) have a 20 percent uncertainty at the least. Current meter measurements of low flow, which they encountered, have uncertainties of at least 5 or 10 percent. It is plausible that undesirable water may flow long distances within an alluvial aquifer, but this was not proven by that study for the water that emerges in Columbine Park.

There are four independent lines of evidence that collectively demonstrate that little of the water emerging in Columbine Park traveled great distances within the Red River alluvial aquifer.

1. Along the Red River, water in the alluvial aquifer repeatedly flows toward bodies of debris-fan sediments that are extensive and have low hydraulic conductivity. At each body of debris-fan sediment a substantial amount of the ground water is forced to the surface where it becomes streamflow. Thus at each body of debris-fan sediment, a hypothetical plume of undesirable water would be divided, with a substantial amount emerging where it would become diluted by streamflow, and the constituents would be unlikely to reenter the shallow aquifer through streambed infiltration. The portion of the plume that remained in the aquifer would be diluted or at least laterally partitioned by tributary aquifer inflows. The fact that these processes would be repeated, because there are numerous bodies of debris-fan sediment, suggests that little of the plume could remain in the subsurface over distances of many kilometers.
2. Because a portion of the hypothetical plume must emerge at each body of debris-fan sediment the geochemical signature of the plume should be detectable at each site of emerging water. This was not the case, however. The geochemical signature of the water emerging in Columbine Park is unique, and that signature was not observed at any sites of emerging water upstream (McCleskey and others, 2003; Kimball and others, 2006).
3. If all of the water observed emerging in the Columbine Park reach (226 L/s according to Kimball and others, 2006) was derived from a hypothetical plume, it would necessarily have passed through the narrow alluvial aquifer just upstream from the confluence with Columbine Creek. That area is called reach 2 in figure 15. In order for 226 L/s to pass through reach 2, a hydraulic conductivity of 0.8 cm/s is required, but that is almost three times larger than any hydraulic conductivity measured in the study area (fig. 15; table 3). There are numerous narrow reaches upstream from reach 2, and it seems unlikely that each narrow reach would have the exceptionally high hydraulic conductivities needed to transmit the hypothetical plume.
4. Hydrologic observations made near Cabin Springs in Columbine Park clearly demonstrate that the shallow alluvial aquifer is recharged locally in the subsurface from a bedrock or colluvium source on the north side of the valley at precisely the site of the largest geochemical loading observed along the Red River by the 2001 tracer study.

In conclusion, the assumption of a far traveled plume of ground water has not met the tests presented in this report. It seems unlikely for the high-manganese water observed emerging in the Columbine Park reach to have traveled many kilometers within the alluvial aquifer. Instead, the alluvial aquifer is recharged by acidic water passing from bedrock or colluvium adjacent to Cabin Springs. The alluvial aquifer may also have been recharged a few kilometers upstream from Columbine Park, where ground water emerges to become streamflow. The Questa mine is adjacent to Columbine Park, but this study has not demonstrated that mining activities caused the high levels of manganese in the emerging ground water. A spatial association does not prove causality.

Summary

Landforms, and the specific geomorphic processes that created them, influence the alluvial ground-water hydrology in the Red River Valley, between the towns of Questa and Red River, New Mexico. These landforms, their history, and their influence on the alluvial ground water are the subject of this report.

The bedrock of the Taos Range surrounding the Red River is composed of Proterozoic rocks of various types, which are intruded and overlain by Oligocene volcanic rocks associated with the Questa caldera. Locally, these rocks were altered by hydrothermal activity, and the alteration zones that contain sulfide minerals are particularly important because they constitute the commercial ore bodies of the region and, where exposed to weathering, form sites of rapid erosion referred to as alteration scars.

The valley of the Red River developed over the past 26 million years following cessation of volcanism, which had created a broad plateau. Subsequently, the Red River and its tributaries incised in direct response to the creation of relief, at the western front of the Taos Range, by faulting associated with development of the Rio Grande rift. The result is the rugged mountainous terrain visible today. Over the past 26 million years, hillslopes eroded at a modest rate of about 0.02 millimeter per year, on average. The rate of hillslope erosion likely increased through time because the area consisting of steep hillslopes increased through time and the landscape had to erode through hundreds of meters of more resistant rock before the altered rock became exposed. A second process caused the Red River to incise in the late Quaternary. Prior to a million years ago, the Red River was essentially the headwater of the Rio Grande. In response to stream capture of the San Luis Basin, the Rio Grande incised 260 meters (840 feet) over the past 600–700 thousand years, creating the Rio Grande gorge. The Red River was thus relegated to the status of a tributary, and downcutting of the master stream caused the Red River to downcut as well. The rate of this stream incision apparently decreased through time. This episode of incision created the gorge at the mouth of the Red River and the valley at the site of Questa but apparently had relatively little influence on the Red River Valley within the Taos Range upstream from Questa.

During the late Quaternary, erosion and deposition within the Red River watershed were variable. The Red River incised the bedrock base of its valley during certain time periods, but the Red River also experienced episodes of sediment aggradation and episodes of reincision into that alluvium. Although the highest areas of the Taos Range were glaciated, glacial ice did not extend down into the study area between the towns of Questa and Red River. Nonetheless, aggradation of the Red River took place during periods of glaciation. The thickness of that accumulated sediment is not known, but it is likely less than 50 or 100 m. The Red River evidently removed most of that sediment from the valley and resumed eroding the bedrock base of the valley immediately following the most recent period of glaciation. Then, the Red River and its tributary streams began to aggrade again about 14,000 years ago, just prior to the beginning of the Holocene. Thus, most deposits of alluvium in the valley are likely less than 10–20 thousand years old. Over the past thousand years, if not over the entire Holocene, erosion rates were spatially variable. Forested hillslopes eroded at about 0.04 millimeter per year, whereas alteration scars eroded at about 2.7 millimeters per year. The erosion rate of the alteration scars is unusually rapid for naturally occurring sites that have not been disturbed by humans. In addition, watersheds containing large alteration scars delivered more sediment to the Red River Valley than the Red River could remove. Consequently, large debris fans, as much as 80 meters thick, developed within the valley. The aggradation of those fans also caused the Red River to aggrade immediately upstream from them and created a characteristic segmentation of the longitudinal profile of the valley. Upstream from a large fan, the alluvial valley bottom is not steep and is relatively wide. The alluvium is composed of gravel deposited by the Red River and is 30–50 m thick. Along the downstream

half of a large fan, the Red River is steep, often consisting of a cascade of water flowing over boulders. The flood plain is narrow or absent, sediment deposited by the Red River is thin, and these features are adjacent to thick and wide debris-fan deposits. Downstream from a large fan, Red River alluvium typically has intermediate gradient, width, and thickness.

The geomorphology of the Red River Valley has several large influences on the hydrology of the shallow alluvial aquifer, and those influences were in effect before mining began within the watershed. Several reaches where alluvial ground water emerges to become Red River streamflow were noted by a tracer dilution study in 2001. Several potential factors could cause ground water to emerge from alluvium where it does. The emergence of ground water from alluvium at certain locations is partially caused by narrowing of the aquifer. The aquifer narrows where erosion-resistant bedrock, which tends to form vertical cliffs, restricts the width of the valley bottom. Although the presence of a shallow bedrock sill, overlain by shallow alluvium, is a plausible cause of ground-water emergence, that cause was not demonstrated in the study area. The water-table gradient can locally decrease in the downstream direction because of changes in the hydraulic properties of the alluvium, and this may be a contributing cause of ground-water emergence. At one site (near Cabin Springs), ground-water emergence could not be explained by spatial changes in geometric or hydraulic properties of the aquifer. Furthermore, the available evidence demonstrates that ground water flowing through bedrock fractures or colluvium entered the north side of the alluvial aquifer, at a rate of about 20 liters per second and is the cause of ground-water emergence. At that location the alluvial aquifer was already flowing full, causing the excess water to emerge into the stream.

An indirect consequence of altered rock in the tributary watersheds is the rapid erosion rate of scars combined with the hydraulic properties of sediments shed from alteration scars. Those sediments have hydraulic conductivity values that are one to two orders of magnitude lower than the conductivity of the well-washed gravel deposited by the Red River. Where alteration scars are large, the debris fans at the mouths of the tributary watersheds substantially encroach into the Red River Valley. At such locations debris-fan materials dominate the width and thickness of the alluvium in the valley, and decrease the flow rate of ground water within the Red River alluvial aquifer. Many hydrologists would refer to the bodies of debris-fan sediments as aquitards. Ground water emerges from Red River gravel immediately upstream from most large debris-fans. A substantial fraction of the ground water approaching a debris fan can emerge to become streamflow. This observation has three implications. First, very little water can flow the entire length of the study area entirely within the alluvial aquifer because the ground water repeatedly contacts debris-fan sediments over that length. Second, it follows that emerging water containing unique elemental constituents must have entered the alluvial aquifer at a relatively short distance upstream. Third, a gravel aquifer downstream from a debris fan can transmit more ground water than flows into it through the debris fan. This observation explains how the water table can be naturally and permanently located well beneath the level of the bed of a perennial stream.

References Cited

- Bates, R.L., and Jackson, J.A., eds., 1980, Glossary of geology: Falls Church, Va., American Geological Institute, 751 p.
- Bauer, P.W., and Kelson, K.I., 2004a, Cenozoic structural development of the Taos area, New Mexico, *in* Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., *Geology of the Taos region: New Mexico Geological Society Guidebook*, v. 55, p. 129–146.
- Bauer, P.W., and Kelson, K.I., 2004b, Rift extension and fault slip rates in the southern San Luis Basin, New Mexico, *in* Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., *Geology of the Taos region: New Mexico Geological Society Guidebook*, v. 55, p. 172–180.
- Beakley, G.C., and Leach, H.W., 1972, *Engineering—An introduction to a creative profession*: New York, Macmillan, 618 p.
- Benson, A.L., 2004, Groundwater geology of Taos County, *in* Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., *Geology of the Taos region: New Mexico Geological Society Guidebook*, v. 55, p. 420–432.
- Birkeland, P.W., 1984, *Soils and geomorphology*: New York, Oxford University Press, 372 p.
- Blanchard, P.J., Bartolino, J.R., Naus, C.A., and Morin, R.H., 2006, Questa baseline and pre-mining ground-water quality investigation. 15. Methods of Phase II and III Well, installation and development and results of water-level data collection in the Red River Valley, New Mexico, 2002–2004: U.S. Geological Survey Scientific Investigations Report 2006–5246, 56 p.
- Briggs, P.H., 2002, The determination of forty elements in geological and botanical samples by inductively coupled plasma-atomic emission spectrometry, *in* Taggart, J.E., ed., *Analytical methods for chemical analysis of geologic and other materials*: U.S. Geological Survey Open-File Report 2002–223, p. G1–20.
- Briggs, P.H., Sutley, S.J., and Livo, K.E., 2003, Questa baseline and pre-mining ground-water quality investigation. 11. Geochemistry of alteration scars and waste piles: U.S. Geological Survey Open-File Report 2003–458, 17 p.
- Brown, Z.A., and Curry, K.J., 2002, Total sulphur by combustion, *in* Taggart, J.E., ed., *Analytical methods for chemical analysis of geologic and other materials*: U.S. Geological Survey Open-File Report 2002–223, p. R1–6.
- Bull, W.B., 1964, Geomorphology of segmented alluvial fans in western Fresno County, California: U.S. Geological Survey Professional Paper 352–E, p. 89–129.
- Bull, W.B., 1968, Alluvial fans: *Journal of Geological Education*, v. 16, p. 101–106.
- Bull, W.B., 1991, *Geomorphic responses to climatic change*: New York, Oxford University Press, 326 p.
- Carrara, P.E., Trimble, D.A., and Rubin, Meyer, 1991, Holocene treeline fluctuations in the northern San Juan Mountains, Colorado, U.S.A., as indicated by radiocarbon-dated conifer wood: *Arctic and Alpine Research*, v. 23, p. 233–246.
- Caine, J.S., 2006, Questa baseline and pre-mining ground-water quality investigation. 18. Characterization of brittle structures in the Questa caldera and speculation on their potential impacts on the bedrock ground-water flow system, Red River watershed, New Mexico: U.S. Geological Survey Professional Paper 1729, 37 p.
- Chapin, C.E., and Cather, S.M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift, *in* Keller, G.R., and Cather, S.M., eds., *Basins of the Rio Grande rift—Structure, stratigraphy, and tectonic setting*: Geological Society of America Special Paper 291, p. 5–25.
- Chappell, John, and Shackleton, N.J., 1986, Oxygen isotopes and sea level: *Nature*, v. 324, p. 137–140.
- Church, S.E., Fey, D.L., and Marot, M.E., 2005, Questa baseline and pre-mining ground-water quality investigation. 8. Lake-sediment geochemical record from 1960 to 2002, Eagle Rock and Fawn Lakes, Taos County, New Mexico: U.S. Geological Survey Scientific Investigations Report 2005–5006, 47 p.
- Connell, S.D., Hawley, J.W., and Love, D.W., 2005, Late Cenozoic drainage development in the southeastern Basin and Range of New Mexico, southeasternmost Arizona, and western Texas, *in* Lucas, S.G., Morgan, G.S., and Zeigler, K.E., eds., *New Mexico's ice ages: New Mexico Museum of Natural History and Science Bulletin no. 28*, p. 125–150.
- Cooke, Ron, Warren, Andrew, and Goudie, Andrew, 1993, *Desert geomorphology*: London, UCL Press, 526 p.
- Czamanske, G.K., Foland, K.A., Kubacher, F.A., and Allen, J.C., 1990, The $^{40}\text{Ar}/^{39}\text{Ar}$ chronology of caldera formation, intrusive activity, and Mo-ore deposition near Questa, New Mexico, *in* Bauer, P.W., Lucas, S.G., Mawer, C.K., and McIntosh, W.C., eds., *Tectonic development of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society Guidebook*, v. 41, p. 355–358.
- Denny, C.S., 1965, Alluvial fans in the Death Valley Region, California and Nevada: U.S. Geological Survey Professional Paper 466, 62 p.
- Dunne, Thomas, and Leopold, L.B., 1978, *Water in environmental planning*: San Francisco, Freeman, 818 p.
- Freeze, R.A., and Cherry, J.A., 1979, *Groundwater*: Prentice-Hall, New Jersey, 604 p.

- Friedman, J.M., Vincent, K.R., and Shafroth, P.B., 2005, Dating floodplain sediments using tree-ring response to burial: Earth surface processes and landforms, v. 30, no. 9, p. 1077–1091.
- Gilbert, C.M., 1938, The Cenozoic geology of the region southeast of Mono Lake, California: Berkeley, University of California, Ph.D. dissertation, 180 p.
- Gilbert, G.K., 1877, Report on the geology of the Henry Mountains: Washington, D.C., U.S. Government Printing Office.
- Graf, W.L., 1988, Definition of flood plains along arid-region rivers, *in* Baker, V.R., Kochel, R.C., and Patton, P.C., eds., Flood geomorphology: New York, John Wiley & Sons, p. 231–242.
- Grauch, V.J.S., and Keller, G.R., 2004, Gravity and aeromagnetic expression of tectonic and volcanic elements of the southern San Luis basin, New Mexico and Colorado, *in* Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., Geology of the Taos region: New Mexico Geological Society Guidebook, v. 55, p. 230–243.
- GSi/water, 1996, Geohydrologic evaluation, Cabin Springs area, Red River Valley, Taos County, New Mexico, Phase II, Pumping of Columbine Well 2—Effects on ground water, surface water, and springs: Report submitted to Molycorp, Inc., pages not given.
- Hearne, G.A., and Dewey, J.D., 1988, Hydrologic analysis of the Rio Grande Basin north of Embudo, New Mexico, Colorado and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 86–4113, 244 p.
- Hooke, R.L., 1968, Steady-state relationships on arid-region alluvial fans in closed basins: American Journal of Science, v. 266, p. 609–629.
- Hooke, R.L., 1972, Geomorphic evidence for late Wisconsin and Holocene tectonic deformation, Death Valley, California: Geological Society of America Bulletin, v. 83, p. 2073–2097.
- Hooke, R.L., and Rohrer, W.L., 1977, Relative erodibility of source-area rock types, as determined from second order variations in alluvial fan size: Geological Society of America bulletin, v. 88, p. 1177–1182.
- Kelson, K.I., Kirkham, R., and Machette, M.N., compilers, 1998, Fault number 2017c, Southern Sangre de Cristo fault, Questa section, *in* Quaternary fault and fold database of the United States, ver 1.0: U.S. Geological Survey Open-File Report 2003–417, <http://qfaults.cr.usgs.gov>.
- Kimball, B.A., Nordstrom, D.K., Runkel, R.L., Vincent, K.R., and Verplank, P.L., 2006, Questa baseline and pre-mining ground-water quality investigation. 23. Quantification of mass loading from mined and unmined areas along the Red River, New Mexico: U.S. Geological Survey Scientific Investigations Report 2006–5004, 44 p.
- Kluth, C.F., and Schaftenaar, C.H., 1994, Depth and geometry of the northern Rio Grande rift in the San Luis Basin, south-central Colorado, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande rift—Structure, stratigraphy, and tectonic setting: Geological Society of America Special Paper 291, p. 27–37.
- Knight, P.J., 1990, The flora of the Sangre de Cristo Mountains, New Mexico, *in* Bauer, P.W., Lucas, S.G., Mawer, C.K., and McIntosh, W.C., eds., Tectonic development of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society Guidebook, v. 41, p. 94–95.
- Knox, J.C., 2000, Sensitivity of modern and Holocene floods to climate change, Quaternary Science Reviews, v.19, p. 439–457.
- Lachmar, T.E., Hadlock, G.L., and McCalpin, J.P., 1999, The hydrogeology of lower Medano Creek, Great Sand Dunes National Monument, Colorado, *in* Schenk, C.J., ed., Hydrologic, geologic, and biologic research at Great Sand Dunes National Monument, Colorado: Proceedings of National Park Service Research Symposium no. 1, p. 31–51.
- Lawton, T.F., and McMillan, N.J., 1999, Arc abandonment as a cause for passive continental rifting—Comparison of the Jurassic Mexican borderland rift and the Cenozoic Rio Grande rift: Geology, v. 27, no. 9, p. 779–782.
- Leopold, L.B., and Bull, W.B., 1979, Base level, aggradation, and grade: Proceedings of the American Philosophical Society, v. 123, p. 168–202.
- Leopold, L.B., 1992, Base level rise—Gradient of deposition: Israel Journal of Earth Science, v. 41, p. 57–64.
- Lipman, P.W., 1983, The Miocene Questa Caldera, northern New Mexico—Relation to batholith emplacement and associated molybdenum mineralization, *in* Proceedings of the Denver Region Exploration Geologists Society symposium; the genesis of Rocky Mountain ore deposits—Changes with time and tectonics: Wheat Ridge, Colorado, Denver Region Exploration Geologists Society, p. 133–147.
- Lipman, P.W., and Reed, J.C., Jr., 1989, Geologic map of the Latir Volcanic Field and adjacent areas, northern New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I–1970, scale 1:48,000.
- Love, D.W., and Connell, S.D., 2005, Late Neogene drainage developments on the southeastern Colorado Plateau, New Mexico, *in* Lucas, S.G., Morgan, G.S., and Zeigler, K.E., eds., New Mexico's ice ages: New Mexico Museum of Natural History and Science Bulletin no. 28, p. 151–170.
- LoVetere, S.H., Nordstrom, D.K., Maest, A.S., and Naus, C.A., 2004, Questa baseline and pre-mining ground-water quality investigation. 3. Historical ground-water quality for the Red River Valley, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 2003–4186, 49 p.

- Ludington, Steve, Plumlee, G.S., Caine, J.S., Bove, Dana, Holloway, J.M., and Livo, K.E., 2005, Questa baseline and pre-mining ground-water quality investigation. 10. Geologic influences on ground and surface waters in the lower Red River watershed, New Mexico: U.S. Geological Survey Scientific Investigations Report 2004-5245, 46 p.
- Maest, A.S., Nordstrom, D.K., and LoVetere, S.H., 2004, Questa baseline and pre-mining ground-water quality investigation. 4. Historical surface-water quality for the Red River Valley, New Mexico, 1965 to 2001: U.S. Geological Survey Scientific Investigations Report 2004-5063, 150 p.
- McCalpin, J.P., 1983, Quaternary geology and neotectonics of the west flank of the northern Sangre de Cristo Mountains, south-central Colorado: Colorado School of Mines Quarterly, v. 77, no. 3, 97 p.
- McCalpin, J.P., 1999, Geomorphology, hydrology, and hydrogeology of Medano Creek, Great Sand Dunes National Monument, Colorado, *in* Schenk, C.J., ed., Hydrologic, geologic, and biologic research at Great Sand Dunes National Monument, Colorado: Proceedings of National Park Service Research Symposium no. 1, p. 8-30.
- McCleskey, R.B., Nordstrom, D.K., Steiger, J.I., Kimball, B.A., and Verplanck, P.L., 2003, Questa baseline and pre-mining ground-water quality investigation. 2. Low-flow (2001) and snowmelt (2002) synoptic/tracer water chemistry for the Red River, New Mexico: U.S. Geological Survey Open-File Report 2003-148, 166 p.
- McLemore, V.T., and Mullen, K.E., 2004, Mineral resources in Taos County, New Mexico, *in* Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., Geology of the Taos region: New Mexico Geological Society Guidebook, v. 55, p. 383-390.
- McLemore, V.T., and Wagner, Anne, 2004, Molycorp tailings facility, Questa, New Mexico, *in* Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., Geology of the Taos region: New Mexico Geological Society Guidebook, v. 55, p. 8.
- McLemore, V.T., Lueth, V.W., and Walker, B.M., 2004, Alteration scars in the Red River Valley, Taos County, New Mexico, *in* Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., Geology of the Taos region: New Mexico Geological Society Guidebook, v. 55, p. 19.
- Merritts, Dorothy, and Vincent, K.R., 1989, Geomorphic response of coastal streams to low, intermediate, and high rates of uplift, Mendocino triple junction region, northern California: Geological Society of America Bulletin, v. 101, no. 11, p. 1373-1388.
- Merritts, D.J., Vincent, K.R., and Wohl, E.E., 1994, Long river profiles, tectonism, and eustasy: A guide to interpreting fluvial terraces: Journal of Geophysical Research, v. 99, no. B7, p. 14031-14050.
- Meyer, J.W., 1991, Volcanic, plutonic, tectonic, and hydrothermal history of the southern Questa caldera, New Mexico: University of California at Santa Barbara, Ph.D. dissertation, 287 p.
- Meyer, J.W., and Leonardson, R.W., 1990, Tectonic, hydrothermal and geomorphic controls on alteration scar formation near Questa, New Mexico, *in* Bauer, P.W., Lucas, S.G., Mawer, C.K., and McIntosh, W.C., eds., Tectonic development of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society Guidebook, v. 41, p. 417-422.
- Miller, Jerry, Germanoski, Dru, Waltman, Karen, Tausch, Robin, and Chambers, Jeanne, 2001, Influence of late Holocene hillslope processes and landforms on modern channel dynamics in upland watersheds in central Nevada: Geomorphology, v. 38, no. 2-4, p. 373-391.
- Milliman, J.D., and Meade, R.H., 1983, World-wide delivery of river sediment to the oceans: Journal of Geology, v. 91, p. 1-21.
- Munsell Color, 2000, Munsell Soil Color Charts: New Windsor, New York, GretagMacbeth, variously paged.
- Myers, N.C., 2000, Characterization and simulation of ground-water flow in the Kansas River Valley at Fort Riley, Kansas, 1990-98: U.S. Geological Survey Water-Resources Investigations Report 2000-4096, 122 p.
- Naus, C.A., McCleskey, R.B., Nordstrom, D.K., Donohoe, L.C., Hunt, A.G., Paillet, F.L., Morin, R.H., and Verplanck, P.L., 2005, Questa baseline and pre-mining ground-water quality investigation. 5. Well installation, water-level data, and surface- and ground-water chemistry in the Straight Creek drainage basin, Red River Valley, New Mexico, 2001-2003: U.S. Geological Survey Scientific Investigations Report 2005-5088, 220 p.
- Newell, D.L., Koning, D.J., Karlstrom, K.E., Crossey, L.J., and Dillon, M., 2004, Plio-Pleistocene incision history of the Rio Ojo Caliente, northern Española basin, and overview of the Rio Grande system in northern New Mexico, *in* Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., Geology of the Taos region: New Mexico Geological Society Guidebook, v. 55, p. 300-313.
- Pazzaglia, F.J., 1989, Tectonic and climatic influences on the evolution of Quaternary depositional landforms along a segmented range-front fault, Sangre de Cristo Mountains, north-central New Mexico: Albuquerque, University of New Mexico, Master's thesis, 246 p., scale 1:24,000.
- Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment- water flows: Geological Society of America Reviews in Engineering Geology, v. 7 p. 1-12.

- Plumlee, G.S., Ludington, Steve, Vincent, K.R., Verplank, P.L., Caine, J.S., and Livo, K.E., in press, Questa baseline and pre-mining ground-water quality investigation. 7. A pictorial record of weathering and erosional processes, and potential debris-flow hazards in scar areas developed on hydrothermally altered rocks: U.S. Geological Survey Open-File Report 2006–1205.
- Powell, J.W., 1875, Exploration of the Colorado River of the West (1869–72): Washington, D.C., 43rd U.S. Congress 1st Session, House Miscellaneous Document 300, 291 p.
- Powers, M.H. and Burton, B.L., 2004, Questa baseline and pre-mining ground-water quality investigation. 1. Depth to bedrock determinations using shallow seismic data acquired in the Straight Creek drainage near Red River, New Mexico: U.S. Geological Survey Open-File Report 2004–1236, 18 p.
- Powers, M.H., and Burton, B.L., 2007, Questa baseline and pre-mining ground-water quality investigation. 24. Seismic refraction tomography for volume analysis of saturated alluvium in the Straight Creek drainage and its confluence with the Red River, Taos County, New Mexico: U.S. Geological Survey Scientific Investigations Report 2006–5166, 19 p.
- Renard, K.G., and Keppel, R.V., 1966, Hydrographs of ephemeral streams in the Southwest: Journal of the Hydraulics Division, American Society of Civil Engineers, v. 92, p. 33–55.
- Robertson GeoConsultants (RGC), January 2001, Background study data report, Questa Mine, New Mexico: Report no. 052008/12 (Questa Mine closeout plan program task A7): submitted to MolyCorp, Inc., 40 p.
- Rockwell, T.K., Keller, E.A., and Johnson, D.L., 1984, Tectonic geomorphology of alluvial fans and mountain fronts near Ventura California, in Morisawa, Marie, and Hack, J.T., eds., Tectonic geomorphology: Boston, Allen and Unwin, Proceedings of the Binghamton Geomorphology Symposium, v. 15, p. 183–207.
- Shaw, Shannon, Wels, Christoph, Robertson, Andrew, and Lorinczi, Geizi, 2002, Physical and geochemical characterization of mine rock piles at the Questa mine, New Mexico—An overview—Tailings and Mine Waste '02: Exton, Pennsylvania, Balkema Publishers, p. 447–458.
- Shaw, Shannon, Wels, Christoph, Robertson, Andrew, Fortin, S., and Walker, B.M., 2003, Background characterization study of naturally occurring acid rock drainage in the Sangre De Cristo Mountains, Taos County, New Mexico: Proceedings Sixth International Conference on Acid Rock drainage, ICARD 2003, Society for Mining, Metallurgy and Exploration, p. 605–616.
- Schilling, J.H., 1956, Geology of the Questa molybdenum (moly) mine area, Taos County, New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources, Bulletin 51, 87 p.
- Schrott, Lothar, and Adams, Till, 2002, Quantifying sediment storage and Holocene denudation in an alpine basin, Dolomites, Italy: Zietschrift fur Geomorphologie, p. 129–145.
- Smith, K.S., Hageman, P.L., Briggs, P.H., Sutley, S.J., McCleskey, Blaine, Livo, K.E., Verplanck, P.L., Adams, M.G., Gemery-Hill, P.A., 2007, Questa baseline and pre-mining ground-water quality investigation. 19. Leaching characteristics of composited materials from mine waste-rock piles and naturally altered areas near Questa, New Mexico: U.S. Geological Survey Scientific Investigations Report 2006–5165.
- Souder, Miller and Associates (SMA), January 2003, Installation, pumping tests, and water quality report for the ground water withdrawal wells in the Red River canyon: report submitted to MolyCorp, Inc., Appendix A, pages not given.
- Souder, Miller and Associates (SMA), June 2000, Mill Well #1 Pumping test report: report submitted to MolyCorp, Inc., table 1, pages not given.
- Souder, Miller and Associates (SMA), May 2000, Mine area slug, pumping, and recovery tests: report submitted to MolyCorp, Inc., table 1, pages not given.
- Souder, Miller and Associates (SMA), March 2000, 1999 Hydrogeologic investigation, Questa Mine, Taos County, New Mexico: report submitted to MolyCorp, Inc., pages not given.
- Stock, J.D., Montgomery, D.R., Collins, B.D., Dietrich, W.E., and Sklar, Leonard, 2005, Field measurements of incision rates following bedrock exposure—Implications for process controls on the long profiles of valleys cut by rivers and debris flows: Geological Society of America Bulletin, v. 117, no. 12, p. 174–194.
- Stuiver, Minze, and Braziunas, T.F., 1993, Sun, ocean, climate and atmospheric $^{14}\text{CO}_2$ —An evaluation of causal and spectral relationships: The Holocene, v. 3, no. 4, p. 289–305.
- Stuiver, Minze, and Reimer, P. J., 1993, Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program: Radiocarbon, v. 35, p. 215–230.
- Stuiver, Minze, Reimer, P.J., Bard, Edouard, Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, Bernd, McCormac, Gerry, van der Plicht, Johannes, and Spurk, Marco, 1998, INTCAL98 radiocarbon age calibration, 24,000–0 cal. BP: Radiocarbon, v. 40, p. 1041–1083.
- Theis, C.V., 1940, The source of water derived from wells, essential factors controlling the response of an aquifer to development: Civil Engineering, v. 10, no. 5, p. 277–280.
- Thomas, C.L., Stewart, A.E., and Constantz, Jim, 2000, Determination of infiltration and percolation rates along a reach of the Santa Fe River near La Bajada, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 2000–4141, 65 p.

- Tinkler, K.J., and Wohl, E.E., 1998, A primer on bedrock channels, *in* Tinkler, K.J., and Wohl, E.E., eds., *Rivers over rock—Fluvial processes in bedrock channels: American Geophysical Union Geophysical Monograph 107*, Washington, D.C., p. 1–18.
- Vail Engineering, 2000, Analysis of acid rock drainage in the Middle Reach of the Red River, Taos County, New Mexico: Interim report submitted to Molycorp, Inc, Questa Division, July 4, 2000, 37 p.
- Vincent, K.R., 1995, Implications for models of fault behavior from earthquake surface-displacement along adjacent segments of the Lost River Fault, Idaho: Tucson, University of Arizona, Ph.D. dissertation, 152 p.
- Vincent, K.R., Bull, W.B., and Chadwick, O.A., 1994, Construction of a soil chronosequence using the thickness of pedogenic carbonate coatings: *Journal of Geological Education*, v. 42, p. 316–324.
- Vincent, K.R., and Chadwick, O.A., 1994, Synthesizing bulk density for soils with abundant rock fragments: *Soil Science Society of America Journal*, v. 58, no. 2, p. 455–464.
- Vincent, K.R., Church, S.E., and Wirt, Laurie, in press, Geomorphology of Cement Creek and its relation to ferricrete deposits, *in* Church, S.E., von Guerard, Paul, and Finger, S.E., eds., *Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651–E16*.
- Vincent, K.R., and Elliott, J.G., in press, Response of the upper Animas River downstream from Eureka to discharge of mill tailings, *in* Church, S.E., von Guerard, Paul, and Finger, S.E., eds., *Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651–E22*.
- Vincent, K.R., Pearthree, P.A., House, P.K., and Demsey, K.A., 2004, Inundation mapping and hydraulic reconstructions of an extreme alluvial fan flood, Wild Burro Wash, Pima County, southern Arizona: Arizona Geological Survey Open-File Report 2004–03, 51 p.
- Wells, S.G., Kelson, K.I., and Menges, C.M., 1987, Quaternary evolution of fluvial systems in the northern Rio Grande rift, New Mexico and Colorado, *in* Menges, C.M., Enzel, Yehouda, and Harrison, Bruce, eds., *Quaternary tectonics, landform evolution, soil chronologies, and glacial deposits—Northern Rio Grande rift of New Mexico: Friends of the Pleistocene, Rocky Mountain Cell Guidebook*, p. 55–69.
- Western Regional Climate Center, 2003, Historical climate information: New Mexico climate summaries, accessed from the World Wide Web at URL <http://www.wrcc.dri.edu/>.
- Wohl, E.E., 1998, Bedrock channel morphology in relation to erosional processes, *in* Tinkler, K.J., and Wohl, E.E., eds., *Rivers over rock—Fluvial processes in bedrock channels: American Geophysical Union Geophysical Monograph 107*, Washington, D.C., p. 133–151.

Appendixes

Appendix 1. Map areas of tributary watersheds, alteration scars within watershed boundaries, and alluvial fans derived from the watersheds.

[All areas were determined using the Geographic Information System database from which plate 1 was derived. The watersheds are labeled with identification numbers on plate 1. The watershed areas include the area of scars, if present. Watersheds 7 and 11 contain subwatersheds identified using letters. The fan at the mouth of Sulfur Gulch was derived from the total area of watershed 11, and the letters na indicate that individual fans are not located at the mouths of the subwatersheds. km², square kilometers]

Number	Name of drainage	Watershed area, km ²	Scar area, km ²	Fan area, km ²
1		0.190	0.000	0.039
2		0.281	0.018	0.025
3		0.207	0.026	0.006
4		0.674	0.000	0.008
5	Capulin Canyon	3.559	0.105	0.067
6		0.187	0.060	0.042
7 (total)		3.420	0.581	0.737
7A	Goat Hill Gulch	2.084	0.546	0.543
7B		1.336	0.035	0.194
8		0.485	0.202	0.128
9		0.724	0.035	0.045
10		0.378	0.200	0.123
11 (total)		5.562	0.513	0.039
11A	Sulfur Gulch	1.893	0.513	na
11B	Blind Gulch	1.379	0.000	na
11C	Spring Gulch	2.290	0.000	na
12		0.207	0.000	0.048
13		0.085	0.000	0.020
14		0.651	0.000	0.004
15		0.203	0.000	0.010
16		0.252	0.000	0.019
17		0.471	0.000	0.019
18		1.637	0.000	0.017
19		0.853	0.185	0.007
20	Hansen Creek	0.957	0.256	0.015
21		0.619	0.015	0.050
22		0.201	0.000	0.073
23	Straight Creek	2.080	0.203	0.271
24		0.379	0.083	0.114
25	Hottentot Creek	1.701	0.298	0.064
26		0.124	0.000	0.286
27	Graveyard Canyon	0.788	0.003	0.044
28		0.423	0.000	0.175
29		1.177	0.007	0.476
30		0.148	0.000	0.005
31		6.445	0.000	0.043
32		0.190	0.000	0.015
33		0.178	0.031	0.080

Appendix 2. Concentration of total sulfur in debris-fan sediments.

[Total sulfur was analyzed by Zoe Ann Brown (U.S. Geological Survey, written commun., 2005) using a combustion method described by Brown and Curry (2002). Church and others (2005) presented other geochemical data for these samples. Each sample was a composite of subsamples randomly selected from the largest exposure of the stratigraphy available. All geochemical analyses were made on the fine-fraction (less than 2 millimeters) of the composite samples. The sampling sites are indicated on plate 1]

Name of drainage	Watershed number (plate 1)	Sample label used in this report (plate 1)	Label used by Church and others (2005)	Total sulfur, percent mass
Graveyard Canyon	27	TF1	03KVTF1	0.28
Hottentot Creek	25	TF2	03KVTF2	0.86
Straight Creek	23	TF3	03KVTF3	1.17
	19	TF4	03KVTF4	1.87
	18	TF5	03KVTF5	0.14
	18	TF5b	03KVTF5b	1.18
Sulfur Gulch	11	TF6	03KVTF6	0.69
Capulin Canyon	5	TF7	03KVTF7	0.65
Goat Hill Gulch	7a	TF8	03KVTF8	1.04
	7b	TF9	03KVTF9	0.68
	31	TF10	03KVTF10	0.07

Appendix 3. Altitudes of bedrock/alluvium contacts shown in figure 13, interpreted from well logs.

[Wells are labeled on plate 1. Most well logs were obtained from Souder, Miller and Associates (March 2000, May 2000, June 2000, and 2003), and a few were provided by MolyCorp, Inc. (written commun., 2003); km, kilometer; m, meter; <, less than]

Well label	Position on profile (km)	Altitude of contact (m)	Well label	Position on profile (km)	Altitude of contact (m)
MMW-45B	0.44	¹ 2,289	MMW-33	4.61	^{4,3} <2,382
MMW-42B	2.04	² 2,308	GW-3	5.11	¹ 2,367
MMW-44B	2.61	^{2,3} 2,305	MMW-32A	5.21	² 2,392
MMW-48B	3.02	² 2,325	MMW-10C&B	5.48	^{1,3} 2,379
MMW-8B	3.28	² 2,358	MMW-31B	5.61	² 2,399
MMW-47	3.53	² 2,363	GW-2	5.64	² 2,376
Cabin 1	3.74	^{1,3} 2,333	MMW-30B	6.01	² 2,401
Columbine 1	3.80	⁴ <2,349	MMW-29	6.40	² 2,401
Cabin 2	3.89	^{1,3} 2,339	GW-1	6.40	¹ 2,392
Columbine 2	4.01	^{1,3} 2,338	MMW-24	6.89	² 2,458
P-2	4.03	⁴ <2,364	MMW-16	6.91	² 2,453
P-1	4.05	¹ 2,346	MMW-28B	7.17	² 2,431
P-4B	4.13	⁴ <2,359	Mill Well 1	7.68	¹ 2,426
P-3	4.17	⁴ <2,359	Lab Well	7.71	⁴ <2,434
MMW-46	4.20	² 2,343	MMW-43A	8.10	¹ 2,435
P-5	4.24	⁴ <2,364	MMW-17	8.56	^{2,3} 2,464

¹Well located near center of valley.

²Well located near side of valley.

³Level of bedrock contact difficult to discern from well log.

⁴Well terminated in alluvium above bedrock.

Appendix 4. Data for the model of ground-water flow within alluvium, deposited by the Red River, during the 2001 tracer study. Model discharge (Q) results are shown in figure 15.

[na means that the cross-section shape model is not appropriate because the top width is too narrow; km, kilometer; m/m, meters per meter; m, meter; min., minimum; m², square meters; max., maximum; cm/s, centimeters per second; L/s, liters per second]

Position along profile (km)	Water-table gradient (m/m)	Aquifer top width (m)	Cross-section area			Hydraulic conductivity (cm/s)	Discharge within gravel aquifer		
			Triangle (min. area) (m ²)	Trapezoid (best area) (m ²)	Rectangle (max. area) (m ²)		Triangle (min. Q) (L/s)	Trapezoid (best Q) (L/s)	Rectangle (max. Q) (L/s)
Reach 1 (mill reach)									
8.4	0.0121	122	1,704	2,605	3,407	0.030	62.1	94.9	124.1
7.9	0.0070	152	2,714	4,294	5,427	0.030	56.8	89.9	113.6
7.7	0.0052	198	3,903	6,754	7,805	0.030	60.8	105.2	121.6
7.2	0.0023	91	2,154	na	4,307	0.030	14.9	na	29.8
Reach 2									
6.4	0.0083	76	896	na	1,792	0.07	5.2	na	10.4
5.8	0.0083	122	1,987	3,329	3,973	0.07	11.5	19.2	23.0
Reach 3 (Columbine Park)									
5.1	0.0168	55	800	na	1,600	0.07	9.4	na	18.8
4.9	0.0168	70	1,141	na	2,282	0.07	13.4	na	26.8
4.6	0.0168	190	3,038	5,486	6,077	0.07	35.7	64.5	71.5
3.6	0.0168	230	4,372	7,909	8,743	0.07	51.4	93.0	102.8
3.0	0.0168	175	3,643	6,285	7,286	0.07	42.8	73.9	85.7
2.7	0.0168	23	524	na	1,048	0.07	6.2	na	12.3
Reach 4									
1.6	0.0189	122	2,042	3,356	4,084	0.07	27.0	44.3	54.0

Appendix 5. Data for the model of ground water flow within alluvium, deposited by the Red River, during the 2002 tracer study. Model discharge (Q) results are shown in figure 16. Flow within reach 1 was not modeled because of uncertainty in the water-table gradient.

[na means that the cross section shape model is not appropriate because the top width is too narrow; km, kilometers; m/m, meters per meter; m, meter; m², square meters; min., minimum; max., maximum; cm/s, centimeters per second; L/s, liters per second]

Position along profile (km)	Water-table gradient (m/m)	Aquifer top width (m)	Cross-section area			Hydraulic conductivity (cm/s)	Discharge within gravel aquifer		
			Triangle (min. area) (m²)	Trapezoid (best area) (m²)	Rectangle (max. area) (m²)		Triangle (min. Q) (L/s)	Trapezoid (best Q) (L/s)	Rectangle (max. Q) (L/s)
Reach 2									
6.4	0.0057	76	748	na	1,496	0.07	3.0	na	6.0
5.8	0.0057	122	1,856	3,356	3,712	0.07	7.5	13.5	14.9
Reach 3 (Columbine Park)									
5.1	0.0162	55	704	na	1,408	0.07	8.0	na	16.0
4.9	0.0162	70	961	na	1,922	0.07	10.9	na	21.8
4.6	0.0162	190	2,797	5,007	5,594	0.07	31.7	56.8	63.4
3.6	0.0150	230	4,209	7,585	8,418	0.07	44.3	79.8	88.5
3.0	0.0150	175	3,576	6,151	7,152	0.07	37.6	64.7	75.2
2.7	0.0150	23	497	na	994	0.07	5.2	na	10.5
Reach 4									
1.6	0.0189	122	2,042	3,356	4,084	0.07	27.0	44.3	54.0

Publishing support provided by:
Denver Publishing Service Center
Manuscript approved for publication, June 29, 2006
Edited by L.J. Binder
Graphics and layout by J.K. Monson

For more information concerning this publication, contact:
Chief, Branch of Regional Research, Central Region
Box 25046, MS 418
Denver, CO 80225
(303) 236-5021

Or visit the USGS National Research Program Web site at:
<http://water.usgs.gov/nrp>
This publication is available online at:
<http://pubs.usgs.gov/sir/2008/5156/>

ISBN 978-141131873-1



9 781411 318731



Printed on recycled paper