Contents

ABSTRACT 1
INTRODUCTION 2
Purpose and Scope 3
Physical Description of Study Area 3
Climate and Vegetation 5
Hydrogeology 5
Surface Water 7
Mining History 7
Acknowledgments 7
METHODS 8
Sampling Sites 8
Well Locations 8
Surface Water 8
Water Sample Collection 13
Ground Water Collection 14
Surface Water Collection 16
Laboratory Methods 16
Quality Assurance and Quality Control 17
GROUND-WATER GEOCHEMISTRY 22
Redox Potentials and Iron Chemistry 40
Manganese Chemistry 46
Aluminum Chemistry 47
Calcium Chemistry and Solubilities of Gypsum, Calcite, and Fluorite 50
Gypsum and calcite solubilities 50
Fluoride Chemistry and Fluorite Solubility 53
Magnesium Chemistry 54
Strontium Chemistry 57
Silica Chemistry 57
Alkali Metal Chemistry 59
Trace Element Chemistry 63
Rare-Earth Elements 69
Dissolved Organic Carbon and Hydrogen Sulfide 70
Stable Isotopes 71
Chlorofluorocarbons, dissolved gases, and tritium 72
Background 72
Chlorofluorocarbons 73
Helium-3 / Tritium Dating 73
Analysis 74
Chlorofluorocarbons 74
Helium-3 / Tritium Dating 75
Results 75
Helium-3 / Tritium Dating 75
Chlorofluorocarbon Data 77
SUMMARY 78
REFERENCES CITED 81

FIGURES

Maps showing:

1. Map showing the location of the mine site, wells sampled, and Hottentot surface water samples and the study area within the Red River valley 4

2. Map showing locations of observation wells in the Straight Creek drainage 9
3. Map showing location of Hottentot Creek well 10
4. Map showing locations of the Hansen Creek, La Bobita, and Phase III wells 11
5. Map showing locations of wells in Capulin Canyon 12
6-32. Graphs showing:
6. **A.** Frequency distribution of charge imbalance in percent using equation 1. **B.** Effective molal ionic strength in relation to total molal ionic strength. **C.** pH in relation to sulfate concentration. **D.** Specific conductance in relation to sulfate concentration with linear fit for Straight Creek debris-fan ground water data. 23
7. **A.** Measured Eh in relation to calculated Eh for all samples. Solid line indicates the 1:1 correspondence; the dotted lines show ±35 mV error range. **B.** The difference between measured and calculated Eh in relation to Fe(II)/Fe(T) ratio for samples with Fe(T) and Fe(II) above method detection limits. **C.** The difference between measured and calculated Eh in relation to Fe(III) concentration. The vertical dotted lines show the lower limit range over which Fe(III) concentration is expected to be electroactive. **D.** Revised plot of figure 7A excluding data points containing non-detectable and non-electroactive Fe(III) concentrations. 41
8. Saturation index for hydrous ferric oxides (ferrihydrite and goethite) as a function of pH. 42
9. **A.** Total dissolved iron concentration plotted in relation to sulfate concentration. **B.** Total dissolved iron concentration plotted in relation to sulfate concentration for the low concentration range (0 – 10 mg/L iron). 43
10. Dissolved iron concentration in relation to total recoverable iron concentration. 44
11. **A.** Ferrous iron concentration in relation to total dissolved iron concentration. **B.** Ferrous iron concentration plotted in relation to sulfate concentration. **C.** Ferric iron concentration in relation to sulfate concentration. 45
12. **A.** Saturation indices for crystalline and disordered siderite as a function of pH for wells of circumneutral pH. **B.** Siderite saturation indices as a function of calcium concentration for wells of circumneutral pH. 46
13. Manganese concentration in relation to sulfate concentration. Dashed line is the best fit of Straight Creek debris-fan well waters (except SC4A). 47
14. **A.** Saturation indices for rhodochrosite in relation to dissolved inorganic carbon. **B.** Saturation indices for rhodochrosite in relation to pH. Solid horizontal line represents the solubility-product constant for poorly crystalline, disordered rhodochrosite and the dashed line represents the solubility-product constant for well-crystallized rhodochrosite. 48
15. **A.** Dissolved aluminum concentration plotted in relation to total recoverable aluminum concentrations along with linear fit. **B.** Dissolved aluminum concentration in relation to dissolved sulfate concentration showing linear fit for selected Straight Creek debris-fan ground water. **C.** The logarithm of the free aluminum ion activity in relation to the pH with the degree of fit for low pH waters (pH < 5) and the range of solubility limits for gibbsite to amorphous $Al(OH)_3$ for the temperature of the ground-water samples. **D.** Amorphous aluminum hydroxide and gibbsite saturation indices in relation to pH.. 49
16. **A.** Calcium concentration in relation to sulfate concentration. Solid line shows stoichiometric gypsum dissolution ending at solubility equilibrium for gypsum in pure water. **B.** Plot of calcium: sulfate molar ratio in relation to pH. Solid line reflects 1:1 ratio of $Ca:SO_4$ and the dashed lines represents the region where gypsum dissolution is predominant. 51
17. **A.** Saturation indices for gypsum in relation to calcium concentration. **B.** Saturation indices for gypsum in relation to sulfate concentration. 52
18. Calcite saturation indices in relation to pH. 53
19. **A.** Fluoride concentration in relation to calcium concentration. Dashed line represents a linear fit of Straight Creek debris-fan wells. **B.** Fluoride concentration in relation to sulfate concentration. Dashed line represents a linear fit of Straight Creek debris-fan wells. **C.** Fluorite saturation indices in relation to calcium concentration. **D.** Fluorite saturation indices in relation to pH. 55

20. **A.** Magnesium concentration in relation to sulfate concentration. Dashed line represents a linear fit of Straight Creek debris-fan wells. Dotted line represents a linear fit of Straight Creek surface water. **B.** Magnesium concentration in relation to calcium concentrations. Dashed line represents a linear fit of Straight Creek debris-fan wells. **C.** Dolomite saturation indices in relation to pH. **D.** Dolomite saturation indices in relation to calcium concentration. 56
21. **A.** Strontium concentration in relation to calcium concentration. **B.** Strontium concentration in relation to sulfate concentration. **C.** Celestite saturation indices in relation to calcium concentration. **D.** Strontianite saturation indices in relation to calcium concentration. 58
22. Silica concentration in relation to sulfate concentration. Linear fit lines are shown for the dilution of the Straight Creek debris-fan ground waters and the dilution of the Straight Creek surface waters. 59
23. Lithium concentration in relation to sulfate concentration with the dashed line displaying the best fit for Straight Creek debris-fan wells. 60
24. **A.** Plot of sodium concentration in relation to sulfate concentration. **B.** Sodium concentration plotted in relation to chloride concentration. **C.** Lithium concentration plotted in relation to sodium concentration. 61
25. **A.** Potassium concentration in relation to sodium concentration. **B.** Potassium concentration in relation to sulfate concentration. 62
26. **A.** Zinc concentration in relation to sulfate concentration. **B.** Zinc concentration in relation to manganese concentration. **C.** Cadmium concentration in relation to zinc concentration. **D.** Copper concentration in relation to zinc concentration. Dashed line represents correlation of Straight Creek debris-fan ground waters. 64
27. Copper concentration in relation to sulfate concentration. Dotted line shows correlation for Straight Creek debris-fan waters. 65
28. **A.** Nickel concentration in relation to sulfate concentration. **B.** Cobalt concentration in relation to nickel concentration. Dashed line shows correlation for Straight Creek debris-fan waters. 66
29. **A.** Barium concentration in relation to sulfate concentration. **B.** Barite saturation indices in relation to pH. **C.** Barite saturation indices in relation to barium concentration. **D.** Dissolved barium concentration in relation to total recoverable barium concentration. 67
30. **A.** Beryllium concentration in relation to sulfate concentration. **B.** Beryllium concentration in relation to aluminum concentration. Dashed lines show correlation for Straight Creek debris-fan ground waters. 68
31. **A.** Beryllium concentration plotted in relation to lithium concentration with solid line showing correlation for debris-fan ground waters and the dotted line showing correlation for Straight Creek surface waters. **B.** Beryllium concentration plotted in relation to fluoride concentration. 69
32. Rare-earth elements normalized against Chondrite for phase II wells. 70
33. Dissolved organic carbon concentration in relation to pH. 70
34. Hydrogen isotopic composition in relation to oxygen isotopic composition with a snow - rain line from Straight Creek, the Rocky Mountain meteoric water line, and the global meteoric water line. 71
35. Sulfur isotopic composition of sulfate in relation to oxygen isotopic composition of sulfate with the region between the dashed lines showing sulfur composition related to ore FeS_2 and MoS_2. 72

TABLES

1. Sample types, container preparation and stabilization methods for filtered samples 13
2. Water-quality parameters, measuring equipment, stabilization criteria, and calibration guidelines 15
3. Analytical techniques, detection limits, typical precision, equipment used, and analytical method references 18
4. Water analyses for Phase II wells and Hottentot Creek and Hansen Creek surface waters 25
5. ICP-MS analyses for selected sampling events for Phase II wells 38

6. The equations of best fit from the Straight Creek data 39
7. Dissolved gas concentrations, helium isotopic composition, and calculated recharge temperature and altitude 75
8. Helium-3 (3He) concentrations associated with different sources, tritiogenic 3He concentrations, tritium (3H) concentrations, and ground-water ages 76
9. Chlorofluorocarbon data 78

Explanation of Abbreviations

---	not analyzed, measured, or calculated
<	less than
°C	degrees Celsius
cc	cubic centimeter
cc/kg	cubic centimeters per kilogram
CFC	chlorofluorocarbon
C.I.	charge imbalance
CVAFS	cold-vapor atomic fluorescence spectrometry
DDW	double-distilled water
DIW	deionized water
DOC	dissolved organic carbon
FA	filtered-acidified
FU	filtered-unacidified
FIAS	flow injection analysis system
GC	gas chromatography
GFAAS	graphite furnace atomic absorption spectrometry
GMWL	global meteoric water line
GW	ground water
HDPE	high-density polyethylene
HGAAS	hydride generation atomic absorption spectrometry
IC	ion chromatography
ICP-MS	inductively coupled plasma-mass spectrometry
ICP-OES	inductively coupled plasma-optical emission spectrometry
ID	identification
ISE	ion-selective electrode
km	kilometers
m	meters
mm	millimeter
meq/L	milliequivalents per liter
mM	millimoles per liter
mg/L	milligrams per liter
MS	mass spectrometry
µg/L	micrograms per liter
µm	micrometer
µS/cm	microSiemens per centimeter
µcc/kg	micro cubic centimeters per kilogram
N	normal
ng/L	nanograms per liter
nm	nanometer
NMED	New Mexico Environment Department
n	number of analyses
pg/kg	picograms per kilograms
PE	polyethylene
QSP	quartz-sericite-pyrite
RA	raw-acidified
REE	rare-earth element
RU	raw-unacidified
RMMWL	Rocky Mountain meteoric water line
σ	standard deviation
SC	specific conductance
SRWS	standard reference water sample
SW	surface water
THGA	transversely heated graphite atomizer
TOC	total organic carbon
TU	tritium units
UV	ultra-violet
v/v	volume per volume

Conversion Factors, Water-Quality Abbreviations, and Datums

SI to Inch/Pound

Multiply	By	To obtain
	Length	
micrometer (µm)	0.00003937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
cubic meter (m^3)	264.2	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L), micrograms per liter (µg/L), nanograms per liter (ng/L), or mM (millimoles per liter).

Coordinate information is referenced to the North American Datum 27 – Continental United States (NAD27-CONUS)