Annotated Bibliography of Environmentally Relevant Investigations of Uranium Mining and Milling in the Grants Mineral Belt, Northwestern New Mexico

By James K. Otton

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Abstract

Studies of the natural environment in the Grants Mineral Belt in northwestern New Mexico have been conducted since the 1930s; however, few such investigations predate uranium mining and milling operations, which began in the early 1950s. This report provides an annotated bibliography of reports that describe the hydrology and geochemistry of groundwaters and surface waters and the geochemistry of soils and sediments in the Grants Mineral Belt and contiguous areas. The reports referenced and discussed provide a large volume of information about the environmental conditions in the area after mining started. Data presented in many of these studies, if evaluated carefully, may provide much basic information about the baseline conditions that existed over large parts of the Grants Mineral Belt prior to mining. Other data may provide information that can direct new work in efforts to discriminate between baseline conditions and the effects of the mining and milling on the natural environment.

Introduction

Uranium mining and milling in the Grants Mineral Belt (GMB), which began in the early 1950s, had an impact on soils, stream sediments, surface water, and groundwater. The GMB was the largest uranium mining district in the United States for several years. It still holds substantial uranium reserves and resources that continue to attract industry exploration and development efforts. The U.S. Environmental Protection Agency (USEPA) Region 6, several State of New Mexico agencies, and several Federal agencies have begun a five-year assessment of the health and environmental impacts of past uranium mining and milling (U.S. Environmental Protection Agency, 2010a). (Note: References cited in the Introduction are included with those in the bibliography). The New Mexico Environment Department began investigations in the San Mateo Creek drainage, the site of four major mills and several mines, in 2008 and early results can be found in New Mexico Environment Department (2010).

The U.S. Geological Survey (USGS), working with the Atomic Energy Commission (AEC), began investigations of uranium deposits in the GMB in the1950s. These studies, which continued to the mid-1980s, were mostly focused on understanding the geologic setting, geology, geochemistry, and genesis of these deposits. The geochemical and mineralogical information in these studies and in studies by other researchers provides data that characterize the ore and associated waste rock in the principal uranium mines in the GMB.

The USGS, USEPA, other Federal agencies, and State agencies also conducted studies of groundwater hydrology and water quality in the GMB, a few of which were prior to the start of uranium mining (for example, Waring and Andrews, 1935; Morgan, 1938; Murray, 1945; Halpenny and Whitcomb, 1949a, b), but most were after mining began. The later investigations were generally in response to reports of, or about, concerns regarding groundwater contamination from mining and milling operations, but many involved efforts to gain a better basic understanding of the sources, availability, and quality of water resources in the region. The earliest of these later studies was in the 1950s and early 1960s (New Mexico Department of Public Health and U.S. Public Health Service, 1957; Chavez, 1961). Under the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978, mill sites in the GMB were subjected to varying amounts of study, remediation, and cleanup with the involvement of the Department of Energy (DOE), the USEPA, and State agencies. These mill-site investigations provide much helpful information about the affected environment.

This report is a compilation of many reports that describe information relevant to understanding the impact of uranium mining and milling on the environment in the GMB. The purpose is to (1) provide access and commentary on past work that may directly describe the pre-mining baseline geochemistry of the soils, rocks, sediments, and waters of the GMB; (2) note reports that may provide data or techniques to discriminate between natural background or baseline conditions and contamination due to mining and milling; and (3) suggest how the use of uranium and other isotopes and trace elements may aid in this discrimination. The focus is on USGS studies that describe the mineralogy and geochemistry of ore deposits, especially those studies that describe ores in specific mines, the hydrology and water chemistry of shallow groundwater and deeper aquifers, the geochemistry of waters near uranium mine and mill contaminant sites, and environmental investigations. Where possible, abstracts, introductions, or summaries of the report findings quoted directly from the publication are included with the entry. Annotation by this author, in the form of notes, is included to describe content in copyrighted or obscure reports, to explain the importance of the entry, or to describe those aspects of a larger report that are deemed to be of specific interest to researchers in the GMB. To avoid duplication, where significant studies were subsequently published in peer-reviewed journals, the newer references are listed without their abstracts. Selected New Mexico State agency reports are included, some with notes, but the list of State agency reports, consultant reports, and DOE- and EPA-funded studies is not comprehensive. Some university theses are also listed that focus on the geochemistry of uranium ore deposits and associated sedimentary rocks.

Studies to determine the sources of uranium and other trace elements present at uranium mine and mill contaminant sites at which uranium and other trace elements are present commonly have to take into account the presence of naturally high background levels of the uranium, other associated radionuclides, and trace elements. Analytical work by the USGS and others at selected sites shows that uranium isotope, sulfur isotope, and trace element data may permit discrimination of contamination by mine or mill wastes from elevated levels that may be in the natural background. Zielinski and others (1997) used uranium isotope ratios, combined with uranium and molybdenum data, to demonstrate the extent of contamination of groundwater by effluent from the Canon City uranium mill site in Colorado. Zielinski and others (2001) and Otton and others (2005) used sulfur isotope analyses to show that high amounts of uranium, arsenic, and sulfate in irrigation return waters and in saline soils in fields north of Denver were derived naturally from dusts and salts blowing from outcrop and small salt-filled depressions (blowouts) of the Upper Cretaceous Pierre Shale during post-glacial times. These dusts and salts formed part of a thick section of loess that covered underlying bedrock not known to contain arsenic and uranium. Otton and others (2010) showed that naturally occurring uranium in groundwater in an alluvial aquifer at Fry Canyon, Utah, can be discriminated from uranium derived from tailings ponds at a uranium upgrader site and from an adjacent copper-uranium heap-leach pile using uranium and sulfur isotopes. Johnson and others (2009) show that elevated levels of uranium, arsenic, and other trace elements in shallow groundwater at an open dump in northeastern Arizona are possibly derived from windblown sediment deposited across the site from upwind anomalous sources, such as the Triassic Chinle Formation, thus indicating that these trace elements may have been transferred to groundwater by natural processes and locally concentrated by evapotranspiration. Uranium isotope analyses show that uranium isotope activity ratios of water from selected wells are above values expected for groundwater containing uranium derived from mine or mill waste.

Uranium isotopic data are limited in studies of the GMB. Dooley and others (1966) reported uranium isotopic data for some prefault (primary or trend) and post-fault deposits in the Ambrosia Lake district. Osmond and Cowart (1981) described the uranium concentrations and uranium activity ratios for groundwater and rock core in a deep, undeveloped uranium deposit in sandstone of the Westwater Canyon Member of the Jurassic Morrison Formation about 50 mi northwest of Grants, N. Mex. Wirt (1993) used uranium isotopes and uranium concentrations in groundwater in the Puerco River drainage to discriminate between natural groundwater and groundwater impacted by uranium mine dewatering effluent and a 1979 mill-tailings pond release. Van Metre and others (1997) used uranium isotopic data to discriminate natural sources of uranium in wells in alluvial aquifers from uranium due to mine dewatering releases to adjacent surface streams.

Sulfur isotope data for uranium ores in the GMB are reported in Dam (1995), Fishman and Reynolds (1982), Fishman and others (1985), and Jensen (1963). Sulfur isotopes for groundwater are reported in Fisk and others (1994). The data show that sulfide sulfur in many of the uranium deposits ranges from –10 to –40 δS^{34}. If there is sufficient contrast between this sulfur isotopic signature and that of sulfate sulfur present in natural soils, sediment, surface water, and shallow groundwater, then such analyses could prove useful when combined with other data to discriminate contamination due to mine waste from natural systems. An investigation described in an unpublished consultant report (Hydro Geo Chem, 1982, cited in Longmire and others, 1984) used sulfur isotopes to track seepage from a uranium mill pond on the Laguna Pueblo. It should be noted that the sulfur isotopic signature of uranium mill waste where sulfuric acid was used to process the ore will likely be dominated by the sulfur isotopic signature of the acid. This signature may contrast with the signature of sulfate sulfur in local soil, sediment, and water.

A series of site-specific environmental reports were prepared for many of the mining and mine reclamation operations in the GMB; the author reviewed some of these documents for this report, (for example, Tennessee Valley Authority, 1978, 1979; U.S. Department of the Interior, 1986) that are in the USGS uranium research files. Other such reports, when accessed, could likely provide significant information about the affected environment near mine and mill operations.

Environmental reports resulting from various investigations, some extensive in scope, have also been prepared for mills located in the GMB. These mills include the following:

1. L-Bar (Seboyeta) mill in the Laguna sub-district;
2. Bokum mill in the Marquez sub-district (built, never operated, and since dismantled);
3. Bluewater, Homestake, Ambrosia Lake, and Phillips mills in the Ambrosia Lake sub-district; and
4. Church Rock mill in the Church Rock sub-district.

A history of all U.S. mills that sold uranium concentrates to the Atomic Energy Commission (AEC) under contract, including five GMB mills, was published by Albrethsen and McGinley (1982). That publication describes the operational history of the GMB mills during the AEC contract period (1947–1970), including the types of ore processing that were conducted (alkaline leach, acid leach, heap leach), sources of ore or other mill feed (sub-district mines or other sources), water treatment, disposal of waste liquids (injection into underlying formations), byproduct recovery, tons of ore processed, average grade of ore, uranium recovery (U_3O_8 in pounds), tailings in tons, surface area and thickness of tailings solids, use of tailings for mine backfill, recovery of uranium from mine waters, presence of nearby residents, radiometric surveys of nearby areas, any remedial actions taken, and current (as of 1982) status of the mills. The publication also references other DOE reports that provide additional information.

The L-Bar (Seboyeta) mill is a site presently managed by the DOE's Legacy Management program. Documentation for this site is at *http://www.lm.doe.gov/lbar/*. The mill tailings pile at the site was examined for radon emanation (USEPA, 1988). The Bluewater mill is a site presently managed by the DOE's Legacy Management program. Documentation of the site is at *http://www.lm.doe.gov/land/sites/nm/bluewater/blue.htm*. The site has also been investigated by the New Mexico Environment Department (2010) as part of their recent study of the San Mateo Creek basin. The Ambrosia Lake (Phillips Petroleum) mill site is documented at *http://www.eia.doe.gov/cneaf/nuclear/page/umtra/ambrosia_title1.html*. The site is being managed by DOE's Long-Term Monitoring and Surveillance program. No groundwater monitoring was done during creation of the disposal cell site and none is planned. The Homestake mill, located about 5 mi north of Milan, N. Mex., is a USEPA Superfund site. It has been the subject of several studies to investigate the dispersion of contaminants. Summaries of the background and recent (2005–2007) investigations for the Homestake mill are reported in Agency for Toxic Substances and Disease Registry (ATSDR) (2009).

The Church Rock mill in the western part of the GMB was not considered by Albrethsen and McGinley (1982), as it was built after the AEC buying program ceased. A lengthy report on the Church Rock mill documenting contamination and remedial actions taken was prepared (USEPA, 2003). A short summary of the status of the Church Rock mill and tailings Superfund site through 2010 is at *http://www.epa.gov/earth1r6/6sf/pdffiles/0600819.pdf*.

The USEPA conducted or funded two major studies of mine- and mill-related contamination in the GMB. The results of the first study are summarized in Kaufmann and others (1975) and related reports. Studies in the mid-1980s conducted by State agencies and funded by the USEPA are reported primarily in Gallaher and Cary (1986).

From 1994–2005, the USEPA, Region 9, conducted a study of contaminated structures and water sources, and abandoned uranium mines on the Navajo Nation. Part of the investigation included the western end of the GMB, notably the Northeast Church Rock mine area. An introduction to the work, links to a comprehensive database and atlas, and progress reports are available online (USEPA, 2010b).

Different types of uranium deposits are present in the Westwater Canyon Member sandstones of the GMB. Some significant differences exist in the mineralogy and geochemistry of the deposit types. Deposits believed to have formed essentially contemporaneously with diagenesis of the host sandstones and some of the overlying rocks are referred to as primary or trend orebodies. During early Tertiary time, the Zuni Mountains south of the GMB were uplifted, and oxidizing groundwaters moved through the uranium-deposit host sandstones of the GMB. These waters leached uranium from primary deposits across a broad belt and deposited the uranium in roll-front deposits along an oxidation-reduction boundary. Mineralogic and geochemical differences occur between the primary and roll-front deposits.

Some primary deposits were only partially leached leaving behind remnant deposits. Other primary deposits were adjacent to major faults. During fluid movement along these faults, these deposits were also oxidized and have geochemical and mineralogic characteristics of roll-front deposits. However, investigations of some deeper primary ore deposits suggest that uranium moved recently in these deposits under conditions that are not well understood (Osmond and Cowart, 1981). Figure 1B and table 1 in McCammon and others (1986) show the distribution and names of the principal trend, remnant, and roll-front uranium deposits in the GMB.

The names "Rio Puerco" and "Puerco River" in reports describing various environmental conditions pertaining to uranium mining and milling are incorrectly used by some authors. According to the U.S Board of Geographic Names (*http://geonames.usgs.gov/*), Puerco River is the correct name for the stream that begins in the west-central part of the GMB and flows westward past Gallup, N. Mex. into Arizona where it drains into the Little Colorado River. Rio Puerco is the correct name for a stream that lies to the east of the GMB and is part of the Rio Grande watershed. In addition, some authors use the name "Churchrock" to describe the mine and other features in the western GMB. "Church Rock" is the name recognized by the U.S Board of Geographic Names.

Bibliography for the Grants Mineral Belt, New Mexico

Agency for Toxic Substances and Disease Registry, 2009, Health Consultation, Homestake Mining Company Mill Site, Milan, Cibola County, New Mexico: Atlanta, Georgia, ATSDR, 33 p., *http://www.atsdr.cdc.gov/hac/pha/homestake/homestakeMCojun091.pdf*.

Summary

In 1958, the Homestake Mining Company (Homestake), located in Milan, New Mexico, opened a mill to process uranium. The mill operated for approximately 30 years, closing in 1990. Today, two tailings (waste) piles remain on the Homestake site. The tailings piles overlie an alluvial groundwater aquifer, into which contaminants from the piles have migrated. The migration of contaminants in mixing zones between the alluvial aquifer and the underlying aquifers, within the Chinle formation, resulted in the cross-contamination of the aquifers, as well as contamination of some private wells that are completed in the alluvial and Chinle aquifers.

Beginning in the mid-1970s, some of the private wells in the Felice Acres, Broadview Acres, Murray Acres, Valle Verde, and Pleasant Valley Estates subdivisions were sampled for radionuclides, chemicals, and metals. Additional sampling continued in the 1980s and 1990s. Sample results indicated uranium, selenium, and molybdenum concentrations in residential wells during the mid-1970s and up until the mid-1980s were one to two orders of magnitude greater than they have been ever since. The lack of consistent monitoring over the years, the considerable concentration differences in wells within the same aquifer, the unknown usage of wells during the alternate water supply period, and anomalies with the sampling data are all factors that make past exposures an indeterminate health hazard.

In September 1983, the United States Environmental Protection Agency (USEPA) placed the Homestake site on the National Priorities List (NPL) primarily because of groundwater contamination in residential wells. In December 1983, USEPA and Homestake entered into a consent decree to provide for an alternate water supply to the owners of wells in these subdivisions. Homestake was required to provide an alternate potable water supply to nearby residences and to pay for such water usage for 10 years. Alternate water supply hookups to residences were completed in April 1985, and Homestake paid the water bills until 1995. Remediation of the contaminated aquifers has been ongoing since 1977, and over the years, contaminant levels have decreased.

Selenium and uranium levels in some of the wells have, however, remained above their respective maximum contaminant level (MCL)— enforceable drinking water standards. The MCL applies to public water systems, which provide water for human consumption through at least 15 connections, or regularly serve at least 25 individuals. The MCL is set at a level that is based upon someone drinking 2 liters of water containing the contaminant per day over a 70 year period with no resulting adverse health effects. These wells are private wells so the MCL does not apply per se, but was used as a reference or comparison in our analysis.

In 2005, USEPA and the New Mexico Environment Department (NMED) initiated work to determine if area residents had access to uncontaminated potable drinking water. As part of that work, a well survey was conducted by USEPA and NMED in September 2005, which identified 5 of 34 well owners who were using their wells as a primary drinking water source, with the remaining 28 using the alternate water supply (Village of Milan). The September 2005 sampling event identified approximately two-thirds of the wells (22 out of 34) had uranium concentrations above the MCL, three wells had selenium concentrations above the MCL, and one had nitrate above the MCL.

USEPA and NMED conducted an additional round of well sampling in May 2006. Nine of the wells sampled in September 2005 were re-sampled, and an additional 19 wells were sampled that had not been previously. The May 2006 sampling event identified 16 of the 19 wells that were being used as a primary source of drinking water. It is unknown if six other well owners, who had their well sampled during this time, were using their wells. Seven wells were sampled in May 2007. One of these wells had been sampled previously (#20) and another is located where the residence has been connected to the alternate water supply. A total of 57 residential wells were sampled over the three year period. The New Mexico Environment Department (NMED) did notify well owners of the results of their well samples and advised those with MCL exceedances not to use these wells as potable water sources.

Because of remediation efforts and aquifer recharging, concentrations of uranium, arsenic, selenium, and molybdenum have declined in most of the wells. Arsenic concentrations were above the MCL in the past, but were below the MCL during the most recent sampling. Molybdenum does not have an enforceable standard, but it did exceed ATSDR’s drinking water comparison value in the past. Molybdenum concentrations from the most recent sampling were below ATSDR’s comparison value. Selenium and uranium concentrations in the mid-1970s, 1980s, and in some cases the 1990s were one to two orders of magnitude greater than the last three sampling rounds. Some of the wells still have levels of contaminants above their respective drinking water standard and/or guideline and could still have them after the remedial actions at the site are completed. It is estimated that the on-going remediation will lower the concentrations of contaminants down to background by 2015, but some of the contaminant concentrations will be above their respective drinking water standard. Homestake’s groundwater remedial action is only required to achieve federally–approved background contaminant concentration standards, most of which exceed MCLs.

In accordance with accepted public health practice, ATSDR recommends that well owners that are using their well as a source of potable water and have contaminant concentrations above the MCL should obtain another source of potable water. Also, individuals who have obtained a connection to the alternate source of water should continue to use this source of water. This will ensure that they are not exposed to elevated levels of uranium and selenium in the alluvial and Chinle aquifers.

ATSDR calculated exposure doses for the contaminants above health comparison values and MCLs in well sample results from 2005 through 2007 and determined that those being used as a source of potable water were not at levels that would produce known adverse health effects. However, there are a few wells (#12, #16, # 26, #27, and #41) that have uranium concentrations well above the background concentration that are not being used and should not be used. ATSDR has categorized the groundwater in the private wells not connected to the Milan water supply as a no apparent public health hazard. ATSDR defines the no apparent public health hazard category as those sites where exposure to site-related chemicals might have occurred in the past or is still occurring, but the exposures are not at levels likely to cause adverse health effects.

Albrethsen, Holger, Jr., and McGinley, F.E., 1982, Summary history of domestic uranium procurement under U.S. Atomic Energy Commission contracts, final report: Department of Energy Report GJBX-220(82), 166 p., *http://www.osti.gov/bridge/servlets/purl/6743792-rnieXf/.*

Andrews, B.J., King, K.A., and Baker, D.L., 1995, Radionuclides and trace elements in fish and wildlife of the Puerco and Little Colorado Rivers, Arizona: U.S. Fish and Wildlife Service online report, 20 p. *http://www.fws.gov/southwest/es/Documents/R2ES/RadionuclidesAZ.pdf.* (Note that the link takes the reader directly to the abstract and report.)

Abstract

Aquatic invertebrates, fish (whole body), and birds were collected in 1993 from several locations along the Puerto (sic) and Little Colorado Rivers in northeastern Arizona for trace element and radionuclide analysis. Aluminum, arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium and zinc were elevated in fish from several locations on the Little Colorado River. Aluminum, cadmium and mercury were detected in one or more fish samples at concentrations that could cause secondary poisoning of avian predators that consume a large portion of fish in their diet. One fathead minnow sample contained copper (92.34 pg/g wet weight) at four times the highest copper concentration (23.1 pg/g wet weight) detected during the 1976-1984 National Contaminant Biomonitoring Program sampling (Schmitt and Brumbaugh 1990). Arsenic and lead were detected in fish from the Little Colorado River at levels which could possibly limit their reproduction. Due to natural geographic variations of radioactivity throughout the United States and the lack of background data from our study area with which to compare our findings, radionuclide data interpretation is impractical at this time. The radiological contaminant levels reported in this study will serve as background information for future studies on the effects of radionuclides on fish and wildlife in northeastern Arizona. Additional studies are needed to adequately characterize the effects of contaminants from the Puerto (sic) and Little Colorado Rivers on fish and wildlife resources.

Austin, S.R., 1983, An investigation of sedimentary, mineralogical, chemical and color patterns and associations in the Rio de Oro mine, McKinley County, New Mexico: U.S. Department of Energy Report GJBX-30(83), 47 p.

NOTE: This report provides detailed hand-drawn sketches and geochemical data for underground mine wall surfaces in the Rio de Oro (Dysart No. 1) mine in the Ambrosia Lake district. The sketches were made and samples taken at five sites in the mine (shown on a mine map and in the figures). Detailed descriptions of the sampled locations at each site are included as are petrographic information from thin sections. Chemical analyses for 43 samples include percent cU_3O_8 (chemical uranium oxide), percent eU_3O_8 (“equivalent” uranium oxide, based on a gamma measurement), percent V_2O_5 and percent $CaCO_3$. The author notes that uranium and vanadium are closely associated, but that molybdenum typically occurring as jordisite is generally separated from the other two. Ferroselite, a selenium mineral, is noted in the petrographic descriptions.

Baldwin, J.A., and Anderholm, S.K., 1992, Hydrogeology and ground-water chemistry of the San Andres-Glorieta aquifer in the Acoma embayment and eastern Zuni uplift, west-central New Mexico: U.S. Geological Survey Water-Resources Investigations Report WRI 91-4033, 304 p., *http://pubs.er.usgs.gov/djvu/WRI/wrir_91_4033.djvu*.

Abstract

The San Andres Limestone and the underlying Glorieta Sandstone of Permian age comprise the San Andres-Glorieta aquifer in west-central New Mexico. The San Andres Limestone is composed mainly of limestone and some sandstone and is unconformably overlain by the Chinle Formation. The Glorieta Sandstone conformably overlies the Yeso Formation and is composed of well-sorted, well-cemented, fine- to medium-grained sandstone.

Most of the water in the San Andres-Glorieta aquifer is transmitted in solution channels, cavernous zones, and fractures in the San Andres Limestone. Seven transmissivity zones were identified in the study area on the basis of aquifer-test results and the lithology of the aquifer. Values of transmissivity of the zones range from 10 to 50,000 feet squared per day. Zones with values of transmissivity of 50,000 feet squared per day are located in the Grants area and in an area east and

south of the Zuni uplift. The zone with the smallest transmissivity, 10 feet squared per day, is located at the eastern margin of the study area.

Recharge to the San Andres-Glorieta aquifer occurs on outcrops along the Zuni uplift and Lucero uplift by infiltration of precipitation and surface water. The quantity of recharge is related to the areal extent of outcrops of the aquifer. Recharge to the San Andres-Glorieta aquifer also occurs south of the Zuni uplift where the aquifer subcrops beneath The Malpais. Recharge to the aquifer also is the result of leakage from Bluewater Lake and Bluewater Creek. Surface water and ground water used for irrigation also may infiltrate and recharge the aquifer in the Grants-Bluewater area.

Ground-water movement in the San Andres-Glorieta aquifer generally is outward from the Zuni uplift (recharge area). In the northwestern part of the study area, ground water moves toward the northeast. The direction of movement changes to the east at distance from the Zuni uplift. Ground water moves east away from the Zuni uplift and toward the Rio Grande rift in the eastern part of the study area.

Discharge of ground water from the San Andres-Glorieta aquifer is by spring discharge, withdrawal from wells, underflow out of the study area, and leakage to adjacent rocks. Prior to development of the ground-water resources in the Grants area, Ojo del Gallo probably was a major discharge point in the part of the aquifer northwest of Grants. Discharge did not take place at Ojo del Gallo during 1953 to 1982. This cessation in discharge at Ojo del Gallo probably was due to the large volume of ground-water withdrawal in the Grants-Bluewater area and to changes in the quantity of precipitation, which affects recharge.

Discharge from the San Andres-Glorieta aquifer at Horace Springs also has been postulated. Evaluation of hydrologic, geologic, and water-chemistry data, however, indicates that water discharging from Horace Springs is derived from the alluvial aquifer.

Discharge from the San Andres-Glorieta aquifer in the Grants-Bluewater area increased substantially in the mid-1940's when wells were first used as a source of irrigation water. Withdrawals peaked in 1956, when 14,210 acre-feet of water was pumped from the aquifer. The large volume and changes in location of pumpage with time probably resulted in changes in the direction of ground-water movement in the aquifer. Water-chemistry data indicate changes in ground-water chemistry in the area during this time.

The mechanism for discharge of water from the San Andres-Glorieta aquifer east of the Zuni uplift is not known, but several possibilities exist. Underflow of ground water into the Rio Grande rift sediments is one possibility; however, in the area north of the Lucero uplift where this underflow could possibly occur, the San Andres-Glorieta aquifer is in fault contact with fine-grained sediments and leakage into these sediments probably is very small. Discharge from Pennsylvanian rocks east of the San Andres-Glorieta aquifer does occur in the Lucero uplift area. The source of this water may be downward leakage from the San Andres-Glorieta aquifer (discharge) through the Yeso and Abo Formations.

The specific conductance of ground water derived from the San Andres-Glorieta aquifer in the Thoreau area ranges from 470 to 1,390 microsiemens per centimeter at 25 degrees Celsius. Calcium and magnesium are the dominant cations and bicarbonate and sulfate are the dominant anions in ground water in this area. In the Grants-Bluewater area, calcium generally is the dominant cation and bicarbonate and sulfate generally are the dominant anions in ground water. Changes in concentrations of dissolved sulfate, chloride, and nitrate in ground water in the Grants-Bluewater area indicate variations in overall water chemistry over time. These changes probably are in part due to human activities. Ground water from west to east in the Acoma embayment area increases in specific conductance from approximately 1,000 to greater than 14,000 microsiemens. As in the

Grants-Bluewater area, calcium is the dominant cation and bicarbonate and sulfate are the dominant anions in ground water near the recharge area on the western side of the Acoma embayment area. As ground water moves eastward in the Acoma embayment area, dissolved-sodium, sulfate, and chloride concentrations increase substantially.

NOTE: This report provides comprehensive summaries of the stratigraphy of the GMB region, hydrogeology of the alluvial aquifer, the Triassic Chinle Formation, the San Andres-Glorieta aquifer (the major regional aquifer), and older units. Major-element groundwater chemistry is described for the San Andres–Glorieta aquifer in the Thoreau, Grants–Bluewater area, and the Acoma embayments (eastern Cibola County south of the Rio San Jose). A map (plate 2) shows the surficial geology and concentrations of selected dissolved constituents (sodium-potassium, calcium, magnesium, sulfate, chloride) and properties (specific conductance) of water from wells in the Grants–Bluewater area.

The "previous investigations" section of the report (p. 8) includes a list of hydrologic investigations dating from 1938 to 1986. Potentially significant reports cited in the publication and not available to the author for evaluation include the following:

1. Hydro-Search, Inc., 1977, Hydrogeology of the Bluewater Mill tailings pond area, Valencia County, New Mexico: Consultant's report to Anaconda Copper Company, 111 p.
2. Hydro-Search, Inc., 1978a, Supplement to the hydrogeology report of October 17, 1977, Bluewater Mill area, Valencia County, New Mexico: Consultant's report to Anaconda Copper Company, November 15, 1978, 69 p.
3. Hydro-Search, Inc., 1978b, Ground-water monitoring program, Bluewater Mill area, Valencia County, New Mexico: Consultant's report to Anaconda Copper Company, November 15, 1978, 25 p.
4. Hydro-Search, Inc., 1981, Regional ground-water hydrology and water chemistry, Grants-Bluewater area, Valencia County, New Mexico: Consultant's report to Anaconda Copper Company, May 15, 1981, 85 p., 9 plates., 6 appendixes, 2 volumes.
5. Jacob, C.E., 1956, Preliminary report on mine drainage and groundwater supply in Ambrosia Lake area, McKinley County, New Mexico: Consultant's report to Kermac Nuclear Fuels Corporation, Grants, New Mexico, October 1957, 24 p., 10 appendixes.

Baldwin, J.A., and Rankin, D.R., 1995, Hydrogeology of Cibola County, New Mexico: U.S. Geological Survey Water Resources Investigations Report 94-4178, 102 p., *http://pubs.er.usgs.gov/djvu/WRI/wrir_94_4178.djvu*.

Abstract

The hydrogeology of Cibola County, New Mexico, was evaluated to determine the occurrence, availability, and quality of ground-water resources. Rocks of Precambrian through Quaternary age are present in Cibola County. Most rocks are sedimentary in origin except for Precambrian igneous and metamorphic rocks exposed in the Zuni Uplift and Tertiary and Quaternary basalts in northern and central parts of the county. The most productive aquifers in the county include (youngest to oldest) Quaternary deposits, sandstones in the Mesaverde Group, the Dakota-Zuni-Bluff aquifer, the Westwater Canyon aquifer, the Todilto- Entrada aquifer, sandstone beds in the Chinle Formation, and the San Andres-Glorieta aquifer. Unconsolidated sand, silt, and gravel form a mantle ranging from a few inches to 150 to 200 feet over much of the bedrock in Cibola County. Well yields range from 5 to 1,110 gallons per minute. Dissolved-solids concentrations of ground water range from 200 to more than 5,200 milligrams per liter. Calcium, magnesium, bicarbonate, and sulfate are the predominant ions in ground water in alluvial material. The Mesaverde Group mainly occurs in three areas of the county. Well yields range from less than 1 to 12 gallons per minute. The predominant ions in water from wells in the Mesaverde Group are calcium, sodium,

and bicarbonate. The transition from calcium-predominant to sodium-predominant water in the southwestern part of the county likely is a result of ion exchange. Wells completed in the Dakota-Zuni-Bluff aquifer yield from 1 to 30 gallons per minute. Dissolved-solids concentrations range from 220 to 2,000 milligrams per liter in water from 34 wells in the western part of the county. Predominant ions in the ground water include calcium, sodium, sulfate, and bicarbonate. Calcium predominates in areas where the aquifer is exposed at the surface or is overlain with alluvium. Sandstones in the Chinle Formation yield from 10 to 300 gallons per minute to wells in the Grants-Bluewater area. In the western part of the county, sodium and bicarbonate predominate in water from the Chinle Formation. In the eastern part of the county, water quality is more variable than elsewhere and the predominant constituents include calcium, sodium, sulfate, and chloride. Well yields from the San Andres-Glorieta aquifer in the Grants- Bluewater area are as much as 2,830 gallons per minute, whereas the maximum recorded pumping rate from the aquifer in other areas of the county is 88 gallons per minute. Dissolved-solids concentrations of ground-water range from about 130 to 4,200 milligrams per liter, and the water generally is a calcium bicarbonate sulfate type.

Beard, H.R., Salisbury, H.B., and Shirts, M.B., 1980, Absorption of radium and thorium from New Mexico uranium mill-tailings solutions: U.S. Bureau of Reclamation Report 8463, 14 p.

Berry, F.A.F., 1959, Hydrodynamics and geochemistry of the Jurassic and Cretaceous Systems in the San Juan Basin, northwestern New Mexico and southwestern Colorado: Ph.D. dissertation, Stanford University, Stanford, California, 192 p.

Bliss, J.D., 1982, Surface and ground-water references index for the Navajo Indian Reservation, Arizona, New Mexico, and Utah: U.S. Geological Survey Open-File Report 82-413, 16 p., *http://pubs.er.usgs.gov/djvu/OFR/1982/ofr_82_413.djvu*.

NOTE: This report provides numerous references to surface-water and groundwater studies in the Navajo Nation and adjacent areas including the GMB through 1981. It includes several studies by New Mexico State agencies.

Brierley, C.L., and Brierley, J.A., 1981, Contamination of ground and surface waters due to uranium mining and milling. Volume I: Biological processes for concentrating trace elements from uranium mine waters: New Mexico Bureau of Mines and Mineral Resources Open-File Report, 105 p.

Abstract (from the Department of Energy's Energy Citations Database at *http://www.osti.gov/energycitations/product.biblio.jsp?query_id=0&page=8&osti_id=6445124*). Wastewater from uranium mines in the Ambrosia Lake district near Grants, N. Mex., contains uranium, selenium, radium, and molybdenum. A novel treatment process for waters from two mines, sections 35 and 36, to reduce the concentrations of the trace contaminants was developed. Particulates are settled by ponding and the waters are passed through an ion exchange resin to remove uranium; barium chloride is added to precipitate sulfate and radium from the mine waters. The mine waters are subsequently passed through three consecutive algae ponds prior to discharge. Water, sediment, and biological samples were collected over a 4-year period and analyzed to assess the role of biological agents in removal of inorganic trace contaminants from the mine waters.

Brierley, C.L., and Brierley, J.A., 1981, Biological processes for concentrating trace elements from uranium mine waters: New Mexico Water Resources Research Institute Technical Completion Report 140 (abs), *http://wrri.nmsu.edu/publish/techrpt/abstracts/abs140.html*.

Abstract

Wastewater from uranium mines in the Ambrosia Lake district near Grants, New Mexico, U.S.A., contains uranium, selenium, radium and molybdenum. The Kerr-McGee Corporation has a novel treatment process for waters from two mines, sections 35 and 36, to reduce the concentrations of the trace contaminants. Particulates are settled by ponding, and the waters are passed through an ion exchange resin to remove uranium; barium chloride is added to precipitate sulfate and radium from the mine waters. The mine waters are subsequently passed through three consecutive algae ponds prior to discharge. Water, sediment and biological samples were collected over a 4-year period and analyzed to assess the role of biological agents in removal of inorganic trace contaminants from the mine waters.

Conclusions derived from chemical analyses of waters and sediments of the mine water treatment facility are:

1. The concentrations of soluble uranium, selenium and molybdenum were not diminished in the mine waters by passage through the series of impoundments which constituted the mine water treatment facility. Uranium concentrations were reduced but this was due to passage of the water through an ion exchange column.
2. The particulate concentrations of the mine water were reduced at least ten-fold by passage of the waters through the impoundments. Since uranium, selenium and molybdenum were associated with the suspended particulates reduction in the concentration of total suspended solids reduced the concentration of contaminants in the final effluent.
3. The ponds were well oxygenated. This was probably due to the shallow depth of the ponds and growth of algae.
4. The pH remained near neutral during all collections and this would indicate that the major soluble species of trace contaminants would be molybdate, uranyl carbonate species, selenite (and possibly selenate at the higher pH values).
5. The temperature remained higher than 10°C in winter suggesting that plant and microbial life could remain viable and that the volume of water was great enough to lessen large temperature fluctuations.
6. Phosphate and nitrate were present in high enough concentrations to support limited algal and microbial activity.
7. The sediments were anoxic and enriched in uranium, molybdenum and selenium. The deposition of particulates and the formation of insoluble compounds were proposed as mechanisms for sediment enrichment.

Algal populations in the mine water treatment facility were identified and their contribution in removal of inorganic trace contaminants was assessed by field and laboratory studies. The predominant algae identified in the impoundments were the filamentous algae Spirogyra and Oscillatoria, and the benthic alga, Chara. Seasonal variations in both uranium and molybdenum levels in the filamentous algae were observed in field-collected samples. This suggested that adsorptive processes were important in the accumulation of the metals in the algae cells, since extent of adsorption depends not only on the amount of metal available per unit of surface area but also on the length of exposure of the surface to the metal. The results of 24-hour uptake experiments in the laboratory supported the field evidence. Short-term uptake of uranium and molybdenum was not observed in Chara, which accumulated both metaIs at much lower levels than the filamentous algae in the field. In the Spirogyra 24-hour test, the cell material showed a limited capacity to adsorb molybdenum, while uranium uptake increased with higher external concentrations.

> The long-term laboratory studies indicated that the pond algae, in the form of particulate, decaying material, can be instrumental in removing metals from solution. However, the patterns of retention and release of uranium and molybdenum as the algae decayed in the presence of sediment indicated that maintenance of reducing conditions in the sediment or in the algal cultures was critical to the sequestering of the metals. The implication from the laboratory studies is that, while the algae are instrumental in removing metals from solution, the process was reversible unless the system contained substantial organic material. Also, while organic material accelerated the rate of removal and sometimes the extent of removal from water, retention of the metals in sediments was also reversible unless the system contained a high volume of sediment. These conclusions point to major problems in improving the existing pond system in respect to removal of uranium and molybdenum. Calculations of existing pond productivity and the current removal of uranium and molybdenum by the algae present indicated that both greater algal populations and pond areas are necessary for removal of the trace contaminants.
>
> Large populations of microorganisms were found in the waters pumped from the uranium mines and water passing through the pond system. Of particular interest was the presence of the sulfate reducing bacteria, believed to be Desulfovibrio and/or Desulfotomaculum. Laboratory experimentation indicated that the sulfate-reducing bacteria may have a role in removal of uranium, selenium, and possibly molybdenum from solution. Sulfide production by the organisms may be important since molybdenum can be precipitated as a sulfide. The reducing conditions may be responsible for converting soluble hexavalent uranium to the insoluble quadrivalent form. Although a large population of sulfate-reducing bacteria was found in the pond sediments, there was no decrease of soluble sulfate, which remained at 700 ppm in the water flowing through the system. Reduced forms of sulfur may be oxidized by the aerobic thiobacilli in oxidizing regions, returning the sulfur to the soluble sulfate species. The system may be nutrient limited and the activity of the sulfate-reducing bacteria quite slow.

NOTE: This abstract provides a more complete statement of the findings of the related report and a link to another version of the same report.

Brod, R.C., 1979, Hydrogeology and water resources of the Ambrosia Lake–San Mateo area, McKinley and Valencia Counties, New Mexico: M.S. Thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico. 200 p., *http://ces.nmt.edu/alumni/papers/1979t_brod_rc.pdf*.

NOTE: This thesis describes the hydrogeology and water quality of the Ambrosia Lake-San Mateo area north of Grants. The area evaluated includes the upper part of the San Mateo Creek drainage and extends from the Mt. Taylor mine site at San Mateo northwest to the Ambrosia Lake area where several named mines and a large mill are located (see fig. 3 in the report). Hydrogeologic information for the formations in the area include lithology, known wells, well yields, and basic water-quality information (total dissolved solids and water type). Brod (1979) noted that:

> Twenty-five wells are believed to be completed in the alluvium in the study area. A few of these are observation wells near Ambrosia Lake. Before the discharge of mine wastewater in the area, ground water in most of the alluvium was characterized by TDS (total dissolved solids) concentrations of 500 to 1000 mg/L (milligrams per liter). Most of the water in the alluvium now seems to contain thousands of mg/L TDS (Table 4).

Other significant formations evaluated include the Cretaceous Menefee Formation (22 wells), Point Lookout Sandstone (3 wells), Crevasse Canyon Formation (1 well), Gallup Sandstone (no wells in the study area, but several wells 10–20 miles to the north), Mancos Shale (4 wells in lower sandstones), and Dakota Sandstone (5 wells); the Jurassic Morrison Formation (about 50 wells in various units), Bluff Sandstone (2 wells), Summerville Formation (no wells), Todilto Limestone (2 wells), Entrada Sandstone (no wells) and Wingate Sandstone (no wells); the Triassic Chinle Formation (3 active wells); and the Permian San Andres Limestone and Glorieta Sandstone (discussion of some well information).

Brod (1979) (1) reviewed the general geochemistry of selected formations using Piper diagrams (figs. 10 and 11 in the report); (2) summarized the geochemical work by the U.S. Environmental Protection Agency (1975a, b); (3) estimated general groundwater quality using borehole logs in the parts of the study area where water wells are absent, and also for the deep, untapped aquifers; (4) mapped the distribution of total dissolved solids data for the study area using measured and estimated data; (5) evaluated recharge to bedrock from alluvium to various bedrock units; (6) reported transmissivity and hydraulic conductivity data for selected units; and (7) discussed natural and mine water discharge, and municipal, domestic, and ranch water use. Table 3 (in the report) provides well records used in the thesis and table 4 provides major element geochemical data for 66 water samples from the thesis study and other published and unpublished sources. Brod (1979) cited the following references not located for this report:

City of Gallup, 1977, Research study on use of uranium mine water as a municipal supply for the City of Gallup, New Mexico: Unpublished report, City of Gallup, New Mexico, 100 p.

New Mexico Environmental Institute, 1974, An environmental baseline study of the Mount Taylor Project Area of New Mexico: Las Cruces, New Mexico, 244 p.

Brod, R.C., and Stone, W.J., 1981, Hydrogeology of Ambrosia Lake–San Mateo area, McKinley and Cibola Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrogeology Sheet 2.

Abstract (from DOE's Energy Citations Database at *http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=5498242*).

The Ambrosia Lake-San Mateo area is located about 10 mi north of Grants, New Mexico, in the heart of the Grants uranium region, which spans the southern edge of the San Juan Basin. The climate is semiarid and local streams are ephemeral, except where discharge from mines or tailings ponds has made them perennial. Ground water is thus the main source of water in the area. Major aquifers include alluvium, sandstones of the Mesaverde Group, sandstones of the Mancos Shale, Dakota Sandstone, Morrison Formation, Bluff Sandstone, Todilto Limestone, Chinle Formation, San Andres Limestone, and Glorieta Sandstone. Although shallow unconfined ground water flows southwesterly, deeper, confined ground water flows toward the northeast and east. Ground water in the area generally has a total-dissolved-solids content of 400 to 2000 mg/L; waters in the notheast are more saline (2000 to 5000 mg/L). Because the uranium occurs in a regional artesian aquifer (Westwater Canyon Member of the Morrison Formation), extensive dewatering is required: approximately 164 mgd. A new state law brings mine dewatering under the jurisdiction of the State Engineer and permits use of excess uranium-mine water. Private or municipal wells presently provide adequate supplies of water for most domestic and stock purposes.

NOTE: This is a short summary of the first author's M.S. thesis listed earlier.

Brookins, D.G., 1976, Uranium deposits of the Grants, New Mexico, mineral belt (I): U.S. Energy Research and Development Administration Final Report GJBX-16 (76), 120 p.

Brookins, D.G., 1979, Uranium deposits of the Grants, New Mexico mineral belt (II): U.S. Department of Energy Report GJBX-141(79), 411 p.

NOTE: The Brookins (1976, 1979) reports are related and describe the results of geochemical studies by D.G. Brookins and students at the University of New Mexico. The first report focuses on the ore in the deposits studied, whereas the second report focuses on the associated rocks. In volume II, page 1, the author notes the similar geochemistry and mineralogy of most of the deposits, with iron (primarily as pyrite), uranium (coffinite, lesser uraninite, and a uranium-humate complex), vanadium (oxides and silicates), molybdenum (jordisite), selenium (native and ferroselite), and organic carbon (humate and fossil wood) occurring in essentially all the deposits, but in differing proportions.

Brookins, D.G., Lee, M.J., and Riese, W.C., 1977, Trace elements as possible prospecting tools for uranium in the southern San Juan Basin, *in* Fassett, J.E., James, H.L., and Hodgson, H.E., eds., Guidebook of San Juan Basin III, northwestern New Mexico, New Mexico Geological Society Twenty-Eighth Field Conference, September 15-17, 1977: New Mexico Geological Society Guidebook, p. 263-269.

NOTE: This brief paper reviews the trace element geochemistry for about 100 samples of rock from outcrop, drill-hole core, drill-hole cuttings, and mine workings. Samples were selected to represent oxidized barren rock, near-ore oxidized rock, ore, and barren reduced rock. Whole-rock samples and the clay fraction of whole rocks were analyzed. Trace elements sought and evaluated included rare earth elements (REE), Cr, Ta, Co, Ni, Sc, Mn, As, Br, Rb, Cs, Ba, Sb, Hf, Th, and U. There are little data presented in this report for samples from individual mines, but these trace element summaries may provide insights useful for understanding geochemical data gathered by other researchers near mine- or mill-contaminated sites and for new contaminant studies. Of specific interest is the discussion of enrichments of trace elements in ores compared to barren rock. For example, the authors note that thorium seldom shows enrichment in any of the GMB uranium ores, whereas arsenic is commonly enriched. Vanadium, selenium, and molybdenum are not discussed in the report. Their association with GMB uranium deposits is widely reported elsewhere.

Bureau of Indian Affairs, Department of the Interior, 1979, Uranium development in the San Juan Basin region: a report on environmental issues: Albuquerque, New Mexico, San Juan Basin Regional Uranium Study, variously paginated.

Bureau of Indian Affairs, San Juan Basin Regional Uranium Study, 1980, Environmental issues and uranium development in the San Juan Basin region: Albuquerque, New Mexico, U.S. Bureau of Indian Affairs, Second draft for public revue and comment, variously paginated.

NOTE: The document provides an overview of the development of uranium mining in the San Juan Basin region and its economic, socio-political, cultural, ecosystem, and environmental impacts.

Busby, M.W., 1979, Surface water environment in the area of the San Juan Basin regional uranium study, New Mexico, Colorado, Arizona, and Utah: U.S. Geological Survey Open-File Report 79-0997, 128 p., *http://pubs.er.usgs.gov/usgspubs/ofr/ofr791499*.

Abstract

Streamflows in the lowland areas of the San Juan Basin are highly variable, responding to short-duration, high-intensity thunderstorms occurring in the late spring and summer. The thunderstorms can cause floods of large magnitude, but of localized extent. Most streams of the lowlands are ephemeral or intermittent. Streams of the high mountain areas are much less variable. Most of their flow is from snowmelt, which results in low-intensity flood peaks with long, gradual recessions. Most large mountain streams are perennial. Small ephemeral lakes and ponds in the low-lying areas have little effect on flood flows. Larger reservoirs in the basin have varying effects on flows of rivers, ranging from complete flow control to minor regulation. The streams of the low-lying areas are high in dissolved solids content. Sodium, bicarbonate, and sulfate are the predominant ions. The

quality of the water varies during a single-flow event and seasonally. Streams in the mountains are low in dissolved solids content. Radiochemical constituents are fairly low in most of the natural streamflow, but concentrations are higher than in streams outside of the basin.

NOTE: This report includes peak discharge data, ranges of physical and chemical properties, trace element and radiochemical data, and suspended sediment data for surface waters of the San Juan Basin including streams that drain the GMB. Key data include uranium concentrations in the Puerco River at Gallup (1975–1977), the Rio Paguate below the Jackpile mine (1977–1978), and the Rio San Jose near Laguna (1977).

The San Juan Basin regional uranium study noted in the title of this report addressed the impacts of the uranium mining and milling industry in the San Juan Basin as a whole. It was ordered by the Secretary of the Interior with the Bureau of Indian Affairs as the lead agency. In scope, the study resembled an environmental impact assessment, but it has limited technical detail. Chapter V describes the impacts on water resources. It includes (1) descriptions of the surface water and groundwater environments; (2) some limited surface water specific conductance measurements; (3) dissolved solids and radionuclide data for selected surface waters in northwest New Mexico; (4) major and minor element, trace element (vanadium, molybdenum, and selenium) and radiochemical (uranium and radium-226) data for mine effluent and surface waters in the Church Rock and Ambrosia Lake–San Mateo areas; and (5) ranges in chemical and physical properties of groundwater for several different aquifers in the San Juan Basin. This study was published as Bureau of Indian Affairs, Department of the Interior (1979).

Callahan, J.T., and Cushman, R.L., 1955, Geology and ground-water supplies of the Fort Wingate Indian School area, McKinley County, New Mexico: U.S. Geological Survey Circular 360, 12 p., *http://pubs.er.usgs.gov/djvu/CIR/circ_360.djvu*.

Abstract

A study of the local geology in relation to ground-water occurrence was made in the vicinity of the Fort Wingate Indian School which lies in McKinley County, N. Mex., just east of the town of Gallup.

The geologic formations studied range in age from Permian to Triassic. The San Andres formation of Permian age is composed of the Glorieta sandstone member and an overlying limestone member. The formation, which contains water under artesian conditions, is a single aquifer because water occurs in both the sandstone and the limestone members and no impermeable strata separate them. Other formations present in the area, all of Triassic age, are the Moenkopi formation, the Shinarump conglomerate, and the Chinle formation. These three relatively impermeable formations confine the water in the underlying San Andres formation. Three water-bearing sandstones are present in the Chinle formation. The authors believe that the production of large amounts of water from these sandstone beds is impractical.

The recharge area for the San Andres formation lies higher in the Zuni Mountains, immediately south of the Fort Wingate Indian School, and includes some 80 square miles. The recharge area for the Chinle formation consists of narrow bands of sandstone in and near the school lands. These sandstones are recharged by relatively small amounts of water.

Water from the San Andres formation differs in chemical constituents from that of the Chinle formation. Water from the San Andres formation is very hard and contains several hundred parts per million of sulfate. Water from sandstone of the Chinle formation is only moderately hard, but it contains increasingly greater amounts of dissolved solids downdip from the recharge areas.

Probable reasons are given for the wide range in the amount of flow from the several wells that penetrate the San Andres formation, and suggestions are given to guide future ground-water development from the San Andres formation.

Cannon, H.L., 1953, Geobotanical reconnaissance near Grants, New Mexico: U. S. Geological Survey Circular 264, 8 p., *http://pubs.er.usgs.gov/djvu/CIR/circ_264.djvu*.

Abstract

The application of geobotanical methods of prospecting in uranium-bearing areas in McKinley County, near Grants, N. Mex., has been investigated briefly. The uranium deposits occur in the Todilto limestone member of the Wanakah formation and in the overlying Morrison formation, both of Jurassic age. Carbonaceous uranium ore in the Morrison formation contains a high percentage of selenium, and selenium-indicator plants are commonly associated with these deposits. Such plants have not been observed on the Todilto deposits.

The average uranium content in the ash of trees rooted in ore deposits of the Todilto limestone member is more than 20 parts per million, and trees rooted in barren limestone average about 10 ppm. The uranium content of the plant ash is detectable by fluorimetric methods. Uranium analysis of trees growing on the Todilto bench and mapping of selenium-indicator plants on the sandstones of the Morrison formation are recommended as a method of prospecting.

Cary, S.J., and Gallaher, B.M., 1984, Natural surface-water quality in the Grants Mineral Belt, *in* Stone, W.J., compiler, 1984, Selected papers on water quality and pollution in New Mexico: Proceedings of a symposium on water quality and pollution in New Mexico, April 12, 1984, Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 7, p. 24-33.

NOTE: This report describes and contrasts the trace element and radionuclide content of water in perennial streams during normal flow conditions and in streams and washes during flood events. The total trace element and radionuclide content of water during flood events is highly variable and dependent on the amount of suspended sediment in the flow. The dissolved concentrations of most trace elements in the study for both perennial flow and the flood waters (after filtration) are below detection limits; however, the detection limits in the study were relatively high (5 µg/L for uranium-natural). Suspended sediment concentration in nine samples of flood waters ranged from 3,680 to 561,000 mg/L.

Chavez, E.A., 1961, Progress report on contamination of potable groundwater in the Grants-Bluewater area, Valencia County, New Mexico: Roswell, New Mexico State Engineer Office. Unknown pages.

NOTE: This report is referenced in U.S. Environmental Protection Agency (1975a) but was not reviewed by the author.

Clark, D.S., and Havenstrite, S.R., 1980, Geology and ore deposits of the Cliffside mine, Ambrosia Lake area, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 52-58.

Cooley, M.E., 1979, Effects of uranium development on erosion and associated sedimentation in southern San Juan Basin, New Mexico: U. S. Geological Survey Open-File Report 79-1496, 25 p., *http://pubs.er.usgs.gov/usgspubs/ofr/ofr791496*.

Abstract

A reconnaissance was made of some of the effects of uranium development on erosion and associated sedimentation in the southern San Juan Basin, where uranium development is concentrated. In general, the effects of exploration on erosion are minor, although erosion may be accelerated by the building of access roads, by activities at the drilling sites, and by close concentration of drilling sites. Areas where the greatest effects on erosion and sedimentation from mining and milling operations have occurred are: (1) in the immediate vicinity of mines and mills, (2) near waste piles, and (3) in stream channels where modifications, such as changes in depth have been caused by discharge of excess mine and mill water. Collapse of tailings piles could result in localized but excessive erosion and sedimentation.

Cooley, M.E., Harshbarger, J.W., Akers, J.P., and Hardt, W.F., 1969, Regional hydrology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 521-A, 61 p., *http://pubs.er.usgs.gov/djvu/PP/pp_521_a.djvu*.

NOTE: This older report describes the regional hydrology of the Navajo and Hopi Reservations including the areas around Gallup, Thoreau, and Crownpoint in the western end of the GMB. Included are regional maps of water quality for fluoride and calcium carbonate. The reference list includes 34 published papers that were part of the large study summarized in this report.

Cooper, J.B., and John, E.C., 1965, Ground-water occurrence and geology of southeastern McKinley County, New Mexico: U.S. Geological Survey Open-File Report, 263 p., 7 figs.

NOTE: This report is not available online and was not located for review herein. A related paper was published as Cooper and John (1968).

Cooper, J.B., and John, E.C., 1968, Geology and ground-water occurrence of southeastern McKinley County, New Mexico: New Mexico State Engineer Technical Report 35, 108 p.

Corbett, R.G., 1963, Uranium and vanadium minerals occurring in Section 22 Mine, Ambrosia Lake area, *in* Kelley, V.C., compiler, Geology and technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources Memoir 15, p. 80-81.

Corbett, R.G., 1964, The geology and mineralogy of Section 22 mine, Ambrosia Lake uranium district, New Mexico: University of Michigan, Ann Arbor, unpublished Ph.D. dissertation, 161 p.

Cravens, P.W., and Hammock, P.W., 1958, Geology and ground-water conditions in the Ambrosia Lake-Grants area (with emphasis on ground-water pollution): New Mexico State Engineer Open-File Report, 29 p.

Cronk, R. J., 1963, Geology of the Dysart No.1 Mine, Ambrosia Lake area, *in* Kelley, V.C., compiler, Geology and technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources Memoir 15, p. 60-65, 7 figs.

Curtis, D.B., and Gancarz, A.J., 1978, Lead isotopes as indicators of environmental contamination from the uranium mining and milling industry in the Grants Mineral Belt, New Mexico: Los Alamos National Laboratory Report LA-UR-78-2147, 8 p., *http://library.lanl.gov/cgi-bin/getfile?00247050.pdf*.

Abstract

The unique isotopic composition of lead from uranium ores can be useful in studying the impact of ore processing effluents on the environment. Common lead on the earth's surface is composed of 1.4% ^{204}Pb, 24.1% ^{206}Pb, 22.1% ^{207}Pb, and 52.4% ^{208}Pb. In contrast, lead associated with young uranium ores may contain as much as 95% ^{206}Pb. These extreme differences provide the means to quantitatively evaluate the amount of lead introduced into the environment from the mining and milling of uranium ores by measuring variations of the isotopic composition of lead in environmental samples. The use of Pb isotopes as diagnostic tools in studying the hydrologic transport of materials from U ore dressing plants in the Grants Mineral Belt, New Mexico, is discussed. Preliminary measurements on effluents intimately associated with processing wastes are

consistent with a simple model in which radiogenic lead from the ores is mixed with common lead from the uncontaminated environments.

NOTE: This brief report outlines differences in lead from uranium mining and mill wastes and lead in the natural near-surface environment. Not all lead in uranium deposits will contain as much radiogenic ^{206}Pb as young uranium ores, but the differences should be substantial. Recent improvements in measurements of lead isotopes may make this an important technique especially where other techniques may give ambiguous results.

Curtis, J.M., 2008, An assessment of surface water-groundwater interactions and water quality in Bluewater Creek, New Mexico: Albuquerque, New Mexico, Master of Water Resources Professional Project, The University of New Mexico, 146 p., *https://repository.unm.edu/dspace/bitstream/1928/9223/1/FINAL.pdf*.

NOTE: This project report evaluates the hydrology and surface water-groundwater interactions of a 4-mi section of Bluewater Creek in the mountains south of the GMB. The study period was from late 2003 to 2007. It evaluates the influence of these interactions on the geochemistry of the stream section. Geochemical data for the creek may provide a baseline for understanding the impacts of uranium mining and milling on Bluewater Creek as it flows from the Zuni Mountains into the GMB.

Dam, W.L., 1995, Geochemistry of ground water in the Gallup, Dakota, and Morrison aquifers, San Juan Basin, New Mexico: U.S. Geological Survey Water Resources Investigations Report 94-4253, 76 p., *http://pubs.er.usgs.gov/djvu/WRI/wrir_94_4253.djvu*.

Abstract

Ground water was sampled from wells completed in the Gallup, Dakota, and Morrison aquifers in the San Juan Basin, New Mexico, to examine controls on solute concentrations. Samples were collected from 38 wells primarily from the Morrison aquifer (25 wells) in the northwestern part of the basin. A series of samples was collected along ground-water flow paths; dissolved constituents varied horizontally and vertically. The understanding of the flow system changed as a result of the geochemical analyses. The conceptual model of the flow system in the Morrison aquifer prior to the study reported here assumed the Westwater Canyon Member of the Morrison aquifer as the only significant regional aquifer; flow was assumed to be two dimensional; and vertical leakage was assumed to be negligible. The geochemical results indicate that the Westwater Canyon Member is not the only major water-yielding zone and that the flow system is three dimensional. The data presented in this report suggest an upward component of flow into the Morrison aquifer. The entire section above and below the Morrison aquifer appears to be controlled by a three-dimensional flow regime where saline brine leaks near the San Juan River discharge area. Predominant ions in the Gallup aquifer were calcium bicarbonate in recharge areas and sodium sulfate in discharge areas. In the Dakota aquifer, predominant ions were sodium bicarbonate and sodium sulfate. Water in the Morrison aquifer was predominantly sodium bicarbonate in the recharge area, changing to sodium sulfate downgradient. Chemical and radioisotopic data indicate that water from overlying and underlying units mixes with recharge water in the Morrison aquifer. Recharge water contained a large ratio of chlorine-36 to chlorine and a small ratio of bromide to chloride. Approximately 10 miles downgradient, samples from four wells completed in the Morrison aquifer were considerably different in composition compared to recharge samples. Oxygen stable isotopes decreased by 2.8 per mil and deuterium decreased 26 per mil, relative to recharge. Carbon-14 radioisotope activities were not detectable. Chloride-36 radioisotope ratios were small and bromide-to-chloride concentration ratios were large. These results suggest two potentially viable processes: ion filtration or trapping of ancient dilute water recharged under a humid climate. For water samples near the San Juan River, pH decreased to about 8.0, chloride concentrations increased to more than 100 milligrams per liter, and ratios of chlorine-36 to chlorine and bromide to chloride were small. Leakage of deep basin brine into the fresher water of the Morrison aquifer appears to control ion concentrations.

NOTE: This report provides an overview of the regional geochemistry of three important aquifers across the San Juan Basin derived from sampling of 38 wells in the three aquifers plus data from a few other sources. It includes geochemical data for 25 wells in the Morrison Formation, three of which are in or near the GMB. These Morrison wells are northeast of Gallup (#38), southeast of Crownpoint (#37), and south of Chaco Canyon (#36). Multiple samples were taken from some wells from 1986–1988. Major, minor and trace element and dissolved gas data are reported for these and other wells, as well as stable and radioactive isotope data. Sulfur isotope data are reported for most wells including #36, #37 and #38. The two wells near Gallup and Crownpoint show negative $\delta^{34}S$ (sulfate) values from –10 to –20, whereas the Chaco Canyon well was +12.8.

Dam, W.L., Kernodle, J.M., Levings, G.W., and Craigg, S.D., 1990, Hydrogeology of the Morrison Formation in the San Juan structural basin, New Mexico, Colorado, Arizona, and Utah: U.S. Geological Survey Hydrologic Investigations Atlas HA-720-J, scales 1:1,000,000 and 1:2,000,000, 2 sheets.

NOTE: The Morrison Formation is a major water-bearing unit in the regional aquifer system. Data used in this report were from samples collected during the study or were derived from the USGS' computerized National Water Information System (NWIS). Formation tops and physical parameter water data were also derived from files of the Petroleum Information System. Several wells in the atlas are north of the outcrop of the Morrison Formation in the GMB. Dam and others (1990) summarized the effect of mining on the formation hydrology as follows:

> One of the major influences on water levels in the Morrison Formation has been aquifer dewatering associated with uranium mining. The location and approximate extent of selected uranium mines in the study area is shown in Figure 11. Uranium mining has a modest beginning in the late 1940's, but by the early 1950's the industry was well established. Ore production increased in the mid-1960's and overall mining peaked in the late 1970's. By 1981-1982, low demand and prices forced the closure of some mines (primarily the open-pit and underground operations). By 1986 all but one mine had ceased operation. Ground-water levels in the Morrison declined as a result of increased mine dewatering and ore leaching during the growth years of the industry. Later, as mining activity decreased and eventually almost came to an end, ground-water levels began to recover.
>
> All of the wells in the southern part of the study area for which water level hydrographs have been drawn exhibit some degree of response to uranium mining activities. Operation of the mines requires the removal of ground water from the aquifer, this results in a reduction in potentiometric head in the aquifer. The rate and extent of reduction are less near the outcrop where water in the aquifer is under water-table conditions, than in confined areas in the interior of the basin where the Morrison Formation is a confined aquifer. The primary uranium ore body is the Westwater Canyon Member of the Morrison Formation.
>
> Three methods of ore extraction have been used in the study area. Open-pit mining techniques were used in the area east of Grants, New Mexico (and to a lesser extent in the discovery area west-northwest of Grants). This mining method commonly can use gravity flow and existing drainages to remove mine seepage. Open-pit mines usually are within or very near the outcrop area of the formation; the effects of dewatering for open-pit mining are buffered by water-table storage

coefficients and reduced transmissivity of the water-bearing units (a function of reduced saturated thickness). Also, the regional base elevation for ground-water discharges usually is only slightly altered from preexisting natural conditions.

Deep underground mining methods were used east, north, and northwest of Grants, New Mexico, and northeast of Gallup, New Mexico. Underground mining is still being used at one mine north of Grants. This mining practice has more immediate and intense impact on regional ground-water levels than open-pit mining because the aquifer is under confined, artesian conditions rather than unconfined, water-table conditions. Typically, potentiometric heads in the artesian part of an aquifer will respond two or three orders of magnitude faster to a change in withdrawal than in the unconfined part. Also, at any specific time after initiation of withdrawal, equal changes in potentiometric head in the artesian part of the aquifer will be measured at distances at least one order of magnitude greater than in the unconfined part.

In situ leaching techniques were used at several mines in the Crownpoint, New Mexico, area. Commonly, a leach solution is injected into the mineralized zone in a pattern of wells forming a square. At the center of the square a single well is used to extract the leachate that contains the uranium. In the process, more fluid is extracted than is injected, causing a net decline in pressure head that propagates through the artesian aquifer.

Table 1 in the report provides ranges of physical and chemical data for Morrison Formation wells used in the study. The chemical data include major and minor elements (50-57 wells) plus arsenic (19 wells), selenium (17 wells), and radium-226 (17 wells). Total dissolved solids are given (fig. 15) for 26 of the wells extending from the area north of Gallup to the Rio Puerco on the Laguna Pueblo. Values range from 280 ppm TDS near Crownpoint and Gallup to 2310 ppm TDS just north of Morrison outcrops south of Crownpoint. Stiff diagrams for 16 wells (fig. 16) through the same area show that waters typically are dominated by sodium with variable amounts of bicarbonate or sulfate.

This report is part of a series of hydrologic atlases for major stratigraphic units in the San Juan Basin that provide regional hydrologic and geochemical data for the units. The purposes of the studies were to (1) define and evaluate the aquifer system; (2) assess the effects of past, present, and potential groundwater use on aquifers and streams; and (3) determine the availability and quality of groundwater. The use of data from the NWIS means that data presented in this report represent a synthesis of data not summarized elsewhere.

The entire atlas series includes the following stratigraphic units:

HA-720-A- San Jose, Nacimiento, and Animas Formations
HA-720-B- Ojo Alamo Sandstone
HA-720-C- Kirtland Shale and Fruitland Formation
HA-720-D- Pictured Cliffs Sandstone
HA-720-E- Cliff House Sandstone
HA-720-F- Menefee Formation
HA-720-G- Point Lookout Sandstone
HA-720-H- Gallup Sandstone
HA-720-I- Dakota Sandstone
HA-720-J- Morrison Formation (see above)

A summary of the study findings is in Levings and others (1996).

Day, H.C., Spirakis, C.S., Zech, R.S. and Kirk, A.R. , 1983, Distribution of trace elements in drilling chip samples around a roll-type uranium deposit, San Juan Basin, New Mexico: U.S. Geological Survey Open-File Report 83-56, 28 p., *http://pubs.er.usgs.gov/usgspubs/ofr/ofr8356*.

Abstract
Chip samples from rotary drilling in the vicinity of a roll-type uranium deposit in the southwestern San Juan Basin were split into a whole-washed fraction, a clay fraction, and a heavy mineral concentrate fraction. Analyses of these fractions determined that cutting samples could be used to identify geochemical halos associated with this ore deposit. In addition to showing a distribution of selenium, uranium, vanadium, and molybdenum similar to that described by Harshman (1974) in uranium roll-type deposits in Wyoming, South Dakota, and Texas, the chemical data indicate a previously unrecognized zinc anomaly in the clay fraction downdip of the uranium ore.

NOTE: Characterization of the geochemistry of ore in the GMB may allow discrimination of elevated soil or water trace element levels derived from natural sources from those derived from uranium mine or mill waste derived from the uranium mines.

deLemos, J.L., Bostick, B.C., Quicksall, A.N., Landis, J.D., George, C.C., Slagowski, N.L., Rock, Tommy, Brugge, Doug, Lewis, Johnnye, and Durant, J.L., 2008, Rapid dissolution of soluble uranyl phases in arid, mine-impacted catchments near Church Rock, NM.: Environmental Science and Technology, v. 42, no. 11, p. 3951-3957.

NOTE: The authors evaluated whether or not the primary mechanism for contaminant transport of uranium from mine waste sites in the upper Puerco River watershed was movement of particulates or another mechanism. Analysis of some 100 sediment and suspended sediment samples showed that uranium in these samples was not elevated above background. However, samples collected from a mine waste pile had water soluble uranium where laboratory leachates contained as much as 4.15 mg/L U in a bath simulation where 1g of sample was leached in 10mL of water. Detailed study of the samples showed the presence of highly soluble uranyl phases. Alternate experimental wetting and drying cycles showed ongoing significant releases of uranium from mine waste samples.

Della Valle, R.S., 1981, Geochemical studies of the Grants Mineral Belt, New Mexico: Albuquerque, New Mexico, University of New Mexico Ph.D. dissertation, 667 p.

Abstract (from the Department of Energy's Energy Citations Database at *http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=5593834*)
Numerous sandstone and shale samples from the Morrison (Late Jurassic) and Dakota and Mancos Formations (Cretaceous) from northwestern New Mexico have been analyzed for the major elements Na, K, Fe and the trace elements Sc, Cr, Co, Rb, Sb, Cs, Ba, Hf, Ta, Th, U and the rare earth elements (REE) in whole rocks and clay sized fractions by instrumental and delayed neutron activation analysis. The distribution of these elements in barren rocks of the Grants Mineral Belt (GMB) indicate that the Brushy Basin Member of the Morrison Formation was a source of sodium and carbonate rich uranium bearing fluids that formed at least some of the uranium deposits of the GMB. Using the REE contents and distribution as a guide it can be estimated that approximately 50% of the uranium has been leached from the Brushy Basin Member. Uranium (as carbonate species) was then concentrated through a mixed model of chelation, adsorption on organics and inorganic, reduction processes (i.e.), precipitation of uraninite or coffinite depending on silica activities). Organometallic compounds (such as nitrogen bearing quinolines) can be present in humic acids previously concentrated (through lithologic controls) in the Westwater Canyon Member.

NOTE: Although the main purpose of this study was to evaluate the origins of uranium deposits in sandstones of the Westwater Canyon Member of the Morrison Formation, the geochemical data

reported for sandstone and shale samples in this study may provide baseline data for these sedimentary units that may contrast with mine waste.

De Voto, R.H., Mead, R.H., Martin, J.P., and Bergquist, L.E., 1980, Use of helium in uranium exploration, *in* Rautman, C.A., 1980, complier, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 368-379.

NOTE: This paper provides data for helium in soil gas along selected road traverses through the GMB (fig. 6) and uranium and helium in groundwater in Jurassic and Cretaceous aquifers in 17 wells extending from San Mateo to sites north of Crownpoint (fig. 11). The aquifer sampled is given in most cases. Uranium concentrations vary from <2 ppb for wells in the Point Lookout Sandstone near San Mateo to 980 ppb for a well in an aquifer beneath the Morrison Formation at a site between Grants and Ambrosia Lake.

Dinwiddie, G. A., 1963, Groundwater in the vicinity of the Jackpile and Paguate mines, *in* Kelley, V.C., compiler, Geology and technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources Memoir 15, p. 217-218.

Dinwiddie, G.A., and Motts, W.S., 1964, Availability of ground water in parts of the Acoma and Laguna Indian Reservations, New Mexico: U.S. Geological Survey Water-Supply Paper 1576-E, 65 p., 12 figs. Text- *http://pubs.er.usgs.gov/djvu/WSP/wsp_1576_e.djvu*.
Plate- *http://pubs.er.usgs.gov/djvu/WSP/wsp_1576_e_plt.djvu*.

Abstract

The need for additional water has increased in recent years on the Acoma and Laguna Indian Reservations in west-central New Mexico because the population and per capita use of water have increased; the tribes also desire water for light industry, for more modern schools, and to increase their irrigation program. Many wells have been drilled in the area, but most have been disappointing because of small yields and poor chemical quality of the water. The topography in the Acoma and Laguna Indian Reservations is controlled primarily by the regional and local dip of alternating beds of sandstone and shale and by the igneous complex of Mount Taylor. The entrenched alluvial valley along the Rio San Jose, which traverses the area, ranges in width from about 0.4 mile to about 2 miles. The climate is characterized by scant rainfall, which occurs mainly in summer, low relative humidity, and large daily fluctuations of temperature. Most of the surface water enters the area through the Rio San Jose. The average annual streamflow past the gaging station Rio San Jose near Grants, N. Mex. is about 4,000 acre-feet. Tributaries to the Rio San Jose within the area probably contribute about 1,000 acre-feet per year. At the present time, most of the surface water is used for irrigation. Ground water is obtained from consolidated sedimentary rocks that range in age from Triassic to Cretaceous, and from unconsolidated alluvium of Quaternary age. The principal aquifers are the Dakota Sandstone, the Tres Hermanos Sandstone Member of the Mancos Shale, and the alluvium. The Dakota Sandstone yields 5 to 50 gpm (gallons per minute) of water to domestic and stock wells. The Tres Hermanos sandstone Member generally yields 5 to 20 gpm of water to domestic and stock wells. Locally, beds of sandstone in the Chinle and Morrison Formations, the Entrada Sandstone, and the Bluff Sandstone also yield small supplies of water to domestic and stock wells. The alluvium yields from 2 gpm to as much as 150 gpm of water to domestic and stock wells. Thirteen test wells were drilled in a search for usable supplies of ground water for pueblo and irrigation supply and to determine the geologic and hydrologic characteristics of the water-bearing material. The performance of six of the test wells suggests that the sites are favorable for pueblo or irrigation supply wells. The yield of the other seven wells was too small or the quality of the water was too poor for development of pueblo or irrigation supply to be feasible. However, the water from one of the seven wells was good in chemical quality, and the yield was large enough to supply a few homes with water. The tests suggest that the water in the alluvium of the Rio San Jose valley is closely related to the streamflow and that it might be possible to withdraw from the alluvium in summer and replenish it in winter. The surface flow in summer might be decreased by extensive pumpage of ground water, but on the other hand, more of the winter flow could be retained in the area by storage in the ground-water reservoir. Wells could be drilled along the axis of the valley, and the water could be pumped into systems for distribution to irrigated farms. The chemical quality of ground water in the area varies widely from one stratigraphic unit to another and laterally within each unit and commonly the water contains undesirably large amounts of sulfate. However, potable water has been obtained locally from all the aquifers. The water of best quality seemingly is in the Tres Hermanos Sandstone Member of the Mancos Shale and in the alluvium north of the Rio San Jose. The largest quantity of water that is suitable for irrigation is in the valley fill along the Rio San Jose. Intensive pumping of ground water from aquifers containing water of good quality may draw water of inferior chemical quality into the wells.

NOTE: Page 64 (table 4) of the report gives water-quality data for major and some minor elements in 20 wells in alluvium, the Cretaceous Mancos Shale and Dakota Sandstone and the Triassic Chinle Formation. Additional water-quality discussion is given in the text. Two wells, P_3 and P_5, located on plate 3, penetrate alluvium along the Rio Paguate upstream from the Jackpile-Paguate mine complex. Chemical data for these wells, which were sampled in early 1960, are given in table 6. The results of this study are briefly discussed in an abstract (Dinwiddie, 1963).

Dooley, J.R., Jr., Granger, H.C., and Rosholt, J.N., 1966, Uranium-234 fractionation in the sandstone-type uranium deposits of the Ambrosia Lake District, New Mexico: Economic Geology, v. 61, p. 1362-1382.

NOTE: Thirty sandstone samples in five vertical suites through ore horizons exposed in mine walls of the Ambrosia Lake deposits were analyzed for ^{238}U, ^{235}U, and ^{234}U. No $^{238}U/^{235}$ variations were noted within the accuracy of the methods used. The samples are derived from prefault (primary or trend) orebodies (three suites) and postfault orebodies (two suites) where uranium has been redistributed by fluid moving along the faults. Samples were collected from positions above and below the premining water table. In addition to uranium isotopic analyses, the ores were analyzed for mineral and organic carbon, calcium, vanadium, iron, barium, molybdenum, selenium, ^{230}Th, ^{231}Pa, ^{226}Ra, ^{222}Rn, and ^{210}Pb. Uranium concentrations range from 0.011–0.99 percent. Molybenum, selenium , vanadium, uranium, and organic carbon are concentrated in and near prefault orebodies. Postfault orebodies are enriched only in uranium and vanadium and, to some extent, selenium.

The ore zones are variably depleted and enriched in ^{234}U with respect to ^{238}U. The three-sample suites of prefault ore show varying ranges in the activity ratio (A.R. , converted here from the $\delta^{234}U$ values in the report): suite 19G59 ranged from 0.94 to 1.18, suite 22G59 ranged from 0.99 to 1.30, and suite 9G59 ranged from 0.99 to 1.14. Activity ratios <1 show depletion of ^{234}U with respect to ^{238}U whereas values >1 show enrichment. Samples from suites of post-fault ore have lower overall grades and more variability to the A.R.: suite 18G59 ranged from 0.42 to 1.16 and suite 63G59 ranged from 0.82 to 1.27. Overall, the prefault ores are enriched in ^{234}U, whereas the postfault ores are significantly depleted in one suite and slightly enriched in the other. The authors note that calcite cement and organic carbon content seem to limit the degree of isotopic fractionation.

Downs, W.F., and Runnells, D.D., 1975, Trace element concentrations in pyrite from sandstone uranium deposits: Economic Geology, v. 70, no. 7, p. 1320.

Dreesen, D.R., Bumker, M.E., Cokal, E.J., Denton, M.M., Starner, J.W., Thode, E.F., Wangen, L.E., and Williams, J.M., 1983, Research on the characterization and conditioning of uranium mill tailings, I. Characterization and leaching behavior of uranium mill tailings: Los Alamos Scientific Laboratory Report LA-9660-UMT, V. 1, 136 p.

NOTE: Although this report describes results of leaching studies of tailings primarily from sites outside of the GMB, a tailings composite (fines) from the Ambrosia Lake mill site is included. Extensive geochemical data are reported for the sites. The report compares results of these tailings studies to GMB soil leachates from two sites at Grants and Bluewater.

Dreesen, D.R., and Marple, M.L., 1979, Uptake of trace elements and radionuclides from uranium mill tailings by four-wing saltbush (*Atriplex canescens*) and Alkalai Sacaton (*Sporobolis airoides*): Los Alamos Scientific Laboratory Report LA-UR-79-3045, 18 p., *http://library.lanl.gov/cgi-bin/getfile?00416276.pdf*.

Abstract

A greenhouse experiment was performed to determine the uptake of trace elements and radionuclides from uranium mill tailings by native plant species. Four-wing saltbush and alkali sacaton were grown in alkaline tailings covered with soil and in soil alone as controls. The tailings material was highly enriched in Ra-226, Mo, U, Se, V, and As compared with three local soils. The shrub grown in tailings had elevated concentrations of Mo, Se, Ra-226, U, As, and Na compared with the controls. Alkali sacaton contained high concentrations of Mo, Se, Ra-226, and Ni when grown on tailings. Molybdenum and selenium concentrations in plants grown in tailings are above levels reported to be toxic to grazing animals. These results indicate that the bioavailability of Mo and Se in alkaline environments makes these elements among the most hazardous contaminants present in uranium mill wastes.

Dreesen, D.R., 1981, Biogeochemistry of uranium mill wastes, program overview and conclusions: Los Alamos Scientific Laboratory Report LA-8861-UMT, 11 p., *http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=4B59272F5450DEA46A2387D7F629A76B?purl=/6270243-6NQpV6/*.

Abstract

The major findings and conclusions are summarized for research on uranium mill tailings for the U.S. Department of Energy and the U.S. Nuclear Regulatory Commission. An overview of results and interpretations is presented for investigations of ^{222}Rn emissions, revegetation of tailings and mine spoils, and trace element enrichment, mobility, and bioavailability. A brief discussion addresses the implications of these findings in relation to tailings disposal technology and proposed uranium recovery processes.

NOTE: This report summarizes some early work by Los Alamos National Laboratory researchers on uranium mill tailings issues at six tailings sites in the Western United States including Milan and Ambrosia Lake in New Mexico. The report describes the following:

1. Radon flux data from tailings piles,
2. Attenuation of radon flux by soil covers,
3. Problems with establishing vegetation on bare tailings material and use of rock and boulder covers to facilitate establishment of vegetation,
4. Uptake of trace elements and radium by vegetative cover,

5. Trace element and radiochemical enrichment in tailings,
6. Aqueous mobilization of trace elements from tailings,
7. Groundwater transport of contaminants from tailings piles, and
8. Uptake of trace elements and radiochemicals by plants in field irrigated with waste water.
   The report concludes with recommendations to address the problems identified.

Dregne, H. E., and Maker, H. J., 1954, Irrigation well waters of New Mexico; Chemical characteristics, quality, and use: New Mexico State University, Las Cruces, Agricultural Experiment Station Bulletin 386, 28 p., 8 figs.

Duval, J.S., 1988, Aerial gamma-ray contour maps of regional surface concentrations of uranium, potassium, and thorium in New Mexico: U. S. Geological Survey Geophysical Investigations Map GP-0979, 3 sheets, scale 1:750,000.

Duval, J.S., 1989, Aerial gamma-ray contour maps of regional surface concentrations of potassium, uranium, thorium, and composite-color maps of uranium, potassium, thorium, and their ratios in New Mexico: U. S. Geological Survey Geophysical Investigations Map GP-0980, 7 maps on four sheets, scale 1:1,000,000.

NOTE: Neither Duval (1988) nor Duval (1989) is available online. The maps in these two reports provide data on the potassium, uranium, and thorium concentrations and ratios of these elements in near-surface soils and other materials in New Mexico including the GMB. The maps are derived from gamma-ray data collected along flightlines by aircraft during the National Uranium Resource Evaluation aeroradiometric surveys. The flightline spacing controls the detail that can be expected. Individual flightline profiles, available in folios published by the Department of Energy, can pinpoint locally high uranium concentrations in surface materials within a few hundred meters on either side of the flightline. The instruments typically detect gamma rays from materials no more than about 40 cm beneath the surface.

Eadie, G.G., and Kaufman, R.F., 1977, Radiological evaluation of the effects of uranium mining and milling operations on selected ground water supplies in the Grants Mineral Belt, New Mexico: Health Physics, v. 32, p. 231-241.

Eadie, G.G., Kaufmann, R.F., Markley, D.J., and Williams, Roosevelt, 1976, Report of ambient outdoor radon and indoor radon during November 1975 at selected locations in the Grants Mineral Belt, New Mexico: Las Vegas, Nevada, Office of Radiation Programs, U.S. Environmental Protection Agency Technical Note ORP/LV-76-4, 45 p.

Abstract

This report presents the results of measurements of ambient outdoor radon concentrations and indoor radon progeny working level determinations during November 1975 for 10 locations throughout the Ambrosia Lake area and vicinity, New Mexico. For that portion of the study area in the vicinity of uranium mines and mills, statistical evaluation of the data indicates that ambient outdoor radon concentrations and the indoor radon progeny levels (WL) are in excess of typical background levels. Better definition of background levels and a more thorough evaluation of specific source terms in the immediate Ambrosia Lake area is strongly suggested. For locations in proximity to a uranium mill site, gamma radiation exposure rates and the radium-226 content of surface soils are also above normal background conditions. To assure compliance with State and Federal regulations, it is recommended that further studies be conducted over at least a one-year period for comparison to the applicable radiation protection guides for those areas in the vicinity of

uranium mill sites. Radiation exposures to the general population occupying areas in the immediate vicinity of uranium mining and milling operations should also be evaluated.

Fishman, N.S., and Reynolds, R.L., 1982, Origin of the Mariano Lake uranium deposit, McKinley County, New Mexico: U.S. Geological Survey Open-File Report 82-888, 56 p., *http://pubs.er.usgs.gov/usgspubs/ofr/ofr82888*.

Abstract

The Mariano Lake uranium deposit, hosted by the Brushy Basin Member of the Jurassic Morrison Formation, occurs in the trough of an east-west trending syncline at the western end of the Smith Lake-Mariano Lake group of uranium deposits near Crownpoint, New Mexico. The orebody, which contains abundant amorphous organic material, is situated on the reduced side of a regional reduction-oxidation (redox) interface. The presence of amorphous organic material suggests the orebody may represent a tabular (primary) deposit, whereas the close proximity of the orebody to the redox interface is suggestive that uranium was secondarily redistributed by oxidative processes from pre-existing tabular orebodies. Uranium contents correlate positively with both organic carbon and vanadium contents. Petrographic evidence and scanning electron microscope-energy dispersive analyses point to uranium residence in the epigenetically introduced amorphous organic material, which coats detrital grains and fills voids. Uranium mineralization was preceded by the following diagenetic alterations: precipitation of pyrite ($\delta^{34}S$ values ranging from-11.0 to-38.2 per mil); precipitation of mixed-layer smectite-illite clays; partial dissolution of some of the detrital feldspar population; and precipitation of quartz and adularia overgrowths. Alterations associated with uranium mineralization include emplacement of amorphous organic material (possibly uranium bearing); destruction of detrital iron-titanium oxide grains; coprecipitation of chlorite and microcrystalline quartz, and precipitation of pyrite and marcasite ($\delta^{34}S$ values for these sulfides ranging from -29.4 to -41.6 per mil). After mineralization, calcite, dolomite, barite, and kaolinite precipitated, and authigenic iron disulfides were replaced by ferric oxides and hydroxides. Geochemical data (primarily the positive correlation of uranium content to both organic carbon and vanadium contents) and petrographic observations (epigenetically introduced amorphous organic matter and uranium residence in this organic matter) indicate that the Mariano Lake orebody is a tabular-type uranium deposit. Oxidative processes have not noticeably redistributed and reconcentrated primary uranium in the immediate vicinity of the deposit nor have they greatly modified geochemical characteristics in the ore. Preservation of the Mariano Lake deposit may not only be related to its position along the synclinal trough, where oxidative destruction of the orebody has been inhibited by stagnation of oxidizing ground waters by the structure, but also due to the deflection of ground waters (resulting from low orebody porosity) around the orebody.

NOTE: This report provides both geochemical and minerologic data that may distinguish uranium mine wastes derived from mining of this deposit from other deposits. The sulfur isotope data may allow discrimination of sulfate from weathering of near-surface sulfate sources from sulfate derived from the oxidation of sulfide in mine waste. Mill waste may be less amenable to such discrimination because of the use of sulfuric acid in processing most ores in the GMB.

Fishman, N.S., and Reynolds, R.L, 1983, Geochemical characteristics of the Church Rock 1 and 1 East uranium deposits, Grants uranium region, New Mexico: U.S. Geological Survey Open-File Report 83-0194, 28 p., *http://pubs.er.usgs.gov/usgspubs/ofr/ofr83194*.

Abstract

In the Church Rock 1 and 1 East mines, Grants uranium region (GUR), New Mexico, uranium orebodies occur within three sandstone units in the upper part of the Westwater Canyon Member of the late Jurassic Morrison Formation. Geochemical analyses reveal that organic carbon contents in ore samples from all three sand units are uniformly low (most are less than 0.01 percent). Vanadium (ranging from 0.0002 to 0.19 percent) and sulfur (ranging from <0.01 to 0.74 percent) typically show positive correlations with uranium; however, vanadium contents rarely exceed those of uranium in ore samples. Although no systematic relationship of either selenium or molybdenum to uranium is evident, some ore samples contain anomalously high concentrations of either of these elements. Geochemically, the ore deposits of the Church Rock area contrast greatly with primary (tabular) uranium orebodies in the GUR which contain abundant organic carbon and greater amounts of vanadium and sulfur. These differences and radiometric age determinations strongly suggest that the Church Rock ores formed as a result of the redistribution of uranium from preexisting uranium deposits within the last 1 m.y. However, the Church Rock deposits differ geochemically from redistributed orebodies in the Westwater Canyon Member elsewhere in the GUR. Specifically, redistributed orebodies in the Ambrosia Lake district, which are comparable in contents of uranium and organic carbon with the Church Rock deposits, are characterized by vanadium contents typically higher than those of uranium. Similarly, sulfur contents in the redistributed deposits of the Ambrosia Lake district are greater than those found in the Church Rock ores. In addition, anomalously high concentrations of molybdenum have rarely been found in other redistributed orebodies of the GUR.

NOTE: The geochemical characterization of various types of deposits may allow discrimination of wastes from different mine sources.

Fishman, N.S., Reynolds, R.L., and Robertson, J.F., 1985, Uranium mineralization in the Smith Lake District of the Grants uranium region, New Mexico: Economic Geology, v. 80, no. 5, p. 1348-1364.

NOTE: This outside published paper by USGS authors describes the geology, geochemistry, and paragenesis of the Mariano Lake and Ruby 1 deposits in the Smith Lake District of the GMB. These primary ore deposits are enriched in vanadium, organic carbon, and selenium. The sulfur isotope data may be useful in distinguishing sulfate sulfur in wastes derived from mining of these deposits from natural sulfate in the surface environment. Ore-stage iron disulfide minerals yield δ^{34} S values that range from –29 to –42 per mil, whereas authigenic iron disulfides formed prior to mineralization show δ^{34}S values that range from –11 to –38 per mil.

Fisk, G.G., Ferguson, S.A., Rankin, D.R., and Wirt, Laurie, 1994, Chemical, geologic and hydrologic data in the Little Colorado River basin, Arizona and New Mexico, 1988-91: U.S. Geological Survey Open-File Report 94-356, 468 p., *http://pubs.er.usgs.gov/djvu/OFR/1994/ofr_94_356.djvu*.

Abstract

In June 1988, The U.S. Geological Survey began a 4-year study of the occurrence and movement of radionuclides and other chemical constituents in ground water and surface water in the Little Colorado River basin in Arizona and New Mexico. Radionuclides and other chemical constituents occur naturally in water, rock, and sediment throughout the region; however, discharge of mine--dewatering effluents released by mining operations increased the quantity of radionuclides and other chemical contaminants. Additionally, in 1979, the failure of a tailings-pond dike resulted in the largest known single release of water contaminated by uranium tailings in the United States. Ground-water data and surface-water data were collected from July 1988 through September 1991. Sixty-nine wells were sampled, and collected data include well- construction information, lithologic logs, water levels and chemical analysis of water samples. The wells include 31 wells drilled by the U.S. Geological Survey, 7 wells drilled by the New Mexico Environment Department, 11 private wells, and 20 temporary drive-point wells; in addition, 1 spring was sampled. Data from nine continual-record and five partial-record streamflow-gaging stations include daily mean discharge, daily mean suspended-sediment concentration and discharge, and chemical analysis for discrete water and sediment samples. Precipitation data also were collected at the nine continual-record stations.

NOTE: This is a basic data release for a large study, the results of which were published in several other reports. The groundwater data include (1) daily water levels, (2) discrete water levels, (3) well construction and lithology, (4) geophysical logs, (5) chemical analyses, and (6) radionuclide and grain-size analyses of well-core sediment. The surface-water data include (1) daily mean discharge; (2) daily mean suspended-sediment concentration; (3) daily mean suspended-sediment discharge; (4) chemical analyses including stable isotopes (nitrogen, oxygen, and sulfur), trace elements, and radionuclides; and (5) radionuclides on suspended sediment.

Sulfur isotope data are reported for 11 wells in alluvium; they range narrowly from –1.70 to –4.10 $\delta^{34}S$.

Frenzel, P.F., 1992, Simulation of ground-water flow in the San Andres-Glorieta aquifer in the Acoma embayment and eastern Zuni uplift, west-central New Mexico: U.S. Geological Survey Water Resources Investigations Report 91-4099, 381 p., *http://pubs.er.usgs.gov/djvu/WRI/wrir_91_4099.djvu*.

Abstract

The San Andres-Glorieta aquifer and overlying valley fill were studied in cooperation with the New Mexico State Engineer Office, the Pueblo of Acoma, the Pueblo of Laguna, and the U.S. Bureau of Indian Affairs. The purpose of the study was to determine the effects of current and projected water development on flow in the Rio San Jose and on hydraulic heads in the San Andres-Glorieta aquifer.

A digital flow model containing 2 layers, 76 rows, and 43 columns was constructed. This model simulated ground-water flow in the San Andres- Glorieta aquifer in an area from the Continental Divide on the west to the Rio Grande rift on the east and from Hospah, New Mexico, on the north to the Rio Salado on the south. In addition to simulating ground-water flow in the valley fill near The Malpais, Grants, and Bluewater, the model also simulated flow to and from Bluewater Lake, Bluewater and Cottonwood Creeks, and the Rio San Jose. Ojo del Gallo (rooster spring) and Horace Springs were simulated as streams.

Historical ground-water withdrawals and recharge were simulated for the period of fall 1899 to fall 1985. Measured hydraulic heads and streamflows were considered to have been matched reasonably well by the simulated values. Simulated drawdowns caused by historical ground-water development were about 8 feet at a location east of the San Rafael fault.

Projections were made from 1985 to 2020 in which the current (1986) level of ground-water development was simulated; in addition, 10,000 acre-feet per year of withdrawal from the San Andres-Glorieta aquifer near the west side of the Pueblo of Acoma was simulated. Model results indicate that drawdowns would be about 200 feet after 35 years east of San Rafael fault and about 20 feet at locations west of the fault. However, the accuracy of the drawdowns is uncertain because of (i) the assumed degree of hydraulic disconnection at San Rafael fault being critical to the simulation of cross-fault drawdowns, (2) the possible effects of leakage from confining beds, (3) the southward extent of the aquifer being unknown, and (4) the uncertainty of the artesian storage

coefficient. The projected withdrawal of 10,000 acre-feet per year did not result in significant springflow or streamflow depletion, most of the withdrawal being derived from ground-water storage.
Steady-state springflows at Horace Springs were about 5.6 cubic feet per second, whereas simulated historical springflows were between 5.1 and 5.6 cubic feet per second. Projected springflows at Horace Springs were not greatly affected by projected ground-water development. Simulated decreases in flow of the Rio San Jose at Horace Springs were variable but averaged about 6 cubic feet per second. The reappearance of spring discharge at Ojo del Gallo during the early 1980's was simulated as a result of abnormally high streamflows and little ground-water irrigation, but when more normal streamflow and ground-water usage were projected, simulated springflows at Ojo del Gallo ceased.

NOTE: This report does not discuss the possible movement of contaminated groundwater in the simulated systems, but the modeling may provide an estimate of such movement where groundwater contamination may be identified. There are no geochemical data in the report.

Frenzel, P.F., and Lyford, F.P., 1979, Estimates of vertical hydraulic conductivity and regional ground-water flow rates in rocks of Jurassic and Cretaceous age, San Juan Basin, New Mexico and Colorado: U.S. Geological Survey Water-Resources Investigations Report 82-4015, 67 p., *http://pubs.er.usgs.gov/djvu/WRI/wrir_82_4015.djvu*.

Abstract

The San Juan structural basin northwestern New Mexico was modeled in three dimensions using a finite-difference, steady-state model. The modeled space was divided into seven layers of square prisms that were 6 miles on a side in the horizontal directions. In the vertical direction, the layers of prisms ranged in thickness from 300 to 1,500 feet. The model included the geologic section between the base of the Entrada Sandstone and the top of Mesaverde Group. Principal aquifers in this section are mostly confined and include the Entrada Sandstone, the Westwater Canyon Member of the Morrison Formation, and the Gallup Sandstone. Values for vertical hydraulic conductivities from 10 to the minus 12th power to 10 to the minus 11th power feet per second for the confining layers gave a good simulation of head differences between layers, but a sensitivity analysis indicated that these values could be between 10 and 100 times greater. The model-derived steady-state flow was about 30 cubic feet per second. About one-half of the flow was in the San Juan River drainage basin about one-third in the Rio Grande drainage basin, and one-sixth in the Puerco River drainage basin.

Frenzel, P.F., Craigg, S.D. and Padgett, E.T., 1981, Preliminary data report for the San Juan Basin-Crownpoint surveillance study: U.S. Geological Survey Open-File Report 81-484, 36 p., 5 oversize sheets, *http://pubs.er.usgs.gov/usgspubs/ofr/ofr81484*.

Abstract

Geohydrologic data that may be used to predict the effects of mining on Navajo water resources in the San Juan structural basin are reported as well as the current availability of data from other government agencies. Emphasis is on the vicinity of Crownpoint, New Mexico.

NOTE: This report includes information from observation wells screened in multiple formations and includes major (table 2) and minor (table 3) chemical constituents of water from selected wells in the vicinity of Crownpoint, N. M., including a few analyses for uranium.

Gallaher, B.M., and Cary, S.J ., 1986, Impacts of uranium mining of surface and shallow ground waters, Grants Mineral Belt, New Mexico: Santa Fe, New Mexico Environmental Improvement Division Report EID/GWH-86/2, 152 p.

NOTE: This report describes the results of a multiyear study funded by the USEPA to evaluate the impacts of uranium mining in the GMB. The report identifies mine dewatering effluents and mine spoils piles as the principal potential sources of contamination from the mining process. Because of the large volumes of water involved, the mine dewatering has generated regional surface-water impacts with more than 140 mi of stream flow being sustained by mine effluent in 1980 in otherwise dry stream channels. Mine spoils, which include mine waste and subeconomic ore, have more local impacts through erosion of the piles, but dissolved contaminant concentrations may be higher by many orders of magnitude.

The study provides alluvial groundwater-level data for wells along the north fork of the Puerco River (Church Rock district), the Arroyo del Puerto, and San Mateo Creek. Surface-water monitoring sites were established along these three streams and the Rio Paguate and Rio Moquino near the Jackpile-Paguate mine complex on the Laguna Reservation. Ten well clusters were established along two drainages to monitor groundwater at various depths—five along the north fork of the Puerco River between Gallup and the United Nuclear Church Rock mill and five in the San Mateo Creek drainage. Composite samples of waste rock piles from six mines were leached (UNC-NE, Church Rock; Kerr-McGee-I, Church Rock; Hyde; Vallejo; Poison Canyon; and Old San Mateo). Runoff sampling stations were established upstream and downstream along ephemeral drainages adjacent to waste rock piles at six mine areas (Old San Mateo, Marcus, Poison Canyon, Vallejo, Church Rock, and Hyde).

The report provides several summaries and comparisons of data from the sites studied, and draws conclusions about impacts, but notes that for many systems pre-mining data are not available.

Gabelman, J.W., 1970, The Flat Top uranium mine, Grants, New Mexico: U.S. Atomic Energy Commission Report RME–4112, 81 p.

Gallaher, B.M. and Goad, M.S., 1981, Water-quality aspects of uranium mining and milling in New Mexico, *in* Wells, S.G., Lambert, Wayne, and Callender, J.F., eds., Environmental geology and hydrology in New Mexico: Socorro, New Mexico, New Mexico Geological Society Special Publication 10, p. 85-91. Available for purchase through *http://geoinfo.nmt.edu/publications/nmgs/special/10/*.

Goad, M.S., Nylander, C.L., Gallaher, B.M., Dudley, J.G., and Perkins, B.L., 1980, Water-quality data for discharges from New Mexico uranium mines and mills in New Mexico: Santa Fe, New Mexico, New Mexico Environmental Improvement Division Report, 87 p.

Gordon, E.D., 1961, Geology and ground-water resources of the Grants-Bluewater area, Valencia County, New Mexico, with a section on Aquifer characteristics, by H. L. Reeder, and with a section on Chemical quality of the ground water, by J. L. Kunkler: New Mexico State Engineer Technical Report. 20, 109 p.

Gordon, E.D., Reeder, H.O., and Kunkler, J.L, 1960, Geology and ground-water resources of the Grants-Bluewater area, Valencia County, New Mexico: U.S. Geological Survey Open-File Report, 224 p., 17 plates.

Abstract

Ground water has been developed extensively for irrigation and industrial use in the Grants-Bluewater area of north-central Valencia County, New Mexico, an area in or near which are about two-thirds of the Nation’s known uranium reserves. The development of ground water has created many problems; this report appraises the problems and their causes.

The principal aquifer in the area is formed by the Glorieta sandstone and the overlying San Andres limestone, which crop out on the flanks of the Zuni Mountains and underlie the eastern two-thirds of the area. Interbedded alluvium and basalt of Quaternary age form an aquifer of secondary importance.

The Glorieta sandstone is less permeable than the San Andres, and few wells tap it exclusively. The Glorieta transmits water to the overlying San Andres limestone, however, as pumping decreases the hydraulic pressure in the San Andres. Well-connected cavernous zones and solution channels have developed in the San Andres, and the transmissivity of the limestone is great in most places.

The alluvium and basalt yield adequate quantities of water for stock and domestic use at most places and for irrigation and municipal use locally.

The first irrigation well was drilled in 1944, and the number had increased to 23 in 1951. The use of ground water for irrigation reached a peak of 12,600 acre-feet in 1954 and has since decreased. Several of the irrigation wells have been converted for industrial and municipal supply, and ground water for these uses increased from 250 acre-feet in 1951 to 6,000 acre-feet in 1957. The total withdrawal stabilized at about 13,000 acre-feet per year from 1950 to 1957. Withdrawal of ground water has caused water levels to decline 40 to 45 feet north of Bluewater Village and 18 to 20 feet from Bluewater Village southeast to near Grants.

The largest yields are obtained from wells penetrating both of the major aquifers in the southwestern part of the Grants-Bluewater Valley between Bluewater Village and Milan. The yields of wells in that area range approximately from 500 to 2,200 gpm (gallons per minute); the specific capacities of the wells that were measured averaged 200 gpm per foot of drawdown. The specific capacity of only one well that taps the alluvium and basalt was determined; it was 31 gpm per foot of drawdown.

The chemical quality of the water in both aquifers varies widely in short distances. The quality of the water yielded by a few wells that tap the San Andres limestone has changed in the last decade; some water has improved in quality and some has deteriorated, according to the proximity of the recharge area. The agricultural utility of water from both aquifers generally is satisfactory, although the salinity hazard of water in some areas is high. Water used for the municipal supply of Grants is too hard and too saline to be desirable, and the sulfate concentration is high enough to impart an objectionable taste to the water. The water of best quality is obtained from both aquifers between Bluewater Village and Milan, where the largest average yields also are obtained.

NOTE: The copy of this report reviewed by the author was obtained from the U.S. Geological Survey library in Reston, Va. It is not available online. This report reviews the climate, mining development, geology, groundwater flow and discharge, aquifer tests, and water quality of the Grants–Bluewater area. The water-quality section reviews the source of recharge for the aquifers and the geologic influences on water quality, then summarizes what is known and not known about water quality in the formations. Gaged flow data for Bluewater Creek from 1913 to 1956 are presented with some data for irrigation water usage from 1932 to 1952. Three detailed lithologic logs are given for holes drilled into the San Andres Limestone, two by uranium mining companies seeking water supply. Well records for 156 wells (table 6) and data for 5 springs (table 7) are given. Major and minor element geochemical and physical property data are given for 78 wells and springs with multiple analyses over several years for many wells (table 8). Geochemical data for selected public water supply wells for San Rafael, Milan, Grants and Bluewater are given. The water quality in the Glorieta Sandstone and San Andres Limestone, the Chinle Formation, alluvium, and basalt are discussed. Table 8 provides geochemical data for 78 wells and springs with the aquifer source noted. Most wells have multiple sample dates. The data include major and minor elements and physical parameters. The concentrations or activities of uranium and other radionuclides are not in the data.

This paper also appears to have been published as Gordon (1961).

Graf, J.B., Wirt, Laurie, Swanson, E.K., Fisk, G.G., and Gray, J.R., 1996, Streamflow transport of radionuclides and other chemical constituents in the Puerco and the Little Colorado River basins, Arizona and New Mexico: U. S. Geological Survey Water-Supply Paper W 2459, 89 p., *http://pubs.er.usgs.gov/usgspubs/wsp/wsp2459.*

Abstract

Samples of water and sediment were collected from 1988 to 1991 at nine streamflow-gaging stations in the Little Colorado River Basin to determine the occurrence and transport of selected radionuclides and other chemical constituents. More than two decades of uranium mining and a single spill of uranium-mine tailings due to the failure of a tailings-pond dike released high levels of radionuclides and other chemical constituents to the Puerco River, a tributary of the Little Colorado River. The releases caused public concern that streams downstream from mining areas were contaminated. Concentration and radioactivity of selected radionuclides and other chemical constituents were compared with applicable water-quality standards, and quality of streamflow was found to depend primarily on the concentration of suspended sediment. Typically, streamflow samples met drinking-water standards for the dissolved fraction, but unfiltered samples exceeded the drinking-water standards for a large suite of constituents. The combination of high suspended-sediment concentration, large particle- surface area, and the abundance of clay-sized particles with high cation-exchange capacity provides nearly optimal conditions for transport of radionuclides and other chemical constituents on sediment in streams in the study area. More than 99 percent (by mass) of analyzed constituents in a given sample were transported on suspended sediment.

Radioactivity of suspended sediment collected during the study period is related to location in the basin rather than to proximity of the sampling site to past uranium mining. Suspended- sediment radioactivity from uranium-238, uranium-234, radium-226, thorium-230, and thorium-232 was higher at sample sites on the Puerco and Zuni Rivers and Black Creek, which drain the northeastern part of the Little Colorado River Basin, than on the Little Colorado River. Suspended-sediment radioactivity for those isotopes was about 1.3 to 2.1 picocuries per gram for samples from those three streams and about 0.9 to 1.5 picocuries per gram for samples from the Little Colorado River. Radioactivity of suspended sediment measured in this study, therefore, probably represents natural conditions for the sampled streams rather than an effect of mining. During the study period, radionuclide load increased downstream because suspended-sediment load increased downstream. For water year 1991, suspended-sediment load was estimated to be 0.31×10^6 megagrams on the Puerco River near Church Rock, New Mexico, and 6.6×10^6 megagrams on the Little Colorado River near Cameron, Arizona. Radioactivity load from uranium was estimated to be 0.83 and 14 curies at the two streamflow-gaging stations, respectively. Radioactivity of sediment and water transported downstream from the mines by the Puerco River has decreased significantly since the cessation of mining. Comparison of chemical analyses of samples collected during the present study with analyses of samples of mine-dewatering effluent collected during mining indicates that the uranium load of the Puerco River near Church Rock in 1991 was about 4 percent of that during an average year of mine dewatering.

Granger, H.C., 1960, Pitchblende identified in a sandstone-type uranium deposit in the central part of the Ambrosia Lake District, New Mexico, *in* Geological Survey Research 1960; Short papers in the geological sciences*:* U. S. Geological Survey Professional Paper 400B, p. B54-B55.

Abstract

Pitchblende is very scarce in the central part of the Ambrosia Lake district, where the dominant U mineral is coffinite. The pitchblende here described is believed to have been derived from coffinite.

NOTE: This report is not available online.

Granger, H.C., 1962, Clays in the Morrison Formation and their spatial relation to the uranium deposits at Ambrosia Lake, New Mexico, *in* Geological Survey Research 1962: Short papers in geology, hydrology, and topography; Articles 120-179: U.S. Geological Survey Professional Paper 450D, p. D15-D20.

Abstract

Montmorillonite is the dominant clay mineral in the sandstones of the Westwater Canyon Member of the Morrison Formation [Jurassic] where the Westwater Canyon is overlain by mudstones of the Brushy Basin Member. Kaolinite is the dominant clay mineral where the Dakota Sandstone [Cretaceous] directly overlies the Westwater Canyon. Montmorillonite gives way to chlorite within prefault U-ore bodies.

NOTE: This report is not available online. Clay minerals of specific types may be distinctive of ore zones and may allow discrimination of clays contained in natural surface sediments and soils from those contaminated by clays in mine waste.

Granger, H.C., 1963, Radium migration and its effect on the apparent age of uranium deposits at Ambrosia Lake, New Mexico, *in* Geological Survey Research 1963: U. S. Geological Survey Professional Paper 475-B, p. B60-B63, *http://pubs.er.usgs.gov/djvu/PP/pp_475_b.djvu*.

Abstract

Considerable radium (Ra-226) has migrated out of the uranium ores and has been partly reconcentrated in barite, cryptomelane, and along the surfaces of mudstone bodies. The loss of Ra-226, which ultimately decays to Pb-208, indicates that the apparent Pb-207 /Pb-208 age of the ores would be too great and that the Pb-206 /U-238 age would be too small.

NOTE: The presence of radiobarite or radioactive cryptomelane (a potassium-manganese oxide mineral) in soil or stream sediment could be indicative of mine waste.

Granger, H.C., and Ingram, B.L., 1966, Occurrence and identification of jordisite at Ambrosia Lake, New Mexico, *in* Geological Survey Research 1966: U.S. Geological Survey Professional Paper 550-B, p. B120-B124.

Abstract

Certain black-stained zones in sandstone associated with primary uranium ore bodies at Ambrosia Lake, N. Mex., contain as much as several tenths of a percent molybdenum. Chemical and X-ray studies of impure separates of the black material indicate that it contains appreciable amounts of the amorphous molybdenum disulfide, jordisite.

NOTE: This report is not available online. Molybdenum should be present in anomalous amounts in mine waste and mill tailings derived from several, but not all, GMB mines. Natural surface soils and sediments in the Western U.S., and possibly also in the GMB, may contain less molybdenum than such wastes except where ore deposits are close to the surface and trace elements from them raise

the background level of the natural environment. See Smith and Huyck (1998), cited herein, for an overview of trace metals in surface environments.

Granger, H.C., and Santos, E.S., 1982, Geology and ore deposits of the Section 23 Mine, Ambrosia Lake District, New Mexico: U. S. Geological Survey Open-File Report 82-0207, 74 p., *http://pubs.er.usgs.gov/djvu/OFR/1982/ofr_82_207.djvu*.

Abstract

The section 23 mine is one of about 18 large uranium mines opened in sandstones of the fluvial Westwater Canyon Member of the Jurassic Morrison Formation in the Ambrosia Lake mining district during the early 1960s. The Ambrosia Lake district is one of several mining districts within the Grants mineral belt, an elongate zone containing many uranium deposits along the southern flank of the San Juan basin. Two distinct types of ore occur in the mine. Primary ore occurs as peneconcordant layers of uranium-rich authigenic organic matter that impregnates parts of the reduced sandstone host rocks and which are typically elongate in an east-southeast direction subparallel both to the sedimentary trends and to the present-day regional strike of the strata. These are called prefault or trend ores because of their early genesis and their elongation and alinement. A second type of ore in the mine is referred to as postfault, stacked, or redistributed ore. Its genesis was similar to that of the roll-type deposits in Tertiary rocks of Wyoming and Texas. Oxidation, related to the development of a large tongue of oxidized rock extending from Gallup to Ambrosia Lake, destroyed much of the primary ore and redistributed it as massive accumulations of lower grade ores bordering the redox interface at the edge of the tongue. Host rocks in the southern half of sec. 23 (T. 14 N., R. 10 W.) are oxidized and contain only remnants of the original, tabular, organic-rich ore. Thick bodies of roll-type ore are distributed along the leading edge of the oxidized zone, and pristine primary ore is found only near the north edge of the section. Organic matter in the primary ore was derived from humic acids that precipitated in the pores of the sandstones and fixed uranium as both coffinite and urano-organic compounds. Vanadium, molybdenum, and selenium are also associated with the ore. The secondary or roll-type ores are essentially free of organic carbon and contain uranium both as coffinite and uraninite. They also contain vanadium and selenium but are virtually devoid of molybdenum. Although much has been learned about these deposits since the time this study was conducted, in 1966, a great deal more study will be required to completely elucidate their geologic history.

NOTE: This work was also published as Granger and Santos (1986).

Granger, H.C., and Santos, E.S., 1986, Geology and ore deposits of the Section 23 Mine, Ambrosia Lake District, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, Neil, eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: Tulsa, Oklahoma, American Association of Petroleum Geologists Studies in Geology 22, p. 185-210.

Gray, J.R., and Fisk, G.G., 1992, Monitoring radionuclide and suspended-sediment transport in the Little Colorado River basin, Arizona and New Mexico, USA, *in* Bogen, J., Walling, D.E., and Day, T., eds., Erosion and sediment transport monitoring programmes in river basins: International Association of Hydrological Sciences International Symposium on Erosion and Sediment Transport Monitoring Programmes in River Basins, Oslo, Norway, Aug. 24-28, 1992, IAHS-AISH Publication 210, p. 505-516.

Gray, J.R., and Van Metre, P.C., 1996, Uranium-mining releases from the Grants Mineral Belt to the Little Colorado River basin, Arizona and New Mexico, *in* Stevens, P.R., and Nicholson, eds., Joint U.S. Geological Survey, U.S. Nuclear Regulatory Commission workshop on research related to low-level radioactive waste disposal, May 4-6, 1993, National Center, Reston, Va; Proceedings: U.S. Geological Survey Water-Resources Investigations Report 95-4015, p. 14-18, *http://pubs.er.usgs.gov/djvu/WRI/wrir_95_4015.djvu*.

Introduction

The USGS studied the presence of radionuclides and other trace metals downgradient from uranium-mining activities in New Mexico's Grants Mineral Belt during 1988-91. This paper summarizes the occurrence and probable sources of selected radionuclides in streamflow and near-channel alluvial ground water of the Puerco River, Arizona and New Mexico.

Gray, J.R., and Webb, R.H., 1991, Radionuclides in the Puerco and lower Little Colorado River basins, New Mexico and Arizona, before 1987, *in* Gundersen, L.S. and Wanty, R.B., eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 297-311, *http://pubs.er.usgs.gov/djvu/B/bull_1971.djvu*.

Abstract

Radionuclides in the Little Colorado River and tributaries have several sources in the Little Colorado River basin of Arizona and New Mexico. Naturally occurring radionuclides of the uranium-238 and thorium-232 decay series enter the hydrologic cycle through natural erosion. Uranium-mining operations in two areas of the basin- the Grants Mineral Belt of New Mexico and the Cameron Uranium Mining Belt of Arizona-also resulted in releases of radionuclides. A cumulative 22 years of mine dewatering between 1960 and 1986 from the Grants Mineral Belt upstream from Gallup, N. Mex., and a tailings-pond spill in 1979 resulted in releases of radionuclides to the Puerco River. Mine pits left open from wildcat operations in the 1950's and early 1960's in the Cameron Uranium Mining Belt now contain water that has elevated activities of radionuclides. The impact of mining on contamination of water resources of the region, however, is not well understood.

In Arizona, surface water in the Puerco River at Chambers and the Little Colorado River at Cameron typically contains total gross alpha plus gross beta activities of several thousand picocuries per liter, or about 2 orders of magnitude larger than Arizona's maximum allowable limit of 30 picocuries per liter for surface water. Gross alpha plus gross beta activities in streamflow at both stations are associated primarily with the suspended phase. Measured radionuclides include large activities of uranium, thorium, radium, and lead-210.

In December 1986, water from 5 of 14 wells that penetrate the alluvium adjacent to the Puerco River contained gross alpha minus uranium and radon activities equal to or greater than the Environmental Protection Agency's maximum contaminant level of 15 picocuries per liter for drinking water. Water samples from several wells, springs, and open pits near Cameron, Ariz., contain activities of gross alpha plus gross beta in excess of 30 picocuries per liter. If a "plume" of radionuclide-rich water exists in the alluvial aquifer underlying the Puerco or lower Little Colorado River, its areal extent cannot be determined from the data.

The presence and extent of radionuclide activities in the Little Colorado River basin are generally unknown. A lack of understanding of processes of radionuclide movement in and between surface water and ground water presently limits assessments of trends in radionuclide contamination.

Gray, J.R., and Webb, R.H., 1993, Radionuclides in the Puerco and lower Little Colorado River basins, New Mexico and Arizona, before 1987, *in* Gundersen, L.C.S., and Wanty, R.B., eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 297-311, *http://pubs.er.usgs.gov/djvu/B/bull_1971.djvu*.

Abstract
Radionuclides in the Little Colorado River and tributaries have several sources in the Little Colorado River basin of Arizona and New Mexico. Naturally occurring radionuclides of the uranium-238 and thorium-232 decay series enter the hydrologic cycle through natural erosion. Uranium-mining operations in two areas of the basin--the Grants Mineral Belt of New Mexico and the Cameron Uranium Mining Belt of Arizona--also resulted in releases of radionuclides. A cumulative 22 years of mine dewatering between 1960 and 1986 from the Grants Mineral Belt upstream from Gallup, N. Mex., and a tailings-pond spill in 1979 resulted in releases of radionuclides to the Puerco River. Mine pits left open from wildcat operations in the 1950's and early 1960's in the Cameron Uranium Mining Belt now contain water that has elevated activities of radionuclides. The impact of mining on contamination of water resources of the region, however, is not well understood. In Arizona, surface water in the Puerco River at Chambers and the Little Colorado River at Cameron typically contains total gross alpha plus gross beta activities of several thousand picocuries per liter, or about 2 orders of magnitude larger than Arizona's maximum allowable limit of 30 picocuries per liter for surface water. Gross alpha plus gross beta activities in streamflow at both stations are associated primarily with the suspended phase. Measured radionuclides include large activities of uranium, thorium, radium, and lead-210. In December 1986, water from 5 of 14 wells that penetrate the alluvium adjacent to the Puerco River contained gross alpha minus uranium and radon activities equal to or greater than the Environmental Protection Agency's maximum contaminant level of 15 picocuries per liter for drinking water. Water samples from several wells, springs, and open pits near Cameron, Ariz., contain activities of gross alpha plus gross beta in excess of 30 picocuries per liter. If a "plume" of radionuclide-rich water exists in the alluvial aquifer underlying the Puerco or lower Little Colorado River, its areal extent cannot be determined from the data. The presence and extent of radionuclide activities in the Little Colorado River basin are generally unknown. A lack of understanding of processes of radionuclide movement in and between surface water and ground water presently limits assessments of trends in radionuclide contamination.

Halpenny, L.C., and Whitcomb, H.A., 1949a, Water-supply investigation at Baca School, near Prewitt, McKinley County, New Mexico: U.S. Geological Survey Open-File Report 49-77, 16 p., 1 fig.
NOTE: This report is not available online through the USGS and was not reviewed by the author.

Halpenny, L.C., and Whitcomb, H.A., 1949b, Water-supply investigation at Thoreau, McKinley County, New Mexico: U.S. Geological Survey Open-File Report 49-79, 15 p., 1 plate.
NOTE: This report is not available online through the USGS and was not reviewed by the author.

Hansley, P.L, 1983, The nonopaque, detrital heavy mineralogy of the Morrison Formation near Crownpoint, San Juan Basin, New Mexico: U.S. Geological Survey Open-File Report 83-191, 34 p., *http://pubs.er.usgs.gov/djvu/OFR/1983/ofr_83_191.djvu.*
Abstract
Description and quantification of the nonopaque, detrital heavy mineralogy of the Upper Jurassic Morrison Formation in the southwestern part of the San Juan Basin have helped to identify stratigraphic trends, source-area lithologies, and zones of post-depositional alteration possibly related to uranium mineralization. A synthesis of stratigraphic variations in mineral species and diversity in Morrison sandstones reveals an increasing upward igneous component, characterized by euhedral zircon and subhedral apatite. Complementing this trend, the predominantly well-

rounded assemblage of the Recapture Member changes to a mixed assemblage of rounded and angular grains in the Westwater Canyon Member. Overall, the low diversity in mineral species indicates a sedimentary, low- to medium-grade-metamorphic, and acid igneous parentage for Morrison sediments; however, post-depositional processes have played a significant role in determining the present mineralogy. The roles that diagenesis and weathering have played in determining the present aspect of the assemblage, which is a mature garnet-zircon-apatite-tourmaline suite, cannot be overemphasized. For instance, the presence of authigenically etched to skeletal garnet and staurolite implies that entire grains have been destroyed. Comparison of cores with measured sections indicates that near-surface weathering has caused the destruction of some minerals, notably apatite, sensitive to acidic conditions. Therefore, in order to interpret the sedimentology, stratigraphic intervals in which post-depositional processes have affected the mineralogy were identified. These diagenetic zones may prove to be most useful in delineating the past movements and compositions of interstitial, possibly ore-forming, fluids.

NOTE: Identification of heavy minerals derived from the Morrison Formation in surface soils or stream sediments may permit discrimination of mine waste from native surface soils and sediments. Many heavy minerals will likely survive mining operations and exposure at the surface in mine waste piles.

Hearne, G.A., 1977, Evaluation of a potential well field near Church Rock as a water supply for Gallup, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 77-98, 21 p.

NOTE: Not available online at USGS. This report describes the hydrogeologic setting of the Westwater Canyon Member of the Morrison Formation in the Church Rock area and the operational dewatering of the Westwater at three mines in the immediate area. It notes the high concentration of radium-226 and trace elements in mine waters as documented by the study of Kaufman and others (1976). It then simulates the effects of groundwater withdrawal on the aquifer for a water supply for the City of Gallup.

Hilpert, L.S., 1969, Uranium resources of northwestern New Mexico: U. S. Geological Survey Professional Paper 603, 166 p., *http://pubs.er.usgs.gov/djvu/PP/pp_603.djvu*.

NOTE: This report describes the uranium resources of several uranium mining districts in rocks of all ages in northwestern New Mexico, including deposits in the Morrison Formation and the Todilto Limestone Member of the Wanakah Formation in the GMB. The report describes semiquantitative spectrographic, radiometric, and chemical (arsenic, selenium, uranium and zinc) analyses of mill pulp samples from 19 uranium deposits in the Morrison Formation and 31 deposits in the Todilto Member. These data could be useful in discriminating mine wastes from different mines and for distinguishing mine waste from background soils and sediment.

Hiss, W.L., 1977, Uranium mine waste water; a potential source of ground water in northwestern New Mexico.: U.S. Geological Survey Open-File Report 77-625, 10 p. and map, *http://pubs.er.usgs.gov/djvu/OFR/1977/ofr_77_625.djvu*.

Abstract

Substantial quantities of water are being pumped from the Morrison Formation of Late Jurassic age in uranium mines in the Grants mineral belt in northwestern New Mexico. The water often contains unacceptable amounts of dissolved uranium, radium, iron, and selenium and suspended solids, but with treatment it can be made suitable for municipal and industrial purposes. Water salvaged from current and projected mining operations constitutes the most readily available water in this otherwise water-deficient area.

NOTE: Table 1 contains data for dissolved and suspended chemical constituents in water samples from one mining company water well at Crownpoint, two mining company water wells at northeast Church Rock, four mine seepages at northeast Church Rock, one mine seepage at Church Rock, and one water-supply well for a gasification plant. The data include well location, major and minor cations and anions, gross alpha and beta (suspended and dissolved), dissolved radium-226, dissolved uranium, and total residue (filterable and non-filterable). Sampling conditions are described. Also published as Hiss (1977b).

Hiss, W.L., 1977, Uranium mine waste water; a potential source of ground water in northwestern New Mexico, *in* Fassett, J.E. and James, H.L., eds., Guidebook of San Juan Basin III, northwestern New Mexico: New Mexico Geological Society Guidebook 28, Supplement (on microfiche), p. 49-54.

Holen, H.K., and Hatchell, W.O., 1986, Geological characterization of New Mexico uranium deposits for extraction by in situ leach recovery: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 251, 93 p., *http://geoinfo.nmt.edu/publications/openfile/downloads/OFR200-299/251-275/251/ofr_251.pdf*.

NOTE: This report describes the sandstone-uranium-deposit types, the mineralogical and geochemical content of the ores, past pilot in-situ leach (ISL) projects in New Mexico, proposed ISL projects, stope-leach projects, and mine-water recovery operations. The authors noted the distribution of primary (unfavorable for ISL) and redistributed (favorable for ISL) ores in the principal mining districts.

Hydro Geo Chem, 1982, Use of sulfur isotopes to trace uranium mill pond seepage: Consulting report submitted to Pueblo of Laguna, Laguna, New Mexico, 33 p.

NOTE: This paper is cited in Longmire and others, 1984. Although it was not examined by this author, it is recommended that it should be examined to understand the methods used by Hydro Geo Chem, the sulfur isotope data provided, and contrasts between sulfur isotopes in the mill-pond seepage and other waters.

Jacobi, G.Z., and Smolka, L.R., 1984, Reconnaissance survey of Bluewater Creek, Cibola County, June 20-21, 1983: Environmental Improvement Division, Santa Fe, New Mexico, EID/WPC-83-10, 9 p.

Jacobs Engineering Group, Inc., 1995, Supplement to the site observational work plan for the UMTRA project site at Ambrosia Lake, New Mexico: U.S. Department of Energy Report DOE/AL/62350-159S, 65 p., *http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=1CD66911485279A10795CB4455C05452?purl=/171310-OTt8wL/webviewable/*.

NOTE: This document describes hydrographs, groundwater velocity, and water-quality data for alluvium, weathered Mancos Shale, and the Tres Hermanos-C member of the Mancos Shale in the immediate vicinity of the Ambrosia Lake mill site. Stiff and Piper diagrams describe the changes in groundwater geochemistry in the alluvium/weathered Mancos Shale unit, the Tres Hermanos-C Sandstone unit, the Tres Hermanos-B Sandstone unit, and the Dakota Sandstone. Water samples were periodically collected from a U.S. Department of Energy monitor well network from 1980 through 1994.

The report notes that:

> The majority of the contaminated ground water contained in the alluvium/weathered Mancos Shale unit and Tres Hermanos-C Sandstone units in the area of the milling site was derived from water

pumped from the Ann Lee Mine No. 1, Phillips mill-process waste water, and some tailings seepage. The discharge of water from the Quivira Mill to the outcrop of the Tres Hermanos-A Sandstone, Tres Hermanos-B Sandstone, and the Dakota Formation probably caused contamination of these units (Bostick, 1985). Because of the large ground water depression created by mine pumping, ground water from all overlying units will tend to migrate downward through mine shafts and vent holes into the Westwater Canyon Member of the Morrison Formation.

Although this report does not give radiochemical or trace element data for the sampled wells, the major element characterization of the waters upgradient and downgradient from the tailings disposal cell may provide a basis for comparison to other areas of similar geology where the presence of contaminated groundwater is less certain.

Jensen, M.L., 1963, Sulfur isotopes and biogenic origin of uraniferous deposits of the Grants and Laguna districts, *in* Kelley, V.C., compiler, Geology and technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources, Memoir 15, p. 182-190.

NOTE: This report provides sulfur isotope data for 67 samples from 2 mines in the Ambrosia Lake area, 2 mines in the Grants district, 4 mines in the Laguna district, and 7 mines in the Ambrosia Lake area. With the exception of the Woodrow mine in the Laguna district—a breccia-pipe-hosted deposit—most ore samples show negative $\delta^{34}S$ per mil. Pyrite was the dominant mineral sampled.

John, E.C., and West, S.W., 1963, Ground water in the Grants District, *in* Kelley, V.C., compiler, 1963, Geology and technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources Memoir 15, p. 219-221.

NOTE: This brief report describes groundwater availability, mine usage, and general water quality (in ppm total dissolved solids) for aquifers in the GMB including the San Andres Limestone, Chinle Formation, San Rafael Group, Morrison Formation, Dakota Sandstone, and the alluvium and basalt.

Johnson, R.H., Otton, J.K, and Horton, R.J., 2009, Results and interpretations of U.S. Geological Survey data collected in and around the Tuba City open dump, Arizona: U.S. Geological Survey Open-File Report 2009-1154, 125 p., *http://pubs.usgs.gov/of/2009/1154/*.

Kaufmann, R.F., Eadie, G.G., and Russell, C.R., 1975, Summary of ground-water quality impacts of uranium mining and milling in the Grants Mineral Belt, New Mexico: Las Vegas, Nevada, U.S. Environmental Protection Agency, Office of Radiation Programs- Las Vegas Facility, Technical Note ORP/LV-75-4, 71 p. The report is available online through the U.S. Environmental Protection Agency's National Service Center for Environmental Publications, *http://nepis.epa.gov* . The entire URL is not given here as it is several lines long.

Abstract

Ground-water contamination from uranium mining and milling results from the infiltration of radium-bearing mine, mill, and ion-exchange plant effluents. Radium, selenium, and nitrate were of most value as indicators of contamination. In recent years, mining has increased radium in mine effluents from several picocuries/liter (pCi/1) or less, to 100-150 pCi/1. The shallow aquifer in use in the vicinity of one mill was grossly contaminated with selenium, attributable to the mill tailings. Seepage from two other mill tailings ponds averaged 67,400,000 liters/year and, to date, has contributed an estimated 1.1 curies of radium to ground water. At one of these, an injection well was used to dispose of over 3,400,000,000 liters of waste from 1960-1973. The wastes have not been properly monitored and have apparently migrated to more shallow, potable aquifers. No adverse impacts on municipal water quality in Paguate, Bluewater, Grants, Milan, and Gallup were observed.

NOTE: This important report provides data describing the impacts of uranium mining on groundwater in the GMB. The study was conducted by the USEPA at the request of the New Mexico Environmental Improvement Agency in 1974. Water sampling and analysis occurred in 1975. The major summary and conclusions (p. 3–6) are quoted here.

1. Ground water is the principal source of water in the study area. Extensive development from the San Andreas limestone aquifer occurs in the Grants-Bluewater area where the water is used for agriculture, public water supply and uranium mill feed water. Development of shallow, unconfined aquifers developed in the alluvium also occurs in this area. Principal ground-water development in the mining areas at Ambrosia Lake, Jackpile-Paguate, and Churchrock is from the Morrison Formation and, to a lesser extent, from the Dakota Sandstone or the Tres Hermanos Member of the Mancos Shale. The Gallup water supply is derived primarily from deep wells competed in the Gallup Sandstone.
2. Contamination of ground water, largely used for livestock watering, results from the infiltration of 1) effluents from mill tailings pond, 2) mine drainage water that is introduced to settling lagoons and natural water courses, and 3) discharge (tailings) from ion exchange plants. It is unlikely that seepage from these sources returns to the deep bedrock aquifers. Deterioration of water quality in the latter occurs in the mining areas as a result of penetration or disruption of the ore body coincident with underground mining. The most dramatic changes are greatly increased dissolved radium and uranium. Induced movement of naturally saline ground water into potable aquifers is also likely but undocumented.
3. With the exception of the area south and southwest from the United Nuclear-Homestake Partners mill, widespread ground-water contamination from mining and milling was not observed in the study area. In the vicinity of the Anaconda mill, radium and nitrate concentrations in the alluvial aquifer decline with distance from the tailings ponds, but nowhere does either parameter exceed the drinking water limit. Contamination of ground water with radium was not observed despite concentrations of as much as178 pCi/l in mine and mill effluents. Radium removal is pronounced, primarily due to sorptive capacity of soils in the area.
4. Mining practices, per se, have an adverse effect on natural water quality. Initial penetration and disruption of the ore body in the Churchrock mining area increased the concentration of dissolved radium in ground water pumped from the mines from 0.05 to 0.62 pCi/1 to over 8 pCi/l. Subsequent development work over a two-year period increased the concentration to over 20 pCi/l, or 23 times the natural concentration. If the pattern in Ambrosia Lake is repeated, ultimate concentrations of 50 to 150 pCi/1 are expected.
5. Ground water in parts of the shallow aquifer downgradient from the United Nuclear-Homestake Partners mill is contaminated with selenium, and alternative supplies should be developed. The best alternative is deeper wells completed in the Chinle Formation or, preferably, the underlying lying San Andres Limestone.
6. Seepage from the Anaconda tailings pond at Bluewater is estimated to average 183 million liters/year (48.3 million gallons) for 1973 and 1974. The average volume injected for the same time period was 348 million liters/year (91.9 million gallons). Therefore, approximately one-third of the waste enters the shallow aquifer, which is a source of potable and irrigation water in Bluewater Valley. From 1960 through 1974, seepage is estimated to have introduced 0.41 curies

of radium to the shallow potable aquifer. Adequate monitoring of the movement of these wastes is not underway.

7. There are indications that wastes injected into the Yeso Formation by the Anaconda Company are not confined to that unit as originally intended in 1960. Three nearby monitoring wells, completed in the shallower San Andres Limestone and/or the Glorieta Sandstone show a trend of increasing chloride and uranium with time. Positive correlations of water quality fluctuations with the volumes of waste injected are a further indication of upward movement. The absence of monitoring wells in the injection zone is a major deficiency in the data collection program.
8. The maximum concentration of radium observed in shallow ground water adjacent to the Kerr-McGee mill at Ambrosia Lake was 6.6 pCi/l. Calculated seepage from the tailings ponds occurs at the rate of 491 million liters/year (130 million gallons/year), and has contributed an estimated 0.7 curies of radium to the ground water to date. This is 29 percent of the influent to the "evaporation ponds" and attests to their poor performance in this regard. Radium and gross alpha in the seepage are 56 pCi/l and 112,000-144,000 pCi/l, respectively. Wells completed in bedrock and in alluvium along water courses containing mine drainage and seepage from tailings ponds contain elevated levels of TDS, ammonia, and nitrate. One well, now contaminated with 3.7 pCi /l of radium, contained 1.0 pCi /l in 1962. Sorption or bio-uptake of radium is pronounced, hence concentrations now in ground water are not representative of ultimate concentrations.
9. Contamination of the Gallup municipal water supply by surface flows consisting mostly of mine drainage is extremely unlikely because of geologic conditions in the well field. Another well field north of the City will, in no way, be affected by the drainage.
10. Water quality data from 11 wells over a 200-square kilometer area in the Puerco River and South Fork Puerco River drainage reveal essentially no noticeable increase in concentrations of radionuclides as well as gross and trace constituents in ground water as a result of mine drainage. Natural variations in the uranium content of sediments probably account for differences in radium content in shallow wells. Dissolved radium in shallow ground water underlying stream courses affected by waste water is essentially unchanged from areas unaffected by mine drainage. None of the samples contained more than recommended maximum concentrations for radium-226, natural uranium, thorium-230, thorium-232, or polonium-210 in drinking water. However, the paucity of sampling points and the absence of historical data make the foregoing conclusion a conditional one, particularly in the reaches of the Puerco River within approximately 10 kilometers of the mines.
11. Four wells sampled in the vicinity of the Jackpile mine near Paguate contained 0.31 to 3.7 pCi/l radium-226. With the exception of the latter value from the new shop well in the mine area, remaining supplies contain 1.7 pCi/l or less radium. The Paguate municipal supply contains 0.18 pCi/l. None of the wells were above MPC for the other common isotopes of uranium, thorium, and polonium. Ground water from the Jackpile Sandstone may contain elevated levels of radium as a result of mining activities. Mine drainage water ponded within the pit contained 190 pCi/l radium and 170 pCi/l of uranium in 1970. The impacts of mining on ground-water quality down gradient from the mining area are unknown due to the lack of properly located monitoring wells. No adverse impacts from mining on the present water supply source for Paguate are expected.
12. Of the 71 ground-water samples collected for the study, only two potable water supplies have radium-226 in excess of the 3 pCi/l PHS drinking water standard. These are located downgradient from the Kerr-McGee mill and in the Jackpile mining area.

13. The highest isotopic uranium and thorium, and polonium-210 contents for any potable water supply in the study area are less than 1.72 percent of the total radionuclide population guide-MPC as established in NMEIA regulations.
14. The lowest reported concentrations (background levels) are summarized as follows:

Radionuclide	Range (pCi/l)	Average (pCi/l)
Radium-226	0.06-0.31	0.16
Polonium-210	0.27-0.57	0.36
Thorium-230	0.013-0.051	0.028
Thorium-232	0.010-0.024	0.015
U-natural	14-68	35

15. The uranium isotopes (uranium -234, -235, and -238) are the main contributions to the gross alpha results; however, in several determinations, the gross alpha result underestimated the activity present from natural uranium.
16. No correlation was found relating a gross alpha content greater than 5 pCi/l to a radium-226 content in excess of the 3 pCi/l PHS drinking water standard.
17. It is doubtful that the gross alpha determination can even be used as an indicator of the presence of other alpha emitters (e.g., U-natural and polonium-210); and since the gross alpha results have such large error terms, no meaningful determinations of percentage of other radionuclides to gross alpha result can be implied.
18. Gross alpha determinations also fail to indicate the possible presence of lead-210 (a beta emitter) which, because of the low MPC of 33 pCi/l, may be a significant contributor to the radiological health hazard evaluation of any potable water supply.
19. Radium-226 in ground water is a good radiochemical indicator of waste water from mines and mills. It also provides the best means of health evaluations due to the low maximum permissible concentration.
20. Polonium-210, thorium-230 and thorium-232 concentrations in ground water fluctuate about background levels and are poor indicators of ground-water contamination from uranium mining and milling activities.
21. For routine radiological monitoring of potable water supplies, isotopic uranium and thorium, and polonium analyses do not appear to be necessary due to their high maximum permissible concentrations. (Chemical toxicity of uranium may be a significant limiting factor, however.)

The report also comments on the adequacy of company water-quality monitoring networks, self-monitoring data, analytical procedures, and reporting requirements, and makes recommendations for subsequent monitoring and other follow-up studies.

Tabulated data in the study include the following:

Table 2. Sampling point locations and gross chemical data;
Table 3. Selenium and vanadium concentrations in selected groundwater samples;
Table 4. Radiological data for selected groundwater samples;
Table 5. Typical background radionuclide concentrations by geographic area and aquifer;
Table 6. Summary of reported concentrations of radium, gross beta, and natural uranium in groundwater;
Table 7. Locations with radium-226 in excess of standard; and
Table 8. Radium concentrations for municipal water supplies.

The entire report, not reviewed by this author, is published as U.S. Environmental Protection Agency (1975). The results of this study were subsequently published in Kaufmann and others (1976) and Eadie and Kaufman (1977) with additional analysis of the data.

Kaufmann, R.F., Eadie, G.G., and Russell, C.R., 1976, Effects of uranium mining and milling on ground water in the Grants mineral belt, New Mexico: Ground Water, v. 14, no. 5, p. 296-308, 9 figs., *https://info.ngwa.org/GWOL/pdf/762502233.PDF*.

Kelley, N.E., 1978, Vegetational stabilization of uranium spoil areas, Grants, New Mexico: Albuquerque, New Mexico, University of New Mexico, Ph.D. dissertation, 89 p.

Kelley, V.C., compiler, 1963, Geology and technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources Memoir 15, 277 p.

NOTE: This multi-chaptered report describes the tectonic setting, stratigraphy, and structure of the GMB. One chapter describes in detail the mineralogy of the oxidized and unoxidized portions of ore bodies in the district. Other chapters describe the geology of selected mines, including, in many cases, discussion of the geochemistry of a given mine. The mines for which geochemical data or discussions of associated trace elements are given include the Black Jack #1, sections 15 and 22, Ann Lee, and Cliffside mines in the Ambrosia Lake area, the Todilto Limestone mines, the Jackpile-Paguate mines in the Laguna area, and the Woodrow breccia-pipe deposit. Sulfur isotope data are given for 69 samples from various deposits (p. 186–189). Two papers describe groundwater conditions in the Jackpile and Paguate mine areas (Dinwiddie, 1963, in this referenced volume; however, see Dinwiddie and Motts, 1964, for a more complete discussion) and in the Grants area (John and West, 1963, cited separately with a brief note herein).

Kelly, T.E., Link, R.L., and Schipper, M.R., 1980, Effects of uranium mining on ground water in Ambrosia Lake area, New Mexico, *in* Rautman, C.A., 1980, complier, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 313-319.

NOTE: This report focuses on groundwater conditions in the vicinity of the Ambrosia Lake, Ann Lee, and Johnnie M mines. It briefly describes the stratigraphy of the Ambrosia Lake area, mine discharge volumes, the changes in the potentiometric surface from pre-mining levels to 1979, and describes water quality changes during mining. Piper and Stiff diagrams are used to illustrate changes. Increases in sulfate concentrations in the Westwater Canyon Member of the Morrison Formation aquifer are attributed to leakage from the Dakota Sandstone aquifer.

Kernodle, J.M., 1996, Hydrogeology and steady-state simulation of ground-water flow in the San Juan Basin, New Mexico, Colorado, Arizona, and Utah: U.S. Geological Survey Water-Resources Investigations Report 95-4187, 117 p.

Abstract

As part of a multidisciplinary regional aquifer-system analysis, a three-dimensional steady-state ground-water-flow model was constructed for the San Juan Basin in parts of New Mexico, Colorado, Arizona, and Utah. The model simulated ground- water flow in 12 hydrostratigraphic units representing all of the major sources of ground water from aquifers of Jurassic and younger age. Ten map reports in the U.S. Geological Survey Hydrologic Investigations Atlas 720 series were prepared in conjunction with this investigation. The units that were described in the atlases were the San Jose, Nacimiento, and Animas Formations; Ojo Alamo Sandstone; Kirtland Shale and Fruitland Formation; Pictured Cliffs Sandstone; Cliff House Sandstone; Menefee Formation; Point

Lookout Sandstone; Gallup Sandstone; Dakota Sandstone; and Morrison Formation. Additional descriptions of the alluvial and landslide deposits, Chuska and Crevasse Canyon Sandstones, Lewis and Mancos Shales, Wanakah Formation, and Entrada Sandstone are included in this report. Much of the information in the HA-720 series was generated from digital computer data bases that were directly usable by the computer for compilation of input data for the model. In essence, the major components of the ground-water- flow model were described and documented in the series of hydrologic atlases. The primary finding resulting from the ground-water-flow simulation was that boundary conditions and internal geometry of the aquifers are the major controls of steady-state ground-water flow and hydraulic heads in the San Juan Basin. Another significant finding was that the computed steady-state ground- water flux is a very minor component (about 1 percent) of the total water budget of the basin.

NOTE: See Dam and others (1990) for more information about the HA-720 series.

Kirk, A.R., Huffman, A.C., Zech, R.S., Leventhal, J.S., Schmitt, L.J., Hansley, Paula, Reynolds, R.L., and Whitney, C.G., 1982, San Juan Basin drilling project, McKinley County, New Mexico (abstract), *in* Geological Survey research 1982: U.S. Geological Survey Professional Paper 1375, p. 39.

Complete text:

The principal objective of the Mariano Lake-Lake Valley drilling project under the direction of A. R. Kirk, A. C. Huffman, and R. S. Zech, was to provide core samples and geophysical logs for petrologic, sedimentologic, geophysical, and geochemical studies of the Upper Jurassic Morrison Formation. Other objectives included the following: stratigraphic and coal studies of Upper Cretaceous rocks; hydrologic and water monitoring of well no. 2; control for a proposed seismic study of the same geographic area; and development of water wells by the Navajo Tribal Water and Sanitation Department. The general drilling plan called for most holes to be rotary drilled into the Upper Cretaceous Dakota Sandstone and then cored into or through the Recapture Shale Member of the Morrison Formation.

The following suite of geophysical logs was included in the general drilling project: natural gamma, self potential, neutron-neutron porosity, resistance, resistivity, temperature, deviation, gamma-gamma density, caliper, magnetic susceptibility, gamma ray spectrometer (KUT), induced polarization, conductivity, and high resolution 4-arm digital dipmeter.

A total of 28,529 ft were drilled with 4,208 ft of core recovered. Four holes (3, 4, 7, 7 A) encountered uranium mineralization; all but hole no. 1 penetrated coal beds in Upper Cretaceous rocks; two holes (9 and 10) produced artesian flows of water admixed with oil from the Upper Cretaceous Point Lookout Sandstone.

The core was described in the field, taped, boxed, and shipped to the USGS Core Library in Denver where it was frozen, split, and reboxed. A split of the core has been archived for reference and future study. Cores 1, 3, 6, and 7 were sampled by J. S. Leventhal for geochemistry, L. J. Schmitt for petrography, Paula Hansley for heavy minerals, R. L. Reynolds for paleomagnetism, and C. G. Whitney for clay mineralogy.

NOTE: This text provides a summary of drilling done during an investigation of the Morrison Formation by the U.S. Geological Survey. Data from these drill holes may be useful in understanding the hydrology of the basin.

Kunkler, J.L., 1979, A reconnaissance study of selected environmental impacts on water resources due to the exploration, mining, and milling of uraniferous ores in the Grants Mineral Belt, Northwest New

Mexico: Albuquerque, New Mexico, San Juan Basin Regional Uranium Study, Working Paper #22, 146 p. with an appendix.

NOTE: This study provides background information about the processes of uranium exploration, mining, and milling, and an overview of the environmental issues associated with these processes. Examples are provided from the Grants region, including the environmental characteristics of uranium, thorium, radium, radon, selenium, molybdenum, and vanadium, and a discussion of specific environmental impacts associated with development of the GMB. The various sections cite examples from the GMB with or without data. For example, the discussion of Ra-226 compares background radium data for unpolluted aquifers in the San Juan Basin (n=9) to 70 analyses of radium for polluted aquifers in the study by Kaufman and others (1976). The radon section cites radon emissions from uranium mill tailings, an estimate of the radon emissions from mines in the GMB, and data on radon flux from soils in the GMB. The report describes the impacts of the July 1979 Churchrock (Church Rock) tailings pond accidental release providing both visual observations and data (both pre-accident and post-accident). In the appendix, data are given for human and livestock uptake from the accident.

The report gives data on the following:

1. Chemical and radiochemical (uranium, radium, and radon) analyses for two municipal water wells near Santa Fe, N. Mexico,
2. Radon-222 in groundwater in N. M.,
3. Chemical and radiochemical analyses for waters at selected sites in the southern San Juan Basin,
4. Chemical and radiochemical analyses showing the effects of neutralizing and diluting millpond acid,
5. Chemical and radiochemical analyses for irrigation and drainage water from a horticulture experiment, and
6. Chemical and radiochemical analyses of treated and untreated produce from a horticulture experiment.

The copy of this report evaluated by the author was obtained through the Colorado School of Mines Arthur Lake Library, Golden, Colo. It is also available from the New Mexico State Library, Santa Fe, N. M.

Landa, Edward, 1980, Isolation of uranium mill tailings and their component radionuclides from the biosphere; some earth science perspectives: U.S. Geological Survey Circular 814, 32 p., *http://pubs.er.usgs.gov/usgspubs/cir/cir814*.

Abstract

Uranium mining and milling is an expanding activity in the Western United States. Although the milling process yields a uranium concentrate, the large volume of tailings remaining contains about 85 percent of the radioactivity originally associated with the ore. By virtue of the physical and chemical processing of the ore and the redistribution of the contained radionuclides at the Earth's surface, these tailings constitute a technologically enhanced source of natural radiation exposure. Sources of potential human radiation exposure from uranium mill tailings include the emanation of radon gas, the transport of particles by wind and water, and the transport of soluble radionuclides, seeping from disposal areas, by ground water. Due to the 77,000 year half-life of thorium-230, the parent of radium-226, the environmental effects associated with radionuclides contained in these tailings must be conceived of within the framework of geologic processes operating over geologic time. The magnitude of erosion of cover materials and tailings and the extent of geochemical mobilization of the contained radionuclides to the atmosphere and hydrosphere should be

considered in the evaluation of the potential, long-term consequences of all proposed uranium mill tailings management plans.

NOTE: Includes brief discussion of groundwater studies near mill tailings sites in the GMB.

Landa, E.R., Dinwiddie, G.A., and Trask, N.J., 1986, Uranium mill tailings; radium geochemistry, *in* U.S. Geological Survey research in radioactive waste disposal, fiscal years 1983, 1984, and 1985: U.S. Geological Survey Water-Resources Investigations 87-4009, p. 107-109, *http://pubs.er.usgs.gov/djvu/WRI/wrir_87_4009.djvu*.

NOTE: This brief report describes several geochemical and mineralogic aspects of radium occurrence in mill tailings and the processes that may control transport of radium in natural aqueous systems. It describes leaching of molybdenum and arsenic from tailings samples and the release of radium from sulfate minerals into aqueous solutions in sulfate-reducing bacteria incubations of mill tailings. References to other studies are given.

Landa, E.R., Stevens, P.R., and Nicholson, T.J., 1996, Geochemical characterization of uranium mill tailings and radionuclide mobilization processes, *in* Stevens, P.R., and Nicholson, T.J., eds., Joint U.S. Geological Survey, U.S. Nuclear Regulatory Commission workshop on research related to low-level radioactive waste disposal: U.S. Geological Survey Water-Resources Investigations 95-4015, p. 18-24, *http://pubs.er.usgs.gov/djvu/WRI/wrir_95_4015.djvu*.

NOTE: This report describes mechanisms for radium release from mill tailings studied by the author and others during the previous several years.

Landa, E.R., Trask, N.J., and Stevens, P.R., 1991, Uranium mill tailings; radium geochemistry, *in* U.S. Geological Survey research in radioactive waste disposal, fiscal years 1986-1990: U.S. Geological Survey Water Resources Investigations 91-4084, p. 88-90, *http://pubs.er.usgs.gov/djvu/WRI/wrir_91_4084.djvu*.

NOTE: This brief summary report is an expanded description of results from studies reported in 1986. References to related studies by the senior author (Landa) from 1986 to 1990 are given.

Lapham, S.C., Millard, J.B., and Samet, J.M., 1989, Health implications of radionuclide levels in cattle raised near U mining and milling facilities in Ambrosia Lake, New Mexico: Health Physics, v. 56, no. 3, p. 327-340.

NOTE: Radionuclide tissue levels from cows raised near Ambrosia Lake, a site of 30 years of uranium mining, were compared to data for identical material from cows from the Crownpoint area where no surface mining had occurred. Water, grasses, and soils from grazing areas were also sampled. Radionuclide activity concentrations (^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Pb, and ^{210}Po) for almost all types of materials (soils, water, plants, and cattle) were higher in the Ambrosia Lake area than near Crownpoint; however, health risks of eating cattle were concluded to be minimal.

Lee, M.J., 1976, Geochemistry of the sedimentary uranium deposits of the Grants Mineral Belt, southern San Juan Basin, New Mexico: Albuquerque, University of New Mexico Ph.D. dissertation, 241 p.

Leventhal, J.S., Gent, C.A., and Lichte, F.E., 1990, Geochemistry of Mariano Lake-Lake Valley cores, McKinley County, New Mexico: U.S. Geological Survey Bulletin 1808–I, p. I1-I53.

Abstract

The primary goal of the U.S. Geological Survey-Bureau of Indian Affairs drilling project in the Upper Jurassic Morrison Formation in McKinley County, New Mexico, was to better understand the relationship between host-rock stratigraphy and uranium mineralization. As part of this project, geochemical studies of approximately 280 samples from 8 cores and 1 outcrop were undertaken; samples from 4 of the cores show uranium enrichment. Geochemical relationships between samples of weathered outcrop, oxidized core, reduced (unmineralized) core, and ore-bearing core were contrasted by comparison of element abundances.

The uranium ores are mainly secondary or redistributed; the highest ore grade is 0.24 percent U. One in two of the ore-bearing cores is a dark-gray, roll-type ore, whereas ore in the other two ore-bearing cores occurs as black clots in interstitial positions between quartz and pink feldspar grains. All of the samples, including ore-bearing samples, contain very low (< 0.03 percent) amounts of organic carbon. The ore-bearing samples have lower vanadium contents than most ores of the Grants uranium region. Although there are no obvious trace element anomalies above or below the mineralized zones, the ore zones are erratically enriched in vanadium and selenium. Molybdenum and arsenic are not enriched in or near the ores. One core has a clay layer at the base of the ore zone that probably localized the ore. The geochemistry of this layer indicates that the uranium-bearing solution originated above the clay layer.

Special comparative studies of sandstone and clay chemistry were made using results from X-ray diffraction, optical petrography, and chemical analysis.

Levings, G.W., Kernodle, J.M., and Thorn, C.R., 1996, Summary of the San Juan structural basin regional aquifer-system analysis, New Mexico, Colorado, Arizona, and Utah: U.S. Geological Survey Water-Resources Investigations Report 95-4188, 55 p.

Longmire, P.A., 1983, Geochemistry, diagenesis and contaminant transport of uranium tailings, Grants Mineral Belt, New Mexico: M.S. thesis, Department of Geology, University of New Mexico, Albuquerque, New Mexico, 182 p.

Longmire, P., 1985, Geochemistry and alteration processes of uranium tailings in groundwater, Grants Mineral Belt, New Mexico, *in* B. Hitchon, Brian, and Wallick, E.I., eds., Practical Applications of Groundwater Geochemistry, Proceedings 1st Canadian/American Conference on Hydrogeology: National Water Well Association, Dublin, Ohio, p. 190–199.

Longmire, P.A., and Brookins, D.G., 1982, Geochemical studies of discharge water from a uranium acid-leach process, *in* Callender, J.F., Grambling, J.A., and Wells, S. G., eds., Albuquerque Country II, New Mexico Geological Society, 33rd Annual Field Conference, Albuquerque, New Mexico, Nov. 4-6, 1982: New Mexico Geological Society, v. 33, p. 367-370.

Longmire, P.A., Thomson, B.M., and Brookins, D.G., 1984, Uranium industry impacts on groundwater in New Mexico, *in* Stone, W.J., compiler, 1984, Selected papers on water quality and pollution in New Mexico: proceedings of a symposium on water quality and pollution in New Mexico, April 12, 1984, Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 7, p. 167-183.

NOTE: This paper describes the thermodynamic controls on the geochemistry of the principal contaminants in mill tailings and raffinates (aqueous solutions formed during milling): uranium, iron, selenium, and molybdenum, and some of the controlling mineral reactions. It notes differences in the aqueous geochemistry of raffinates and the seepage from mill tailings between those derived from acid-leach mill processes and those derived from alkaline-leach mill processes. Contamination of groundwater from acid-tailings seepage is characterized by SO_4, Cl, NO_3, Fe, Al, Mn, V, and other metals. Contamination of groundwater from alkaline-tailings seepage is characterized by As, Na, HCO_3,

NO_3, Se, Mo, SO_4, and U. Arsenic, molybdenum, selenium, and uranium tend to be higher in the alkaline raffinate sampled, whereas vanadium and sulfate are higher in the acid-leach raffinate. The report gives the range of analyses for 14 unfiltered samples from raffinate tailings ponds at 4 acid mills and 5 unfiltered samples from 1 alkaline mill collected 1978 to 1981 (table 1). It notes differences between the geochemistry of the raffinate pond liquid and a monitoring well down gradient (table 2) and suggests reasons why the geochemistry may be different. Average values for physical measurements (temperature, pH, and so forth), uranium, major elements, and trace elements in samples of mine-stope water, slurry liquor, sandfill decant, and surface discharge from one mine are given (table 3). The authors note a study by Hydro Geo Chem (1982) in which the amount of sulfate derived from mine dewatering discharge into the Rio del Puerto, inflow from the Tres Hermanos Sandstone, and tailings seepage was estimated using sulfur isotopes. They (1) describe in detail the characteristics of contamination near an acid-leach mill 17 mi north of Grants and an alkaline-leach mill 5 mi north of Milan; (2) describe aquifer contamination associated with the underground mining activities, noting that As, Mo, S, Se, Th, V, and U are typically observed in mine water; and (3) note that backfilling of mine openings with tailings may impact water quality during mining operations while dewatering occurs, but after the mine floods it is expected that reducing conditions would be re-established thereby limiting contamination.

Ludwig, K.R., Rubin, Bruce, Fishman, N.S., and Reynolds, R.L., 1982, U-Pb ages of uranium ores in the Church Rock uranium district, New Mexico: Economic Geology, v. 77, no. 8, p. 1942-1945.

Ludwig, K.R., Simmons, K.R., and Webster, J.D., 1984, U-Pb isotope systematics and apparent ages of uranium ores, Ambrosia Lake and Smith Lake districts, Grants Mineral Belt, New Mexico: Economic Geology, v. 79, no. 2, p. 322-337.

Lyford, F.P., 1979, Ground water in the San Juan Basin, New Mexico and Colorado: U.S. Geological Survey Water Resources Investigations Report 79-73, 22 p.

Abstract

Principal aquifers in the San Juan Basin of New Mexico and Colorado are the Entrada Sandstone, Westwater Canyon Member of the Morrison Formation, Gallup Sandstone of the Mesaverde Group, several sandstones in the Mesaverde Group above the Gallup (Dalton Sandstone Member of the Crevasse Canyon Formation, Point Lookout Sandstone, Menefee Formation, Cliff House Sandstone), and sandstones of Tertiary age. Most ground water flows from topographically high outcrop areas toward the San Juan River and Rio Grande valley. Much of the water may move through confining layers to other aquifers or to the land surface rather than discharging directly to the streams. Transmissivities of the sandstones range from 50 to 300 square feet per day. Lowest dissolved-solids concentrations occur in or near outcrops of the sandstones and increase in the direction of groundwater flow. Concentrations range from less than 500 milligrams per liter to more than 30,000 milligrams per liter.

NOTE: This report is not available online.

Lyford, F.P., and Frenzel, P.F., 1979, Projected ground-water pumpage from uranium mines in northwestern New Mexico (abs.), *in* Geological Survey Research 1979: U.S. Geological Survey Professional Paper 1150, p. 125.

Abstract

F.P. Lyford and P. F. Frenzel used a three-dimensional digital model to predict dewatering rates, effects on water levels in the Jurassic Morrison Formation, and effects on surface flows to the year 2000 for three projected levels of development of uranium mines in northwestern New Mexico.

Mines that are currently operating or that are scheduled for future operation (a maximum of 33 in 1985) will produce 7.1x10 8 m^3 of water from the Morrison Formation by the year 2000. The maximum dewatering rate will be about 1.0 m^3 /s in 1985, with drawdowns of 600 m or more expected near the deepest mines.

A maximum of 72 mines in 1985 would produce about 1.6 x 10^9 m^3 of water by 2000; the maximum dewatering rate would be about 2.6 m^3/s with drawdowns of 1,200 m or more near the deepest mines. A maximum of 105 mines in 1985 would produce nearly 2.5 X 10^9 m^3 of water by 2000; the maximum dewatering rate would be about 3.3 m^3/s with drawdowns of 1,200 m or more near the deepest mines.

By the year 2000, dewatering of uranium mines and other ground-water developments would reduce flow in the San Juan River by less than .001 m^3 /s, and flow toward the Rio Grande Valley might be reduced by .015 m^3 /s.

Lyford, F.P., Frenzel, P.F., and Stone, W.R., 1980, Preliminary estimates of effects of uranium-mine dewatering on water levels, San Juan Basin, New Mexico, *in* Rautman, C.A. , compiler, Geology and Technology of the Grants Uranium Region 1979: New Mexico Bureau of Mines and Mineral Resources, Memoir 38, p. 320-333.

Lynn, R.D., and Arlin, Z.E., 1962, Deep well construction for the disposal of uranium mill tailing water by the Anaconda Company at Grants, New Mexico: American Institute Mining, Metallurgical and Petroleum Engineers, Society of Mining Engineering Transactions, v. 223, no. 3, p. 230-237.

Maassen, L.W., Bolivar, S.L., Ashley, W.H., Duchane, D.V., Minor, M.M., Gallimore, D.L., Hansel, J.M., Bunker, M.E., and Thomas, G.J., 1979, Uranium hydrogeochemical and stream sediment reconnaissance of the Albuquerque NTMS quadrangle, New Mexico, including concentrations of forty-three additional elements: Los Alamos Scientific Laboratory informal report LA-7508-MS, Los Alamos, New Mexico, U.S. Department of Energy, Grand Junction, Colo., GJBX-145(79), 193 p.

NOTE: See later discussion of the related report by Purson and others (1981).

Maassen, L.W., Delfe, C.M., Trujillo, D., Minor, M.M., Gallimore, D.L., Martell, C.J., Martinez, R.G., and McInteer, C., 1980, Uranium hydrogeochemical and stream sediment reconnaissance for the Gallup NTMS quadrangle, New Mexico/Arizona, including concentrations of forty-two additional elements: Los Alamos Scientific Laboratory informal report LA-8002-MS, Los Alamos, New Mexico, U.S. Department of Energy, Grand Junction, Colorado, GJBX-186(80), 164 p.

NOTE: See later discussion of the related report by Purson and others (1981).

Marple, M.L., 1980, Radium-226 in vegetation and substrates at inactive uranium mill sites: Los Alamos Scientific Laboratory Report LA-8183-T (thesis), 64 p. *http://www.osti.gov/energycitations/servlets/purl/5593725-cj2HVm/* .

Abstract

Results of a study of the content of radium-226 in plants growing on inactive uranium mill tailings sites in the Four Corners Region of the southwestern United States and in plants grown under greenhouse conditions with minimal surficial contamination are reported. Field plant samples and associated substrates were analyzed from two carbonate tailings sites in the Grants Mineral Belt of New Mexico. Radium activities in air-cleaned samples ranged from 5 to 368 pCi/g (dry weight) depending on species and location: activities in plants growing on local soils averaged 1.0 pCi/g. The tailings and local soils contain 140 to 1400 pCi/g and 2.1 pCi/g, respectively. An evaluation of cleaning methods on selected samples showed that from 17 to 79% of the radium activity measured in air-cleaned samples was due to surficial contamination, which varied with species and location. A survey of 18 inactive uranium mill sites in the Four Corners Region was performed. Radium activity in plant tissues from nine species ranged from 2 to 210 pCi/g on bare tailings and from 0.3 to 30 pCi/g on covered tailings. The radium content in most of the soil overburdens on the covered tailings piles was 10 to 17 pCi/g. An experiment was performed to measure radium-226 uptake by two species grown on tailings covered with a shallow (5 cm) soil layer. A grass, *Sporobolus airoides* (alkali sacaton) and a shrub, *Atriplex canescens* (four-wing saltbush), were studied. The tailings were a mixture of sands and slimes from a carbonate pile. The tailings treatments were plants grown in a soil cover over tailings; the controls were plants grown only in soil. Three soil types, dune sand, clay loam, and loam, were used. The radium activity of the plant tissue from the tailings treatment compared to that of the appropriate control was 1 to 19 times greater for the grass and 4 to 27 times greater for the shrub.

McCammon, R.B., Finch, W.I., Kork, J.O., and Bridges, N.J., 1986, Estimation of uranium endowment in the Westwater Canyon Member, Morrison Formation, San Juan Basin, using a data-directed numerical method, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, Neil, eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: Tulsa, Oklahoma, American Association of Petroleum Geologists Studies in Geology 22, p. 331-355.

McLemore, V.T., 1983, Uranium and thorium occurrences in New Mexico—distribution, geology, production, and resources, with selected bibliography: New Mexico Bureau of Mines and Mineral Resources Open-File Report 183, 1541 p.

McLemore, V.T., and Chenoweth, W.L., 1989, Uranium resources in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Resource Map 18.

McLemore, V.T. and Chenoweth, W.L., 1991, Uranium mines and deposits in the Grants district, Cibola and McKinley Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 353, 35 p., *http://geoinfo.nmt.edu/publications/openfile/downloads/OFR300-399/351-375/353/ofr_353.pdf*.

NOTE: The authors describe the purpose of this report as follows:

The purpose of this report is to present a series of maps showing the approximate outlines of uranium deposits and areas of significant mineralization. Mines and prospects are also shown on the maps. The data presented here are intended to supplement McLemore and Chenoweth (1989) and to aid exploration and mining companies in locating and developing these deposits. The data may also be useful for administrators in local, state, and federal government agencies who require this information for environmental studies, land-use decisions, and other planning actions. The data will be updated periodically and ultimately published by NMBMMR in the future and any updates and/or corrections will be greatly appreciated.

NBMMR is the New Mexico Bureau of Mines and Mineral Resources. The tables and seven maps in the report cover the major uranium mining areas in the GMB, providing location, mine name, uranium deposit and mine outlines in plan view, production data for uranium and vanadium (1952-1991), host rock, and producer name. The extent of oxidized and reduced sandstone is delineated on these maps.

For a comprehensive summary (1,541 pages) of statewide uranium and thorium occurrences, including all uranium mines in the San Juan Basin, see McLemore (1983).

Meneely, S.C., Duzan, S.L., and Schemnitz, S.D., 1980, Impacts of uranium mining and milling upon the fish and wildlife resources of the New Mexico San Juan Basin Region: U.S. Geological Survey Report FWS/OBS 80/56, 159 p.

NOTE: This is one of the few studies of fish and wildlife and the potential faunal impacts published for the GMB area. Fish and wildlife species in the San Juan Basin of New Mexico, Arizona, and Colorado on Indian lands are inventoried in the report in a series of tables. Field inventories were taken on existing and proposed uranium development sites during the summer of 1979 to determine the distribution of wildlife species. Tabulated species information is given for wildlife (mammals, birds, amphibians, reptiles, and fish) observed at uranium mine and mill sites (table 7); wildlife in actively mined and potential mining areas (table 8); and wildlife observed in the study area but not on proposed or active mine and mill sites (table 9). Other tabular data include descriptions of various habitats in existing or proposed mining areas (Sa Nos Tee, Churchrock (Church Rock), Crownpoint, Ambrosia Lake–San Mateo, and Laguna). The inventories indicate species migration and emigration associated with this type of mining activity. The report projects potential impacts that may result at different stages of uranium development based on projections from the Bureau of Indian Affairs. Some species benefited as a result of water impoundments, in water discharge and fencing to restrict grazing activity from the site. Direct impacts of uranium mining and milling include habitat alteration, contamination of aquifers, and contamination of soils and surface waters by radionuclides and toxic elements from uranium mill ponds and tailing piles.

Mercer, J.W.. and Cooper, J.B., 1970, Availability of ground water in the Gallup-Tohatchi area, McKinley County, New Mexico: U.S. Geological Survey Open-File Report, 182 p.

NOTE: This report describes the aquifers that provide water in the Gallup-Tohatchi area west of the GMB, which include the Gallup Sandstone, Dakota Sandstone, and the Westwater Canyon Member of the Morrison Formation. The description includes transmissivity, storage-coefficient, and well-yield data. The report also includes (1) water quality data from drill-stem tests for a 1968 test well that penetrated the Gallup Sandstone, the Dakota Sandstone, the Westwater Canyon Member of the Morrison Formation, and the Cow Springs Sandstone, as well as water-quality data for 25 other selected wells; and (2) a summary table describing the ranges of selected chemical constituents for the three principal aquifers. The compiled information thus provides background water-quality data for important aquifers that extend into the GMB; however, no uranium or other radionuclide data are included.

Miera, F.R., Jr., 1980, Measurements of uranium in soils and small mammals: Los Alamos Scientific Laboratory Report LA-8624-T (thesis), UC-11, 43 p.

NOTE: These comments focus on the GMB site studied by the author. The author measured uranium concentrations in soils and a small mammal (white-footed deer mouse, *Peromyscus maniculatus rufinus* (Merriam)) at a Los Alamos Scientific Laboratory (LASL) weapons testing site contaminated with natural and depleted uranium and adjacent to the active Phillips uranium mill tailings pile at Ambrosia Lake northwest of Grants. Soils at the weapons testing site contained fragments of depleted and natural uranium metal of low solubility, whereas soils at the tailings pile contained wind-blown dust and water-deposited sediment from the tailings pile where the uranium was in a highly soluble form. Soils were sampled at two depth intervals, 0–5 cm and 5–10 cm. Soils were also sieved into 6 size fractions and analyzed. The gastrointestinal (GI) tract, pelt, kidney, carcass (bone and skeletal muscle), lung, and liver were analyzed in the deer mouse specimens. Analyses were done by delayed neutron activation for the mill tailings site and by instrumental neutron activation analysis for the LASL site.

Measurement of physical characteristics of the mice (weight, total length, tail length, hind foot length, and ear height) are similar for the LASL (20 individuals) and tailings pile (9 individuals) populations. The means are within the range reported for this species.

All soil and deer mice tissue samples were more highly contaminated with uranium at the LASL site than at the tailings pile site. At the tailings pile site, soils were sampled north (12 sites), east (12 sites), and south (8 sites) of the pile. For the 0–5 cm depth, all soils had a mean uranium concentration of 65 µg/g, with the east side having the highest mean of 86 µg/g. For the 5–10 cm depth, all soils had a mean uranium concentration of 74 µg/g, with the east side having the highest mean of 105 µg/g. Tissues from nine individual deer mice were collected and analyzed at the tailings pile site. The GI tract samples ranged from 62 to 590 µg/g with a median of 170 µg/g; pelt samples ranged from 40 to 430 µg/g with a median of 91 µg/g; kidney samples ranged from 4 to 130 µg/g with a median of 29 µg/g: carcass samples ranged from 1.8 to 7 µg/g with a median of 4.4 µg/g; lung samples ranged from 1.3 to 8.4 µg/g with a median of 5.4 µg/g; and liver samples ranged from 0.5 to 17 µg/g with a median of 2.2 µg/g. In this report, the author concludes the following:

> Perhaps one of the more significant findings of this study was that median uranium concentrations in kidneys of mice from the mill tailings study area were 6 times greater and significantly different from values for other internal tissues. This observation was not detected for the LASL study area. Low uranium values detected in lung tissues for both study sites indicated that inhalation of respirable size particle was not occurring during the sample period, and that the major route for contamination was via ingestion.
>
> Observed concentration ratios (CR) of animal tissue uranium to soil uranium (µg/g) for all tissue groupings composited were larger for mill tailings samples (CR>1) than for LASL samples (CR= 10^{-1}) . The observed concentration ratio was used to provide an estimate of the amount of uranium moving across physiological barriers under conditions of their passge through the biological system. The LASL results indicated that only a small portion of ingested uranium was metabolically assimilated. However, the mill tailings results indicated a larger amount of ingested uranium to be metabolically assimilated and is attributable to a more soluble form of uranium at this site.

Millard, J.B., Buhl, Thomas, and Baggett, David, 1984, The Church Rock uranium mill-tailings spill—a health and environmental assessment, technical report I, radiological impacts: Albuquerque, New Mexico Health and Environment Department report, 92 p.

NOTE: This report provides radionuclide data for the 1979 accidental mill tailings spill.

Miller, J.R., 1985, Sediment storage, transport, and geochemistry in fluvial and eolian systems-applications to long-term stability and potential dispersal patterns of uranium tailings in the Grants Mineral Belt, New Mexico: Albuquerque, University of New Mexico, M.S. thesis, 160 p.

Miller, J.R., and Wells, S.G., 1986, Types and processes of short-term sediment and uranium-tailings storage in arroyos—An example from the Rio Puerco of the West, New Mexico, *in* Hadley, R.F., ed., Drainage basin sediment delivery: International Association of Hydrological Sciences, International Commission on Continental Erosion, IAHS Publication 159, p. 335- 353, *http://iahs.info/redbooks/a159/iahs_159_0335.pdf*.

Moench, R.H. and Schlee, J.S., 1967, Geology and uranium deposits of the Laguna District, New Mexico: U.S. Geological Survey Professional Paper 519, 117 p.

NOTE: This report is not available online, but is available through the USGS library in Lakewood, Colo. This report describes the stratigraphy, structural geology, geomorphology, and uranium deposits of the Laguna area with specific information on the Jackpile, Saint Anthony, Windwhip, Woodrow, Pit I (Sandy mine) and Crackpot deposits. Semi-quantitative and quantitative geochemical data are provided for most of these deposits. The authors note that Be, Co, Cr, Cu, Pb, V, Y, and Yb are concentrated in ores in the Jackpile, Windwhip, Woodrow, and Sandy deposits.

Morgan, A.M., 1938, Ground water conditions in a portion of the Rio San Jose–Bluewater Valley near Grants, New Mexico: U.S. Geological Survey Open-File Report 38-009, 24 p.

NOTE: The geology and surface-water and groundwater hydrology of the Bluewater Creek and San Jose River drainages from the headwaters in the Zuni Mountains to the confluence with the Rio Puerco are described. The depth of Quaternary valley-fill deposits including the basalt flows, depths to water along the valley, water-table springs, geologic controls on water flow and availability, and probable sources of groundwater in the valley fill are also discussed. No water-quality data are given.

Murray, C.R., 1945, Preliminary conclusions on ground-water conditions in the Bluewater area, Valencia County, New Mexico: U.S. Geological Survey Open-File Report, 4 p.

NOTE: This report was not found by the author or the USGS library staff but may be in other libraries.

MWH, 2006, St. Anthony Mine site closeout plan, prepared for United Nuclear Corporation: Colorado Springs, Colo., MWH, 35 p., *http://www.emnrd.state.nm.us/mmd/marp/Documents/MK006RE_20060113_St_Anthony_Closeout_Plan.pdf*.

NOTE: This report provides background and detailed information about mining at the St. Anthony mine site, site geology, surface water, groundwater, pit water, and mine waste piles (n=7). Mine-site-plan maps show the existing topography and proposed regraded site configuration. Detailed geochemical and radiochemical data are given for six monitoring wells, seven pit-water samples, and upgradient and downgradient arroyo sites. Pit-water samples range from 110 ppb to 5500 ppb uranium.

New Mexico Department of Public Health and U.S. Public Health Service, 1957, Report on an investigation of ground water pollution, Grants-Bluewater, New Mexico: New Mexico Department of Health Report, 12 p.

New Mexico Environment Department, 2010, Geochemical analysis and interpretation of ground water data collected as part of the Anaconda Company Bluewater Uranium Mill Site Investigation and San Mateo Creek Site Legacy Uranium Sites Investigation, McKinley and Cibola County, New Mexico (Draft for public review released May 2010): Albuquerque, New Mexico, New Mexico Environment Department, 128 p., *http://www.nmenv.state.nm.us/gwb/documents/FinalPublicDraftofGeochemofBluewaterandSMCGroundWaterSamples.pdf*.

Executive summary

The Grants Mining District (GMD) in New Mexico produced more uranium (U) than any other district in the world during the period of 1951-1980. In the largest sub-district, Ambrosia Lake, there are 96 documented former producing mines and four mills, some of which have documented contaminant releases. Investigation of the isotopic ratios of C, O, H, S, and the U series from a limited number of ground water samples from two areas within the GMD were analyzed to

determine if discrepancies in the isotopic ratios could distinguish background water quality from ground water impacted by releases from U mining and milling operations. This method of systematic investigation is called “environmental forensics.” Utilization of environmental forensic methods for determining specific geochemical properties of the ground water was expected to more accurately define baseline water quality conditions in ground water sources with and without possible anthropogenic impacts. The ground water samples were collected as part of the site investigations of Anaconda Bluewater Mill and the San Mateo Creek Basin under the authority of the Comprehensive Environmental Response, Compensation, and Liability Act, as amended, 42 United States Code (U.S.C.) §§ 9601 to 9675 (CERCLA).

The 3,300-acre Anaconda Company Bluewater Uranium Mill site, now called the Bluewater Disposal site by the U.S. Department of Energy (DOE), is located in the southwest corner of the SMC basin in north-central Cibola County. Anaconda processed ore from the nearby Jackpile mine in Paguate, New Mexico at the mill from 1953-1982. This mill operated a carbonate-leach process with a capacity of 300 tons per day until 1957. An acid-leach mill was operated from 1957-1982, reaching a production capacity of 6,000 tons per day in 1978. A waste water disposal well was used to inject millions of gallons of acidic mill raffinate water into formations below the San Andres-Glorieta aquifer. The Atlantic Richfield Company (ARCO) reclaimed the Bluewater Mill site between 1991 and 1995, which included ground water remedial activities to address contamination in the alluvial and San Andres Limestone-Glorieta Sandstone aquifer. Title to the site was transferred to the DOE for long-term stewardship in 1997. Ground water contaminants that may be associated with the site, as derived from historical documentation; include radium (Ra), uranium (U), nitrate (NO3), chloride (Cl), molybdenum (Mo), asbestos, selenium (Se), magnesium (Mg), thorium (Th), aluminum (Al), manganese (Mn), iron (Fe), and polychlorinated biphenols (PCB).

The San Mateo Creek (SMC) basin comprises approximately 321 square miles within the Rio San Jose drainage basin in McKinley and Cibola counties, New Mexico, and includes the Ambrosia Lake mining sub-district. In 2008-2009 the New Mexico Environment Department (NMED) performed a Site Investigation, which included the collection, analysis, and evaluation of ground water samples to characterize and evaluate the impacts of legacy U mining and milling activities on the SMC regional ground water system. Aquifers within the SMC ground water system include the Permian age San Andres Limestone-Glorieta Sandstone (SAG); the Triassic Chinle Formation; the Jurassic Morrison Formation, the Cretaceous Dakota Sandstone, Tertiary basalt flows, and Quaternary alluvial material. The SAG is an important agricultural, industrial, municipal, and private water supply source in the area. Table ES-1 summarizes geochemical distinctions between the alluvial and bedrock aquifers in the San Mateo Creek Basin.

From the Bluewater Mill site, the SAG dips northeast to the nearby and downgradient Homestake Mining Company U mill Superfund site (HMC). HMC is located in a hydrogeologically complex area where the SAG and Alluvial aquifers may be hydraulically interconnected, and the source of increasing concentrations upgradient is not clear from existing monitoring data. Alluvial water quality upgradient of HMC appears to be impacted by releases from legacy sites in the northern part of the SMC basin around the Ambrosia Lake area. The SMC alluvial system south of HMC has been impacted by contamination from HMC. The Alluvial aquifer in the vicinity of HMC is underlain by the Triassic Chinle Formation, which is a predominantly thick sandstone, siltstone, and shale formation. The SAG regional aquifer underlies the Chinle Formation in this area.

In 2008, NMED conducted a Site Investigation (SI) of the Bluewater Mill site, collecting 33 water samples from wells known or assumed to be completed in the SAG both up and down gradient of the site. In 2009 NMED conducted an SI of the SMC basin, collecting 29 water samples from various alluvial and bedrock wells in the SMC basin, primarily upgradient of HMC. Sampling included duplicates and blanks for various quality assurance-control protocols. The samples were analyzed for field parameters, dissolved major ions, dissolved metals, and radioactivity. A limited number of samples from selected wells in the Bluewater Mill and SMC SI areas were collected for laboratory analysis of 13C, 2H, 18O, 34S, 238U, 235U, and 234U. In concert with laboratory measurements of the dissolved concentrations of metals and major ions and radiochemistry (gross alpha/beta, Ra, and total U), isotopic data on ratios of C, O, H, S, and the U series were evaluated to determine whether the isotopic signatures could help distinguish background water quality from ground water impacted by releases from U mining and milling operations.

Historical water quality data from previous investigations in the SMC area is extremely sparse because sampling was conducted intermittently, and the number of parameters for which samples were analyzed was often limited and geochemically inadequate to distinguish indications of anthropogenic contribution. During the period of active operation, water samples from U mine dewatering and mill discharges to drainages were elevated in total dissolved solids (TDS); select compounds like NO3 and SO4; trace elements like As, Se, Cl, Fe, Mo, Ra, and U; and radioactivity (gross alpha/beta). Depending on the discharge source, the pH of the discharge water was also more alkaline or more acidic than the natural ground water in the area. Baseline sampling to determine the natural, background concentrations of ground water quality parameters prior to legacy U mining and milling operations was not performed, and this drawback continues to hamper ongoing quantitative geochemical assessments of legacy impacts on ground water.

A properly designed network of monitoring wells to characterize and assess the natural concentrations in ground water and at potential release sites in the SMC basin does not exist. Many of the existing wells that were sampled in these investigations were not optimally located to assess the geochemistry of the basin at points along the presumed flow path from up gradient to down gradient. Many of the well construction completions were unavailable and the water producing interval(s) unknown. Nevertheless, the number of well locations sampled, the area encompassed, and the parameters measured in the samples by laboratory analysis provided a substantial amount of data to characterize and evaluate the ground water quality in the SMC area. The Bluewater Mill SI sample data are mostly considered to be representative of natural conditions without any legacy U components for the SAG, whereas, the SMC SI sample data are considered to include both unimpacted ground water as well as ground water impacted by legacy U activities. Unusual concentrations of geochemical parameters were observed in the Bluewater Mill site monitoring wells, which are assumed to draw water from the SAG that is contaminated by discharges from the legacy milling operations, particularly the unlined waste water evaporation ponds, and possibly a deep injection waste water disposal well.

Evaluation of the water sample analyte concentrations compared to the federal Environmental Protection Agency (EPA) drinking water and state ground water quality standards indicated 38 samples had a total of 107 concentrations that exceeded one or more standards. In 16 of 33 Bluewater Mill SI samples, EPA and state standards were exceeded for: NO3+NO2 (1); gross alpha (2); pH (2); TDS (14); Cl (3); SO4 (3); Fe (2); Mn (1); and U (1). In 22 of 29 the SMC SI samples, EPA and state standards were exceeded for: As (7); NO3+NO2 (5); Se (8); gross alpha (16); gross beta (4); pH (1); TDS (12); SO4 (10); F (1); Fe (2); and U (12).

TDS content in water samples ranged from 254 to 4,720 mg/l and averaged about 1,200 mg/l. TDS concentrations were slightly higher on average in the SMC SI sample set than in the Bluewater Mill SI sample set (1,432 and 1,051 mg/l, respectively). Field pH ranged from 5.40 to 10.21 and averaged about 7.3. Field pH is slightly higher on average in the SMC SI samples than in the

Bluewater Mill SI samples (7.58 and 7.08, respectively). Based on the TDS concentration of the water, the ground water is simply classified as fresh to brackish water. TDS concentrations generally increased from west to east across the Bluewater Mill SI sampling area, and from north to south across the SMC SI sampling area. The sample set order of major ion concentrations from high to low was: SO4>HCO3>Ca>Na>Mg>Cl for the Bluewater SI samples, and SO4>Na>HCO3>Ca>Mg>Cl for the SMC SI samples. NO3+NO2 concentrations ranged from less than one to 22.8 mg/l in the SMC SI samples, and from less than one to 10.0 mg/l in the Bluewater SI samples. Most Bluewater SI water samples were a CaMg-Na/HCO3-Cl-SO4 water type, whereas, most water samples in the SMC SI set were a CaMg-Na/Cl-SO4 water type. The Alluvial aquifer water samples in the SMC SI set were typically the most elevated in TDS concentrations, whereas, the samples from wells completed in bedrock units had lower overall TDS concentrations. Two areas of well locations were observed for elevated TDS: the group of wells above HMC; and the group of wells around the junction of state highways 605-509.

Many concentrations of minor constituents and trace metals were reported at low levels (less than 1.0 mg/l) or below the laboratory reporting limit (2 - 20 ug/l average depending on analyte). Seven trace metals in the Bluewater SI sample set (Ag, Al, Be, Cd, Co, Sb, and Tl) measured less than the laboratory reporting limit in all samples. Twelve trace metals in the SMC SI sample set (Ag, Al, Be, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, and Tl) reported less than the laboratory reporting limit in most samples. Thirteen trace metals reported a combination of less than the laboratory reporting limit and actual values in both sample sets (As, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Se, U, V, and Zn). The number of sample trace metal results measured at less than the laboratory reporting limit is a significant disadvantage for evaluation of geochemical data and observed spatial geochemical changes along a presumed ground water flow path. Five trace elements were used in the analysis of the Bluewater Mill SI sample data (As, Ba, Se, Zn, and U) and seven trace elements were used in the analysis of the SMC SI sample data (As, Ba, Mn, Se, V, Zn, and U). The order of trace element concentrations, from high to low was: Zn>Ba>U>Se>As in the Bluewater SI samples, and Fe>Zn>Se>U>Mn>Ba>As in the SMC SI samples. Dissolved Se averaged 8.8 and 101.8 ug/l in the Bluewater and SMC SI sample sets, respectively. The concentration of dissolved U ranged from a low of less than the laboratory reporting limit (<2 ug/l) to a high of 53.3 ug/l in the Bluewater SI sample set, and from less than the laboratory reporting limit to a high of 240.0 ug/l in the SMC SI sample set. Dissolved U concentrations averaged 12.4 and 67.3 ug/l in the Bluewater and SMC SI sample sets, respectively. Elevated concentrations of dissolved U were observed to have a correlation with elevated levels of dissolved Se at well locations assumed to produce from the Alluvial aquifer.

Gross alpha activity ranged from less than the laboratory reporting limit (<0.1 pCi/l) to 29 pCi/l in the Bluewater Mill SI samples. Gross alpha activity ranged from less than detection to 128.3 pCi/l in the SMC SI samples. Gross beta activity ranged from 0.4 to 16.7 pCi/l in the Bluewater SI samples. Gross beta activity ranged from 2.0 to 83.0 pCi/l in the SMC SI samples. Gross alpha/beta activity averaged 8.3/8.1 and 34.2/23.4 pCi/l, respectively, in the Bluewater and SMC SI sample sets. Most water samples had activity values for other radionuclides that were less than 1.0 pCi/l in both the Bluewater and SMC SI sample sets. 226Ra/ 228Ra activity averaged 0.10/0.41 and 0.20/0.78 pCi/l, respectively in the Bluewater and SMC SI sample sets. The highest 226Ra/ 228Ra activity values (2.90/3.91 pCi/l) was from a well located west of the state highway 605-509 junction and interpreted to produce water from a bedrock unit because of the absence of dissolved Se. Ra was observed to be an unreliable indicator of legacy U operations discharges because the activities measured in the samples were low overall, and the radionuclide does not appear to move very far from the discharge source.

Ground water impacts from uranium mill raffinate waste water may be detected through evaluation of the activity ratio (AR), 234U:238U. Relying heavily on 234U:238U AR data values (approximately 1.0) raffinate waste water, as well as on other concepts from an investigation of a mill site in southwestern Colorado, some of the Bluewater and SMC SI samples are interpreted to contain a possible anthropogenic component because of their low AR values and high dissolved U concentrations. Evaluation of U isotopic data provided an interpretation to separate ground water samples into three simple categories: 1) background; 2) a mixture of background and U mill raffinate impacts; and 3) U mill raffinate impacts. Additional proof-of-concept testing is required to validate the hypothesis that the 234U:238U AR can be used to indicate an anthropogenic component in the ground water. Most of the samples with the low U AR values and elevated dissolved U concentrations are assumed to be from wells that produce from the Alluvial aquifer. Interpretation of 34S isotope data relies heavily on delta (δ)34S data from a 1963 study of U ore samples from the Ambrosia Lake area. The Bluewater SI δ34S sample data suggest the source of S is from a marine limestone origin, whereas the SMC SI δ34S sample data suggest a source of sulfur from a biogenic, reducing environment such as would be associated with the classic model for U roll-front deposit. Again, lacking in direct geochemical evidence, a proof-of-concept test is required to validate such an interpretation. The 13C isotope data were not evaluated at this time because the C cycle in the environment is complex, requiring more geochemical expertise to perform a substantive evaluation. The limited number of O and H isotope samples indicated that there is range of isotopic ratios for these elements, likely reflecting a complex hydrologic ground water system from depleted (winter precipitation recharge?) to enriched (evaporated?) sources. The absence of isotopic data from all wells that were sampled for these investigations, and from recharge sources to the ground water system precluded a more thorough interpretation of the hydrogeochemistry in the SMC basin.

The Bluewater and SMC ground water investigations have provided a more extensive base line of water quality parameters and geochemistry for future investigations and monitoring of legacy U impacts on ground water in the GMD. The SAG appears to be a largely unimpacted ground water supply except possibly at a few well locations near former mill sites. The Alluvial aquifer in the SMC basin appears to contain elevated levels of TDS, metals, and radioactivity from legacy activities, but the degree of interaction between the alluvial and deep bedrock aquifers is unknown. The interpretation of anthropogenic components at some well locations from the utilization of select isotopes in these investigations requires proof-of-concept testing to validate the application of this technique. Many more evaluations of the data from these investigations may be possible to help gain further understanding of the ground water system. Some of the weaknesses identified in these investigations that hamper a more comprehensive understanding of the ground water system in the SMC basin include: 1) lack of properly sited and constructed wells to monitor ground water around and down gradient of legacy U sites; 2) lack of current static water level contour maps to evaluate seasonal and annual flow direction and gradient changes in area aquifers; 3) lack of aquifer pump test data to determine aquifer properties and the associated geologic influences to ground water flow; 4) lack of detailed geologic and stratigraphic information to support the creation of accurate cross sections at important transect locations; and 5) need for an integrated and comprehensive basin wide plan for characterization and assessment of legacy U site impacts to the ground water system in the GMD.

NOTE: This important report represents the initial effort of the New Mexico Environment Department to evaluate contamination due to mining and milling in the San Mateo Creek basin using modern geochemical methodologies including stable and uranium isotopes.

New Mexico Health and Environment Department, 1980, Water-quality data for discharges from uranium mines and mills in New Mexico: Environmental Improvement Division, Water Pollution Control Bureau, Santa Fe, 87 p., 13 figs.

Olsen, C.E., and Brookins, D.G., 1984, Uranium hydrogeochemical and stream sediment pilot survey of a portion of McKinley County, north of Grants, New Mexico: Uranium, v. 1, p. 307-333.

NOTE: This study was designed to sample waters and sediments in an area of eastern McKinley County north of active mining in the San Mateo, Ambrosia Lake, Crownpoint, and Mariano Lake areas. The underlying rocks in the study area are primarily Cretaceous units, which are stratigraphically above the uranium-ore host sandstones in the Morrison Formation. The sites were chosen to detect possible geochemical haloes or vertical leakage from the underlying uranium deposits, determine the geochemistry of the Cretaceous units, and test sampling procedures. Water samples were collected from 248 locations and sediment samples from 1,465 locations. Water samples were collected from natural ponds (n=13), artificial ponds (n=123), wells (n=67), springs (n=2), and streams (n=43). Average uranium concentrations are reported for water in natural ponds (1.16±0.97 ppb), artificial ponds (1.60±1.62 ppb), wells (1.47±1.75 ppb), springs (0.66±0.28 ppb) and streams (1.45±1.05 ppb). Sediment samples were collected from wet streams (n=259), wet springs (n=2), wet ponds (n=81), dry streams (n=887) and dry ponds (n=236). Average uranium concentrations are reported in sediment (–100 mesh fraction) for wet streams (3.46 ±1.16 ppm), wet springs (3.65±0.50 ppm), wet ponds (3.48±0.42 ppm), dry streams (3.28±0.78 ppm) and dry ponds (3.32±0.85 ppm). These data are sufficient to establish the natural baseline for the uranium concentrations for most water and sediment types for the area studied. The authors conclude that the elevated values observed do not suggest extensive mineralization in the exposed sedimentary rocks or migration of uranium from deposits at depth.

Orr, B.R., 1987, Water resources of the Zuni Tribal lands, McKinley and Cibola Counties, New Mexico: U.S. Geological Survey Water Supply Paper 2227, 76 p., *http://pubs.er.usgs.gov/djvu/WSP/wsp_2227.djvu*.

Abstract

An evaluation of the water resources of the Zuni tribal lands in west-central New Mexico was made to determine the yield, variability, and quality of water available to the Pueblo of Zuni. This study is needed to aid in orderly development of these resources. Rocks of Permian to Quaternary age supply stock, irrigation, and domestic water to the Zuni Indians. The Glorieta Sandstone and San Andres Limestone (Glorieta-San Andres aquifer) of Permian age and sandstones in the Chinle Formation of Triassic age provide most of this water supply. Water in the Glorieta-San Andres aquifer is confined by minimal-permeability shales and is transmitted through the aquifer along interconnected solution channels and fractures. Water-level and water-quality information indicate greater hydraulic conductivities along the southern boundaries of Zuni tribal lands. Well yields from the Glorieta-San Andres aquifer are as much as 150 gallons per minute, and aquifer transmissivity ranges from 30 to 1,400 feet squared per day. Long term, water-level declines of as much as 29 feet have been measured near pumping centers at Black Rock. Multiple-well aquifer tests are needed to further define aquifer properties (storage, transmissivity, and leakage from confining units) and the effects of well design on well yields. Dissolved-solids concentrations in

water from the aquifer range from 331 to 1,068 milligrams per liter. Calcium and sulfate are the predominant ions. Water in sandstones of the Chinle Formation is confined by adjacent shales and is transmitted along interconnected fractures. Well yields range from 5 to 125 gallons per minute, and aquifer transmissivity ranges from 40 to 1,400 feet squared per day. Water-level declines of as much as 27 feet have been measured near Zuni Village. Dissolved-solids concentrations in water from the aquifer range from 215 to 1,980 milligrams per liter. Sodium and bicarbonate are the predominant ions. Other sources of ground water are used primarily for livestock watering by means of windmills, with the exception of buried alluvial channel deposits along the Rio Pescado. These deposits provide domestic and irrigation water through springs and wells to Pescado and Black Rock. The Bidahochi Formation of Miocene and Pliocene age could potentially provide an additional supply of water chemically suitable for most uses. Seismic-reflection techniques are being used to locate buried channels eroded in the rocks underlying the Bidahochi Formation. These buried channels may contain thicker sections of saturated sands and gravels that could be developed for stock and domestic use.

NOTE: The Zuni Tribal Lands are located on the southwestern flank of the Zuni Mountains in an area underlain by many of the same formations exposed in the GMB. The report includes well and spring records (table 2), water-quality analyses from wells and springs (major and minor elements, table 3, n=87), and trace element and radiochemical data (table 3, part B, n=10). Arsenic ranges from 1.0 to 8.9 µg/L (n=10) and uranium ranges from <0.6 to 5.0 µg/L (n=3). Well yield, hydrologic properties, and gross chemistry of wells in the Glorieta–San Andres, Chinle, and Zuni–Dakota aquifers are described.

Osmond, J.K., and Cowart, J.B., 1981, Uranium series disequilibrium in ground water and core composite samples from the San Juan basin and Copper Mountain research sites: Department of Energy Report GJBX 364 (81), 126 p.

NOTE: This report provides a model for how uranium-238 and its decay products are likely to move in a uranium ore deposit under conditions that exist in an active roll front. The model describes the expected uranium series disequilibrium conditions in the solid phase and in the water moving through an ore body under fast and slow groundwater-movement conditions. The paper then gives groundwater and core geochemical data and interpretations from seven deep holes drilled through uranium-mineralized rock in a deposit located about 50 mi northwest of Grants, N. M. at a nominal depth of about 2,000 ft. The deposit was previously drilled by a mining company, thus the location of the orebody had previously been established. Four uranium-bearing sands (horizons A–D) are present at the site, but the reported core data are mostly on the B sand, which contains the principal uranium mineralization. Water data include broader intervals above, within, and below the A–D horizons. The combined data, providing information about a little-disturbed uranium deposit that was never mined, focus primarily on uranium, uranium isotopes, and other uranium-decay products. A companion report (Sayala and Ward, 1983) provides much additional information about the solid-phase geochemistry of the mineralized rock, host sandstone, and associated groundwater for this deposit.

Otton, J.K., Zielinski, R.A., and Horton, R.J., 2010, Geology, geochemistry, and geophysics of the Fry Canyon project site, southeastern Utah—indications of contaminant migration: U.S. Geological Survey Scientific Investigations Report 2010-5075, 39 p., *http://pubs.usgs.gov/sir/2010/5075/.*

Otton, J.K., Zielinski, R.A., and Johnson, C.A., 2005, Origin of saline soils in the Front Range area north of Denver, Colorado, *in* Fishman, N.S., ed., Energy resource studies, northern Front Range, Colorado: U.S. Geological Survey Professional Paper 1698, Chapter D, p. 73-87, *http://pubs.usgs.gov/pp/2005/1698/pdf/P1698.pdf.*

Perkins, B.L., and Goad, M.S., 1980, Water quality data for discharge from New Mexico uranium mines and mills: Albuquerque, New Mexico Health and Environment Department, New Mexico Environmental Improvement Division Report, 87 p.

Pierson, C.T., and Green, M.W., 1977, Factors controlling localization of uranium deposits in the Dakota Sandstone, Gallup and Ambrosia Lake mining districts, McKinley County, New Mexico: U.S. Geological Survey Open-File Report 77-0766, 62 p., *http://pubs.er.usgs.gov/usgspubs/ofr/ofr77766*.

Abstract

Geologic studies were made at all of the uranium mines and prospects in the Dakota Sandstone of Early(?) and Late Cretaceous age in the Gallup mining district, McKinley County, New Mexico. Dakota mines in the adjacent Ambrosia Lake mining district were visited briefly for comparative purposes. Mines in the eastern part of the Gallup district, and in the Ambrosia Lake district, are on the Chaco slope of the southern San Juan Basin in strata which dip gently northward toward the central part of the basin. Mines in the western part of the Gallup district are along the Gallup hogback (Nutria monocline) in strata which dip steeply westward into the Gallup sag. Geologic factors which controlled formation of the uranium deposits in the Dakota Sandstone are: (1) a source of uranium, believed to be uranium deposits of the underlying Morrison Formation of Late Jurassic age; (2) the accessibility to the Dakota of uranium-bearing solutions from the Morrison; (3) the presence in the Dakota of permeable sandstone beds overlain by impermeable carbonaceous shale beds; and (4) the occurrence within the permeable Dakota sandstone beds of carbonaceous reducing material as bedding-plane laminae, or as pockets of carbonaceous trash. Most of the Dakota uranium deposits are found in the lower part of the formation in marginal-marine distributary-channel sandstones which were deposited in the backshore environment. However, the Hogback no. 4 (Hyde) Mine (Gallup district) occurs in sandy paludal shale of the backshore environment, and another deposit, the Silver Spur (Ambrosia Lake district), is found in what is interpreted to be a massive beach or barrier-bar sandstone of the foreshore environment in the upper part of the Dakota. The sedimentary depositional environment most favorable for the accumulation of uranium is that of backshore areas lateral to main distributary channels, where levee, splay, and some distributary-channel sandstones intertongue with gray carbonaceous shales and siltstones of the well-drained swamp environment. Deposits of black carbonaceous shale which were formed in the poorly drained swamp deposits of the interfluve area are not favorable host rocks for uranium. The depositional energy levels of the various environments in which the sandstone and shale beds of the Dakota were deposited govern the relative favorability of the strata as uranium host rocks. In the report area, uranium usually occurs in carbonaceous sandstone deposited under low- to medium-energy fluvial conditions within distributary channels. A prerequisite, however, is that such sandstone be overlain by impermeable carbonaceous shale beds. Low- to medium-energy fluvial conditions result in the deposition of sandstone beds having detrital carbonaceous material distributed in laminae or in trash pockets on bedding planes. The carbonaceous laminae and trash pockets provide the necessary reductant to cause precipitation of uranium from solution. High-energy fluvial conditions result in the deposition of sandstones having little or no carbonaceous material included to provide a reductant. Very low energy swampy conditions result in carbonaceous shale deposits, which are generally barren of uranium because of their relative impermeability to migrating uranium-bearing solutions.

NOTE: This report describes factors believed to control uranium mineralization in the Dakota Sandstone, which overlies the Morrison Formation (the principal uranium deposit host in the GMB). The observations were derived from features of uranium mines in the Dakota Sandstone, notably the Hogback no. 4 (Hyde) mine (Gallup district) and the Silver Spur mine (Ambrosia Lake district).

Differences in the sandstone host may allow differentiation of mine wastes derived from these mines from those derived from Morrison Formation mines.

Pierson, C.T., Spirakis, C.S., and Robertson, J.F., 1983, Comparison of abundances of chemical elements in mineralized and unmineralized sandstone of the Brushy Basin Member of the Morrison Formation, Smith Lake District, Grants uranium region, New Mexico: U.S. Geological Survey Open-File Report 83-0818, 47 p., *http://pubs.er.usgs.gov/usgspubs/ofr/ofr83818.*

Abstract

Statistical treatment of analytical data from the Mariano Lake and Ruby uranium deposits in the Smith Lake district, New Mexico, indicates that organic carbon, arsenic, barium, calcium, cobalt, copper, gallium, iron, lead, manganese, molybdenum, nickel, selenium, strontium, sulfur, vanadium, yttrium, and zirconium are concentrated along with uranium in primary ore. Comparison of the Smith Lake data with information from other primary deposits in the Grants uranium region and elsewhere in the Morrison Formation of the Colorado Plateau suggests that these elements, with the possible exceptions of zirconium and gallium and with the probable addition of aluminum and magnesium, are typically associated with primary, tabular uranium deposits. Chemical differences between the Ruby and Mariano Lake deposits are consistent with the interpretation that the Ruby deposit has been more affected by post-mineralization oxidizing solutions than has the Mariano Lake deposit.

NOTE: This study provides geochemical data that may allow discrimination of background from mine waste and discrimination between wastes from different mines.

Place, Jeanne, Della Valle, R.S., and Brookins, D.G., 1980, Mineralogy and geochemistry of Mariano Lake uranium deposit, Smith Lake district, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Technology Memoir 38, p. 172-184.

NOTE: The Mariano Lake uranium deposit is a roll-front deposit that exhibits some geochemical and mineralogic differences when compared to other GMB deposits. For example, concentrations of calcium, molybdenum and selenium are lower whereas sulfur and vanadium are enriched. Major, minor, and trace element data are given for 11 mine samples of the informal Poison Canyon sandstone of the Westwater Canyon Member of the Morrison Formation ranging in uranium concentration from 0.20-0.72 percent. Trace element data are given for an additional 13 samples ranging in uranium concentration from 0.10–01.16 percent. The ores are variably enriched in vanadium, molybdenum, arsenic, and zinc (figs. 11–14).

Popp, C.J., Dehn, M., Hawley, J.W., and Love, D.W., 1988, Use of radiometric (Cs-137, Pb-210), geomorphic, and stratigraphic techniques to date recent oxbow sediments in the Rio Puerco drainage Grants uranium region, New Mexico: Environmental Geology and Water Sciences, v. 11, no. 3, p. 253-269.

Abstract (from DOE’s Energy Citations Database at *http://www.osti.gov/energycitations/product.biblio.jsp?query_id=0&page=11&osti_id=6126886*)

In the absence of historic geochemical baseline data for the Grants uranium region, environmental changes resulting from uranium mine-mill activities can be determined only by indirect methods. A methodology for determining the age of recent sediments in streams draining the region has been established based on combined geomorphic, stratigraphic, and radiometric dating techniques. Because clay-rich sediments retain possible radionuclides and heavy metals derived from mineralization and mined sources, sample sites which contain fine-grained deposits that both predate and postdate mine-mill activity were located in abandoned-channel segments (oxbows) of major streams draining the eastern Grants uranium region. Aerial photographs (and derivative maps) taken between 1935 and 1971 provided the historical and geomorphic documentation of approximate dates of oxbow formation and ages of alluvial fills in the abandoned-channel segments. Pits were dug at these oxbow sites to determine stratigraphy and composition of the deposits. Samples collected from pit walls and auger holes below the pits were subjected to radiometric analysis by gamma ray spectrometry for the artificial radionuclide Cs-137 and the natural radionuclide Pb-210 as well as other U-238 and Th-232 daughters. Because of the dynamic nature of the system, absolute dating with Cs-137 was not possible but samples could be dated as either pre- or post-1950. The 1950 date is important because it marked the beginning of the uranium exploitation in the region. The Pb-210 dating was not possible because background Pb-210 was very high relative to fallout Pb-210.

NOTE: This paper describes the methods for dating river sediments in the Jackpile-Paguate mine area that may predate mining. Popp and others (1984; see below) describe the results of a comparison of pre-mining and post-mining geochemistry.

Popp, C.J., Hawley, J.W., and Love, D.W., 1983, Radionuclide and heavy metal distribution in recent sediments of major streams in the Grants Mineral Belt, New Mexico—Final Report: Socorro, New Mexico, New Mexico Bureau of Mines and Mineral Resources Open-File Report 185, 130 p. plus unpaginated appendices, *http://geoinfo.nmt.edu/publications/openfile/downloads/OFR100-199/176-199/185/ofr_185.pdf*.

Abstract

In the absence of historic geochemical baseline data for the Grants Mineral Belt, environmental changes resulting from uranium mine-mill activities can only be determined by indirect methods. A methodology for determining the age of recent sediments in streams draining the region has been established based on combined geomorphic, stratigraphic, and radiometric dating techniques. Because clay-rich sediments retain possible radionuclides and heavy metals derived from mineralization and mined sources, sample sites which contain fine-grained deposits that both predate and postdate mine-mill activity were located in abandoned channel segments (oxbows) of major streams draining the eastern Grants Mineral Belt. Aerial photographs (and derivative maps) taken between 1935 and 1971 provided the historical and geomorphic documentation of approximate dates of oxbow formation and ages of alluvial fills in the abandoned-channel segments. Pits were dug at these oxbow sites to determine stratigraphy and composition of the deposits. Samples collected from pit walls and auger holes below the pits were subjected to radiometric analysis by gamma ray spectrometry for the artificial radionuclide Cs-137 and the natural radionuclide Pb-210 as well as other U-238 and Th-232 daughters. Because of the dynamic nature of the system, absolute dating with Cs-137 was not possible but samples could be dated as either pre- or post-1950. The 1950 date is important because it marked the beginning of the uranium activity in the region. The Pb-210 dating was not possible because background Pb-210 was very high relative to fallout Pb-210. It may be possible to separate effects of uranium mining and milling activity by comparing U-238 daughter accumulation to daughters in the Th-232 series. Sediments dated by the correlative Cs-137, stratigraphic, and historic techniques were then analyzed for radionuclides and trace metals which would be associated with uranium ores. The U-238 daughters are generally high in the region and little difference was observed for their values between the control site and the sites in the uranium mining and milling region except for the

Paguate Reservoir site. Recent sediments at Paguate clearly show elevated levels of U-238 daughters in sediments unambiguously dated after the mid 1950's. Sediments from the Jackpile uranium mine have been trapped in the reservoir fill.
Trace metals were also analyzed in old and more recent sediments and As, Se, Cd, Hg, and U show elevated values on a regional basis but no correlation with age (i.e. pre- or post-1950). These elevated trace metal values may simply be due to their association with the regionally mineralized material.

Popp, C.J., Love, D.W., Hawley, J.W., and Novo-Gradac, K., 1984, Radionuclide and heavy metal distribution in 20th century sediments of major streams in the eastern part of the Grants uranium region, New Mexico, *in* Stone, W.J., compiler, 1984, Selected papers on water quality and pollution in New Mexico: Proceedings of a symposium on water quality and pollution in New Mexico, April 12, 1984, Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 7, p. 34-48.

NOTE: This study documents the geochemistry of pre-mining and post-mining sediments along the Rio Paguate, Rio San Jose, and Rio Puerco in the eastern part of the GMB. They conducted depth-wise sampling of sediments behind a dam on the Rio Paguate and in abandoned channels on the other two rivers. The presence or absence of cesium-137 established the age of the sediment. Cesium-137 is derived from atmospheric testing of nuclear weapons, which started in 1944 and peaked in the early 1960s. It is commonly incorporated in sediments that are contemporaneous with or post-date the atmospheric testing.

The authors note that "Concentrations of radionuclides and heavy metals in sediments show regionally high values of U, As, Se, Cd, Hg, and U-decay products related to regional mineralization but unrelated to mining." The reference list includes many other helpful papers. A more complete version of this study is in Popp and others (1983) cited above.

Purson, J.D., George, W.E., Hansel, J.M., Garcia, S.R., Hensley, W.K., and Mills, C.F., 1981, Detailed uranium hydrogeochemical and stream sediment reconnaissance data release for the Grants special study area, New Mexico, including concentrations of forty-three additional elements: Los Alamos Scientific Laboratory informal report LA-8480-MS, Los Alamos, New Mexico, U.S. Department of Energy, Grand Junction, Colorado, GJBX-351(81), 311 p.

NOTE: Careful analysis of this large water and stream sediment dataset can yield much information leading to a better understanding of the background and contaminant geochemistry of the GMB. This uranium hydrogeochemical and stream sediment reconnaissance (HSSR) study was conducted in 1979 as a part of the National Uranium Resource Evaluation (NURE) program of the Department of Energy. Although there were earlier HSSR investigations that focused on the 2-degree quadrangle maps that cover northwestern New Mexico (Maassen and others, 1979, 1980; referenced above), this study focused on the public lands of the GMB extending along and north of Interstate 40 from the Acoma Pueblo to the Navajo Nation. A total of 167 water samples (wells and springs) and 3,569 sediment samples (from streams and springs) were collected from 2,601 locations within a 5,250-km^2 area. Special sample locations (187 sites) were selected to represent sediment derived from specific lithologic units: the Menefee Formation, Mancos Shale, Point Lookout Sandstone, Morrison Formation, and Dakota Formation. The analyses include uranium and selected trace elements many of which have significance to understanding the natural background and contaminated systems in the Grants region. Part of the investigation included a study of the clay mineralogy of stream sediments in

the area to determine if regions of kaolinite-rich sediment (as opposed to montmorillonite-rich sediment) might delineate concealed ore deposits.

The entire dataset has been reformatted by the USGS and is available online at *http://pubs.usgs.gov/of/1997/ofr-97-0492/quad/q_gallup.htm* for the part of the dataset that lies in the Gallup 2-degree NTMS quadrangle and at *http://pubs.usgs.gov/of/1997/ofr-97-0492/quad/q_albque.htm* for the part of the dataset that lies in the Albuquerque 2-degree NTMS quadrangle.

Please read the text at those two webpages for details. The dataset can be downloaded as part or all of the data to geographic subdivisions by county, 7.5-minute quadrangles, or 8-digit hydrologic units. The data may also be browsed one sample at a time. For individual sample locations, the approximate location of the site can be viewed in Google map images through links provided.

Purtyman, W.D., Wienke, C.L., and Dreesen, D.R., 1977, Geology and hydrology in the vicinity of the inactive uranium mill tailings pile, Ambrosia Lake, New Mexico: Los Alamos Scientific Laboratory Report LA-6839-MS, 36 p., *http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=7220367*.

Abstract

A study was made of the geology and hydrology of the immediate area around a uranium mill at Ambrosia Lake, New Mexico. The mill was in operation from June 1958 through April 1963 and produced 2.7 x 10^9 kg of tailings. The possible environmental consequences of this inactive tailings pile must first be delineated so that stabilization needs and future stabilization success can be properly assessed. The Ambrosia Lake area is underlain by over 1000 m of alternating shales, siltstones, and sandstones that dip gently to the northeast into the San Juan Basin. Water-bearing sandstones make up less than 25 percent of this sedimentary section. Water quality in the sandstones is fair to poor, with total dissolved solids ranging from 500 to 2000 mg/l. The present total volume of tailings is estimated at 1.5 x 10^6 m^3 and ranges in thickness from about 1 to 10 m. The tailings pile is underlain by the Mancos shale which dips to the northeast. The shale is about 120 m thick with three interbedded silty sandstones that are about 9 m in thickness. One of these sandstones outcrops beneath the western part of the pile; the eastern part of the pile is underlain by shale. Ground water in the shales and sandstones beneath the pile is recharged by runoff north of the pile and from three ponds located north, northeast, and east of the pile. The movement of water in shale and sandstones is to the southwest. Secondary recharge to the water in the shales and sandstone is from the basin within the tailings pile. Water in the southeast part of the tailings basin is forming a ground water mound above the underlying sediments. The major transport mechanisms of tailings and possible contaminants from the pile include wind erosion, surface water runoff, movement of ground water beneath the pile, and gaseous diffusion from the pile (radon).

Rautman, C.A., compiler, 1980, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memior 38, 400 p.

NOTE: This compilation of 49 papers and 4 abstracts provides much data on the geochemistry and mineralogy of ore deposits in the GMB that may be useful in discriminating mine waste and affected waters from the natural background. The specific mines for which data are provided include the following:

1. Mariano Lake roll-front deposit (mineralogy, p. 162–171 and mineralogy and geochemistry, p. 172-184);
2. the Nose Rock roll front (heavy minerals, p. 202–207);

3. Johnny M mine, Ambrosia Lake district (minor jordisite, p. 230–239);
4. Sandstone mine, Ambrosia Lake roll-front (data showing significant radiometric disequilibrium, p. 240–243);
5. Marquez deposit (emission spectrography geochemical data for composite ore and protore samples, p. 252–161);
6. Jackpile-Paguate deposit (analyses of 23 sandstone samples from sites adjacent to pits, in pits, and underground ranging from "barren" to 0.161 percent eU_3O_8); and
7. San Antonio Valley deposit (east of Mt. Taylor, disequilibrium in a trend ore body).

Rayno, D.R., Momemi, M.H., and Sabau, Carmen., 1980, Forage uptake of uranium series radionuclides in the vicinity of the Anaconda uranium mill: Third annual symposium on uranium mill tailings management, Ft. Collins, Colo., U.S.A., 24-25 Nov. 1980, *http://www.osti.gov/energycitations/servlets/purl/6350976-CJQ4sA/*.

Abstract

Radiochemical analysis was performed on samples of soil and eight species of common vegetation growing on the Anaconda uranium mill site, located in New Mexico. The concentrations of the long-lived radionuclides U-238, U-234, Th-230, Ra-226, and Pb-210 in these forage plants were determined. The sampling procedures and analytical laboratory methods used are described. The highest radionuclide concentration found in a forage species was 130 pCi of Ra-226 per gram dry weight for grass growing on the main tailings pile at Anaconda, where the surface soil activity of Ra-226 was 236 pCi/g. A comparison of shoots activity with that of roots and soil was used to determine a distribution index and uptake coefficient for each species. The distribution index, the ratio of root activity to shoot activity, ranged from 0.30 (Th-230) in galleta grass (*Hilaria jamesii*) to 38.0 (Ra-226) in Indian ricegrass (*Oryzopsis hymenoides*). In nearly all instances, the roots contained higher radionuclide concentrations. The uptake coefficient, the ratio of vegetation activity to soil activity, ranged from 0.69 (U-238) in Indian ricegrass roots to 0.01 (U-238) in four-wing saltbush (*Atriplex canescans*) shoots. The range of radionuclide concentrations in plants growing on the Anaconda mill site is compared to that in vegetation from a control site 20 km away.

Repenning, C.A., 1959, Geologic summary of the San Juan Basin, New Mexico, with reference to disposal of liquid radioactive waste: U.S. Geological Survey Trace Elements Investigation Report TEI 603, 57 p., *http://pubs.er.usgs.gov/djvu/OFR/1959/ofr_59_101.djvu*.

NOTE: This paper is a stratigraphic and structural review of the San Juan Basin that briefly describes the oil and gas fields in the basin and notes the downdip increase in the salt content of water toward the center of the basin.

Reynolds, J.F., Cwik, M.J., and Kelley, N.E., 1978, Reclamation at Anaconda's open pit uranium mine, New Mexico: Reclamation Review, v. 1, no. 1, p. 9-17

Abstract (from the DOE's Energy Citations Database at *http://www.osti.gov/energycitations/product.biblio.jsp?query_id=0&page=7&osti_id=5607923*)

Nearly 22 years of open pit uranium mining in the semi-arid grasslands of northwestern New Mexico resulted in 1052 ha of surface disturbance before mining ceased in 1978. A reclamation program to rehabilitate this surface disturbance includes overburden analysis, separation and selective deposition, and physical-vegetational stabilization procedures. Initial short-term revegetation pilot projects indicate that certain types of overburden can support native vegetation comparable to that of surrounding grasslands. Long-term results are needed to establish trends and overall success of stabilization efforts.

Riese, W.C., 1973, Geology and geochemistry of the Mount Taylor uranium deposit, Valencia County, New Mexico: Albuquerque, University of New Mexico, M.S. thesis, 118 p.

Riese, W.C., 1980, Mount Taylor uranium deposit, San Mateo, New Mexico: Albuquerque, University of New Mexico, Ph.D. dissertation, 643 p.

NOTE: A lengthy compilation of the results of the thesis work is given in Brookins (1979).

Riese, W.C. and Brookins, D.G., 1980, Mount Taylor uranium deposit, San Mateo, New Mexico, *in* Rautman, C.A., 1980, complier, Geology and mineral technology of the Grants uranium region 1979 (abs.): New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 397.

NOTE: This abstract summarizes the senior author's thesis work on this major deposit (Riese, 1973, 1980).

Risser, D.W., 1983, Estimated natural streamflow in the Rio San Jose, upstream from the Pueblos of Acoma and Laguna, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 82-4096, 51 p.

Abstract

The development of surface and ground water, which began about 1870 in the upper Rio San Jose drainage basin, has decreased the flow of the Rio San Jose on the Pueblo of Acoma and the Pueblo of Laguna. The purpose of this study was to estimate the natural streamflow in the Rio San Jose that would have entered the pueblos if no upstream water development had taken place. Estimates of natural flow were based upon streamflow and precipitation records, historical accounts of streamflow, records of irrigated acreage, and empirically-derived estimates of the effects on streamflow of Bluewater Lake, groundwater withdrawals, and irrigation diversions. Natural streamflow in the Rio San Jose at the western boundary of the Pueblo of Acoma is estimated to be between 13,000 and 15,000 acre-feet per year, based on 55 years of recorded and reconstructed streamflow data from water years 1913 to 1972. Natural streamflow at the western boundary of the Pueblo of Laguna is estimated to be between 17,000 and 19,000 acre-feet per year for the same period. The error in these estimates of natural streamflow is difficult to assess accurately, but it probably is less than 25 percent.

NOTE: This study provides historical precipitation and streamflow data for several streams in the GMB, including Bluewater Creek and the Rio San Jose. No water quality data are given.

Risser, D.W., Davis, P.A., Baldwin, J.A.. and McAda, D.P., 1984, Aquifer tests at the Jackpile-Paguate uranium mine, Pueblo of Laguna, west-central New Mexico: U.S. Geological Survey Water-Resources Investigations Report WRI 84-4255, 26 p., *http://pubs.er.usgs.gov/usgspubs/wri/wri844255*.

Abstract

The transmissivity of the Jackpile sandstone bed in the Brushy Basin Shale Member of the Morrison Formation, west-central New Mexico, was determined to be 24 sq ft/day at well M2 and 47 sq ft/day at well M3 from constant-discharge aquifer tests conducted at the Jackpile-Paguate Uranium Mine. The storage coefficient of the Jackpile sandstone bed was estimated to be 0.00018 at well M2 and 0.00029 at well M3 from the same tests. An aquifer test conducted at well M21 indicated the transmissivity of the Jackpile sandstone bed was 2.0 sq ft/day and the storage

coefficient was 0.00002. The transmissivity of an unnamed sandstone bed in the Brushy Basin Shale Member of the Morrison Formation was estimated from ' slug-test ' results to be about 20 sq ft/day. Water levels in this sandstone probably did not change due to pumping from the overlying Jackpile sandstone bed for 88 hours at an average discharge of 15.3 gallons/min. A constant discharge aquifer test at well M4C indicated that the transmissivity of the alluvium at this location was about 430 sq ft/day. Water levels in the underlying Jackpile sandstone bed began declining within 15 minutes after withdrawals of groundwater from the alluvial aquifer began.

Risser, D.W., and Lyford, F.P., 1979, Water resources on the Pueblo of Laguna, west-central New Mexico: U.S. Geological Survey Water Resources Investigations Report 83-4038, 308 p., *http://pubs.er.usgs.gov/usgspubs/wri/wri834038.*

Abstract

This study evaluates the quality and quantity of water available on the Pueblo of Laguna, New Mexico. Groundwater for public supply occurs in the valley fill along the Rio San Jose, in the Paguate and Encinal areas, and possibly in the northern part of the Sedillo Grant. The valley fill in the Rio San Jose will supply 50 to 450 gallons per minute of potable water to properly constructed wells. In the alluvium along Rio Paguate, additional development of as much as 250 gallons per minute is possible. Groundwater for irrigation is restricted by available yields and quality to the valley fill along the Rio San Jose and possibly the western part of the Major 's Ranch area. In the Rio San Jose valley yields of 50 to 450 gallons per minute of water containing 500 to 3,000 milligrams per liter are possible. Digital-model simulations of the valley-fill aquifer west of the Village of Laguna show a potential salvage of as much as 900 acre-feet per year of evapotranspiration losses if water levels are lowered. Model studies also indicate that the winter flow of the Rio San Jose could be used to recharge groundwater stored in the valley.

Robertson, J.F., 1979, The Ruby Well No. 1 uranium mine, McKinley County, New Mexico in Geological Survey Research 1979: U.S. Geological Survey Professional Paper 1150, p. 41.

Text

Primary uranium ore in the Ruby Well No.1 mine, southern San Juan Basin, McKinley County, New Mexico, forms a narrow elongate body enclosed within a fluvial arkosic sandstone bed within the Brushy Basin Shale Member of the Morrison Formation (Upper Jurassic). The Ruby Well deposit is one of several uranium deposits alined [sic] west- northwest in the Smith Lake-Mariano Lake ore trend being studied by J. F. Robertson. The ore body, in plan view, is lenticular in shape, 1,500 m long, and about 180 m wide near the middle. It ranges from 0 to 8 m thick. In cross section, the orebody has a roughly C-shaped roll-front configuration, with the relatively thick and ragged convexity on the downdip northeast side. The upper and lower limbs of the roll extend and thin undip.

The host rock dips three degrees or less to northeast and contains planar cross bedding with dips dominantly to north and northeast. A few large-scale trough crossbeds in the sandstone plunge gently N. 60° E. in the probable direction of paleostream flow.

Ore distribution does not seem to be influenced by internal bedding structures in the host sandstone, but it does appear to be closely related to texture and permeability. Present studies indicate that the ore was deposited soon after Morrison deposition. Beginning in the Tertiary Period and extending to the present, oxidizing ground waters have attacked all margins of the deposit and taken uranium into solution. As would be expected in a classic roll-front model, the arkosic sandstone in the interior part of the roll is thoroughly altered. The sandstone exterior to and downdip from the

deposit, however, is also intensively oxidized and leached, which is not the case in the classic roll-front model. This condition was undoubtedly caused by the later ground-water flow, which also markedly depleted pyrite and even secondary limonite and most of the chemical elements originally in the sandstone or associated with the ore. Most of the potash feldspar, still relatively fresh in primary ore, has been thoroughly altered to clay in the adjacent sandstone. No secondary redistribution of uranium is evident in the proximity of the deposit.

Ruttenber, A.J., Jr., and Kreiss, Kathleen, 1981, Radiation exposure assessment following the 1979 Church Rock uranium mill tailings spill, chap. 115: Society of Mining Engineers, Radiation hazards in mining: control, measurement and medical aspects, 8 p. Digital version is available online through *www.onemine.org*.

NOTE: This paper describes in detail the mill operations adjacent to the Church Rock mine, dewatering effluent releases, effluent water treatment, identification of radionuclides released during the spill, and much detailed information about the spill itself, including pathways to human exposure. A similar paper was published as Ruttenber and others (1984).

Ruttenber, A.J., Jr., Kreiss, K., Douglas, R.L., Buhl, T.E., and Millard J., 1984, The assessment of human exposure to radionuclides from a uranium mill tailings release and mine dewatering effluent: Health Physics, v. 47, no. 1, p. 21-35.

Sayala, Dasharatham, and Ward, D.L., 1983, Multidisciplinary studies of a uranium deposit in the San Juan Basin: U.S. Department of Energy Report GJBX-2(83), 236 p.

NOTE: This study was designed to identify halos associated with deep-seated sandstone deposits in the San Juan Basin as a possible aid to uranium exploration. A deep deposit (2000 ft) north of Grants, N. M. was drilled and cored for the study. Geologic, mineralogical, geophysical, geochemical, and emanometric studies were conducted in three dimensions with emphasis on the position of the data with respect to the paleohydrologic gradient during deposit formation and the current hydrologic gradient. The deposit is characterized by high concentrations of V, Ta, Co, Nd, Zr, and Sm. There is no well-developed geochemical zoning of any trace elements; however, there is a poorly developed halo of barium and selenium.

Schilling, F.A., Jr., 1975, Annotated bibliography of Grants uranium region: New Mexico Bureau of Geology and Mineral Resources Bulletin 105, 69 p.

NOTE: This report was not reviewed by the author. It is available for sale at *http://geoinfo.nmt.edu/publications/bulletins/105/*.

Schmitt, L.J., 1982, Petrographic study of sandstones from measured sections of the Morrison Formation and related units, southwestern San Juan Basin, New Mexico: U.S. Geological Survey Open-File Report 82-991, 63 p., *http://pubs.er.usgs.gov/djvu/OFR/1982/ofr_82_991.djvu*.

Introduction

In this study certain petrographic features, grain size, roundness and sphericity and modal petrographic analysis were determined for outcropping sandstones of the Jurassic Morrison Formation and related stratigraphic units in the southwestern part of the San Juan Basin about midway between Gallup and Crownpoint, New Mexico (fig. 1). Here the Morrison Formation is divided into three members, the Recapture (Jmr), the Westwater Canyon (Jmw), and the Brushy Basin (Jmb), in ascending order. The Morrison is overlain by the Cretaceous Dakota Sandstone and underlain by the Jurassic Cow Springs Sandstone (Jcs) and Summerville(?) Formation (Js?).

NOTE: Careful use of information in this report may permit discrimination of sandy sediment derived from natural outcrop from that derived from mined sandstone in uranium mine waste.

Schwendiman, L.C., Sehmel, G.A., Horst, T.W., Thomas, C.W., and Perkins, R.W., 1980, Field and modeling study of windblown particles from a uranium mill tailings pile: Battelle Pacific Northwest Labs Technical Report NUREG/CR-1407, 240 p.

Abstract (from the DOE's Energy Citations Database at *http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=6886214*)

An extensive field study whose primary objective was to obtain knowledge and understanding of the nature and quantity of windblown particles from uranium mill tailings piles was conducted in the Ambrosia Lake District of New Mexico. The following major field tasks were undertaken: determination of physical, chemical, and radioactivity characteristics of mill tailings particles; an investigation of the nature and quantity of tailings particles in soil in the vicinity of tailings piles; and the determination of the nature and flux of particles being transported by wind as a function of wind speed and height. Results of the field study are presented. Particle size distributions and associated radioactivity were measured.

NOTE: Several similar studies by the Department of Energy may be available for other sites in the GMB.

Science and Engineering Resources, Inc., 1976, Ground-water hydrology of the alluvium at United Nuclear-Homestake Partners' mill near Milan, New Mexico: Consultant report to United Nuclear Homestake Partners, 179 p.

Shuey, Chris, 1982, Church Rock revisited: Accident left long-term contamination of Rio Puerco, but seepage problem consumes New Mexico's response: Mine Talk, v. 2, no.1, p. 8-26, *http://www.sric.org/Churchrock/Church%20Rock_Mine%20Talk_1982_64.pdf*.

NOTE: This report summarizes, in detail, data from studies of the 1979 Church Rock mill tailings spill from a variety of sources. It also includes information on groundwater quality adjacent to the mill tailings ponds.

Shuey, Chris, and Robinson, W.P., 1984, Characterization of ground water quality near a uranium mill-tailings facility, and comparison to background levels and New Mexico standards, *in* Stone, W.J., compiler, 1984, Selected papers on water quality and pollution in New Mexico: Proceedings of a symposium on water quality and pollution in New Mexico, April 12, 1984, Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 7, p. 184-193.

Smith, C.T., 1954, Ground-water resources, *in* Geology of the Thoreau quadrangle, McKinley and Valencia Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 31, p. 25-32.

Smith, K.S., and Huyck, H.L., 1998, An overview of abundance, relative mobility, bioavailability, and human toxicity of metals, *in* Plumlee, G.S., and Logsdon, M.J., eds., Environmental geochemistry of mineral deposits: Reviews in Economic Geology, v. 6A, p. 29-70.

Spiegel, Zane, 1957, Present and potential ground-water development in the Ambrosia Lake uranium area: New Mexico State Engineer Open-File Report, 2 p.

Spiegel, Zane, and Galloway, S.E., 1956, Reconnaissance of movement of waste waters from the Anaconda uranium mill disposal pond, Bluewater, New Mexico: Santa Fe, New Mexico, State Engineer Office, 4 p.

NOTE: Available from the New Mexico State Library, Santa Fe, N. M..

Spirakis, C.S. and Pierson, C.T., 1983, Comparison of the chemical characteristics of the uranium deposits of the Morrison Formation in the Grants uranium region, New Mexico: U.S. Geological Survey Open-File Report 83-0380, 22 p., *http://pubs.er.usgs.gov/usgspubs/ofr/ofr83380*.

Abstract

Statistical treatment of the chemical data of samples from the northeast Church Rock area, Ruby deposit, Mariano Lake deposit, and the Ambrosia Lake district indicates that primary ore-forming processes concentrated copper, iron, magnesium, manganese, molybdenum, selenium, vanadium, yttrium, arsenic, organic carbon, and sulfur, along with uranium. A barium halo that is associated with all of these deposits formed from secondary processes. Calcium and strontium were also enriched in the ores by secondary processes. Comparison of the chemical characteristics of the redistributed deposits in the Church Rock district to the primary deposits in the Grants uranium region indicates that calcium, manganese, strontium, yttrium, copper, iron, magnesium, molybdenum, lead, selenium, and vanadium are separated from uranium during redistribution of the deposits in the Church Rock area. Comparisons of the chemical characteristics of the Church Rock deposits and the secondary deposits at Ambrosia Lake suggest some differences in the processes that were involved in the genesis of the redistributed deposits in these two areas.

Spirakis, C.S., and Pierson, C.T., 1986, Some aspects of the genesis of the uranium deposits of the Morrison Formation in the Grants uranium region, New Mexico, inferred from chemical characteristics of the deposits, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, Neil, eds., A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: Tulsa, Oklahoma, American Association of Petroleum Geologists Studies in Geology 22, p. 161-169.

NOTE: In this study, the authors note enrichment of other minor and trace elements in mineralized rock (greater than 100 ppm uranium) of two deposits in the Church Rock district, two deposits in the Smith Lake District, primary and secondary deposits in the Ambrosia Lake district, and deposits in the Jackpile Sandstone Member of the Morrison Formation in the Laguna area. From these data they draw inferences about the genesis of the deposits. These same minor and trace element data may provide a means of characterizing mine- and mill-waste-derived contamination of soils and groundwaters and discriminating it from the natural background.

Spirakis, C.S., Pierson, C.T., and Granger H.C., 1981, Comparison of the chemical composition of mineralized and unmineralized (barren) samples of the Morrison Formation in the Ambrosia Lake uranium area, New Mexico: U.S. Geological Survey Open-File Report 81-0508, 44 p. *http://pubs.er.usgs.gov/djvu/OFR/1981/ofr_81_508.djvu*

Abstract

Existing multielement spectrographic and chemical analyses of samples from the Morrison Formation were used to determine the chemical characteristics of primary and secondary uranium ore, barren sandstones, and mineralized and unmineralized mudstones. The analyses were for 696 sandstone samples and 32 mudstone samples from mines in the Ambrosia Lake area of New Mexico, 100 other sandstone samples from the Ambrosia Lake area, and 321 sandstone samples from elsewhere in the San Juan basin. Statistical treatment of the data indicates that organic carbon, beryllium, vanadium, uranium, molybdenum, selenium, lead, manganese, yttrium, copper, iron, barium, strontium, aluminum, magnesium, potassium and possibly sodium, sulfur, arsenic, and mercury are concentrated in the primary ore; aluminum, uranium, vanadium, selenium, manganese, calcium, strontium, sodium(?), copper, iron, carbonate carbon, and barium are enriched in the secondary ore; and organic carbon, uranium, vanadium, beryllium, manganese, molybdenum, selenium, and lead were added to the mineralized mudstones.

Spirakis, C.S., Pierson, C.T., Santos, E.S., and Fishman, N.S., 1983, Statistical treatment and preliminary interpretation of chemical data from a uranium deposit in the northeast part of the Church Rock area, Gallup mining district, New Mexico: U.S. Geological Survey Open-File Report 83-0379, 44 p.,
http://pubs.er.usgs.gov/usgspubs/ofr/ofr83379.

Abstract

Statistical treatment of analytical data from 106 samples of uranium-mineralized and unmineralized or weakly mineralized rocks of the Morrison Formation from the northeastern part of the Church Rock area of the Grants uranium region indicates that along with uranium, the deposits in the northeast Church Rock area are enriched in barium, sulfur, sodium, vanadium and equivalent uranium. Selenium and molybdenum are sporadically enriched in the deposits and calcium, manganese, strontium, and yttrium are depleted. Unlike the primary deposits of the San Juan Basin, the deposits in the northeast part of the Church Rock area contain little organic carbon and several elements that are characteristically enriched in the primary deposits are not enriched or are enriched to a much lesser degree in the Church Rock deposits. The suite of elements associated with the deposits in the northeast part of the Church Rock area is also different from the suite of elements associated with the redistributed deposits in the Ambrosia Lake district. This suggests that the genesis of the Church Rock deposits is different, at least in part, from the genesis of the primary deposits of the San Juan Basin or the redistributed deposits at Ambrosia Lake.

Squyres, J.B., 1963, Geology and ore deposits of the Ann Lee mine, Ambrosia Lake area, *in* Kelley, V.C., compiler, Geology and Technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources Memoir 15, p. 90-101.

NOTE: This report describes the stratigraphy and structure of the deposit and the form and distribution of the ore bodies. It notes a close relation between amorphous organic matter impregnating the host sandstone and uranium concentrations, but also notes that some organic matter has very low uranium concentrations. Molybenum is present in this barren material at concentrations up to 0.36 weight percent. In the ore, molybdenum is much lower in concentration, 0.02–.002 weight percent. Vanadium is in both the ore (0.10–0.50 weight percent V_2O_5) and the barren material (0.03–0.20 weight percent V_2O_5).

Stephens, D.B., 1983, Groundwater flow and implications for groundwater contamination north of Prewitt, New Mexico, U.S.A.*:* Journal of Hydrology, v. 61, no. 4, p. 391-408.

NOTE: The author describes the hydrologic setting of the alluvial aquifer along Casamero Draw and Mitchell Draw, two small ephemeral streams that flow southward and eastward past Prewitt, N. M. Data include water levels for 39 alluvial wells along these 2 drainages and their tributaries. These streams flow antithetically to the north to northeast dip of the underlying bedrock, which dip to the north to northeast. The author simulates groundwater flow-paths to describe the interaction between the alluvial aquifer and underlying aquitards and aquifers. These simulations are relevant to understanding the potential flow paths of contaminants derived from historical and (or) proposed mine- or mill-related facilities, especially any surface impoundments.

Stevens, Ken, 1984, Aquifer-test data and borehole flow test results from monitoring well 16P52 at the South Trend development area number 1, McKinley County, New Mexico: U.S. Geological Survey Open-File Report 83-539, 37 p., *http://pubs.er.usgs.gov/djvu/OFR/1983/ofr_83_539.djvu*.

Abstract

Mobil Oil Corporation personnel have designated at least four sandstone intervals, A-D (top to bottom), on the single-point resistivity logs of wells drilled in the South Trend Development Area. This report presents time-drawdown data reported by Mobil Oil Corporation from singly (A or B or C or D sandstone interval) and multiply (A, B, C, and D sandstone Intervals) completed wells for the August 16-17, 1982 aquifer test at the South Trend Development Area Site 1. This report also describes the results of flowmeter and brine-injection tests by the U.S. Geological Survey in monitoring well 16P52. Well 16P52 is open to sandstone intervals A, B, C, and D. On July 26, 1982, water was injected at a rate of 1.43 cubic feet per minute above the A sandstone interval in well 16P52. Based on flowmeter data, the calculated rates of flow were 1.23 cubic feet per minute between the A and B sandstone intervals, 0.63 cubic foot per minute between the B and C sandstone intervals, and less than 0.17 cubic foot per minute between the C and D sandstone intervals. Based upon brine-slug-injection tests conducted during August 1982, the calculated flow rates between sandstone intervals A and B are as follows: 0.01 cubic foot per minute upward flow (B to A) about 5 hours after pumping began for the aquifer test; 0.004 cubic foot per minute upward flow (B to A) about 21 hours after pumping began; and 0.0 cubic foot per minute about 46 hours after the pump was turned off. All other brine-slug-injection tests measured no flow.

Stone, W.J., compiler, 1984, Selected papers on water quality and pollution in New Mexico: proceedings of a symposium on water quality and pollution in New Mexico, April 12, 1984, Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 7, 300 p.

NOTE: This reference includes several papers relevant to documenting background and contaminant conditions in the GMB, including Cary and Gallaher (1984), Shuey and Robinson (1984) , Longmire and others (1984), and Popp and others (1984).

Stone, W.J., Lyford, F.P., Frenzel, P.F., Mizell, N.H. and Padgett, E.T., 1982, Hydrogeology and water resources of the San Juan Basin, New Mexico. New Mexico Bureau of Mines and Mineral Resources Hydrology Report 6, 70 p.

Tennessee Valley Authority, Department of the Interior, 1978, Final Environmental Statement, Dalton Pass uranium mine: Norris, Tennessee, Tennessee Valley Authority, v. 1, 229 p., v. 2, Appendices, variously paginated.

NOTE: This two-volume report includes descriptions of the regional and local hydrology of the Dalton Pass mine site and provides selected water-quality data as part of an environmental evaluation of a then-proposed underground mine located in the southeast corner of the Navajo Reservation west of Crownpoint. This mine was never developed, but the drilling pads and roads are visible in recent Google Earth images (viewed by the author November 2010). In volume 1, the location and aquifer source of 10 wells and 2 springs in and near the site are given. The water depth of the wells is also given.

In Table 2.8.1-1of the report, gross alpha, gross beta, uranium, ^{230}Th, dissolved ^{226}Ra, and ^{214}Bidata are given for groundwater from two sites in section 14 on the northwestern part of the proposed mine area and from the water supplies of Crownpoint and Thoreau (four locations). Uranium in the two section-14 water samples ranges from 0.24–1.6 µg/L (five total samples), whereas uranium in the town public-water supplies ranges from 3.4–8.2 µg/L (seven total samples). Table 2.8.1-2 shows gross alpha, gross beta, uranium, ^{230}Th, ^{226}Ra, ^{214}Bi, and ^{137}Cs data for soils and vegetation at two locations on the proposed mine site (sections 14 and 24) and one site in the town of Thoreau. Uranium (dry weight) in the two soil samples from the proposed mine site range from 0.89–2.3 µg/g (6 samples), whereas the three samples from Thoreau ranged from 0.19–0.94 µg/g. Samples were collected in late 1975 and in 1976, with samples taken during one to four sampling trips per site. All vegetation samples ranged from 0.002–0.21 µg/g uranium (nine samples). Table 2.8.1-3 provides gross alpha, gross beta, ^{230}Th, dissolved and total ^{226}Ra, total ^{228}Ra, total ^{210}Pb , and dissolved and suspended uranium data for groundwaters from two locations in section 14 on the property and from five other localities in sections north and southwest of the property.

Dissolved uranium for the five locations distant from the property plus one of the property wells in section 14 range from <1.0-5.3 µg/L. The other location in section 14 was sampled seven times during a period of five months but radiochemical analyses were limited. One sample yielded 41.1 µg/L suspended total uranium, another 49.6 µg/L dissolved total uranium, and a third <1,250 µg/L suspended plus dissolved uranium. No explanation is offered for the "<1,250" value and why it was reported in that way. No information is given for the depth of wells, the source aquifer(s), and the methods used for sampling water, soil, and vegetation.

Tennessee Valley Authority, Department of the Interior, 1979, Final Environmental Statement, Crownpoint uranium mining project: Norris, Tennessee, Tennessee Valley Authority, v. 1, 230 p., v. 2, Appendices, variously paginated.

NOTE: This two-volume report describes the regional and local hydrology of the Crownpoint mine site and provides selected water quality data as part of an environmental evaluation of pre-mining in-situ leach and underground mining operations. Wells and springs within a seven-mile radius of the pre-mining site are included in the evaluation. No mining or related operations were conducted at this site. Groundwater, soil, and vegetation were sampled at selected locations around the proposed mine site from 1975–1977 and analyzed for several radioactive constituents (tables 2.8.1-1 and 2.8.1-2). Water from five wells ranged from <0.01–1.6 µg/L uranium, whereas the Crownpoint and Thoreau public water supplies ranged from 3.4–7.4 and 5.1–9.6 µg/L uranium, respectively. Most well waters were derived from multiple aquifers. Soil and vegetation were sampled near some of the wells. Soils (four sites) ranged from 0.19–1.9 µg/g uranium, and vegetation (three sites) ranged from < 0.05–0.31 µg/g uranium.

Thomson, B.M., and Heggen, R.J., 1983, Water quality and hydrologic impacts of disposal of uranium mill tailings by backfilling, *in* Management of Wastes From Uranium Mining and Milling, IAE-SM-262/51, International Atomic Energy Agency, Vienna (1983), p. 373–384.

Thomson, B.M., Longmire, P.A., and Brookins, D.G., 2003, Geochemical constraints on underground disposal of uranium mill tailings: Applied Geochemistry, v. 1, no.3, p. 335-343.

Thomson, B.M., Longmire, P.A., and Gallaher, B.M., 1982, The hydrologic environment and uranium production in New Mexico, *in* Proceedings of Conference on Water and Energy, Technical and Policy Issues: American Society of Civil Engineers, Fort Collins, Colo., p. 525–531.

Titus, F.B, Jr., 1963, Geology and ground-water conditions in eastern Valencia County, New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources Ground-Water Report 7, 113 p.

U.S. Atomic Energy Commission, 1971, Final tabulation of sulfur-isotope analyses: U.S. Atomic Energy Commission Open-File Report AEC-RPD-13, 76 p.

NOTE: This report is a compilation of sulfur isotope data for ores from the major U.S. uranium districts including several deposits in the GMB. Such sulfur isotope data for ore deposits could allow discrimination of natural sulfate sulfur in surface waters and soils from sulfate sulfur derived from the leaching of mine waste piles consisting of stockpile low-grade ore (protore), but would not apply to mill tailings piles or ponds that may be dominated by sulfate from process sulfuric acid.

U.S. Department of the Interior, 1986, Final environmental impact statement for the Jackpile-Paguate uranium mine reclamation project, Laguna Indian Reservation, Cibola County, New Mexico: Albuquerque, New Mexico, U.S. Department of the Interior, vols. 1 and v. 2, variously paginated.

NOTE: This report describes the condition of the site, technical and socio-economic data, and multiple proposed alternatives for reclamation. Mining in the Jackpile–Paguate area started in 1952. The study notes that 23 protore piles with 21 million tons of material ranging in grade from 0.02–0.059 percent U_3O_8 remain at the site. Table 2-13 describes the size in acres and the radiological characteristics (uranium in µg/g and pCi/g and gamma activity in µR/hr) for several tens of waste piles, pit surfaces, and facility sites. Maps 2-1 and 2-2, and table 2-14 show the results of an aerial radiometric survey of the mine site and contiguous areas. Local background ranges from 6–14 µR/h except along Oak Canyon below the mine and the Rio Paguate above and below the mine, which range from 14–18 µR/h. Outcrop samples of uranium-enriched sedimentary rocks ranges from 18–23 µR/h. The immediate mine site and the exposed sediments on the bottom of Paguate Reservoir downstream from the mine site are greater than 18 µR/h. About 4 percent of the reservoir bottom sediment was greater than 30 µR/h with a maximum reading of 47 µR/h. The mine site pits range from 18–480 µR/h. The study provides gross alpha and gross beta, Ra-226, and uranium isotope data for four wells on the Laguna Pueblo (table 2-23). The specific locations of the wells are not given. All values are below current drinking water standards. Above the mine site, the Rio Paguate and the Rio Moquino contain 6 µg/L and 8 µg/L natural uranium, respectively. Downstream from the mine site at the Ford Crossing and the Paguate Reservoir, the Rio Paguate contains 239 and 236 µg/L natural uranium, respectively. Vegetation sampled on the reclaimed dumps within the mine site have shown radium-226 concentrations ranging from 0.16–1.59 pCi/g and uranium (natural) concentrations ranging from 0.76–7.13 µg/g. More detailed information on the flora is available in the report. The report provides discussion of the surface-water and groundwater hydrology and reports some major and trace element data for the two streams that cross the site and pits within the mine site. Table 2-28 reports major, minor, and trace element data for a series of 15 close-in monitoring wells around the site where the dissolved constituents exceed national standards. Sodium, sulfate, and manganese were the most common exceedances. Ra-226 exceeded the 15 pCi/L limit in one well about 1,100 ft west of the South Paguate pit.

U.S. Environmental Protection Agency, 1975a, Water quality impacts of uranium mining and milling activities in the Grants Mineral Belt, New Mexico: Dallas, Texas, U.S. Environmental Protection Agency Report EPA-9O6/9-75-002, 188 p. This report is available through *http://nepis.epa.gov* using “906975002” in the search box.

NOTE: Following an 18-page introduction, this report consists of two components: (1) “Impacts of uranium mining and milling on surface and potable waters in the Grants Mineral Belt, New Mexico” by the National Enforcement Investigations Center, Denver, Colo. and Region VI, Dallas, Tex.; and (2) “Summary of ground-water quality impacts of uranium mining and milling in the Grants Mineral Belt, New Mexico” by Kaufman, Eadie and Russell. The first report is listed separately below as U.S. Environmental Protection Agency (1975) and the second is listed herein as Kaufmann, Eadie, and Russell (1975). The summary and conclusions for the combined reports (pages 2–10 of the introductory section) provide important information about the status of mine and mill impacts in the GMB in the mid-1970s. Appendix C of the first report gives analytical data in four tables: (1) dissolved gross alpha, dissolved Ra-226, and total uranium in 134 water samples; (2) copper, iron, arsenic, and cobalt in eight selected samples from the first set; (3) molybdenum, sodium, selenium, vanadium and manganese analyses in 134 samples; and (4) TDS and other major analyte data for an additional set of samples. Many sites have multiple sample dates. Many sample numbers in tables do not have site descriptors, but these are obtained by cross referencing to the other tables using the same sample numbers. Samples include mine waters from specific company mines, ion-exchange tailings bypass waters, seepage below tailings ponds, mine-site potable water supplies, injection-well feed, surface-water samples from Puerticito Creek, San Mateo Creek, Rio Puerco (actually the Puerco River), Rio Moquino, Rio Paguate, and Rio San Jose, Grants potable water, water from private wells from selected trailer parks and subdivisions (Zuni Trailer Park, Murray Acres, Broadview Acres in the Grants area), other individual residences in several towns, windmills, and some municipal tap waters. Major, minor, trace element, and radionuclide analyses were not performed for all samples.

U.S. Environmental Protection Agency, 1975b, Impacts of uranium mining and milling on surface and potable waters in the Grants Mineral Belt, New Mexico: U.S. Environmental Protection Agency Report EPA/330/9-75/001, 85 p. See also USEPA, 1975a, where this report is incorporated into a longer document.

Abstract

On September 25, 1974 NMEIA requested EPA Region VI to conduct a survey of water-pollution sources and surface and ground-water quality in the Grants Mineral Belt. Studies conducted from February 24 to March 6, 1975 included industrial waste source evaluation, potable water sampling, and limited stream surveys by NEIC, and ground-water evaluations by ORP-LVF. This report presents the findings of analyses of surface water streams, potable water supplies, and industrial discharges. Appendix C contains raw data for all samples collected during the survey and analyzed by NEIC. The NEIC analysis, when combined with the ORP-LVF report, will present an overall study of water quality in the Grants Mineral Belt.

NOTE: The ORP-LV report referred to is Kaufmann, Eadie, and Russell (1975).

U.S. Environmental Protection Agency, 1988, Radon concentrations around the L-Bar uranium mill site: U.S. Environmental Protection Agency Report EPA/520/6-88-059, 20 p., available from *http://nepis.epa.gov/*

U.S. Environmental Protection Agency, 2003, Second five-year review report for the United Nuclear Corporation Ground Water Operable Unit, Church Rock, McKinley County, New Mexico: Dallas, Texas, United States Environmental Protection Agency Region 6, 456 p., *http://www.epa.gov/superfund/sites/fiveyear/f03-06005.pdf*.

NOTE: This comprehensive report provides useful information about the operational history of the site, geology and hydrology of the site, sources and pathways of contamination of alluvial and bedrock aquifers, descriptions of a major spill in 1979, remedial responses and performance, geochemistry of the groundwater contaminant plumes, site-specific cleanup levels for all contaminants, analytes considered as surrogate indicators of water contamination, plume migration rates, evidence for natural attenuation, and geochemical and radiochemical data for several monitoring wells. Attachment B provides 249 pages of groundwater geochemical data for several wells and Attachment C provides time-series graphs of chemical constituent data for these wells.

A short summary of the status of the Church Rock mill and tailings Superfund site through 2010 can be found at: *http://www.epa.gov/earth1r6/6sf/pdffiles/0600819.pdf*.

U.S. Environmental Protection Agency and U.S. Army Corps of Engineers, 2007, Abandoned uranium mines on the Navajo Nation: Navajo Nation AUM Screening Assessment Report and Atlas with Geospatial Data: Part1, screening report, and Part 2, atlas are available in 12 separate pdf files at *http://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/3dc283e6c5d6056f88257426007417a2/8ed3f74d2f55b845882573f400787a8e!OpenDocument*

NOTE: This document describes the results of extensive studies of abandoned uranium mines (AUM) on the Navajo Nation. The Navajo Nation was divided into six AUM regions. The Eastern AUM Region (fig. 6, index map) includes much of the western part of GMB. The study describes four exposure types: air pathway, soil exposure, groundwater pathway, and surface-water pathway. In the Eastern AUM area, 103 mine sites were identified and numerical scores for each pathway estimated and a combined score calculated (table 9). Part 1, pages 66–77, shows maps of the Eastern AUM region with an index map (fig. 49) and 11 detailed maps that show locations of abandoned uranium mines (as point features and as larger areas occupied by mine waste), uranium mill and reclamation sites (as defined bounded areas), buffers around mine sites at 200 ft, 0.25 mi, 1 mi, 4 mi, and 15 mi, structures within 1 mi of a site, wells within 4 mi of a site and permanent and intermittent streams. The included areas extend from the Grants and Bluewater mill reclamation sites (off the Navajo Nation) near Milan north and west to mine sites just east of Gallup.

The mine features in the Eastern AUM include 53 portals, 4 prospects, 44 rim strip/pits, 36 “vertical,” and 6 waste piles. Figure 5 in Part 2 (Atlas) shows uranium production by AUM region and mines. The vast majority of production on the Navajo Nation was in the Eastern AUM (a little over 100,000,000 pounds U_3O_8 out of about 118,000,000 pounds U_3O_8 for the whole Navajo Nation).

U.S. Environmental Protection Agency, 2010a, Grants mining district, New Mexico, draft five-year plan: Dallas, Texas, U.S. Environmental Protection Agency, Region 6, 53 p. *http://www.epa.gov/earth1r6/6sf/newmexico/grants/nm_grants_index.html*

U.S. Environmental Protection Agency, 2010b, Assessing uranium contamination in the Navajo Nation: U. S. Environmental Protection Agency, Region 9: Superfund. Report index page and online access available at: *http://epa.gov/region9/superfund/navajo-nation/index.html*

Van Metre, P.C. and Gray, J.R., 1992, Effects of uranium mining discharges on water quality in the Puerco River basin, Arizona and New Mexico: Hydrological Sciences Journal, v. 37, no. 5, p. 463–480. The report may be available through a library subscription at *http://pdfserve.informaworld.com/169270__918129201.pdf*

NOTE: This paper evaluates some aspects of the impact of mine dewatering and the 1979 accidental tailings spill on the Puerco River in the western part of the GMB not evaluated by Gallaher and Cary, 1986. The authors graph the time series changes in dissolved alpha and beta, suspended alpha and beta, radium, uranium, molybdenum and selenium in a 5-km reach of the Puerco River near Gallup for the period 1975 to 1990. Using discharge and water-quality data, they also estimate the total mass of uranium and gross alpha activity released during the mine dewatering and during the tailings pond spill. They also evaluate the mechanisms of natural removal of contaminants from solution by alluvial sediment and plant uptake. See Webb, Rink, and Favor, 1987, for data on plant uptake.

Van Metre, P.C., Wirt, Laurie, Lopes, T.J. and Ferguson, S.A., 1997, Effects of uranium-mining releases on ground-water quality in the Puerco River Basin, Arizona and New Mexico: U.S. Geological Survey Water-Supply Paper 2476, 73 p. *http://pubs.er.usgs.gov/djvu/WSP/wsp_2476.djvu*
Abstract

Shallow ground water underlying the Puerco River of Arizona and New Mexico was studied from 1988-91 to determine the effects of uranium mining on water quality. The Puerco River is an ephemeral stream that received effluent from uranium-mine dewatering operations from 1960 until 1961 and from 1967 until mining ceased in February 1986. Activities of dissolved gross alpha, gross beta, uranium, and radium and concentrations of dissolved molybdenum and selenium were elevated in streamflow as far as 140 kilometers downstream from the mines. Mine dewatering released an estimated 560 metric tons of uranium and 260 curies of gross alpha activity to the river. Additionally, on July 16, 1979, a tailings-pond dike failed and released an estimated 1.5 metric tons of uranium and 46 curies of gross alpha activity to the Puerco River. These mining related releases of radionuclides caused concern about the quality of water resources in the basin.

Ground-water analyses indicate that in 1989 a zone of larger concentrations of dissolved uranium in ground water extended about 65 kilometers downstream from where mine effluent entered the Puerco River to near the Arizona-New Mexico State line. Ground-water samples collected in 1990 and 1991 from immediately below the streambed had smaller concentrations of dissolved uranium than in 1989. Uranium-isotope ratios, which distinguish the source of uranium in mine- dewatering effluent from uranium that occurs naturally in the alluvial aquifer, indicate that larger concentrations of uranium in the alluvial aquifer are caused principally by mine-dewatering releases. Except for selected locations near the streambed, all ground-water samples collected from the alluvial aquifer downstream from Gallup, New Mexico, met the U.S. Environmental Protection Agency's maximum contaminant levels for gross alpha, gross beta, and radium and the proposed maximum contaminant level for uranium.

Alluvial ground water, however, has commonly exceeded the U.S. Environmental Protection Agency's secondary maximum contaminant levels for dissolved solids, iron, and manganese. Mass-balance calculations indicate that most of the uranium released by mining-related activities was not in solution in ground water in 1989. Geochemical modeling indicates that most alluvial ground water is undersaturated with respect to uranium minerals and that mine-dewatering effluent, when it flowed in the Puerco River channel, was probably undersaturated with respect to uranium minerals. Sorption of uranium on sediments is a likely fate of some of the uranium. Radionuclide concentrations and uranium-thorium isotope ratios in streambed and well-core sediments indicate that there are larger concentrations of radionuclides and excess uranium on near-channel sediments than on sediments away from the channel.

NOTE: The report gives natural uranium and uranium isotopic data (table 8) for water samples derived from mine effluent, regional and local background surface and groundwater, and samples collected downstream from Pipeline Arroyo (the mill-tailings receiving wash), a tributary of the Puerco River. Several sites have multiple samples collected in successive years. Figure 38 shows a plot of uranium concentration versus the U-234/U-238 activity ratio (A.R.) and indicates that water samples with an A.R. less than 1.3 show evidence of probable contamination from releases of mine waste and mill tailings.

Waring, G.A., and Andrews, D.A., 1935, Ground-water resources of northwestern New Mexico: U.S. Geological Survey Open-File Report, 161 p.

NOTE : This early report describes the geography and climate of northwestern New Mexico (primarily the San Juan Basin), the principal streams and rivers, the geology of the water-bearing formations, and the occurrence of shallow groundwater. Runoff data are reported for the San Juan River and its tributaries and for Bluewater Creek for 1913 through 1933. The text includes some well logs, well yields, and discussion of geochemical data. Wells near Grants, Thoreau, San Mateo, and

Crownpoint are discussed. Geochemical data are given for 52 water samples from springs, dug wells, drilled wells, and artesian wells. All but four samples were collected in October and November 1933. The analytes include total dissolved solids, concentrations of iron, calcium, magnesium, sodium and potassium (calculated), sulfate, chloride, fluoride, and nitrate, and total hardness as calcium carbonate (calculated). Locations of water samples are given by section, township, and range. Maps at a scale of about 1 in equals 7 mi provided at the end of the report show the location of springs and wells across the study area with selected parameters such as spring flow in gallons per minute, discharge of artesian wells, and depth of dug and drilled wells. No formation names are given for water-producing units in wells described in the text. A copy of the report is available from the library of the Office of the State Engineer in Santa Fe, N. M.

Webb, R.H., Rink, G.R., and Favor, B.O., 1987, Distribution of radionuclides and trace elements in ground water, grasses, and surficial sediments associated with the alluvial aquifer along the Puerco River, northeastern Arizona–A reconnaissance sampling program: U.S. Geological Survey Open-File Report 87-206, 105 p., *http://pubs.er.usgs.gov/djvu/OFR/1987/ofr_87_206.djvu*.

Abstract

The concentrations of gross alpha radioactivity minus uranium equaled or exceeded 15 picoCuries/L (pCi/L) in five of 14 wells sampled. The concentration of radium-226 plus radium-228 exceeded the primary water quality standard of 5 pCi/L in one well. The concentration of uranium exceeded a recommended limit of 0.035 mg/L in two wells. Perennial grass and sediment samples had low concentrations of radionuclides. The concentration of trace elements in the sediment samples was not unusual. Water quality of surface water in the Puerco River at Chambers varied as a function of the suspended sediment concentration. Concentrations of total gross alpha radiation fluctuated from 12 to 11,200 pCi/L. Concentrations of total gross beta radiation fluctuated from 45 to 4,500 pCi/L.

NOTE: This study reports data for sites in Arizona along the Puerco River, which drains uranium mining areas in the western part of the GMB. This river received uranium-mine dewatering effluent during the period from the 1950s to the mid-1980s and was the receptor of mill tailings from a July 1979 uranium mill tailings pond dam failure.

Webb, R.H., Rink, G.R., and Radtke, D.B., 1987, Preliminary assessment of water quality in the alluvial aquifer of the Puerco River basin, northeastern Arizona: U.S. Geological Survey Water-Resources Investigations 87-4126, 70 p., *http://pubs.er.usgs.gov/djvu/WRI/wrir_87_4126.djvu*.

Abstract

The quality of groundwater in the alluvial aquifer of the Puerco River basin, northeastern Arizona, was evaluated in order to assess potential contamination from uranium mining and milling operations in New Mexico. A total of 14 wells and 1 spring were sampled to determine if a contaminant plume of radionuclides or trace elements is present. The water is characterized by high dissolved solids with a median of 698 mg/l and high concentrations of alkalinity, sodium, and sulfate. Except for iron, manganese, and strontium, the concentrations of trace elements generally are below the applicable EPA and State of Arizona maximum contaminant levels. Gross alpha activity has a median of 27 picocuries/l and ranges from 4 to 42 picocuries/l. Uranium, which accounts for most of the gross alpha activity, has a median concentration of 19 micrograms/l and ranges from 1 to 38 micrograms/l. Twenty percent to 84% of the gross alpha activity was derived from other undetermined radionuclides. Other radionuclides, including radium-226 and radium-228, generally are not present in activities > 5 picocuries/l in the water. Statistical analysis of the

water quality data suggest that no contaminant plume can be defined on the basis of samples from existing wells. The contamination in the alluvial aquifer apparently does not change in the downstream direction along the Puerco River. The geochemistry of radionuclides indicates that most radionuclides from the uranium-decay series are immobile or only slightly mobile, whereas uranium will not precipitate out of solution but may be removed by sorption in the alluvial aquifer.

Webster, J.D., 1982, Petrography of some Ambrosia Lake, New Mexico prefault uranium ores, and implications for their genesis: U.S. Geological Survey Open-File Report 83-8, 75 p.. *http://pubs.er.usgs.gov/djvu/OFR/1983/ofr_83_8.djvu*.

Abstract

Petrographic and chemical study of prefault uranium ores from the Section 30, Section 30-west, and Section 23 mines in the Ambrosia Lake mining district, New Mexico has revealed that prefault ores commonly contain several authigenic phases including a new V-Ti mineral, which formed from destruction and remobilization of primary constituents in Ti-magnetites. High-grade ore samples also contain diagenetic clausthalite. Microprobe and SEM/EDS study indicate high U concentrations along the contacts of organic matter and surrounding detrital grains. The cores of the organic matter which fill pore spaces are commonly very low in U, as well as Si, Al, V, and Fe. Petrographic relationships as well as the chemistry and U distribution of the titanomagnetite grains and organic matter imply that the U was introduced to the sediments after the organic matter was emplaced and before the sediments were compacted.

Weimer, W.C., Kinnison, R.R., and Reeves, J.H., 1981, Survey of radionuclide distributions resulting from the Church Rock, New Mexico, uranium mill tailings pond dam failure: Washington, D.C., U.S. Nuclear Regulatory Commission, NUREG/CR-2449, 59 p.

Wentworth, D.W., Porter, D.A., and Jensen, H.N., 1980, Geology of Crownpoint Sec. 29 uranium deposit, McKinley County, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 139-144.

West, S.W., 1961, Availability of ground water in the Gallup area, New Mexico: U.S. Geological Survey Circular 443, 21 p., *http://pubs.er.usgs.gov/djvu/CIR/circ_443.djvu*.

Abstract

A thick succession of sedimentary rocks (about 6,000 feet) underlies the town of Gallup and crops out nearby. Although all the sedimentary rocks are capable of yielding some water, only a few units of sandstone and limestone yield water in sufficient quantity and of acceptable quality to be considered as sources of large supplies. The five stratigraphic units that are most productive of ground water form three aquifers, as follows: (a) the Glorieta sandstone and San Andres limestone, (b) the Westwater Canyon member of the Morrison formation and the Dakota sandstone, and (e) the Gallup sandstone. The Glorieta sandstone yields only small amounts of water to wells, except where it is intensely fractured. It probably contributes large amounts of water to the overlying, more permeable San Andres limestone by slow vertical leakage over large areas, as water is withdrawn from the San Andres. The San Andres limestone is discontinuous in the eastern part of the area, wedging out entirely a few miles east of Gallup. Its permeability varies widely because locally the permeability has been greatly increased by fractures and solution channels. On the north flank of the Zuni Mountains, near its outcrop, the San Andres yields as much as 1,100 gpm (gallons per minute) of water to wells. The specific capacity of wells that tap the aquifer formed by this Glorieta sandstone and San Andres limestone ranges from 0.1 to 29 gpm per foot of drawdown. In general, the water in the Glorieta sandstone and San Andres limestone is hard, because it contains much calcium. Both bicarbonate and sulfate anions are abundant. The chemical quality of the water deteriorates with increasing distance from the outcrop. The Westwater Canyon member of the Morrison formation and the Dakota sandstone form a single hydrologic unit extending from about 5 miles east of Gallup westward into Arizona. To the east they are separated by shale of the Brushy Basin member of the Morrison formation. The water-bearing properties of the Westwater Canyon member and the Dakota sandstone are ill defined, because few wells in the area tap either of them exclusively. The specific capacity of wells that tap the Westwater Canyon member, the Dakota sandstone, or both ranges from 0.02 to 2.3 gpm per foot of drawdown. Water in this aquifer generally contains less that 1,000 ppm (parts per million) of dissolved solids. The concentration of sodium and bicarbonate typically is high, and the concentration of sulfate is high locally. The Gallup sandstone is the principal aquifer in the immediate vicinity of, and to the north and south of, Gallup. It yields as much as 260 gpm of water to wells; the specific capacity of wells that tap the Gallup sandstone ranges from 0.08 to 4.7 gpm per foot of drawdown. In general, the water in the Gallup sandstone is potable, although in places it yields water high in iron, sulfate, and dissolved solids; the concentration of dissolved solids generally is less than 1,000 ppm. Because the yields of all the formations tested at Gallup are small, the town needs a better source of water. The San Juan River discharges annually a larger volume of water than is available from any other source in northwestern New Mexico. Gallup has applied for 15,000 acre-feet of San Juan River water a year, an average of 13,400,000 gpd (gallons per day). This water would be expensive, because about 50 miles of pipeline would be required to transport the water, and it would have to be lifted about 1,000 feet over a high ridge north of town. Despite the expense involved, at this time the San Juan River seems to offer the most secure long-term supply of water for the Gallup area.

West, S.W., 1969, Disposal of uranium-mill effluent by well injection near Grants, New Mexico: U.S. Geological Survey Open-File Report, 127 p.

West, S.W., 1972, Disposal of uranium-mill effluent by well injection in the Grants area, Valencia County, New Mexico: U.S. Geological Survey Professional Paper 386, p. D1-D28, *http://pubs.er.usgs.gov/usgspubs/pp/pp386D*.

Abstract

The geologic and hydrologic environment in the vicinity of the Bluewater uranium mill of The Anaconda Co. seems favorable for disposal of mill effluent into a deep well. Beds of sandstone in the Yeso Formation of Permian age, at depths of 950 to 1,423 feet, accept 200 to 400 gallons per minute of water under gravity flow. Water in the injection interval contained 3,900 parts per million of dissolved solids, of which 2,200 was sulfate. A thick interval of siltstone, anhydrite, and gypsum of low permeability in the upper part of the Yeso Formation separates the injection interval from the principal fresh-water aquifer in the Glorieta Sandstone and the San Andres Limestone of Permian age.

The disposal well was tested thoroughly during and following drilling, core samples were analyzed for porosity and permeability, and a set of geophysical logs was made to supplement other data. The well was completed by installing plastic-lined casing, cementing the annulus outside the casing, and gun perforating selected intervals of the casing.

After the well had been completed, it was tested by pumping water out at a rate of 100 gallons per minute for 18 hours. The specific capacity of the well was 0.119 gallons per minute per foot of drawdown. After the pumping tests, additional intervals were perforated, and all the rock intervals were fractured hydraulically. A 90-day injection test followed. Injection was intermittent at rates of

380 to 1,300 gallons per minute. The specific capacity of the well during injection was 3.6 to 3.8 gallons per minute per foot of drawdown.

Operational injection began in December 1960. The injection rate has varied considerably but has ranged generally from 200 to 400 gallons per minute. Water levels in the disposal well during injection ranged to within 10 feet of land surface from a static level about 250 feet below the surface. By the end of 1965, 500 million gallons of water had been injected into the Yeso Formation. The injected water contained an average of 13,200 parts per million of dissolved solids. Between January 1960 and December 1965, a total of 13.89 curies of uranium, 312.6 curies of thorium-230, and 0.612 curie of radium-226 were injected with the water.

The Anaconda Co. has monitored water levels in the disposal well and in seven nearby wells and has monitored chemical and radiochemical quality of water from another 27 wells and springs in the general area of the disposal well since 1959. Seasonal water-level fluctuations of 5 to 10 feet, in response to pumping for irrigation, were typical through 1961. Since the autumn of 1961, water levels have risen almost continuously, largely owing to reductions in pumping. Concentrations of sodium, sulfate, chloride, and nitrate increased from 1956 to 1962 in water from wells that tap the San Andres Limestone in the vicinity of the tailings pond, because of leakage from the pond before the disposal well was constructed. This contamination will mask any contamination from the disposal well (including contamination by radiochemical substances), even if water leaks from the disposal aquifer into the San Andres.

Injection data were used to determine the nature of the aquifer and to compute the transmissivity of the injection interval. Transmissivity values obtained from many test periods of different lengths ranged from 5,100 to 9,400 gallons per day per foot. The most reasonable value seems to be about 5,500 gallons per day per foot. The storage coefficient was computed to be $6.2X10^{-4}$. Computed using these values and the average injection rate of 190 gallons per minute, the pressure increase in the disposal well should have been 88 feet at the end of 5 years. However, the actual increase was only about 5 feet. The small pressure increase indicates that the hydraulic characteristics of the aquifer were not evaluated correctly or that water is leaking to other formations. The data do not clearly indicate which interpretation is correct.

When all the data are considered, well injection of the mill effluent appears to be the most satisfactory method of effluent disposal that is economically feasible.

NOTE: An earlier and more lengthy version of this report is given in West (1969).

Whitney, C.G., and Hatfield, D.B., 1985, Mineral and chemical compositions of authigenic clay minerals in the Morrison Formation, southern San Juan Basin, New Mexico: U.S. Geological Survey Open-File Report 85-0544, 18 p., *http://pubs.er.usgs.gov/djvu/OFR/1985/ofr_85_544.djvu*.

Introduction

The samples described in this paper are from drill cores collected during the Mariano Lake - Lake Valley Drilling Project, which was completed under the supervision of the U.S. Geological Survey in 1980. Lithologic descriptions of all cores and cuttings retrieved during drilling may be found in Huffman and others (1981a, b), Kirk and others (1981a, b, c, d), and Zech and others (1981a, b). Samples from sandstones, were taken from cores 1, 3, 4, 5, 6, and 7 (Sl, S3, etc.). The purpose for studying the clay minerals in these rocks was to gain an understanding of the regional and local variations in the mineralogy and geochemistry of authigenic and diagenetic clay minerals as an independent means of assessing the hydrogeochemical regime that was responsible for the emplacement of the sandstone-hosted uranium deposits in the southern San Juan Basin. An interim report on the results of this study is in Whitney (1985), and details of the paleohydrology (regional) and the ore-forming processes (local) are being prepared for publication in subsequent reports. The present paper contains the raw data set upon which the other reports are based. The samples used for this study are, in many cases, splits of the same samples examined by Steele (1984) and by Hansley (1983 and in press) in studies of the sandstone petrology and the study of heavy minerals.

NOTE: These detailed investigations of clays in drill cores may provide clues to identifying mine waste. The related papers may also provide information relevant to understanding the mine waste at the surface generated by mines near the drill holes in this study. See the paper itself for the citations in the abstract.

Wirt, Laurie, 1993, Use of $^{234}U/^{238}U$ as an environmental tracer of uranium-mining contamination in ground water: American Geophysical Union, v. 74, no. 43, supplement to EOS, p 298.

NOTE: This abstract describes the use of uranium and uranium isotopic data from studies of the effects of a 1979 uranium mill tailings spill that affected the Puerco River (New Mexico and Arizona). The author notes that in natural systems the $^{234}U/^{238}U$ ratio tends to increase as a result of alpha recoil damage to minerals and preferential leaching of the ^{234}U. Groundwater unaffected by mining in the Puerco River basin contains less than 13 µg/L and has a $^{234}U/^{238}U$ ratio between 1.5 and 2.7. In contrast, historic mine effluents in the drainage contained 1 to 8 mg/L uranium. Contaminated groundwater near uranium mines in the Puerco River drainage and ongoing mine effluent discharges from a nearby drainage sampled during the study show a $^{234}U/^{238}U$ ratio of 1:1. Water in the alluvium of the Puerco River is a mixture of seasonal recharge, sewage effluent, and historic uranium mine and mill releases. See Van Metre and others, 1997, cited herein.

Wirt, Laurie, Van Metre, P.C., and Favor, Barbara, 1991, Historical water-quality data, Puerco River basin, Arizona and New Mexico: U.S. Geological Survey Open-File Report 91-196, 339 p., *http://pubs.er.usgs.gov/djvu/OFR/1991/ofr_91_196.djvu*.

Abstract

In June 1988, the U.S. Geological Survey began a 5-year study of the occurrence and movement of radionuclides and other trace metals in ground water and surface water in the Puerco River basin in northeastern Arizona and northwestern New Mexico. Radionuclides and other trace metals occur naturally in water, rock, and sediments in the region; however, mining operations have enhanced their release to the Puerco River through discharges of mine effluents. Additionally, in 1979, the failure of a tailings-pond dike resulted in the largest known single release of water contaminated by uranium tailings in the United States.

This report presents selected historical water-quality data and a bibliography of selected references on the geology, hydrology, and water quality of the Puerco River basin. Historical water-quality data for surface water, ground water, and uranium-mine discharges for water
years 1942 through 1988 were compiled from information from Federal, State, and local agencies.

Sources of data (text from page 9)

Data for this report were compiled by the U.S. Geological Survey from information from Federal, State, and local agencies (table 1) and include data from the Storage and Retrieval (STORET) System of the U.S. Environmental Protection Agency (EPA). The STORET system contains water-quality data for surface water and ground water that have been submitted by participating Federal and State agencies. Analyses are identified by source with a code in the agency column of each table, and those codes are explained in table 1. Some data have been published in other articles and reports. Data that have been deliberately omitted include (1) data from the EPA Superfund investigation of the Church Rock Hine, (2) data from the City of Gallup water-supply well records

and sewage-treatment records, and (3) data from the National Uranium Resource Evaluation. Data from those sources were considered too voluminous to publish here but can be obtained readily from the appropriate agency.

NOTE- The New Mexico portion of the area for which data were tabulated in this study includes the western part of the GMB. Seventy-two surface water and 323 well and spring sites are included in the database. Water-quality data for mine-water discharges are given for the Church Rock I mine, Old Church Rock mine and the Northeast Church Rock mine, as are data for tailings-pond waters. Data sets are comprehensive, including physical parameters, major elements, nutrients, minor and trace elements, and radiochemistry. Total and dissolved analytes are reported for several elements. Pages 41–61 include selected references, many of considerable interest.

Wright, A.F., 1979, Bibliography of the geology and hydrology, San Juan Basin, New Mexico, Colorado, Arizona, and Utah: U.S. Geological Survey Bulletin 1481, 123 p., *http://pubs.er.usgs.gov/djvu/B/bull_1481.djvu*.

Abstract

The San Juan Basin of New Mexico, Colorado, and portions of Arizona and Utah has long been recognized as a source of varied natural resources. This bibliography of over 2,500 references has been compiled to assist physical-science researchers in their study and development of this region.

NOTE: This bibliography includes many non-USGS reports that may be helpful in understanding surface water and groundwater in the San Juan Basin region, including the GMB. Some reports may provide background geochemical data for groundwaters such as that by Dregne and Maker (1954).

Zehner, H.H., 1985, Hydrology and water-quality monitoring considerations, Jackpile uranium mine, northwestern New Mexico: U. S. Geological Survey Water-Resources Investigations Report 85-4226, 61 p., Text: *http://pubs.er.usgs.gov/djvu/WRI/wrir_85_4226.djvu*.
Plate: *http://pubs.er.usgs.gov/djvu/WRI/wrir_85_4226_plt.djvu*.

Abstract

The Jackpile Uranium Mine, which is on the Pueblo of Laguna in northwestern New Mexico, was operated from 1953 to 1980. The mine and facilities have affected 3,141 acres of land, and about 2,656 acres were yet to be reclaimed by late 1980. The intended use of the restored land is stock grazing. Fractured Dakota Sandstone and Mancos Shale of Cretaceous age overlie the Jackpile sandstone and a 200-ft-thick tight mudstone unit of the Brushy Basin Member underlies the Jackpile. The hydraulic conductivity of the Jackpile sandstone probably is about 0.3 ft/day. The small storage coefficients determined from three aquifer tests indicate that the Jackpile sandstone is a confined hydrologic system throughout much of the mine area. Sediment from the Rio Paguate has nearly filled the Paguate Reservoir near Laguna since its construction in 1940. The mean concentrations of uranium, Ra-226, and other trace elements generally were less than permissible limits established in national drinking water regulations or New Mexico State groundwater regulations. No individual surface water samples collected upstream from the mine contained concentrations of Ra-226 in excess of the permissible limits. Ra-226 concentrations in many individual samples collected from the Rio Paguate from near the mouth of the Rio Moquino to the sampling sites along the downstream reach of the Rio Paguate, however, exceeded the recommended permissible concentration of Ra-226 for public drinking water supplies. Concentrations in surface water apparently are changed by groundwater inflow near the confluence of the two streams. The altitude of the water tables in the backfill of the pits will be controlled partly by the water level in the Rio Paguate. Other factors controlling the altitudes of the water tables are the recharge rate to the backfill and the hydraulic conductivities of the backfill, alluvium, Jackpile sandstone, and mudstone unit of the Brushy Basin Member. After reclamation, most of the shallow groundwater probably will discharge to the natural stream channels draining the mine area. Groundwater quality may be monitored as: (1) ' Limited monitoring, ' in which only the change in water quality is determined as the groundwater flows from the mine; or (2) ' thorough monitoring, ' in which specific sources of possible contaminants are described.

Zielinski, R.A., Chafin, D.T., Banta, E.R., and Szabo, B.J., 1997, Use of ^{234}U and ^{238}U isotopes to evaluate contamination of near-surface groundwater with uranium-mill effluent: a case study in south-central Colorado, U.S.A.: Environmental Geology, v. 32, no. 2, p. 124-136.

Zielinksi, R.A., Otton, J.K., and Johnson, C.A., 2001, Sources of salinity near a coal mine spoil pile, north-central Colorado: Journal of Environmental Quality, v. 30, p. 1237-1248.