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Sources and controls of arsenic in the Santa Fe embayment, Santa Fe County, New Mexico

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Sources and Controls of Arsenic in the Santa Fe Embayment,

Santa Fe County, New Mexico

A Professional Project Report Submitted in Partial Fulfillment
of the Requirements for the
Degree of Master of Water Resources
Hydroscience Concentration
Water Resources Program
University of New Mexico
Albuquerque, New Mexico
July 2012

Karen M. Torres

Committee Approval

The Master of Water Resources Professional Project Proposal of Karen Torres

is approved by the committee:

Chair	Date
[signature]	7/9/12
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Abstract

Arsenic is a naturally occurring chemical element closely linked to geologic units and structural elements within aquifers of the Southern Espanola Basin in Santa Fe County, New Mexico. Public water systems are required by the US Environmental Protection Agency (EPA) to reduce arsenic levels below the Maximum Contaminant Level of 10 μg/L but this mandate does not cover private domestic wells. The New Mexico Environment Department (NMED) is aware of this issue and regularly conducts water fairs which allow homeowners to have a chemical analysis performed of their well water at no cost. A water fair conducted in 2009 collected over 300 samples of domestic well water which were analyzed for major anions/ cations, heavy metals and trace elements. These data are used in this study to perform a geospatial analysis of 200 domestic wells to investigate the arsenic occurrence in the Santa Fe Embayment of the Southern Española Basin.

The goal is to determine if conditions exist in which arsenic levels may exceed the EPA maximum contaminant level of 10 ppb. To benefit from recent geologic mapping and geochemical characterization the Santa Fe Embayment of the Espanola Basin was chosen as the project area. This allows incorporation of existing surface and groundwater chemistry and isotopic data into this study. Wells are plotted on geologic and aquifer maps for a regional view of structure, stratigraphy and aquifer type. Four zones of elevated arsenic, named Northwest, Southwest, South and Mountain Front respectively with unique Stratigraphic and structural features were identified.

Each zone is described by its geology, hydrology and geochemical attributes. Spatial and chemical correlations with respect to arsenic were evaluated for each area. Groundwater with elevated arsenic in the South and Mountain Front zones consistently occurs in the saturated volcaniclastic Espinaso Formation, especially if groundwater is saturated with chlorite minerals. In the Southwest zone, wells with elevated arsenic were not drawing water from the volcaniclastic unit but from Lithosome E of the Tesuque Formation, which contains volcanic clasts and reworked Espinaso Formation. The North Zone, which is composed of sand and gravels of Lithosome S of the Tesuque Formation, does not have the same relationship to volcanic rocks at depth. This area is highly faulted and exhibits an upward hydraulic gradient allowing for upwelling, which may be the source of arsenic and is consistent with previous findings. Desorption through ion exchange of arsenic with metal oxides may also contribute to elevated arsenic in groundwater. A combination of both up-welling and desorption is proposed which serves as controls for arsenic concentration in Lithosome S of the Tesuque Formation within the Santa Fe Embayment of the Espanola Basin.

Project Objective:

The objective of this project was to compare the location of arsenic rich water, defined as concentrations greater than 5 (μg/L), with respect to aquifer type, geologic structure and geochemistry through the use of GIS software. The goal was to evaluate whether clear relationships exist to predict the conditions in which arsenic levels may exceed the EPA maximum contaminant level of 10 ppb. This work furthers the investigation into sources of arsenic in groundwater, proposed by Los Alamos National Laboratories (LANL) and New Mexico Bureau of Geology and Mineral Resources (NMBGMR). A comparison to the regional geochemical analysis performed by NMBGMR in 2005 may fill in data gaps and represent change in water chemistry over time. Additionally this work will serve as an informational tool for property owners that rely on a domestic well for water supply.

Sources of Arsenic

Arsenic is a metalloid which exhibits both metallic and non-metallic chemical properties. Arsenic occurs naturally in igneous, sedimentary and metamorphic rock and is used industrially as a wood preservative. In the study area, arsenic is derived from geologic rather than anthropogenic origins. Geologic sources of arsenic include sulfide minerals, such as realgar, orpiment, and arsenopyrite, which form in hydrothermal veins. Sulfide minerals are common in basalt and gabbros and occasionally present in granites, andesites, ultramafic, mudrocks, limestone and dolostone rocks. (Raymond 1993) Typical concentrations of arsenic range from 1 to 13 ppb (table 1) in igneous and sedimentary rocks, streams and oceans.

Table 1: Typical Concentration of Arsenic in Rocks (after Drever)

Granite	Basalt	Shale	Sandstone	Limestone	Streams	Oceans
.002 ppb	.002 ppb	.013 ppb	.001 ppb	.001 ppb	.002 ppb	.003 ppb

Concentrations of arsenic in shales are 2 to 13 times higher than in other rocks and is attributed to the adsorption capacity of clay minerals in the mudstones, which attracts arsenic through ion exchange and is not attributed to the existence of arsenic bearing minerals within shale.

Federal Drinking Water Standards

On January 22, 2001 U. S. Environmental Protection Agency (EPA) adopted a new standard for allowable concentrations of arsenic in drinking water; which lowered the maximum contaminant level from 50 μg/L to 10 μg/L. This new standard became effective on February 22, 2002 but required public water systems to comply by January 23, 2006 (EPA 2001).

Health effects of arsenic are cancer of the bladder, lungs, skin, kidney, nasal passages, liver, and prostate. Non-cancer effects can include thickening and discoloration of the skin, stomach pain, nausea, vomiting; diarrhea; numbness in hands and feet; partial paralysis; and blindness (EPA webpage). In an economic analysis (EPA 2002) the EPA estimated that reducing arsenic from 50 ppb to 10 ppb would prevent the following:

More than 19 – 31 cases and 5 – 8 deaths from bladder cancer per year

More than 19-25 cases and 16 – 22 from lung cancer death

A number of cases of cancerous and noncancerous diseases such as skin cancer and heart disease.

These standards only apply to a public water system which are those that have 15 or more service connections or serves 25 people more than 6 months of a year. Domestic wells are not subject to EPA regulations.

Project Area

The study area is in the Santa Fe embayment within the southern Espanola Basin in central Santa Fe County, New Mexico. Almost all residential and commercial entities within and within close proximity of the City of Santa Fe receive water from a public or private water system. Outside of these service areas, approximately 9,200 residences are supplied by water from domestic wells (Torres, 2009). This study focuses on the areas served by domestic wells outside the Santa Fe metro area (Figure 2).

Regional Geology

The study area is in the Santa Fe embayment within the southern Espanola Basin. The Espanola Basin is a sub basin of the Rio Grande Rift (Figure 1). The embayment is bounded to the east by the Sangre de Cristo Mountains, to the south by the Galisteo Creek, to the west by the Pajarito fault and by Pojoaque Creek to the north. (Grauch 2009). The Rio Grande rift allowed the deposition of Quaternary and Tertiary fluvial sediments named the Santa Fe Group. These rift sediments largely lay conformably on late Tertiary volcaniclastic and fluvial sedimentary rocks as shown cross sections E (Figure 4) and F (Figure 6) (Koning 2010). Flood basalts form the quaternary Cerros del Rio Volcanic Field to the west overlay and intrude into Santa Fe Group units. Intrusive igneous rocks of the Cerrillos intrusion to the southwest tilt tertiary units up to 75°.

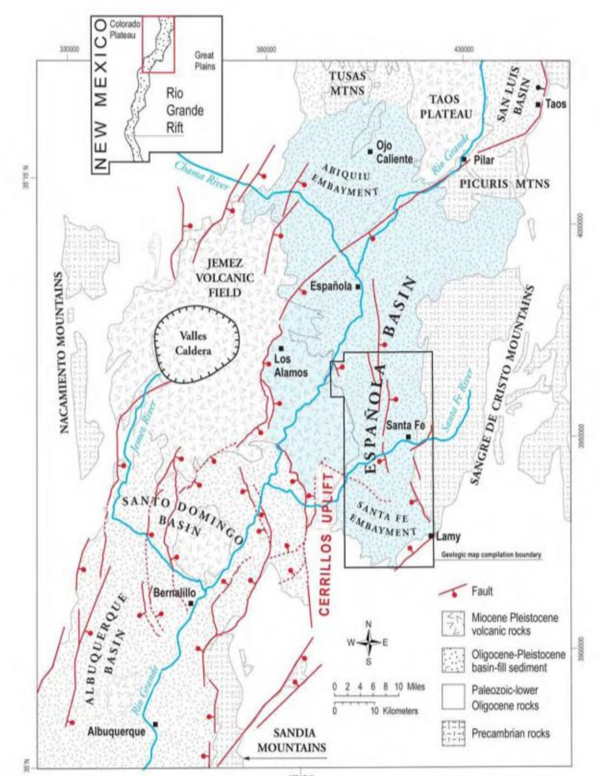


Figure 1 : Generalized Geologic Map of Rio Grande Rift Structural Features (from Johnson 2008) Outlined study area used in Johnson 2008 report and encompasses the study area of this report.

The Santa Fe embayment is a west-sloping topographic low with a prominent northwest plunging syncline of Santa Fe Group sediments called the Rancho Viejo hinge zone. (Johnson 2008) This zone marks the location where the Santa Fe Group sediments sharply thicken to the north. (Minor 2006) The distinct area of thin rift sediments is interpreted as a structurally high region and referred to as the Santa Fe Platform. (Koning 2010)

To the southwest, the Cerrillos uplift is a structural high mostly buried beneath the Cerros del Rio volcanic field and dips east-northeast ward. (Minor 2006). Uplifted tertiary sediments are exposed in the vicinity of La Cienega with the location and extent identified by remote sensing techniques. (Grauch 2009)

The basin is transected by the Agua Fria Fault Zone and several large individual faults. A synclinal fold plunges northwestward giving the basin a bowl shape. (Koning 2010). To the south the Rancho Viejo hinge zone marks the location where the Santa Fe Group sediments sharply thicken to the north (Minor 2009)

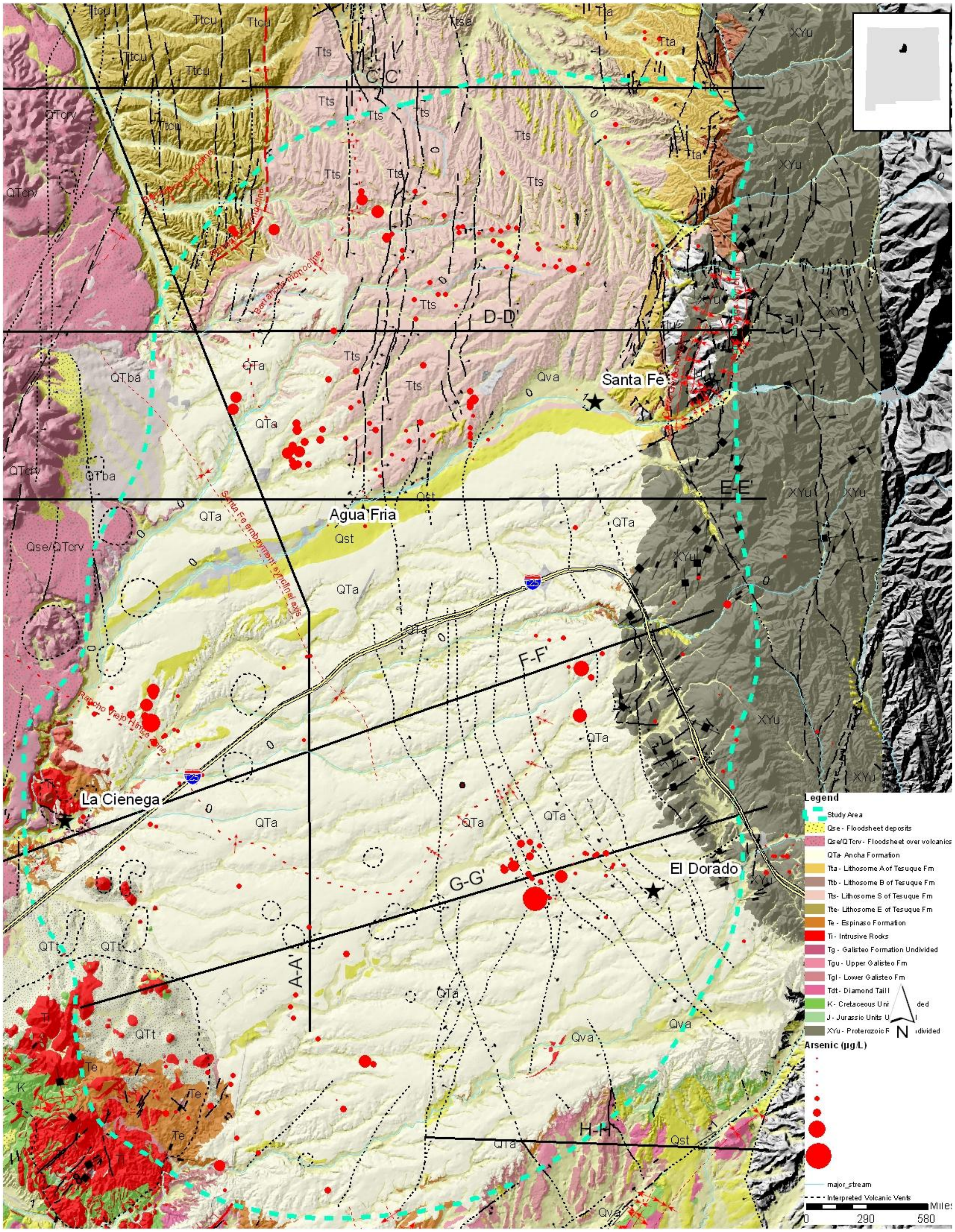


Figure 2: Map of Structural Features and Surface Geology within the Southern Espanola Basin (From Koning 2010) superimposed with study area and wells with elevated arsenic.

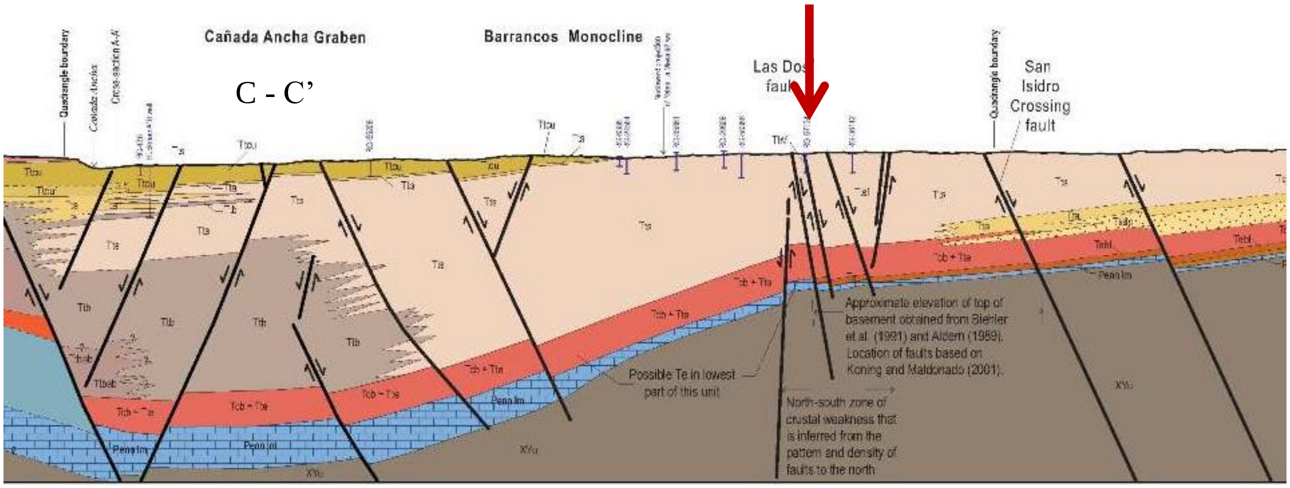


Figure 3:Cross Section C (from Koning 2010) transects north edge of Northwest zone from west to east. Approximate location of wells with elevated arsenic indicated with red arrow. Cross section also enlarged to highlight structure and stratigraphy.

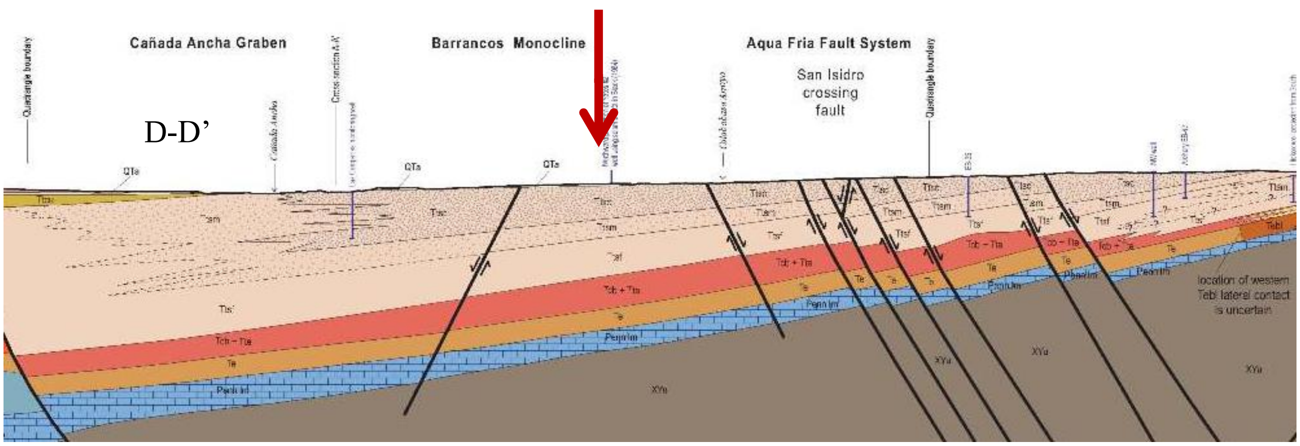


Figure 4: Cross Section E (from Koning 2010) transects the south edge of Northwest zone from west to east. Approximate location of wells in the south part of this zone with elevated arsenic indicated with red arrow. Cross section also inlarged to highlight structure and stratigraphy.

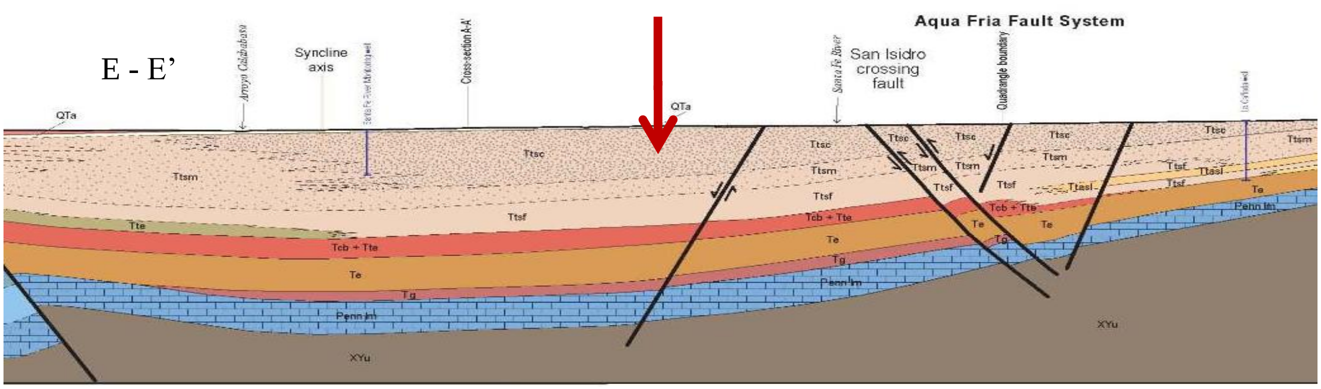
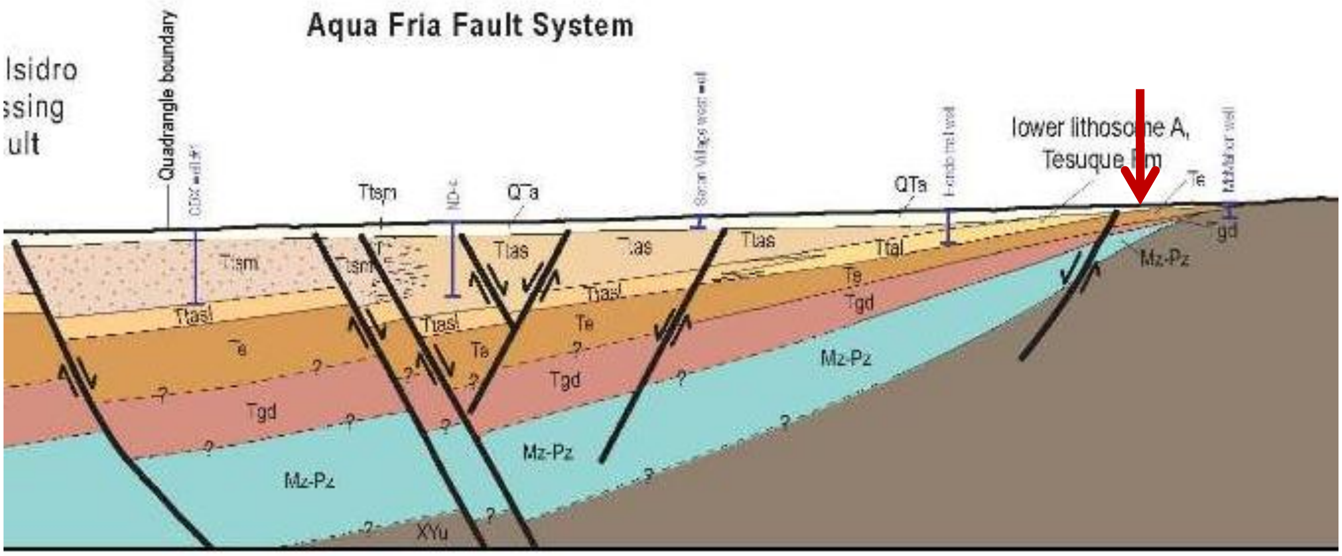


Figure 5: Cross Section D (from Koning 2010) transects middle of Northwest zone from west to east. Approximate location of wells with elevated arsenic indicated with red arrow. Cross section also enlarged to highlight structure and stratigraphy.

F - F' East: Near Mountain Front Zone



F - F' West: Near Southwest Zone

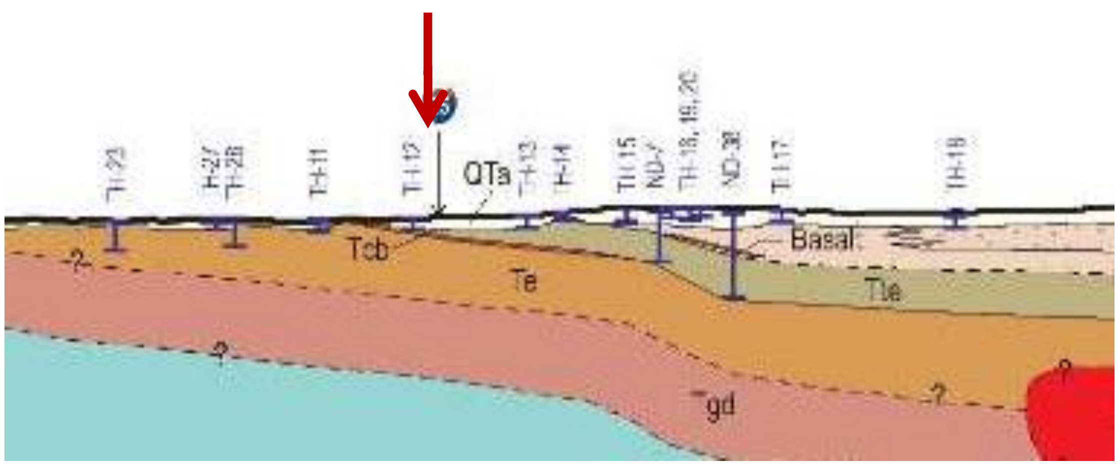
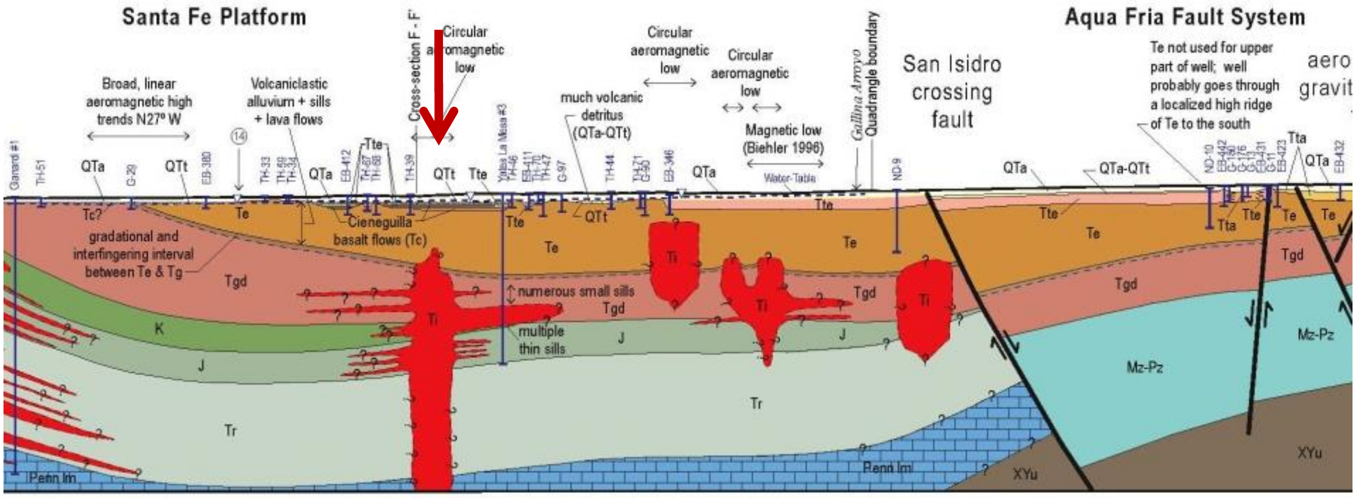


Figure 6: Cross Section F (from Koning 2010) transects the middle of Southwest zone and the upper Mountain Front zone from southwest to northeast. Approximate location of wells with elevated arsenic, within both zones, are indicated with red arrows. Cross section also inlarged for each zone to highlight structure, igneous features and stratigraphy.

G - G' West - South Zone



G - G' East - Mountain Front Zone

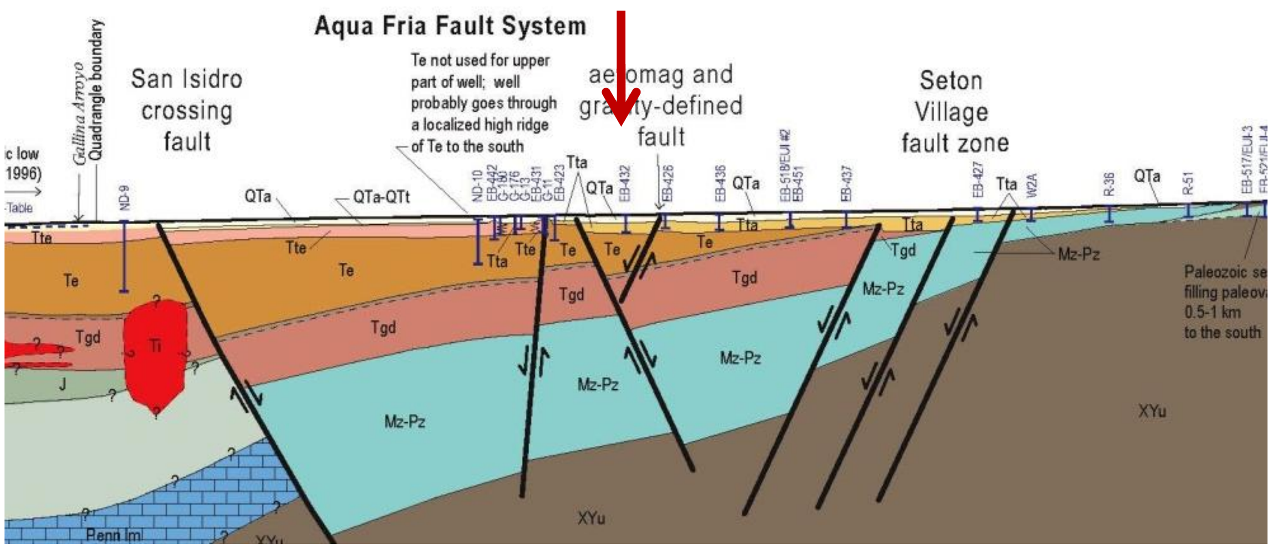


Figure 7: Cross Section G (from Koning 2010) transects the south margin of Mountain Front zone (top figure) and the middle of South zone (bottom figure) from southwest to northeast. Approximate location of wells with elevated arsenic, within both zones, are indicated with red arrows.

Regional Hydrogeology

Surface Water

The study area includes the Santa Fe River, Cienega, North Galisteo Creek and the Canada Ancha drainage areas (Figure 8). The Santa Fe River has perennial flow in the headwaters and the distal reach of Santa Fe River. The lower Santa Fe River has year round flow due to discharge of wastewater effluent from the City of Santa Fe Wastewater Treatment Plant.

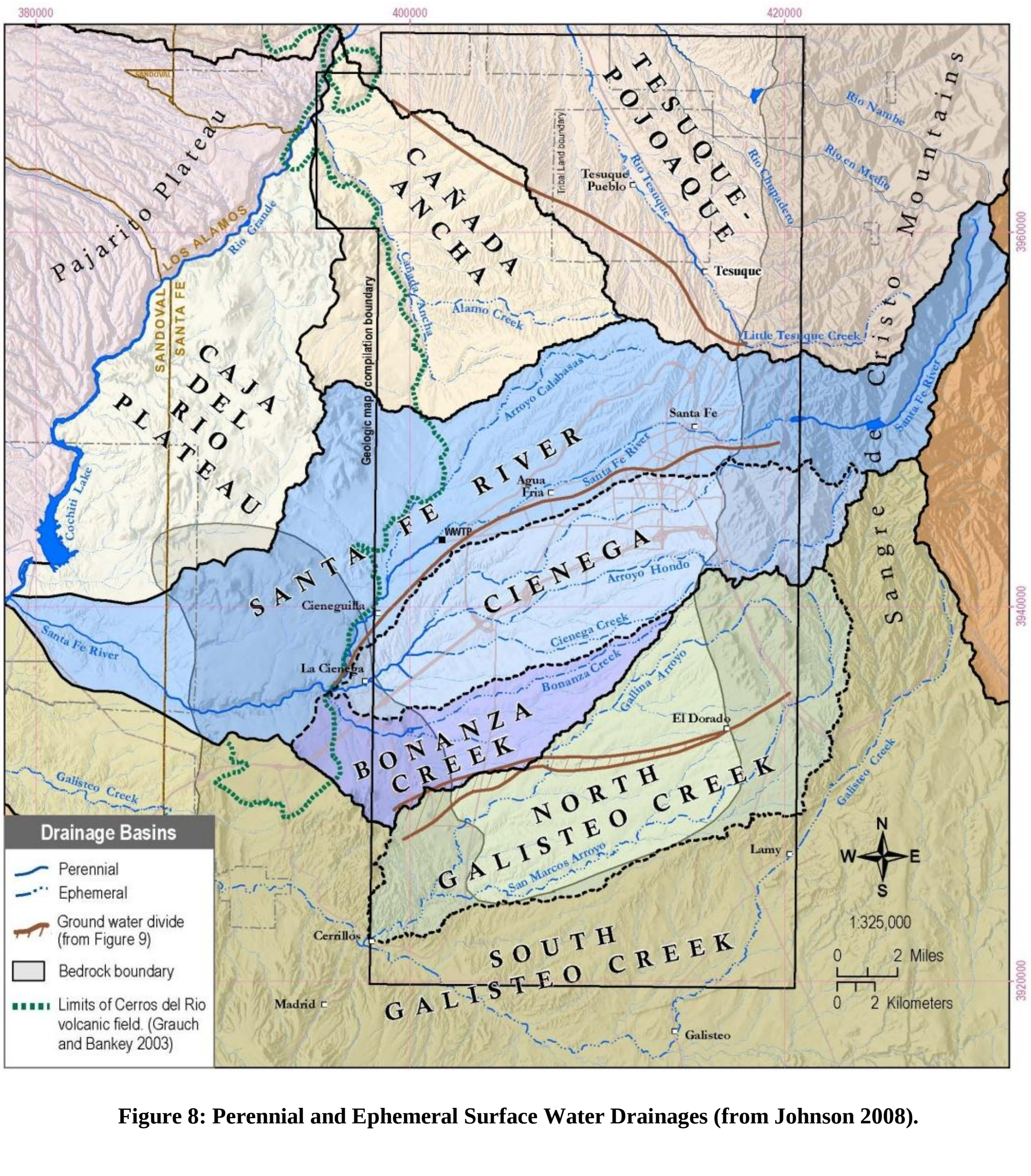


Figure 8: Perennial and Ephemeral Surface Water Drainages (from Johnson 2008).

The middle or urban section of the Santa Fe River between the headwaters and the wastewater treatment plan has no appreciable flows, with the exception of water released from the Municipal Reservoir and precipitation events. The Cienega drainage area has perennial flow in upper Arroyo Hondo, Guicu Creek and La Cienega Creek due to the discharge of groundwater via springs and seeps. Spring flow decreases seasonally due to irrigation withdrawals, seepage and evapotranspiration.

Major ephemeral drainages include Arroyo Mascaras, Alamo Creek, Arroyo de los Chamisos and the Arroyo Calabasas; which primarily contribute storm flows (Gant 2010).and in the lower watershed, or discharge area. The North Galisteo Creek Drainage consists of two major ephemeral drainages, Gallinas Arroyo and San Marcos Arroyo which convey seasonal storm water toward the village of Cerrillos. The Canada Ancha drainage similarly is an ephemeral drainage system where Alamo Creek and Canada Ancha convey seasonal storm water to the Rio Grande

Groundwater

Groundwater flows to the southwest toward the discharge areas of the basin where the springs in La Cienega and San Marcos are located. Depth to water ranges from 10 to 600 feet with the primary aquifer being the Santa Fe Group Tesuque Formation with pre-rift sediments dominating outside the Rancho Viejo hinge zone. Recharge is largely mountain front with stream infiltration proximal to the headwaters. (Anderholm 1994; Moore 2008)

The direction of horizontal groundwater flow in the Santa Fe River Watershed is from east to west ultimately converging in the La Cienega and Santa Fe River above Cieneguilla. (Johnson 2008). Downward vertical gradients are observed near the mountain front and in the discharge area and are consistent with recharge zones. Upward gradients occur in wells completed in the Tesuque Formation on the west side of the basin where water is discharged into the Rio Grande (**Figure 10**).

NMBGMR (Johnson 2008) defined three groundwater flow units based on recharge flow and discharge. Groundwater in the Rio Grande Unit flows from the west face of the Sangre de Cristo Mountains northwest and southwest to the Rio Grande (Figure 10). The La Cienega unit flows from the mountain front south of the City of Santa Fe to La Cienega Springs. The Galisteo groundwater unit captures recharge from the southwest face of the Sangre de Cristo Mountains. Water flows to the southwest and discharges into San Marcos Arroyo. (Johnson 2008) These flow units are hydrologically connected where groundwater pumping in one unit can affect an adjacent unit.

Aquifers

Though fractured Precambrian, igneous and metamorphic rocks serve as productive aquifers within the study area, only sedimentary units will be focused on. Sedimentary units are broken up into broad categories of rift and pre-rift units. Rift sediments were deposited as a result of the Rio Grande Rift and pre-rift were deposited prior to that event.

Figure 9: Simplifed Statigraphic Units within the study area (after Koning 2010)

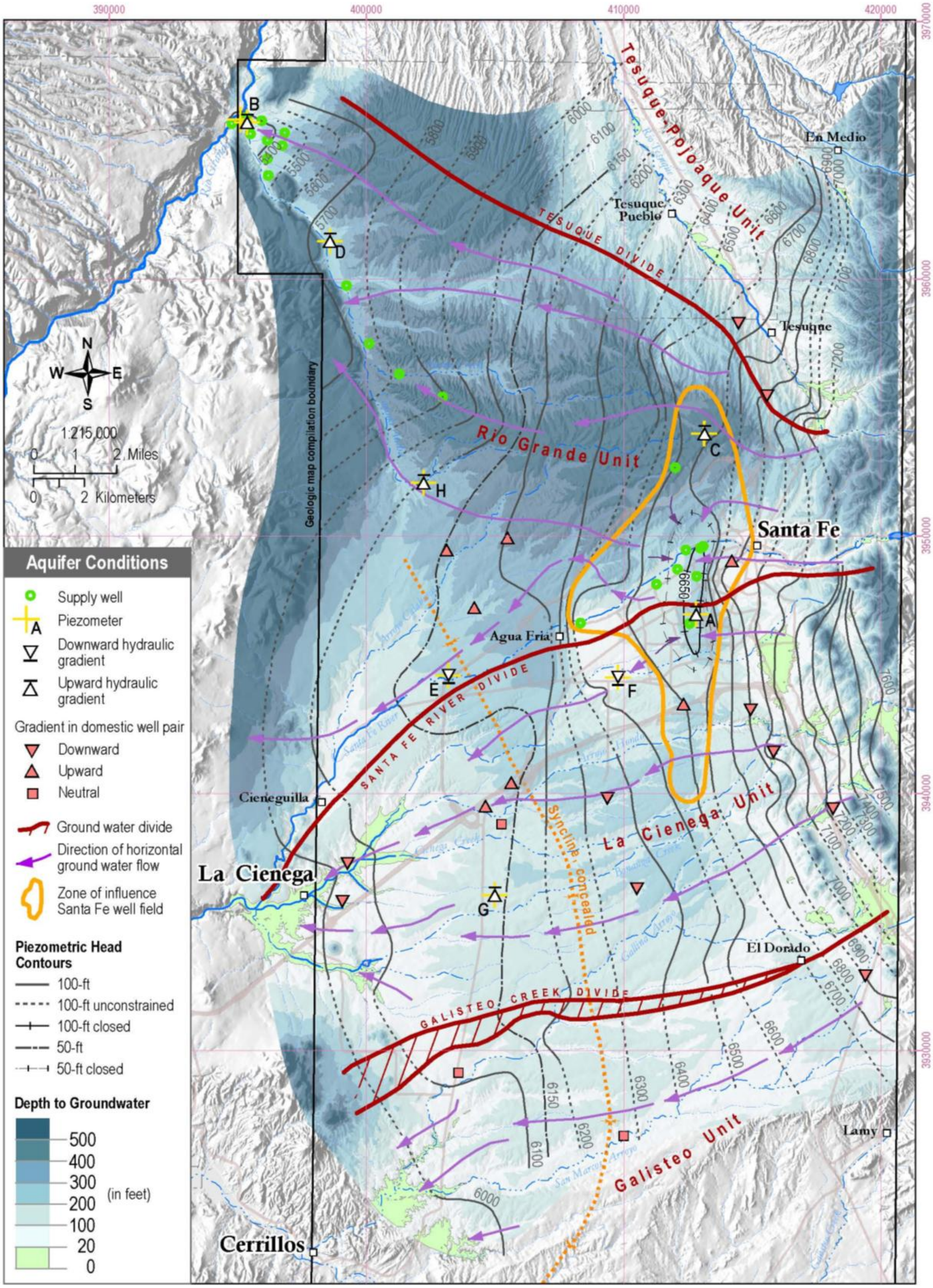


Figure 10: Horizontal groundwater flow, vertical gradients and potentiometric surface of the Southern Espanola Basin. Groundwater flow units are based on discharge to surface water and direction of recharge flow (from Johnson 2008).

Rift Basin Sedimentary Units

Ancha Formation (QTa)

The Ancha Formation is largely unsaturated with the exception of the southwest part of the basin where water discharges into La Cienega Springs. The Ancha Formation is upper Pliocene to lower Pleistocene in age and exists un-conformably over the Tertiary Espinaso and Galisteo Formations in the La Cienega Area. This unit is generally fine to course grained sand and gravels containing clasts originating from the Sangre de Cristo Mountains and ancestral Santa Fe River. (Koning 2005) Due to the potential for water storage this unit has been intensively studied (Koning 2005) but does not have a saturated extent to be considered a major aquifer in the study area.

Tesuque Formation (Tt)

Upper Oligocene through lower Pleistocene in age is composed of siliclastic sediments, siltstone and clay stringers. The formation has been subdivided into four lithofacies distinguished by composition, source area and paleocurrent. (Koning 2010) In the study area the dominant lithosomes are the course and finer grained S and E.

Lithosome S of the Tesuque Formation (Tts)

Lower to middle Miocene in age and associated with a large drainage originating from the Sangre de Cristo Mountains. Composed of pebbly sand channel- fill deposits and fine sandstone, siltstone and mudstone floodplain deposits. This unit is coarser-grained near the mountain front and near the axis of the alluvial fan. Higher water yields are associated with the coarser grained units with the less permeable sediments creating leaky confined conditions within this aquifer. Lithosome S gradationally overlies Lithosome A northward and Lithosome E southward. The maximum thickness of this unit is 7,900 feet (Koning 2010) (Grauch 2009).

Coarser-grained Lithosome S of the Tesuque Formation (Ttsc) - Medium to very course-grained sand and gravel from fluvial deposition.

Finer-grained Lithosome S of the Tesuque Formation (Ttsf) - Fluvial deposits of clay, silt and very fine to medium grained sand.

Lithosome E of the Tesuque Formation (Tte)

Upper Oligocene to lower Miocene in age t located in the southwest part of the Santa Fe Embayment. This unit is located below Lithosome S and has a general gray to brownish sandstone and siltstones. This lithesome contains clasts consisting of varying portions of basalt, latite and Cieneguilla Basanite. (Koning 2010) This unit conformably overlays the Espinaso Formation (Figure 9). Based on cross section F (Figure 6) (Koning 2010) the maximum thickness is estimated at 525 to 560.

Pre-Rift Sedimentary Units

Espinaso Formation (Te)

Upper Eocene to upper Oligocene in age Tertiary unit consists of volcaniclastics associated with volcanism of the Cerrillos Hills complex. (Koning 2010) Generally grey in color with reddish consolidated sandstone like units with grey finer material. Not generally considered a productive aquifer due to low yields and the occurrence of dry wells. The Espinaso is one of the primary aquifers outside of the Rancho Viejo Hinge. The Espinaso Formation has an extensive area of volcaniclastic debris surrounding the volcanic centers. This unit is thickest in the middle of the Santa Fe Embayment and thins to the north. In the study area the maximum thickness is estimated at 1,000 feet based on cross section F (Figure 6) (Koning 2010).

Upper Galisteo Formation (Tgu)

The upper unit within the thick fluvial Galisteo Formation is predominant in the southern edge of Espanola Basin. It underlies the Espinaso Formation and consists of tan to white sandstone with red, rose and gray-green mudstones (Koning 2010). Not a high yielding aquifer but more productive than the lower red, clay rich units.

Lower Galisteo Formation (Tgl)

Dark red to pink sandy mudstones, siltstones and fine arkosic sandstones. Poor yielding aquifer due to fine grained units but marginal production can be found within the sandstone units.

Recharge

Isotopic data can assist in understanding flow paths of younger or deuterium rich water associated with recharge versus older deuterium depleted groundwater. Composition of deuterium within the Southern Espanola Basin was analyzed and spatially defined by Johnson (2008). Ratios of δO^{18} to δH^2 using data from previous studies along with 50 samples collected in 2005 were compared to the meteoric water line developed by Anderholm (1994) Groundwater is enriched in deuterium at it approached the mountain front and nearby streams. A band of younger water transects ephemeral reaches of Arroyo Hondo, Canada Ancha and Cienega Creek. More depleted or older water is present to the north and northwest of the City of Santa Fe with smaller areas, with fewer data points, scattered to the southeast and southwest.

Recharge in the study area is attributed to subsurface flow via mountain front recharge and stream infiltration proximal to the mountain front. Stable isotopes of hydrogen and oxygen from possible sources of recharge to the Tesuque aquifer were measured by Anderholm in the late 1980's (Anderholm 1994). This study indicates recharge occurs primarily in the winter. Mountain front recharge is the most significant while arroyo channel recharge provides little to no contribution. Additionally groundwater in the Buckman area was isotopically depleted compared to other locations proximal to the mountain front which indicates older water that does not benefit from infiltration of modern water.

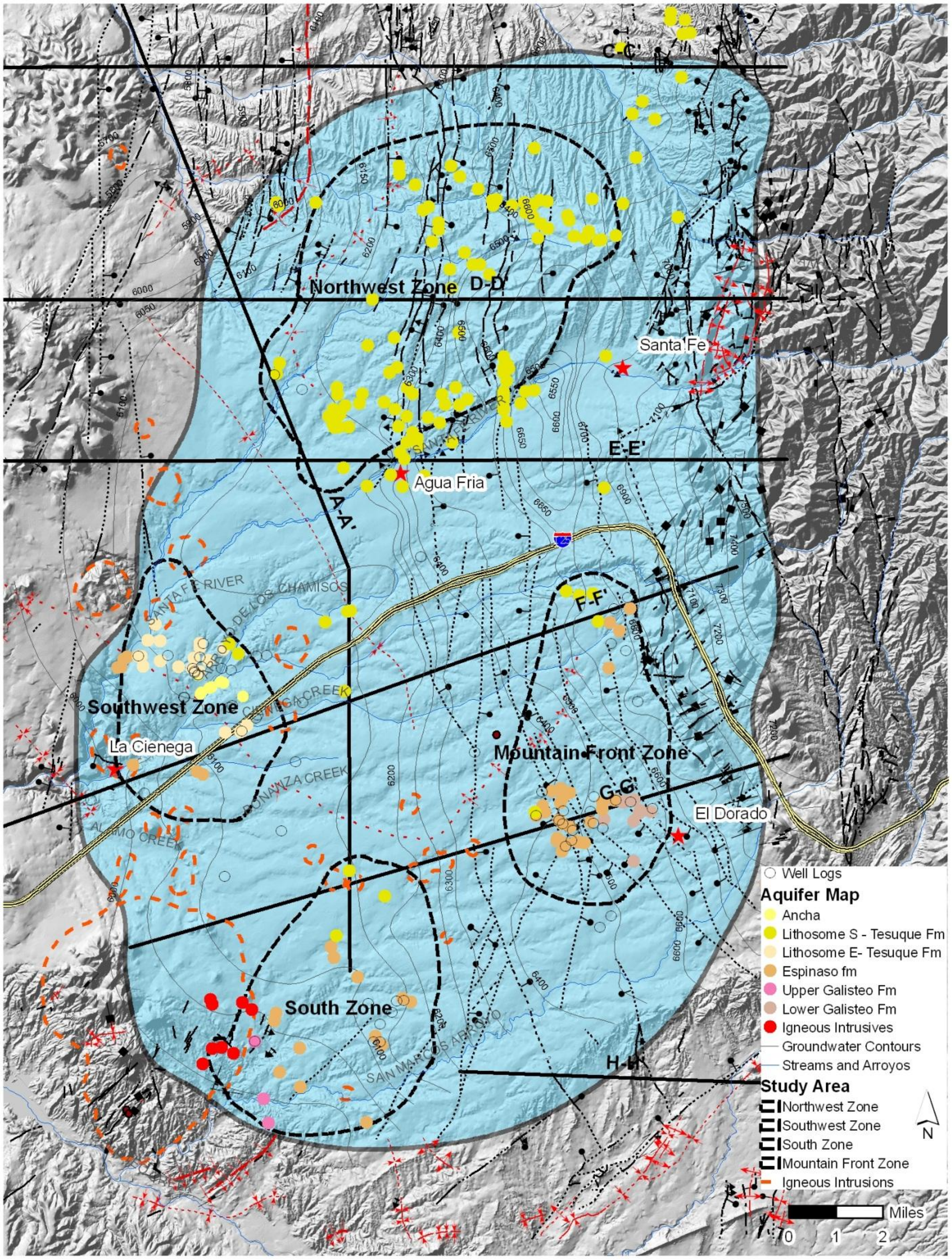


Figure 11: Domestic Wells in the Study Area characterized by aquifer

Moore in the early 2000's utilized temperature and bromide and chloride concentrations to characterize infiltration and recharge along Arroyo Hondo; which flows from the Sangre de Cristo Mountains southwest to La Cienega Creek. This study indicates focused recharge occurs only within the active channel within the upper reach of this drainage. (Moore 2008) Distal reaches did not contribute measurable recharge via infiltration.

Regional Aquifer Decline

The groundwater table is lowering in the study area is a result of groundwater pumping. Cumulative aquifer decline exceeded 150 feet in areas in 2009 within the influence of pumping of the City of Santa Fe wells. Groundwater contours are perturbed where withdrawals of groundwater are significant (Figure 10). This decline does not necessarily represent permanent dewatering of the basin as aquifer recovery is observed where diversion of groundwater is reduced.

NMOSE County Well and Jail Well piezometers (wells E and G from Figure 10 respectively) are outside the direct influence of the city wells but also show a decline of approximately 0.5 foot per year. Groundwater hydrographs from triple level piezometers indicate the shallow aquifer is declining at a greater rate than deeper aquifers. In one case the middle piezometers shows increasing water levels while the shallow piezometer is in decline. (Figure 12) Over 9,000 residences receive their water supply from domestic wells, but due to the low residential density, no observable aquifer declines are currently linked to this additional demand.

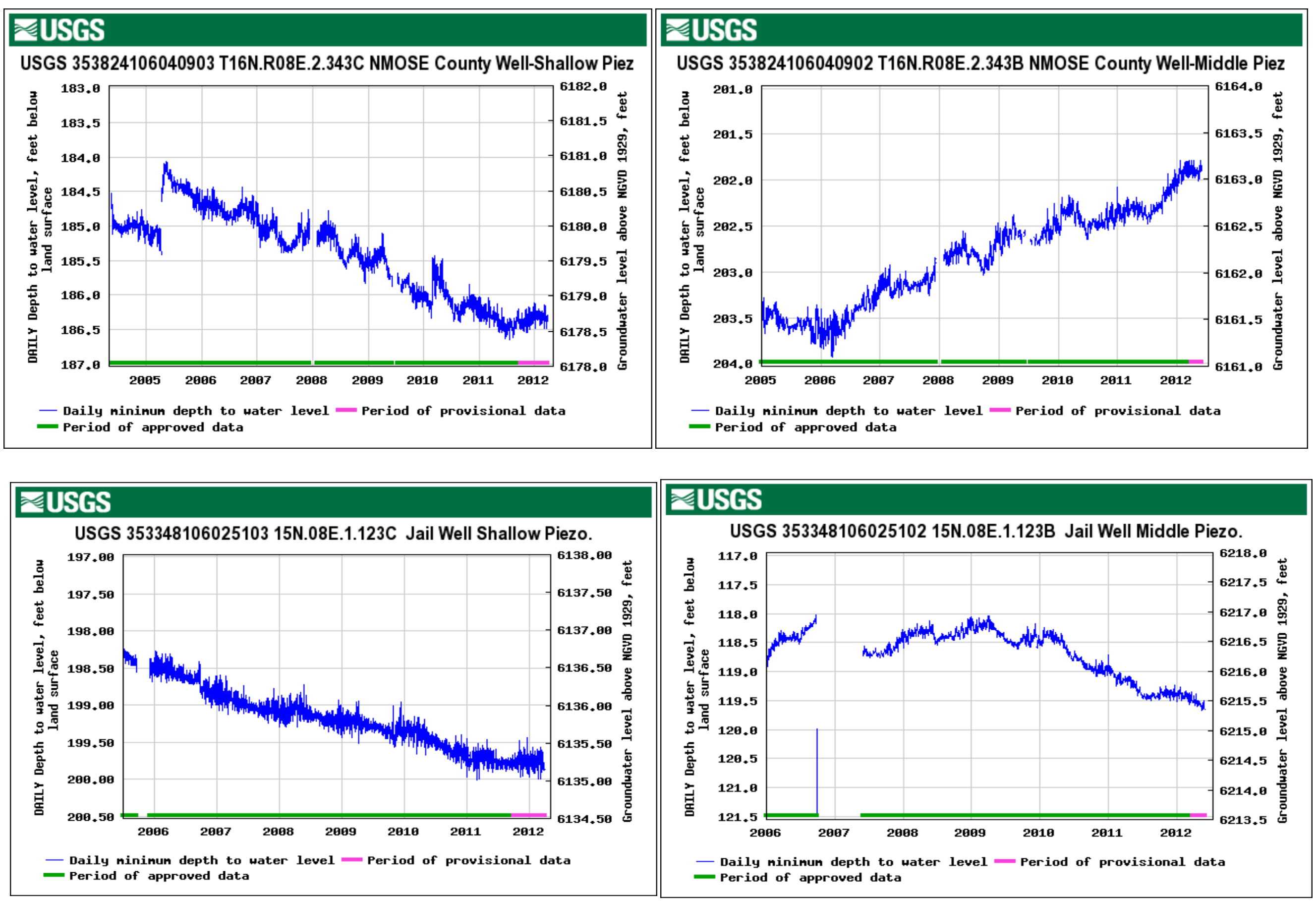


Figure 12: Shallow and Middle Piezometers in Southwest of Study Area.

Previous Work

Spegial and Baldwin (USGS 1963) did extensive geologic mapping and evaluation of water resources in the Espanola Basin in 1955 and 1956. Surface water discharge in the La Cienega area was indirectly measured and described the occurrence of springs in this location is due to shallow saturated course sand and gravels (Ancha Formation) overlying an impermeable volcanic unit.

Stable isotopes of hydrogen and oxygen associated with possible sources of recharge to the Tesuque aquifer were measured by Anderholm in the late 1980's (Anderholm 1994). This study found that recharge occurs primarily in the winter months within the mountain front while infiltration of water in arroyo channels provides little to no contribution. Additionally groundwater in the Buckman area (Northwest Zone of this study) is isotopically depleted compared to other locations proximal to the mountain front, indicating recharge is not occurring with modern water.

Through the use of hydrogen and oxygen isotopes Frost (1996) demonstrated that the age of water at La Cienega Springs is older than 1956 suggesting the source of spring water is not meteoric.

The geologic characteristics of the Ancha Formation (Figure 9) were described by NMBGMR in 2005 with the goal of understanding the hydrogeologic properties. The course grained gravel deposits associated with this unit have the potential for greater aquifer yield than the finer grained units of the Tesuque Formation. This study found the Ancha is hydrologically connected to the Tesuque Formation but is not saturated throughout the basin.

The USGS (Stonestrom 2007) studied infiltration of surface water in Arroyo Hondo, which drains to the southwest from the Sangre de Cristo Mountains to La Cienega Springs, found recharge to be focused in the streambed within the upper portion of the ephemeral reach.

These studies suggest that spring water in the La Cienega area is derived from older groundwater sources not recent precipitation or infiltration. Groundwater chemistry of the shallow aquifer up gradient of La Cienega Springs should be similar to spring water chemistry

Geochemical and mineralogical analysis of a core sample of Santa Fe Group sediments in the Westside of Albuquerque was performed by the USGS in 1996. (Stanton, 2001) Higher arsenic levels >10 ppb were associated with fine grained sediments. Arsenic bearing minerals were not present at detectable levels. Fission –track methods, which examined different minerals that attract arsenic, found an association with secondary iron-oxides which may exist as distinct grains or as coatings on mineral surfaces including clays.

Bexfield and Plummer (Welsh et al. 2002) identified two main sources and a lesser source of elevated arsenic in the Middle Rio Grande Basin. The primary sources are related to contact with volcanic rocks in the Jemez Mountains and mineralized deep water spatial coincident with major structural features. Arsenic in groundwater not originating from these primary sources is attributed to desorption. A positive correlation between pH greater than 8.5 and elevated arsenic was attributed to desorption of arsenic from metal oxides.

The east and central area of Middle Rio Grande Basin, described by Bexfield and Plummer, show variable arsenic concentrations similar to the lower Espanola Basin. Arsenic in the eastern mountain front area of the basin was positively correlated with molybdenum, boron, temperature, sodium; vanadium, chloride and potassium. High chloride levels in this zone are associated with older more mineralized water mixing with low arsenic water associated with recharge. Just west toward the Rio Grande there is a weaker correlation between chloride and a positive correlation with fluoride, boron, sodium, lithium and molybdenum, which is reported to be consistent with a source of deep, old water with elevated concentrations of sodium and minor constituents. They found that arsenic concentrations increase with depth.

A comprehensive geochemical characterization of the Southern Espanola Basin was conducted by the NM Bureau of Geology and Mineral Resources using water samples collected in 2005 and existing data. (Johnson, 2008) Three distinct areas of elevated arsenic were identified in the form of arsenic (V); the highest oxidation state. The proposed source of elevated arsenic in the shallow groundwater table originates from the upwelling of deep ground water and movement through fractured volcanic rocks at the base of the Tesuque Formation. Concentrations of arsenic correlated positively with pH, temperature, sodium, fluoride, boron and lithium and were spatially coincident with sodium-rich groundwater. A spatial association with elevated arsenic and the axis of a plunging syncline was noted and concentrations appear to be independent of depth.

Geologic Map of the Southern Espanola Basin (Koning 2010) is a collected work of 7.5 minute geologic quadrangles, created between 1999 and 2003 created as part of the STATEMAP program, incorporates recent interpretations of basin structure and stratigraphy. (Group sediments sharply thicken to the north (Minor 2009)

) Mapping of Santa Fe Group stratigraphy broke out the Tesuque Formation in the several lithosomes (Figure 9) based on source of sediment and paleocurrent.

Aeromagnetic and gravity data were gathered by the USGS in 1999 as an extension of the analysis performed in the Middle Rio Grande Valley. These data were used to interpret variations in the basin fill thickness, define major structural features, estimate basin floor composition, map the distribution of igneous intrusions and volcanic rock and locate concealed faults. (Grauch et al. 2009) These geophysical interpretations were integrated with geologic mapping of the Southern Espanola Basin (Koning 2010) and distinguished as interpreted faults and volcanic features.

In 2004 and 2009 samples from more than 400 domestic wells throughout the Santa Fe region were analyzed at Los Alamos National Laboratory. The results were compared to EPA – MCLs and distributed to well owners along with information of potential health risks for any exceedance. LANL suggested that in addition to deep upwelling, arsenic also may be released during desorption reactions with clay minerals and hydrous ferric oxide occurring along flow paths in shallow aquifers. Arsenic was positively correlated with pH, sodium, fluoride, lithium and boron.

Methods

This analysis was focused on groundwater geochemistry with the goal of understanding the distribution and source of arsenic concentrations in aquifers within the study area. This is accomplished by modeling chemical conditions contributing to arsenic in solution using traditional statistical and spatial methods. Use of spatial analysis software will assist in the correlation of arsenic concentrations to geologic features and aquifer chemistry parameters.

Sources of Data

Water chemistry data and maps compiled by NMBGMR in 2005 (Johnson 2008) for a study of the geochemistry of the Southern Espanola Basin serve as a key component. This study gave a regional view of water chemistry, groundwater flow and recharge elements.

In 2009 NMED partnered with Los Alamos National Laboratory (LANL) and Santa Fe County to conduct water fairs where 300 domestic well water samples were collected at residences served by domestic wells over a 3 day period. Homes were pre-screened for water treatment and filtering systems so samples could be taken at an appropriate point. The samples were analyzed for major anions/ cations, heavy metals and trace elements. (McQuillan, 2010). Additionally samples of water from 3 springs in the La Cienega area, collected in the fall of 2010, were used to represent spring discharge chemistry.

Well log data were obtained from the Office of the State Engineer through the WATERS web based database. The names and addresses of the residences who participated in the water fair were matched to location and names within the database. When a well log could not be located a nearby well was used to estimate the aquifer of the well sampled.

Annual groundwater sampling results from August 1999 to December 2011 for Monitoring Wells Nos. 1, 2 and 4 for the Caja del Rio Landfill provided by the Santa Fe Solid Waste Management Agency.

Geochemical Modeling

A general overview of the relationship of chemical groundwater properties relative to the location of elevated arsenic Concentrations provide a foundation for the conditions under which arsenic is present. Use of piper diagrams, correlation plots and geochemical modeling serve to identify ground water types and create a baseline for comparison of distinct elevated arsenic areas identified within the study area.

Piper diagrams were generated to identify the water type of facies within the study area. Water chemistries will be compared through correlation plots of arsenic versus HCO_3, boron, calcium, copper, iron, fluoride, lithium, magnesium, selenium, SO_4, uranium and zinc.

Geochemical modeling using PHREEQC (Parkhurst, 1995) software assisted in reconstruction of source minerals via a mass balance approach. (Drever, 1997) The wateq4f database was used for the model simulations which incorporates revised arsenic data from Archer and Nordstrom (2002).

Spatial Analysis

Utilizing ESRI Arc Map 9.3 with the Spatial Analyst 9.3 extension a shape file will be created indicating the location and quantity of arsenic and other chemical properties in the study wells. The ArcGIS Spatial Analyst Natural Neighbor tool is proposed to interpolate areas of varying concentrations of chemistry with respect to location.

Maps of varying concentrations of sulfate, total dissolved solids, alkalinity and calcium were created from the domestic well chemistry data using Arc Map Spatial Analyst Interpolation Tool. The natural neighbor interpolation formula uses concentrations of chemistry data at a well location and assigns weights based on distance and concentration. A value of the area between data points is interpolated to estimate a spatial trend. Use of a subset of local samples that surround a data point serves to smooth out the data. The benefit of this analysis is the ability to overlay other spatial data such as well locations, geologic units and structure to quickly identify spatially coincident features. The downside of this type of analysis is with sparse data concentrations may be interpolated incorrectly between data points resulting in an over or under estimate. Interpolated maps are used as a general overview to evaluate spatial trends not as the sole factor in understanding aquifer chemistry.

A point shape file of domestic wells sampled in the 2009 water fair was created based on GPS coordinates taken at the sampling locations. Locations were verified using the Santa Fe County Parcel Data Set to match well locations to sampling addresses. ESRI Grids with 10 meter by 10 meter cells were created from this data for fluoride, boron, sulfate, total dissolved solids, sodium, sulfate and chloride. These grids serve as a basis for maps to compare the locations of wells with elevated arsenic with changes in groundwater chemistry.

Aquifer map

The aquifer map have color coded wells representing shallow saturated geologic units that is the supply water to the domestic wells in this study (Figure **11**).Well driller's logs near areas of elevated arsenic were used to represent the aquifer type in additional to wells used by NMBGMR (Johnson 2008). Potentiometric surface contours developed in 2005 (Johnson 2008) were obtained from NMBGMR as a shape file and overlain on the aquifer map along with the location of well logs.

Regional Spatial Analysis

Arsenic concentrations in wells considered in this study within the study area, were plotted on a map of the regional geology map as red circles (Figure 2). The size of the circle indicates the arsenic concentration.

Wells with elevated arsenic clustered in highly deformed areas within regional fault zones and outside of these zones. The majority of wells are within the Rancho Viejo hinge zone, where the Santa Fe Group sediments sharply thicken, but also within the Cerrillos Uplift and the Santa Fe Platform structural features; discussed in the previous geology section. Geologic cross sections C - G from Koning 2010 (Figures 3 - 7) indicate varying stratigraphy where arsenic is elevated.

The same well location points were placed on the aquifer map (Figure 11) and overlain with major geologic structures, such as folds, faults and interpreted volcanic vents. Elevated arsenic is associated with the Espinaso, Ancha and Tesuque aquifers at opposite ends of the study area. Four zones of elevated arsenic were identified and labeled as Northwest, Southwest, Mountain Front and South which have unique geologic and aquifer properties. Partitioning the study area in this manor allows a more in-depth analysis of variations in geology, hydrology and chemistry unique to each zone.

Zonal Spatial Analysis

To evaluate the unique conditions for each zone, the geology, hydrology and geochemistry are described. Chemical data for sodium, calcium, sulfate, total dissolved solids and alkalinity as HCO_3 were used to map varying concentrations using spatial interpolation. The data form the basis for maps to compare groundwater chemistry to arsenic concentrations within each zone. Additionally piper diagrams and regression plots were generated to determine the groundwater facies and the magnitude of the linear correlation. Geochemistry was evaluated by the use of PHREEQ to calculate saturation indices of minerals within the zones.

Mountain Front Zone

44 wells are located in the Mountain Front Zone having the highest concentration of arsenic in the study area, ranging from 1 to 90 μg/L. This area is southeast of the City of Santa Fe primarily within the Eldorado Subdivision but also extends north to the Arroyo Hondo area.

Mountain Front Zone Geology

Located outside of the Rancho Viejo Hinge, this zone abuts and is underlain by exposed and buried Precambrian rocks of the Sangre de Cristo Mountains (Figure 13). Cross section F (Koning 2010) transects the northern margin to the southwest with the approximate location of wells indicated with a red arrow (Figure 5). Quaternary to Pennsylvanian sedimentary rocks are displaced by the northwest trending Agua Fria Fault Zone just and the Seton Village Fault and uplifted by the Proterozoic rocks of the Sangre de Cristo Mountains.

Cross section G (Koning 2010) which transects the southern part of this zone (Figure 6) illustrates the boundary of the Santa Fe Platform to the west. This structural high is outside of the major fault zones and is distinguished by the displacement of the sedimentary units. Where the Espinaso Formation is present outside of the Santa Fe Platform and the Rancho Viejo Hinge Zone is where the greatest arsenic concentrations within the study area are located. This formation is not present in the east and southeast side of the Mountain Front zone, where arsenic values are much lower.

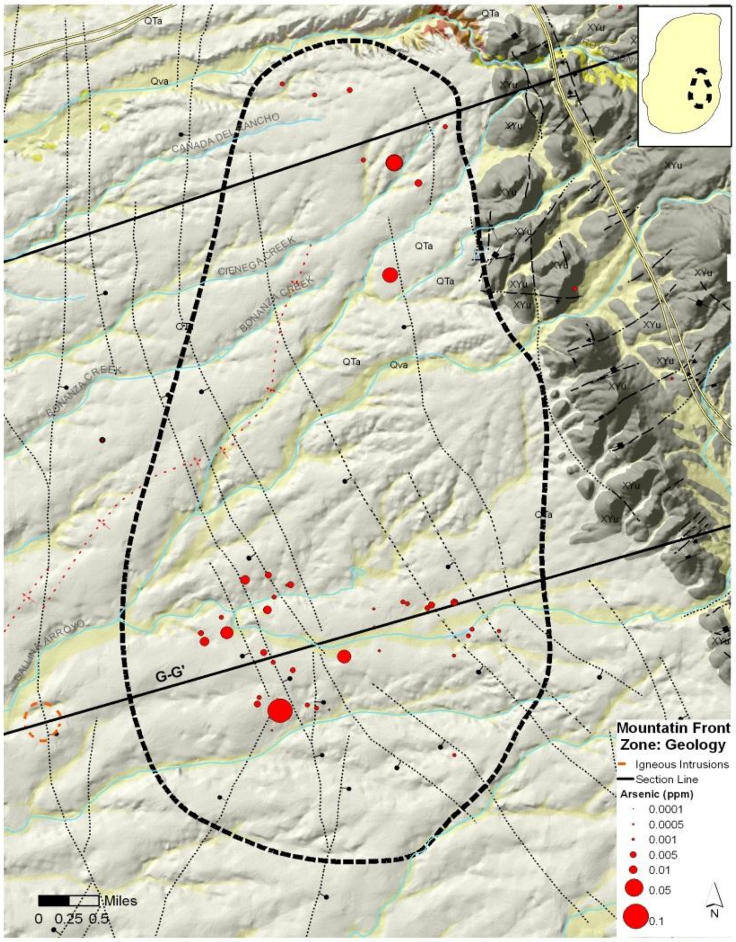


Figure 13: Geology of the Mountain Front Zone

Mountain Front Zone Hydrogeology

Principal water bearing formations for domestic wells in this area are the Tertiary Espinaso, Upper and Lower Galisteo Formations (Figure 11). East of this zone faulting has brought Pennsylvanian Madera Limestone close enough to the surface to supply water to one of the production wells for the Eldorado Area Water and Sanitation District. (Shoemaker 2001)

Wells completed in the crystalline granite, which is a moderate to high yielding aquifer for the area, were not included in this analysis. Water samples with arsenic concentrations greater than 5µg/L are completed in the Espinaso Formation.

Groundwater flow is to the southwest with depth to water ranging from 130 to 260 feet below ground surface. Recharge is attributed to the proximal mountain front with ephemeral streams conveying seasonal storm water. (McAda 1987)

Mountain Front Zone Geochemistry Analysis

Spatial Analysis

Sulfate values range between 6 and 10 ppm for higher values of arsenic and relatively depleted compared to lower arsenic concentrations (Figure 16). Alkalinity as HCO_3 is between 100 to 200 ppm increasing east toward the mountains. Elevated arsenic wells are generally more alkaline, with the exception of one well in the north portion of this zone (Figure 17). TDS is between the 300 – 400 mg/L range for most wells in this zone with increasing values toward the mountain front (Figure 18). This increase in TDS is attributed septic tanks within the fractured granite aquifer, which does not have the same capacity for dilution of contaminants as fluvial units. Low calcium levels (0 – 25 mg/L) are associated with higher arsenic with calcium concentrations increasing to the east (Figure 15)

Mountain Front Piper Diagrams

Piper diagrams or trilinear plots are a visual way to display water chemistry data and serve to classify water into a type or hydrochemical facies. They are made by plotting the proportions of calcium, magnesium and the sum of sodium and potassium on one triangular diagram with the proportions of alkalinity, chloride and sulfate on another. The information from points made on the two triangles is transferred to a quadrilateral diagram at the intersection of lines projected from each point.

Water from the wells located within the Mountain Front Zone were plotted onto a piper diagram. Water with higher arsenic levels and indicated with different colors representing various concentrations in ppm. The groundwater is a mixture of sodium and calcium carbonate facies. Wells with higher arsenic also have increased sodium and are classified as sodium carbonate water. Where arsenic is less than 0.05 µg/L the water has slightly more magnesium than elevated samples. (Figure 14)

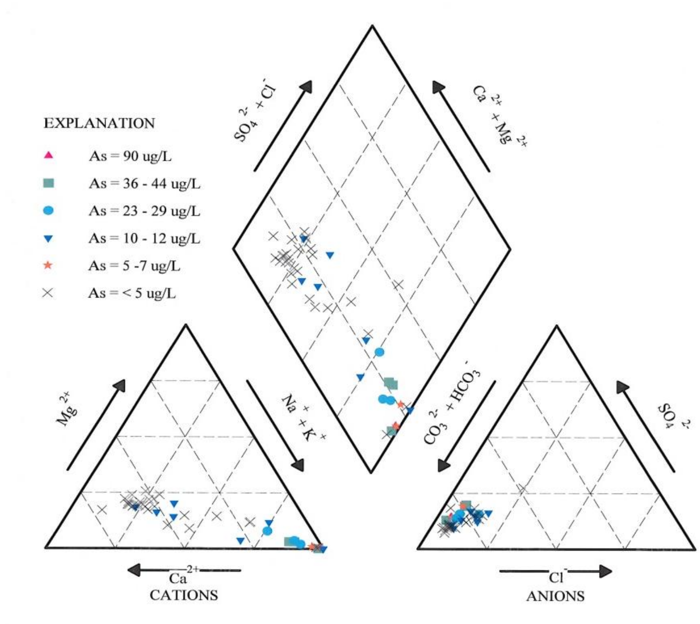


Figure 14: Mountain Front Zone Piper Diagram

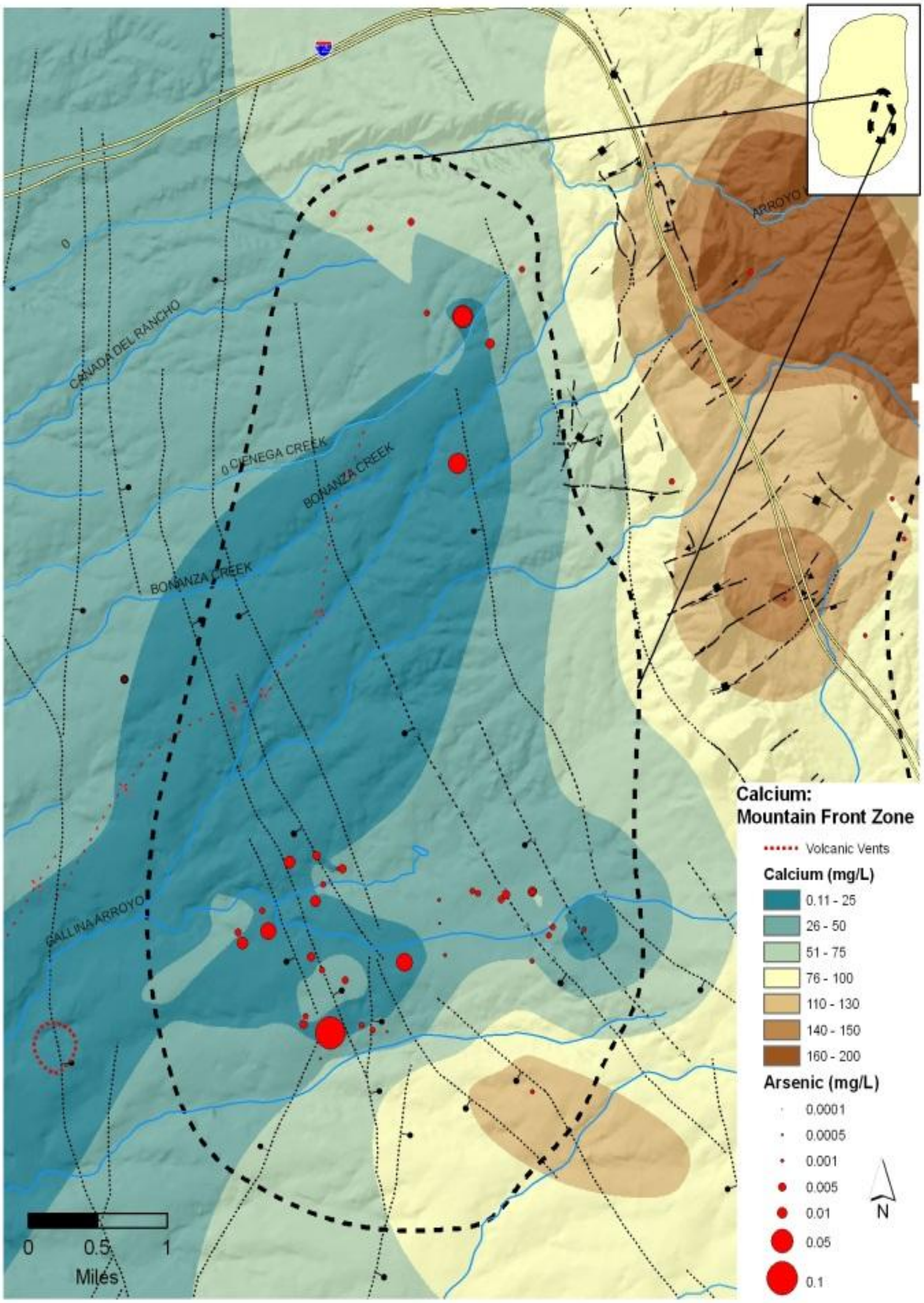


Figure 15: Mountain Front Zone Ca Concentrations

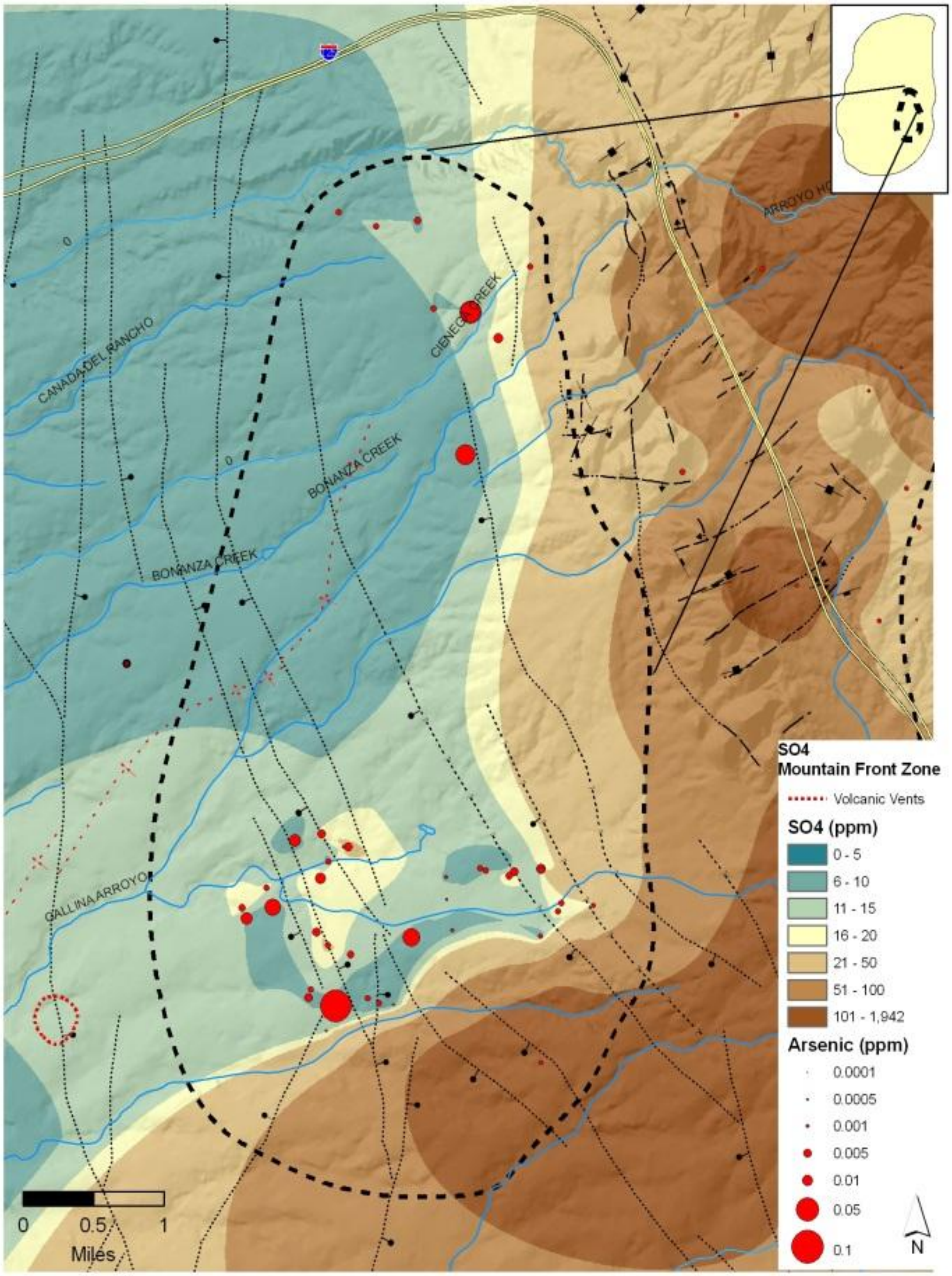


Figure 16: Mountain Front Sulfate Distribution

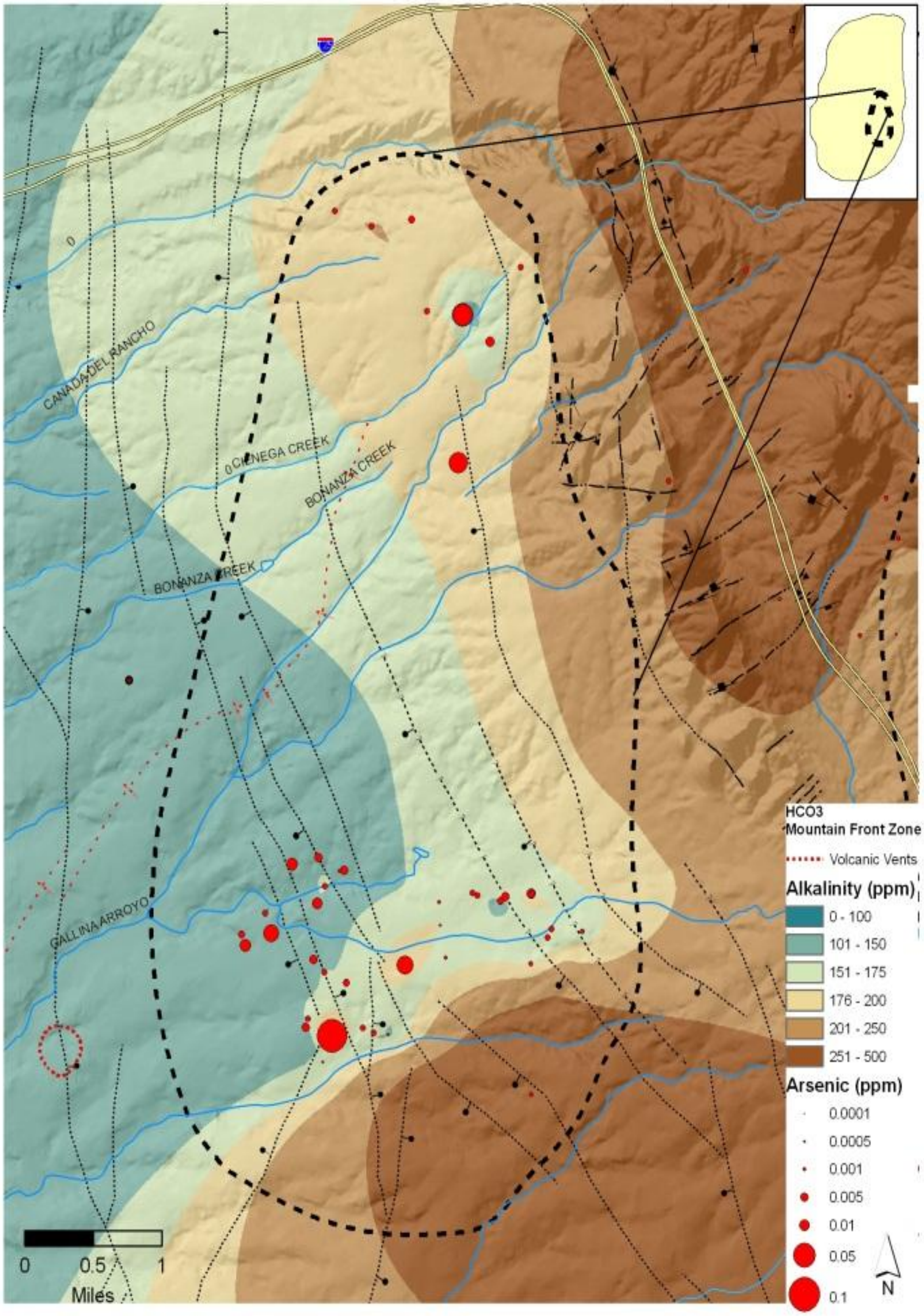


Figure 17: Mountain Front Zone HCO_3 Concentrations

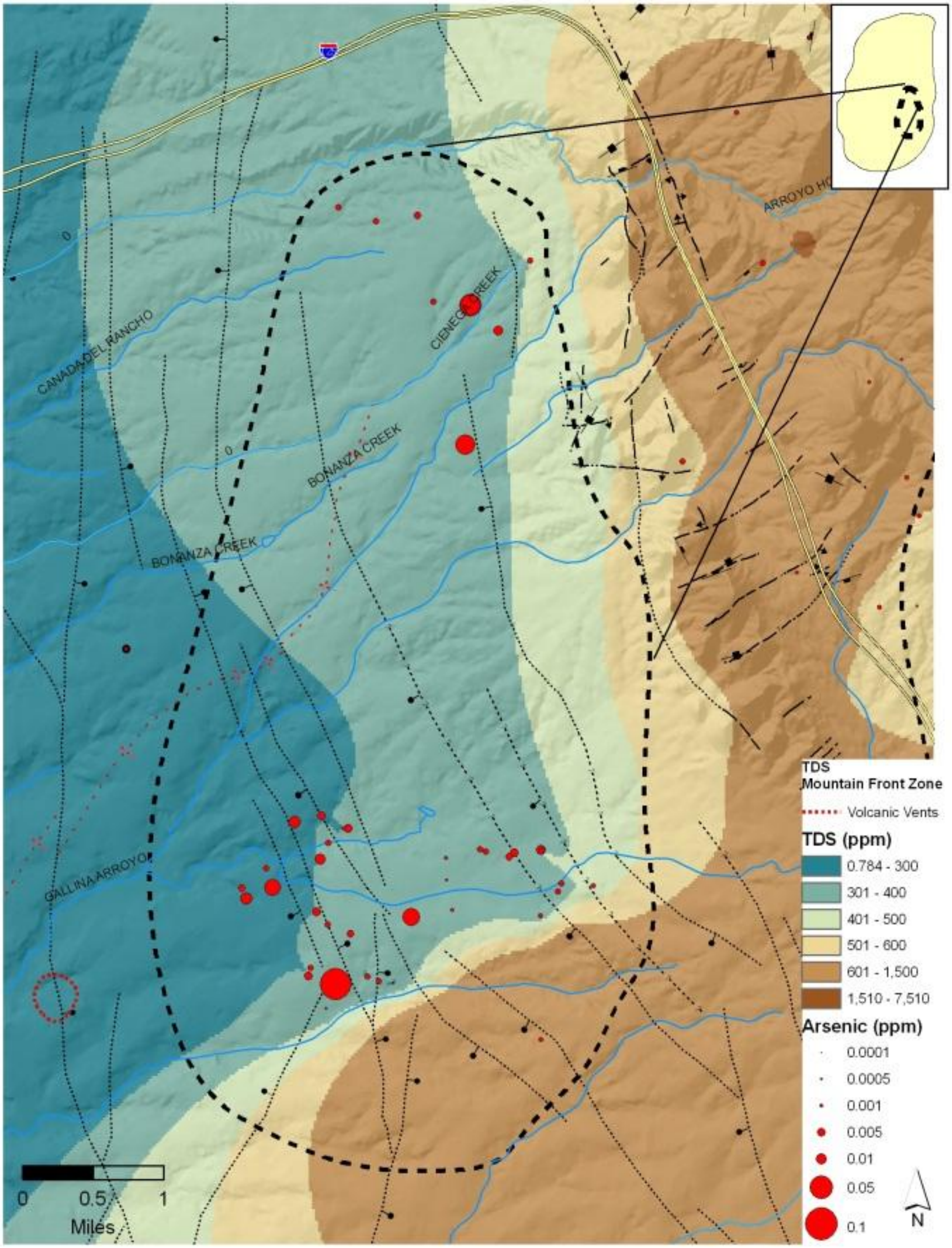


Figure 18: Mountain Front Zone TDS Concentrations

Mountain Front Correlation Plots

Values of increasing arsenic with respect to various metals, anions, cations, SO_4 and alkalinity were plotted to evaluate if a statistical relationship is present. A higher correlation coefficient, or R^2, is a measure of the strength of the relationship between the two variables. All correlations in this study are positive unless specifically stated. A strong correlation, (R^2 greater than 0.7) exists between arsenic and most metals, especially uranium, as well as HCO_3 (Figure 19). A moderate correlation (R^2 of about 0.60) is present for fluoride and magnesium. A weak relationship to calcium supports the piper diagram where wells with elevated arsenic are categorized as sodium carbonate water.

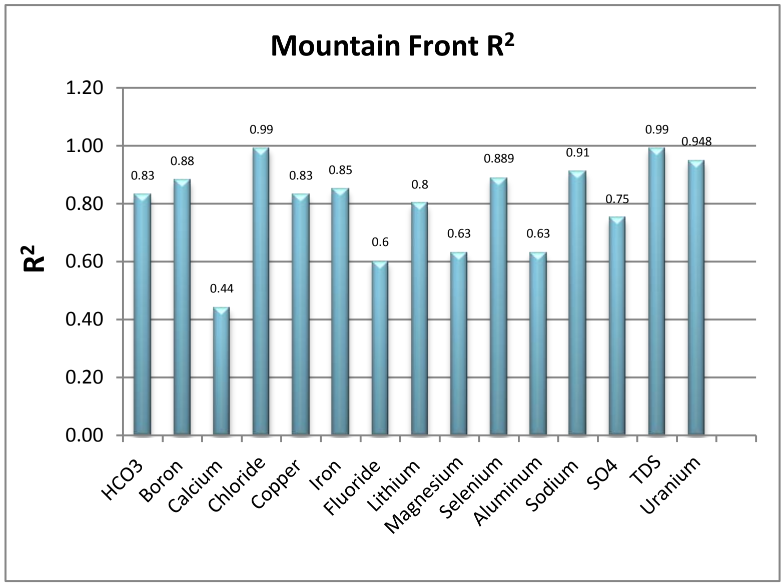


Figure 19: Mountain Front Zone Correlation of Arsenic with HCO_3, B, Ca, Cl, Cu, Fe, Fl, Li, Mg, Se, SO_4, Al, Na, TDS and U.

Mountain Front Saturation Indices

The PHREEQC-2 USGS hydrogeochemical transport model (Parkhurst, 1999) was used to calculate saturated indices for water samples. The term saturation index is used as part of an equation of a chemical dissolution reaction. It is a measure of whether a solution is under saturated or supersaturated with respect to a particular solid phase (Drever 1997). Use of the saturation index can help interpret the reactive mineralogy of the aquifer without analyzing the solid phase. Reactive minerals, such as barite, calcite, ferrihydrite, gypsum, dolomite, clay minerals, pyrite, silicate minerals and organic carbon with a saturation index of ± 0.5 are likely to occur in the aquifer environment and affect composition of the water (Deutsch 1997).

77% of all the groundwater samples in the Mountain Front Zone have a saturation index of ± 0.5 for calcite, 75% for dolomite and 66% for barite. Water samples with the four highest concentration of arsenic (29 to 90 µg/L) are slightly under or over saturated with calcite and aragonite consistently.

Additionally these higher samples were completed in the Espinaso Formation and have a very high positive saturated index for chlorite, diopside and phlogopite. Though not necessarily minerals that are commonly found in solution, this may be a unique characteristic of groundwater with high arsenic within the Espinaso Formation.

Northwest Zone

A total of 102 samples were collected in this area, northwest of the City of Santa Fe, with arsenic concentrations range from 0 to 23 µg/L. Two clusters of elevated arsenic in the southern and northern margins of the zone are identified. (Figure 20)

Northwest Geology

The northwest zone is composed of thick rift sediments highly deformed by faults and folds. The majority of this zone is part of the northwest plunging Broncos monocline and transected by the Agua Fria fault zone. The Caja del Rio Basalts are located to the west but are not considered a barrier to regional groundwater flow. Along the southern margin the Santa Fe Embayment Synclinal axis is to the southwest giving the zone a typical basin bowl shape to the south (Figure 4). Wells with elevated arsenic are clustered near the edge of the Barrancos monocline, west of the Agua Fria fault zone.

Northwest Groundwater

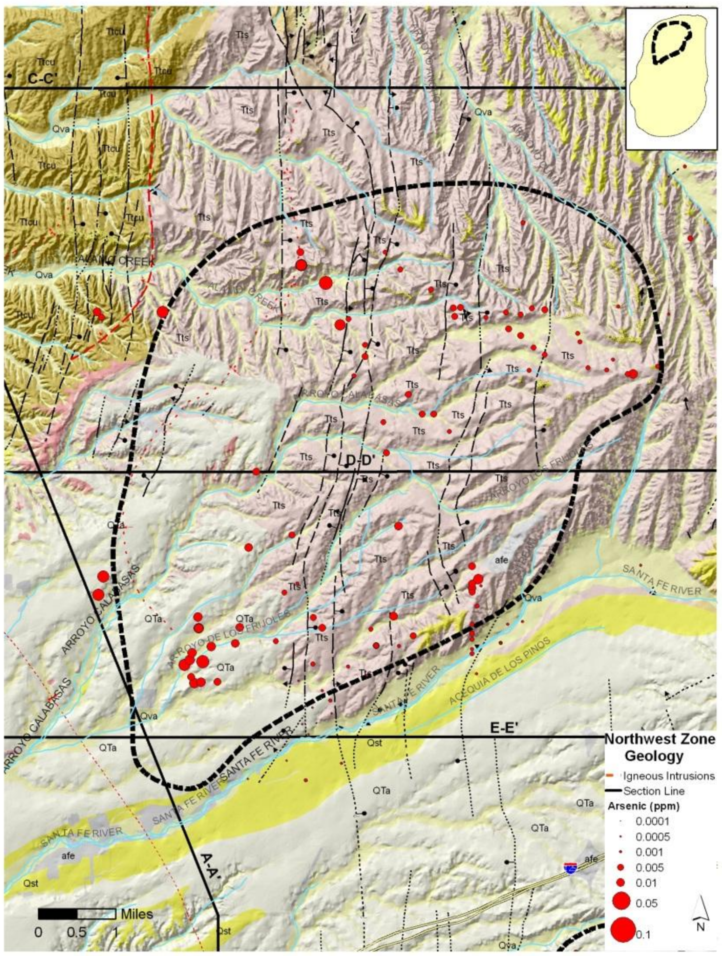


Figure 20: Northwest Geology Map after Koning 2010

Sedimentary rocks of the Tertiary Santa Fe Group are the predominant and only hydrostratigraphic unit in this zone (**Figure 10**). Primary aquifer is Lithesome S (Tts), with course (Ttsc) and finer (Ttsf) sub-units, of the Tesuque Formation (Koning 2010); detailed description of these units can be found in regional hydrogeology section of this report. Cross section D (Figure 5) runs east- west and illustrates the breakout of course and fine units of Lithosome S. Aeromagnetic studies estimate the thickness of Santa Fe Group is 7,000 feet below ground surface within this zone. (Grauch 2009)

Groundwater flow is to the northwest and is influenced by groundwater pumping from the City of Santa Fe Municipal well field, Buckman well field and the city's north well. This influence is evidenced in the NMBGMR map of groundwater units (Figure 10) which show perturbed groundwater contours within this zone (Johnson 2008).

Pumping test data show well yields up to 500 gpm for production wells which demonstrate partially confined aquifer conditions. An upward gradient exists in a triple level piezometer (Well D in Figure 10) and supports the discharge of the Tesuque Aquifer into the Rio Grande and the upwelling of deeper groundwater. (Johnson 2008) Recharge occurs through subsurface flow from the Sangre de Cristo Mountains to the aquifer in this zone but is considered disconnected from meteoric water and much older than water near the mountain front (Anderholm 1994)

Northwest Surface Water

No perennial surface water features are present with the exception of the ephemeral stretch of the Santa Fe River at the southeast boundary of this zone. Current water policy at the City of Santa Fe allows the release of 1,000 acre-feet of water per year, when available, from the mountain reservoirs. Surface water is not expected to flow to this reach of the river but as water is released over time the upper perennial reach may lengthen allowing water released to travel a further distance. Primary surface water drainages are the Arroyo Calabasas and the Arroyo Frijoles which convey seasonal storm water southwest to the lower Santa Fe River. Alamo Creek to the north is ephemeral and drains northwest toward the Rio Grande.

Northwest Zone Geochemistry Analysis

Spatial Analysis

Wells with elevated arsenic have sulfate levels between 0 and 10 mg/L with decreasing concentrations to the west; increasing to the east (Figure 22). Alkalinity values in the majority of wells are within a range of 100 to 150 mg/L. High alkalinity is noted along the Barrancos monocline hinge where it is intersected by a fault pointing toward a possible structural control. (Figure 23) Values for TDS for the entire zone vary from almost 0 to 500 mg/L with most wells within 200 to 300 ppm. Higher values of TDS are to the north and east of this zone (Figure 25). Calcium is primarily between 26 to 50 mg/L and depleted in the same location on the monocline where the alkalinity is elevated (Figure 24).

Northwest Piper Diagrams

49 of the 102 wells have arsenic concentrations exceeding 5 μg/L and are plotted with various colors on Figure 21. This zone is dominated by calcium-carbonate water with a few wells, including the highest arsenic concentration of 28 μg/L, are classified as sodium carbonate water. Arsenic concentrations less than 5 μg/L occur almost exclusively within the calcium carbonate facies with one outlier of low arsenic sodium rich water. No clear geological or chemical explanation for this outlier was found.

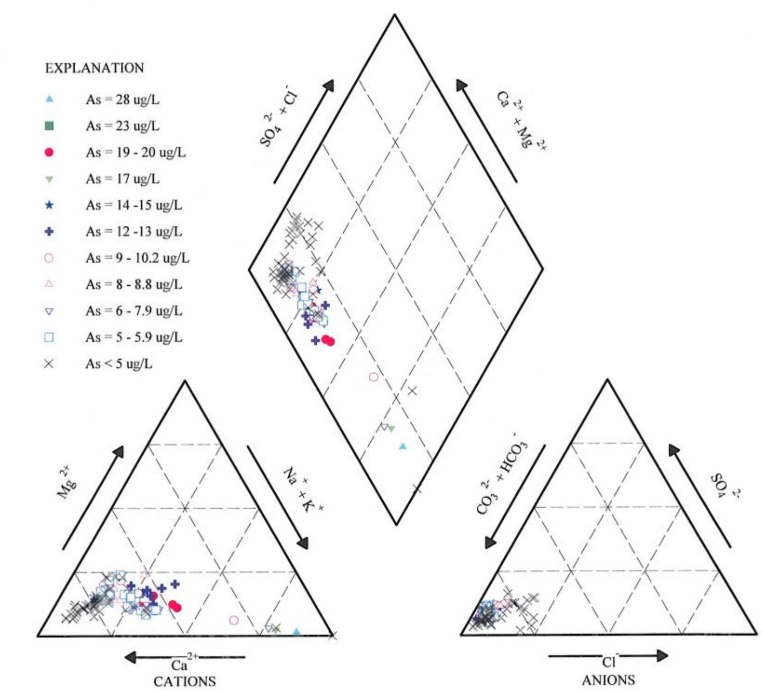


Figure 21: Northwest Zone Piper Diagram

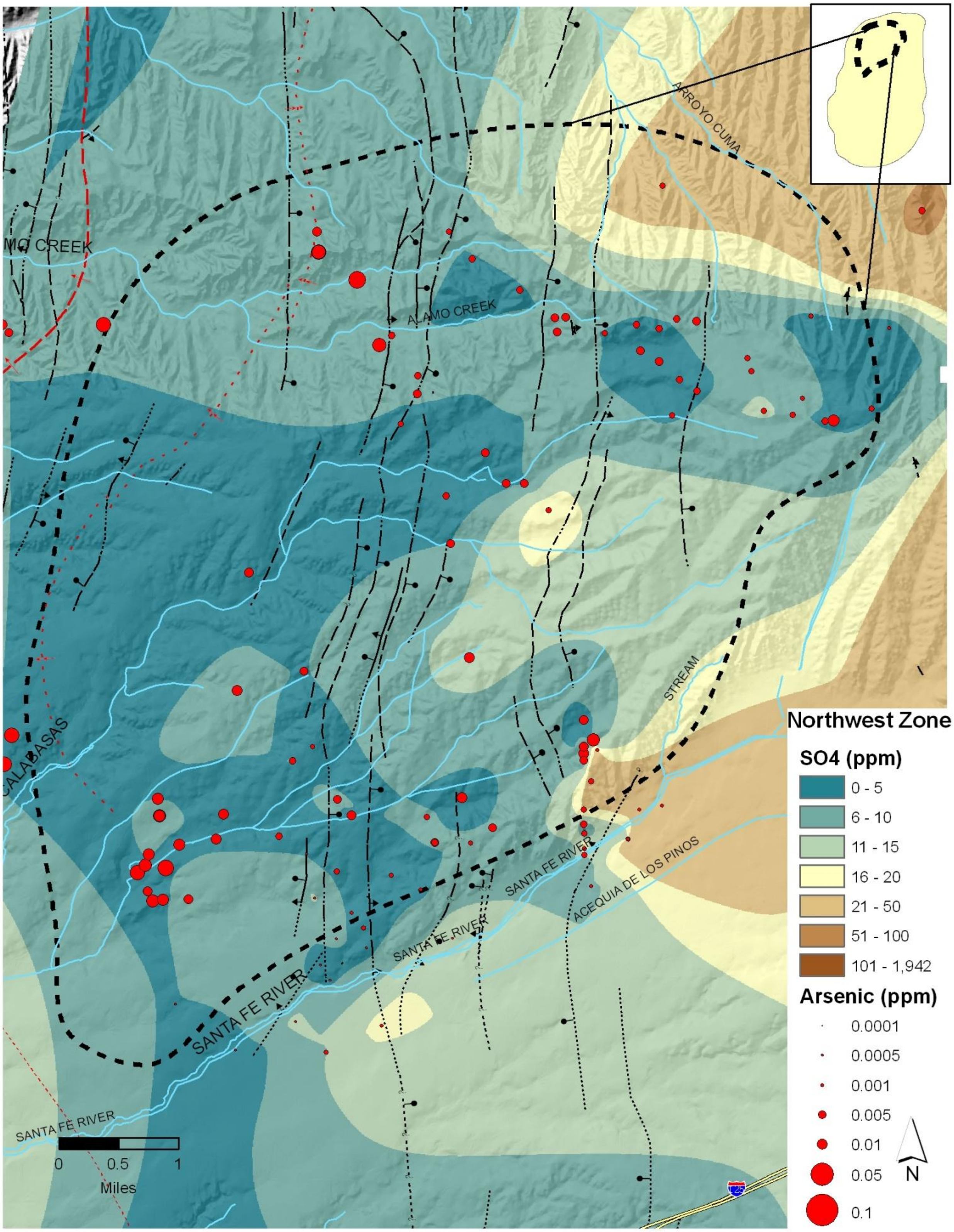


Figure 22: Spatial Analysis of SO4 within the Northwest Zone

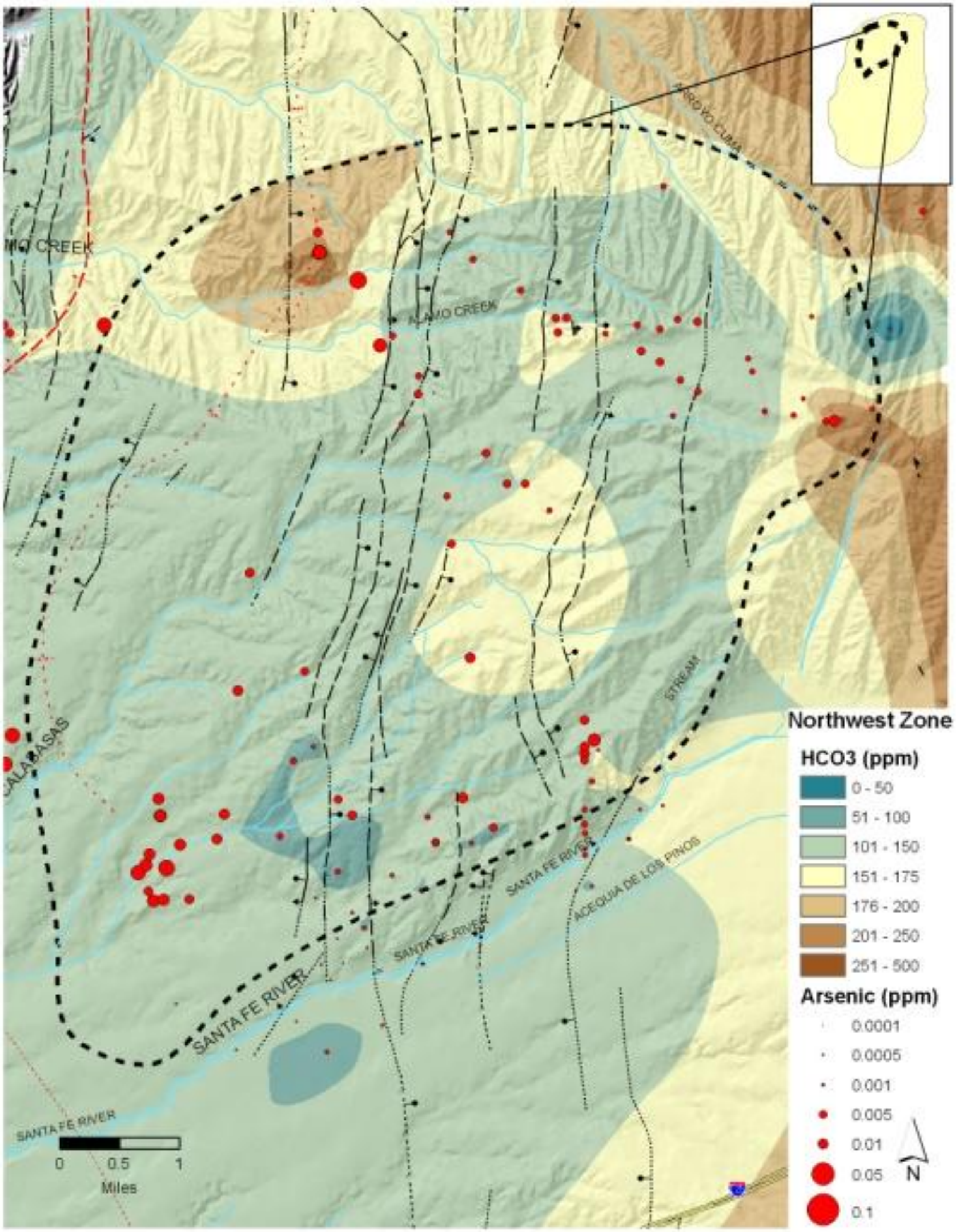


Figure 23: Spatial Distribution of HCO3 within the Northwest Zone. Elevated sulfate concentrations are noted at the north margin near the Barrancos monocline hinge.

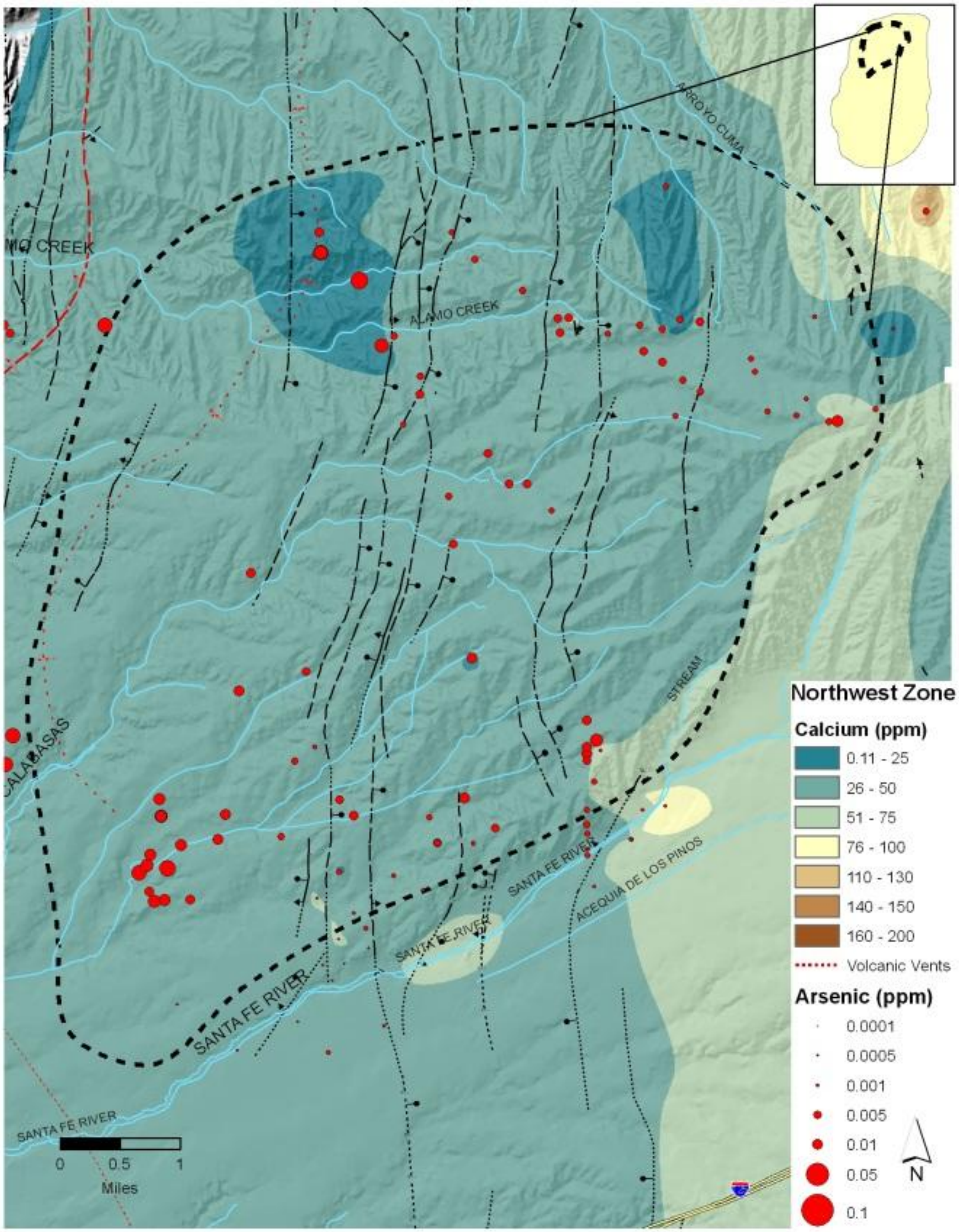


Figure 24: Spatial Distribution of Calcium in the Northwest Zone. Low calcium concentrations are noted at the north margin near the Barrancos monocline hinge.

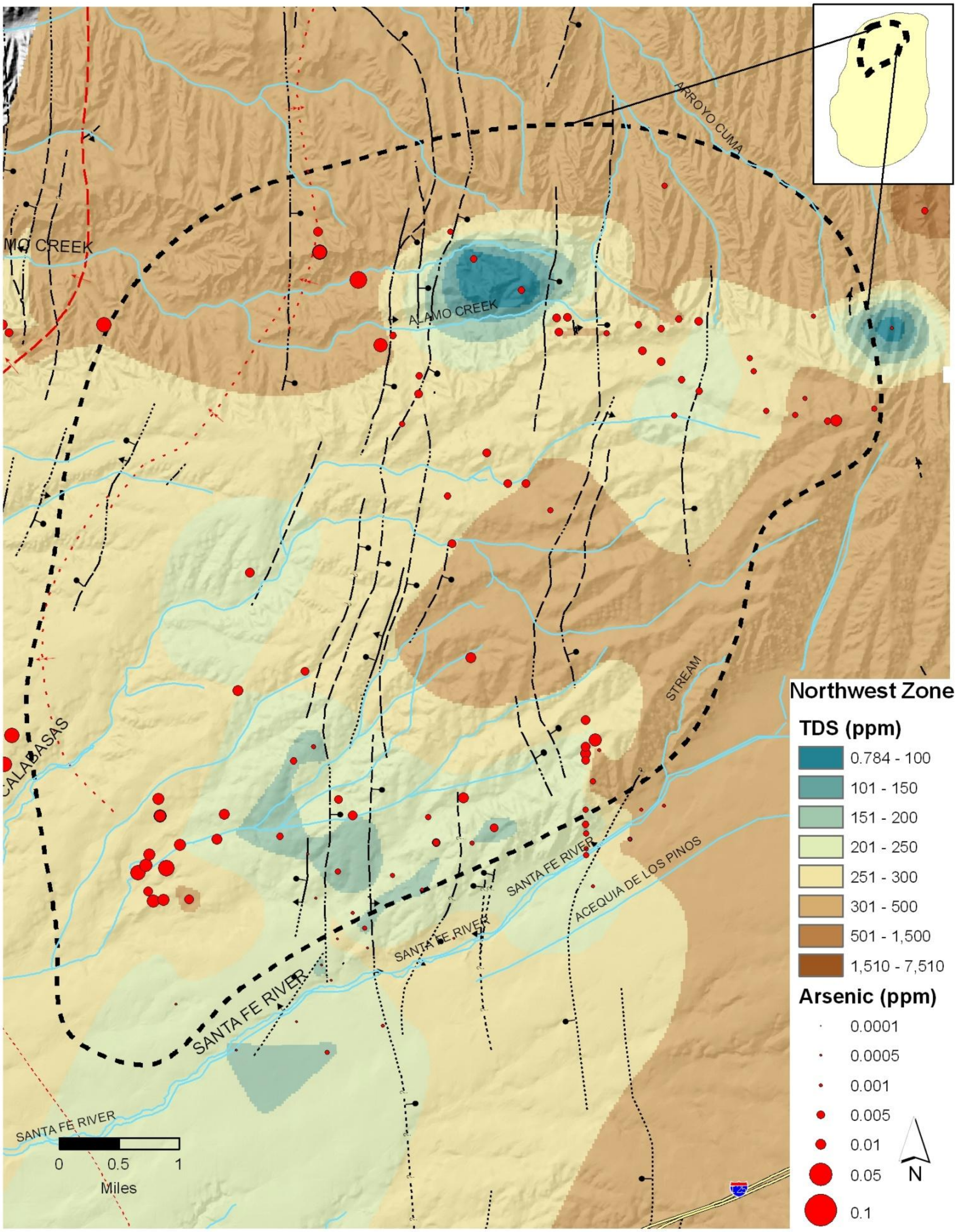


Figure 25: TDS values in the Northwest Zone

Correlation to Arsenic

Water in the Northwest Zone has a high correlation, with R^2 values between 0.71 to 0.97, to all constituents with the exception of iron and chloride. The correlation of arsenic to iron is 0.19 which is low compared to the other zones and a moderate (0.67) correlation to chloride (Figure 26).

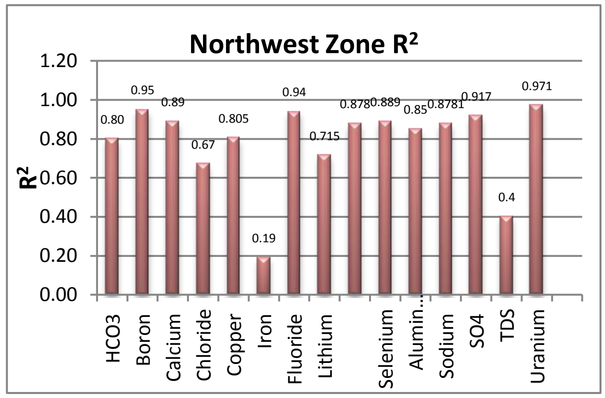


Figure 26: Northwest Zone Correlation of Arsenic with HCO_3, B, Ca, Cl, Cu, Fe, Fl, Li, Mg, Se, SO_4, Al, Na, TDS and U.

Saturation Indices

92% of the groundwater samples in the Northwest Zone have a saturation index of ± 0.5 for calcite, 52% for dolomite and 89% for barite. According to the modeling calcite and barite are the predominant reactive minerals in the groundwater.

South Zone

This zone is south of the City of Santa Fe in the vicinity of Cerrillos. Data from 24 wells with arsenic concentrations ranging from1 to 25 µg/L make up the South Zone.

South Zone Geology

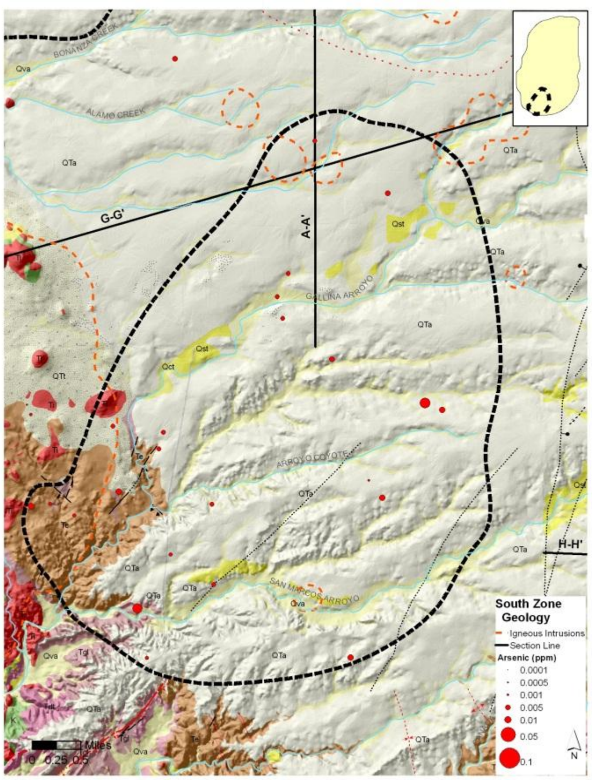


Figure 27: South Zone Geology Map (from Koning 2010)

The South Zone is at the southern boundary of the Espanola Basin in the area called the Santa Fe Platform. Primary geologic units are pre-Rio Grande Rift Espinaso and Galisteo Formations overlain by the unsaturated Ancha Formation (Figure 27). The Cerrillos Hills intrusive complex related to a porphyry belt is in the southwest corner of this zone. Interpreted volcanic vents from aeromagnetic data (Grauch 2009) are indicated on figure 27 as dashed shapes. Cross section G (Figure 7) which transects this zone to the north, illustrates these igneous features. Two minor, relative to the faulting in the other zones, concealed northeast trending faults were mapped in the southeast area by NMBGMR (Koning 2010).

South Zone Hydrogeology

Groundwater flow is to the southwest regionally but is directed to the south in the lower part of this zone due to Cerrillos Hills intrusion complex acting as a barrier to flow (Figure 10). Surface water features are ephemeral drainages which carry seasonal storm flows to the southwest draining into Galisteo Creek.

Primary aquifers are the Tertiary Espinaso Formation and the upper Galisteo Formation. A few wells are completed in rocks associated with the intrusive complex but are not included in this study (Figure 11). Aquifer yields reported in well driller logs range from 2 to 10 gpm primarily derived from fractures within consolidated volcaniclastic units of the Espinaso Formation and sandy units in the Upper Galisteo.

South Zone Geochemical Analysis

Spatial Analysis

As with previous zones, wells with elevated arsenic were plotted on interpolated maps. The sulfate levels are between 6 to 20 mg/L greatly increasing to the southwest toward the Cerrillos Hills but no clear relationship to arsenic levels (Figure 30). Alkalinity ranges from 50 to150 mg/L increasing toward the southwest. (Figure 31) Total dissolved solids range from 200 to 400 mg/L with higher levels near the intrusion complex. The igneous rocks in this zone influence the groundwater chemistry.

South Zone Piper

Groundwater in this area is slightly more alkaline compared to the samples in the southwest, northwest and mountain front zones. Wells with higher arsenic, which are indicated as the colored symbols in Figure 28, have a hydrochemical facies ranging from calcium-carbonate to sodium carbonate. Arsenic concentrations less than 5µg/L have a predominant water type closer to the calcium-carbonate end of the spectrum.

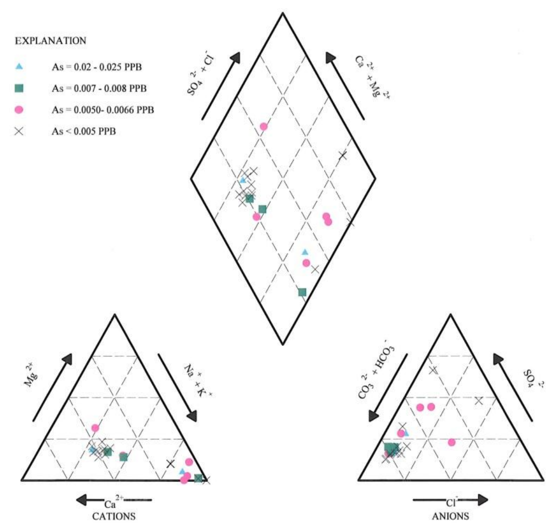


Figure 28: South Zone Piper Diagram

South Zone Correlation to Arsenic

All correlations are positive with arsenic and the constituents in Figure 29. The greatest correlation in the south zone is arsenic and uranium with an R^2 value of 0.91. Arsenic is poorly correlated with zinc with a weak correlation of iron and aluminum. A relatively high correlation, $R^2 = 0.7$, between SO_4 and arsenic exists which was not identified in the spatial analysis.

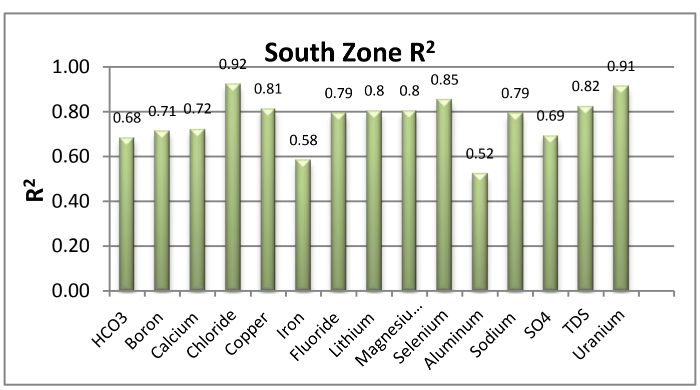


Figure 29: South Zone Correlation of Arsenic with HCO_3, B, Ca, Cl, Cu, Fe, Fl, Li, Mg, Se, SO_4, Al, Na, TDS and U.

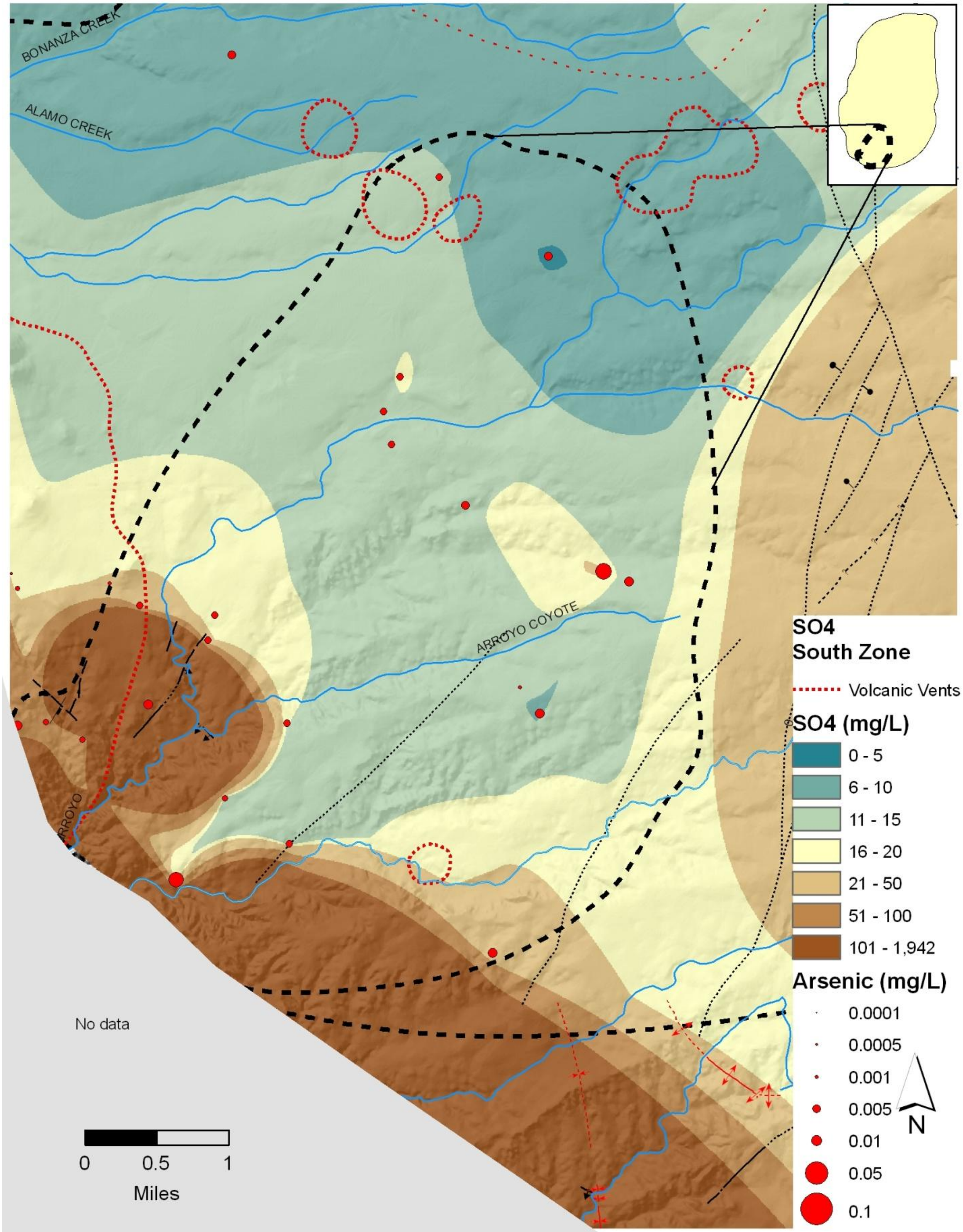


Figure 30: South Zone SO_4 Concentrations

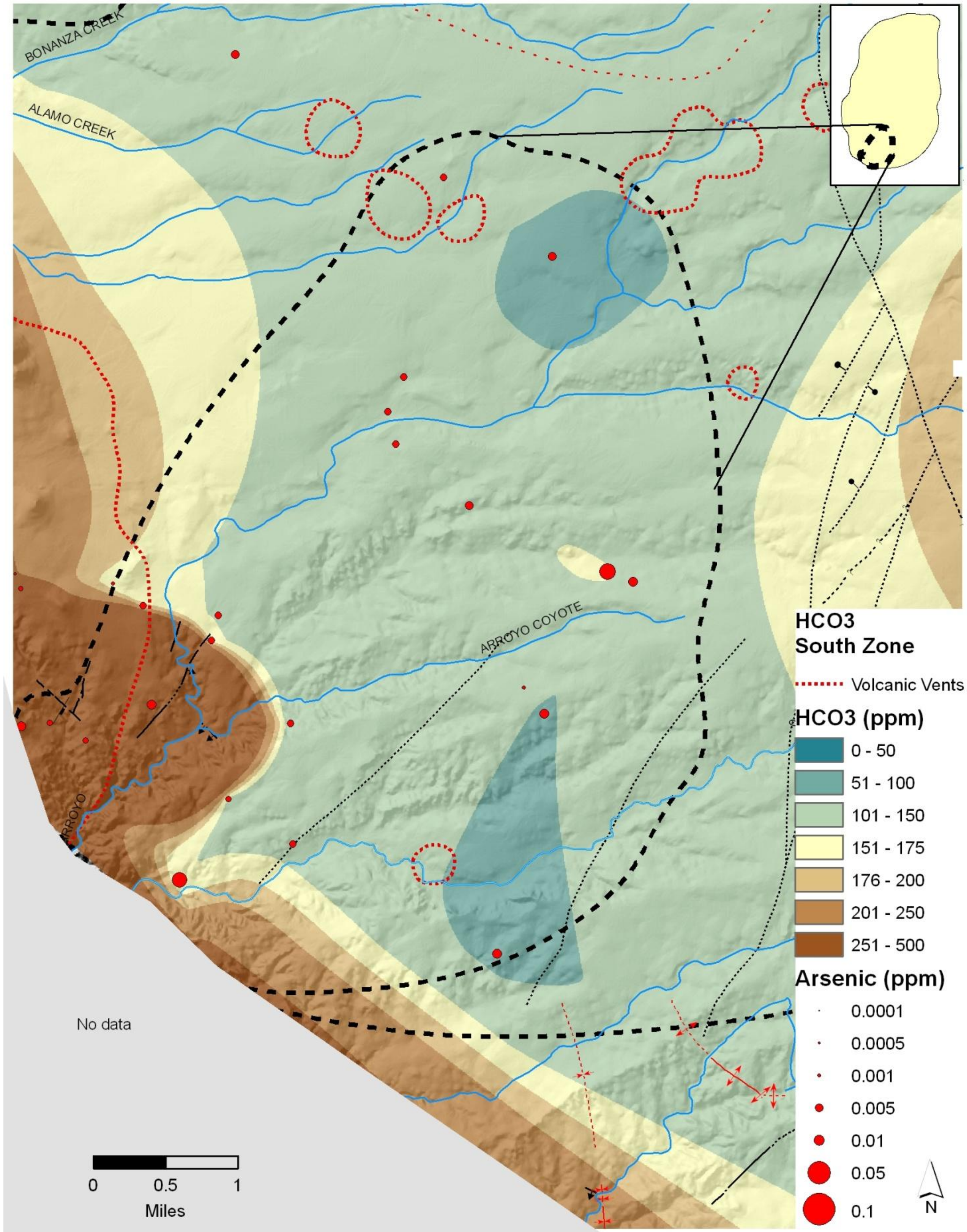


Figure 31: South Zone HCO_3 Concentrations

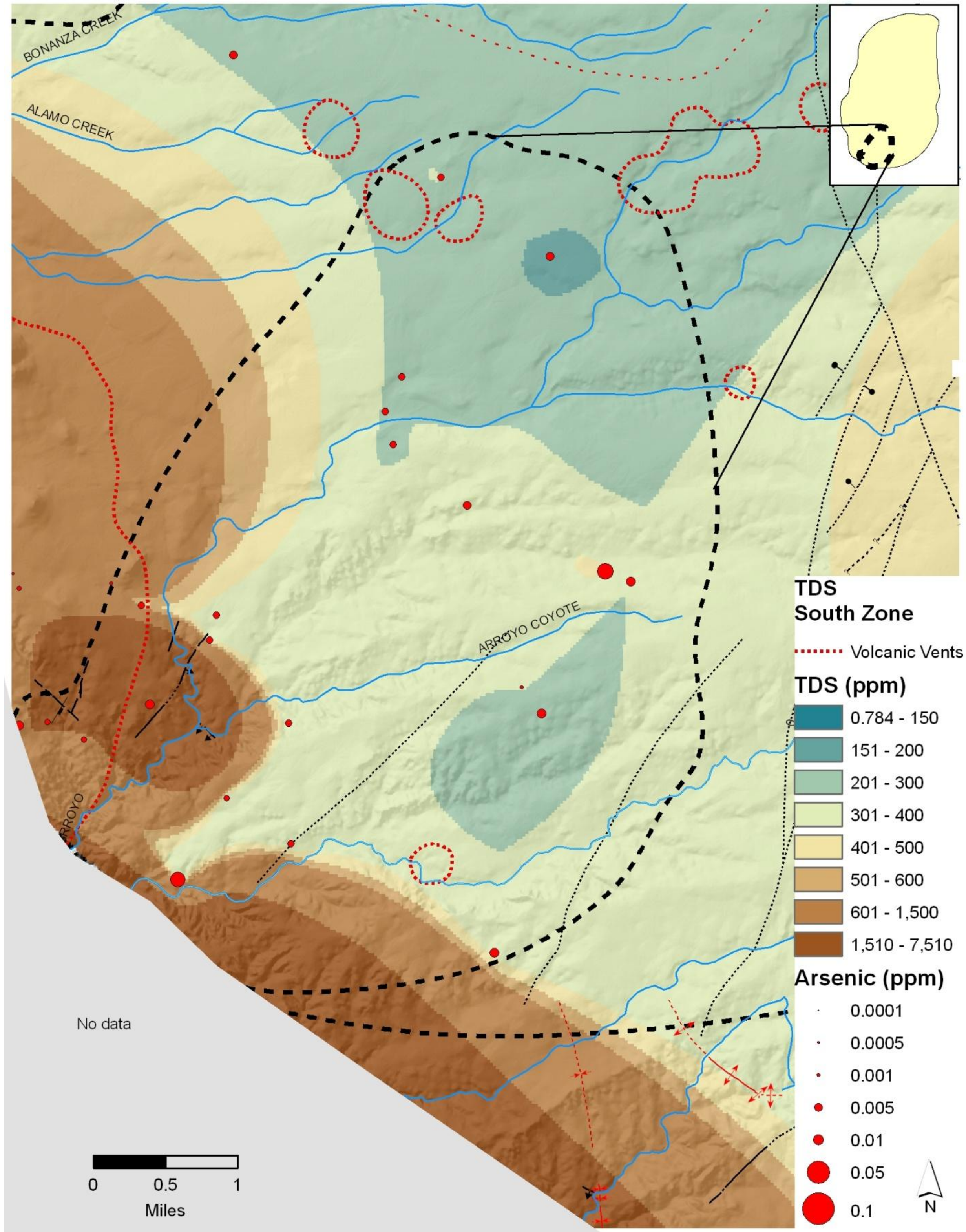


Figure 32: South Zone TDS Concentrations

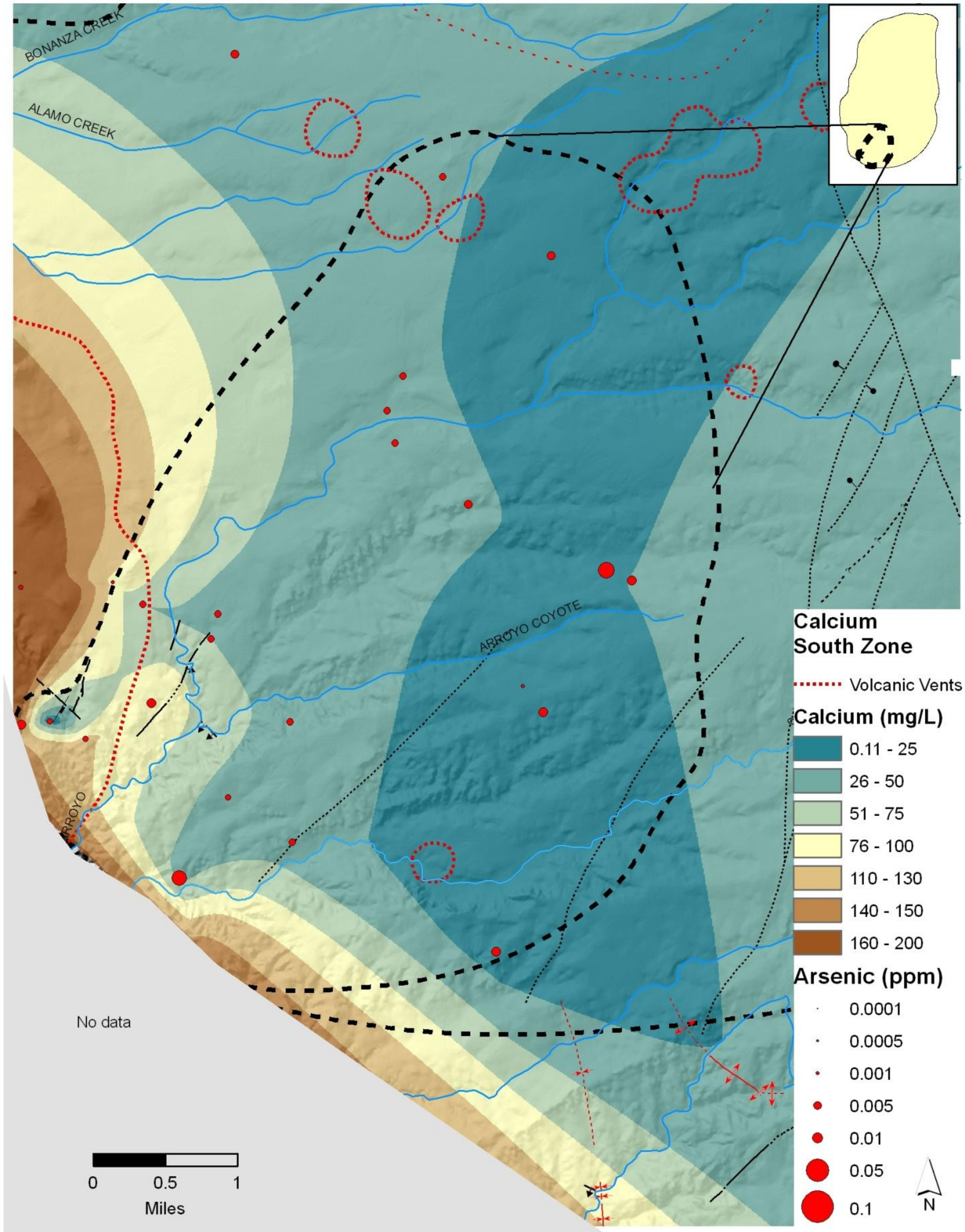


Figure 33: South Zone Ca Concentrations

Saturation Indices

Groundwater samples in the South Zone a have saturation index of ± 0.5 for calcite in 60% of the samples, 52% with dolomite and 76% of the samples with barite. In natural water dolomite occurs as an alteration product of calcite or aragonite but rarely at low temperatures (Drever 2002). The conversion of calcite to dolomite is impacted by the absence of SO_4 and speeds up the reaction.

Southwest Zone

This zone is located in the La Cienega area southwest of the City of Santa Fe. Data from 34 domestic wells and 8 surface water features were utilized and have arsenic concentrations ranging from 0 to 52 µg/L.

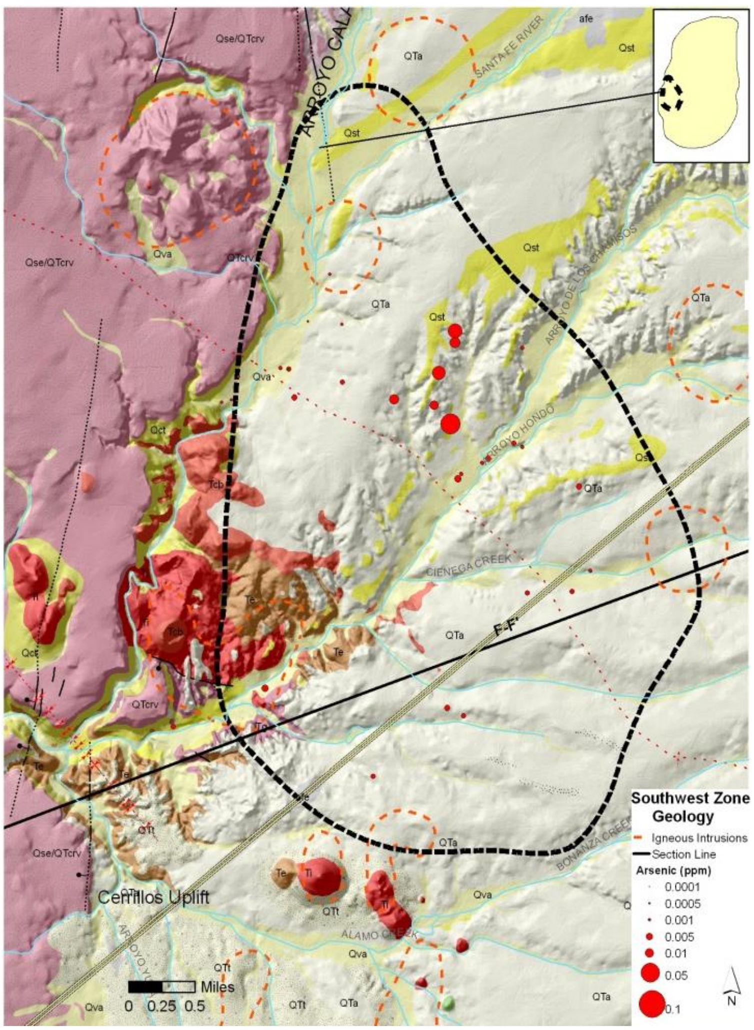


Figure 34: Surface Geology Map of the Southwest Zone

Southwest Geology

The south zone is partially within the Rancho Viejo Hinge Zone, which marks the point where sediments of the Santa Fe Group sharply thicken to the north. Outside of this zone pre-rift sedimentary and igneous rocks are present. On the west side of stratigraphic cross section F (Figure 6) the middle of the Southwest Zone lies approximately where I-25 is and indicated a red arrow. An igneous shallow intrusion (Grauch 2009) illustrated to the lower left is interpreted from reverse polarity data as volcanic vents associated with the Espinaso Formation. These vents are present in and near this zone but elevated arsenic in this sample set is not spatially coincident directly on top these vents but potential influence cannot be dismissed.

Southwest Zone Hydrogeology

The southwest zone is the discharge area of the Santa Fe Watershed (**Figure 10**) the direction of horizontal groundwater flow is from east to west ultimately converging in La Cienega Creek and Santa Fe River below Cieneguilla. Several drainages have perennial flow due to spring discharge with seasonal fluxuations. Historically water captured from springs was and currently is used for irrigation through the acequia system. The lower perennial portion of the Santa Fe River receives almost all its water though discharge from the City of Santa Fe Waste Water Treatment Plant with contributions from spring discharge. Strong connection between surface and groundwater exists as the spring water is not younger meteoric water but older water consistent with the shallow aquifer (Frost 1997).

The aquifers within the Rancho Viejo hinge zone, indicated by a red dashed line, (Figure 11) are the Ancha and the Tesuque Formation of the Santa Fe Group. Outside of the hinge zone is the Espinaso Formation to the southwest. There is good evidence that Lithosome E of the Tesuque Formation is present in this area. This is significant as this lithesome contains clasts if igneous rocks and reworked Espinaso Formation, which is spatially coincident with elevated arsenic.

Southwest Zone Geochemistry Analysis

Spatial Analysis

Sulfate is low (0 – 10 mg/L) in elevated arsenic wells with the exception of one well southwest of Arroyo Hondo and along the Santa Fe River below the WWTP, which have levels between 50 and 100 mg/L. (figure 29) This well is in the same aquifer so it is not clear what has caused this difference but the water in this zone is effluent dominated from septic tanks and the treatment plant so it is conceivable this elevation is due to anthropogenic influence on aquifer chemistry.

Alkalinity is between 100 to 200 mg/L for wells with the higher arsenic wells between 150 – 200 mg/L for the remainder of the wells. (figure 30) Lower alkaline concentrations exist proximal to Arroyo Hondo which increase to the southwest in the pre-rift sediments and northwest to the Santa Fe River.

Total dissolved solids range between 200 and 300 mg/L for wells with elevated arsenic with higher values located proximal to the interpreted volcanic vents. A zone of low TDS exists along the Arroyo Hondo and the Arroyo de los Chamisos drainages. (figure 21) Calcium is depleted where the highest arsenic levels were measured with higher concentrations near the Santa Fe River and the same anomalous well (figure 32).

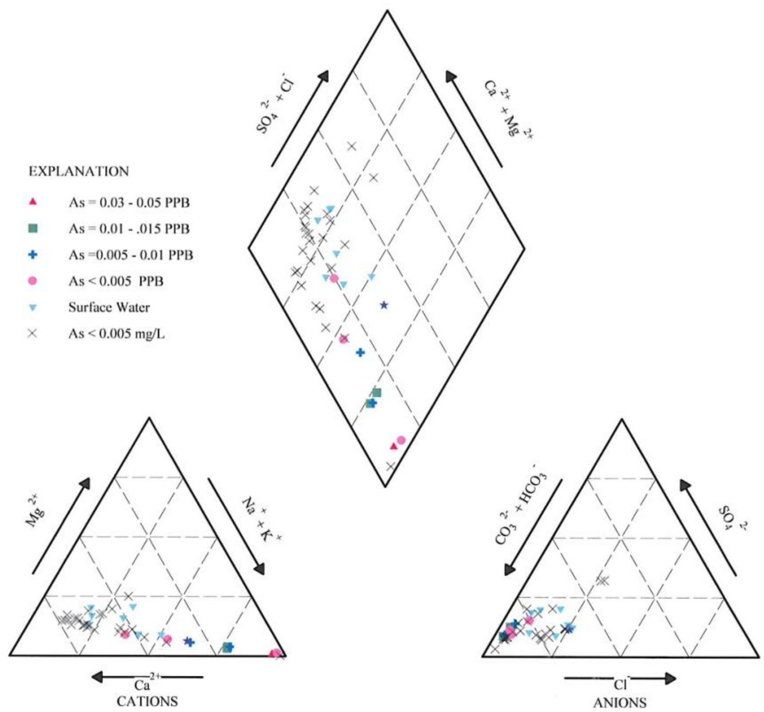


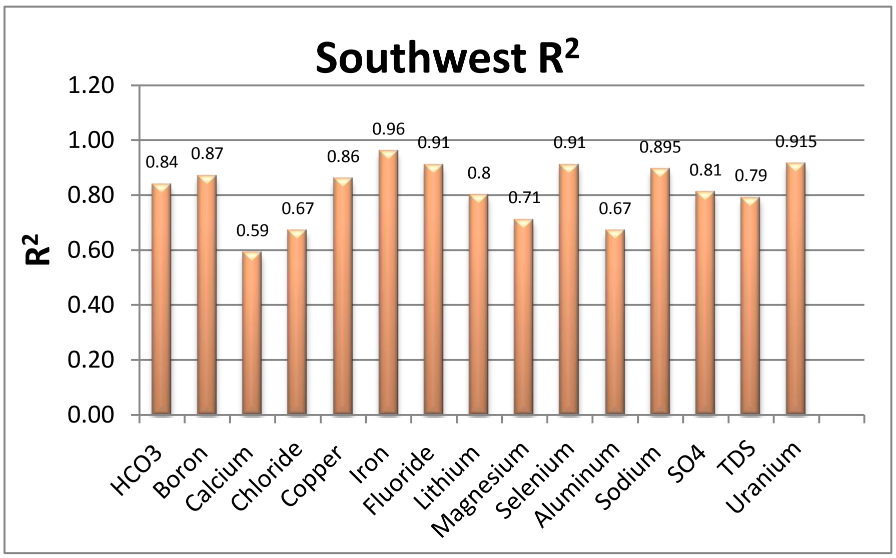
Figure 35: Piper Diagram of Southwest Zone

Southwest Zone Piper

Due to the presence of spring water data in this zone groundwater data were plotted with surface water as a comparison. Groundwater with elevated arsenic is more sodium rich than water with lower concentrations. Spring water from Arroyo Hondo, which has twice the arsenic of the other springs in the area, plotted similarly to the rest of the springs. Wells with low to moderate arsenic is classified as calcium carbonate water.

Southwest Zone Correlation Plots

The highest correlation to arsenic in the Southwest zone is iron at an R^2 value of 0.96. Other metals are also well correlated with R^2 values from 0.7 to 0.92. The lowest correlation is to arsenic is calcium which is spatially consistent with Figure 39.



Saturation Indices

Surface water samples from the springs at La Cienega and groundwater samples in the Southwest Zone were near equilibrium for calcite in 83% of the samples, 79% with barite and 43% with dolomite. This zone has the only two samples near equilibrium with ferrihydrite.

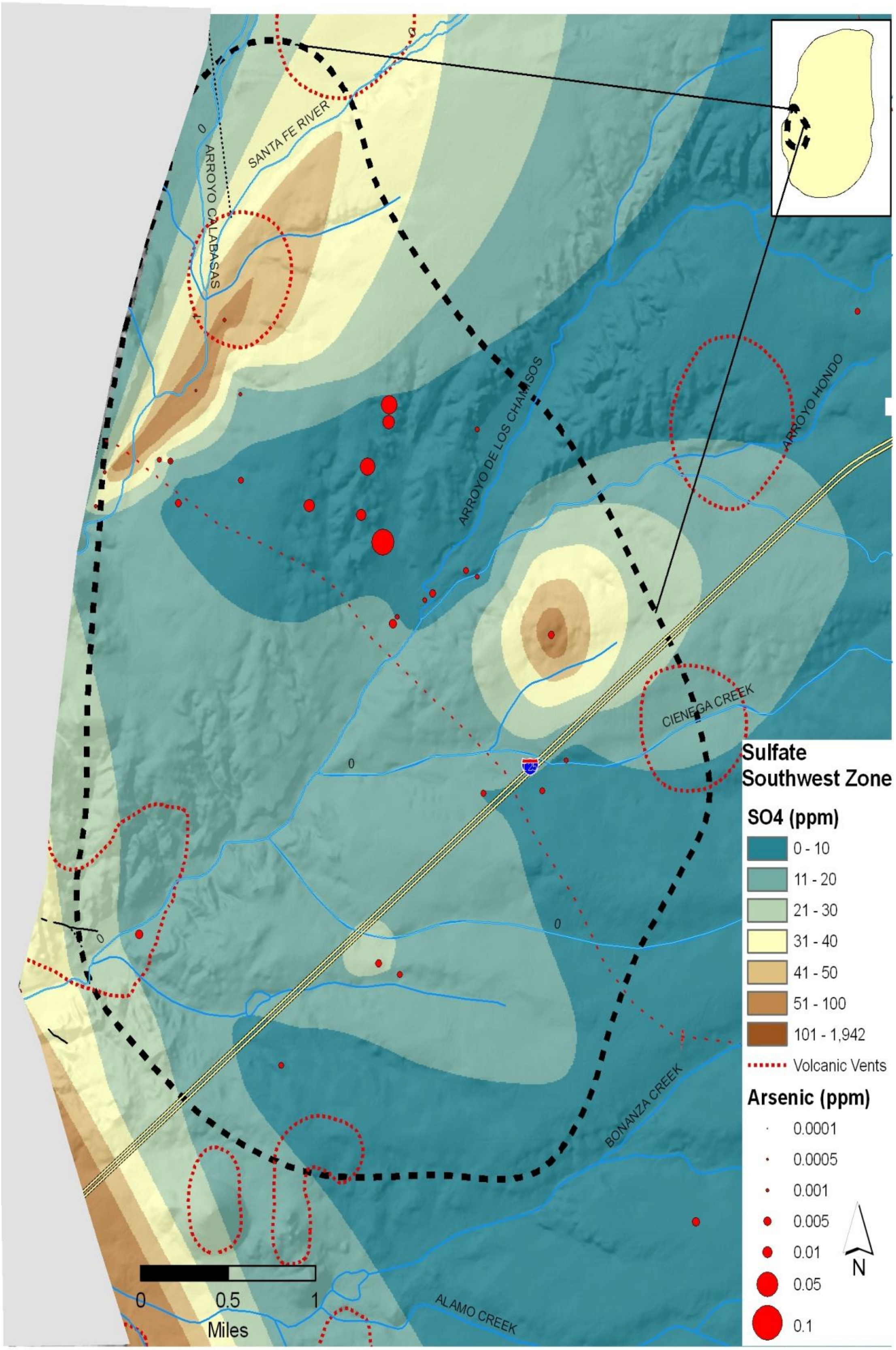


Figure 36: Sulfate Levels in the Southwest Zone

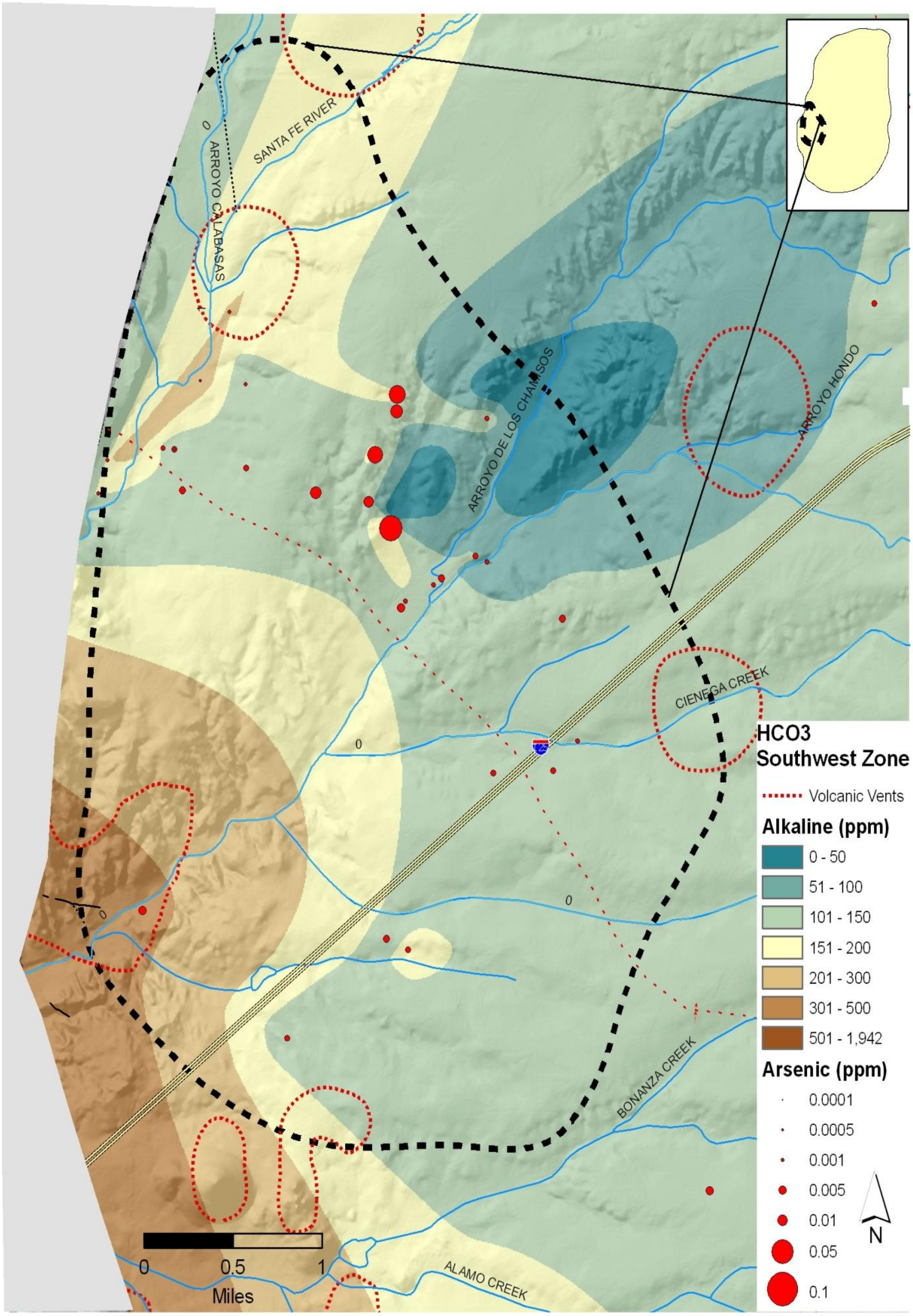


Figure 37: Southwest Zone Alkalinity

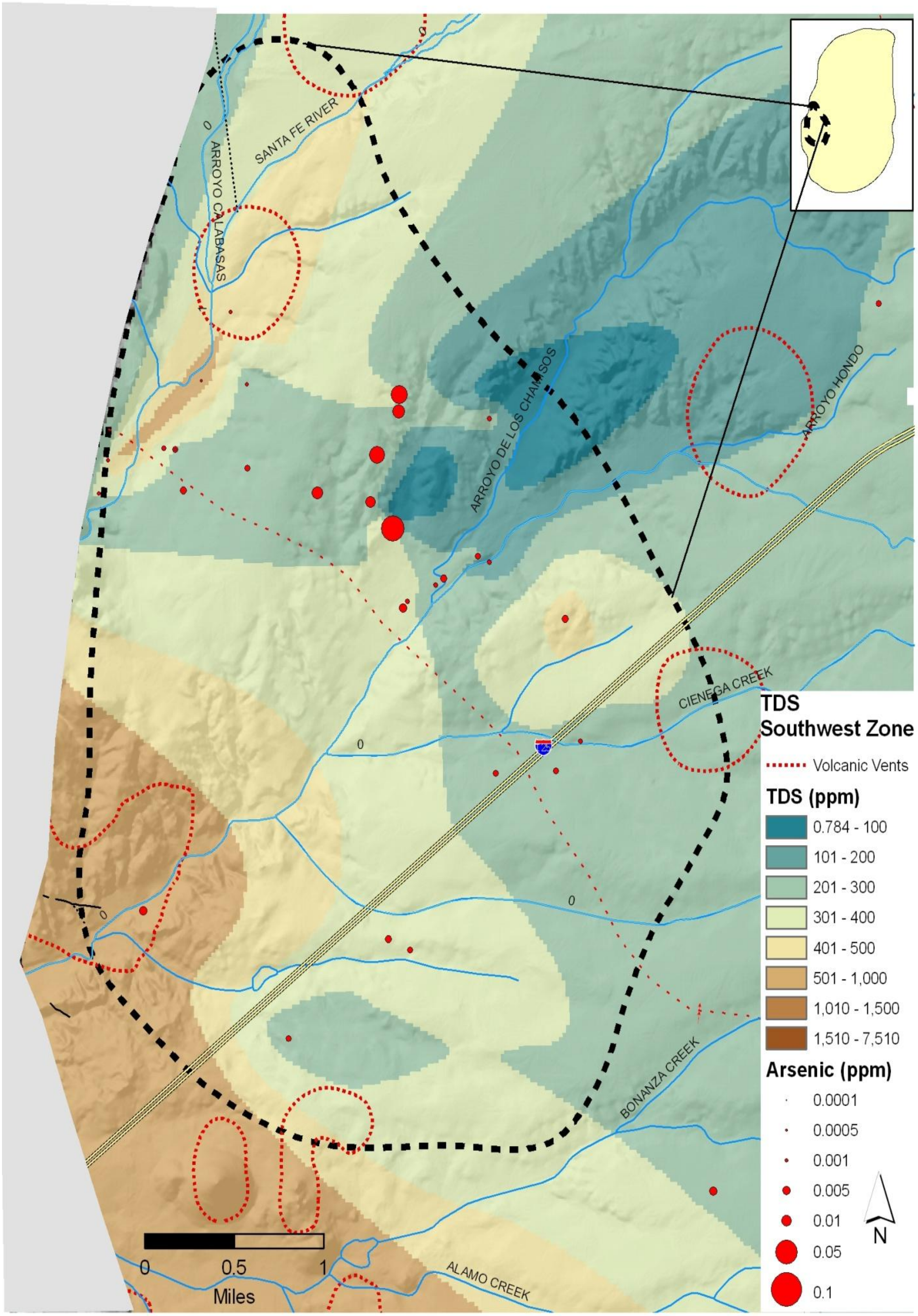


Figure 38: Spatial Distribution of TDS in the Southwest Zone

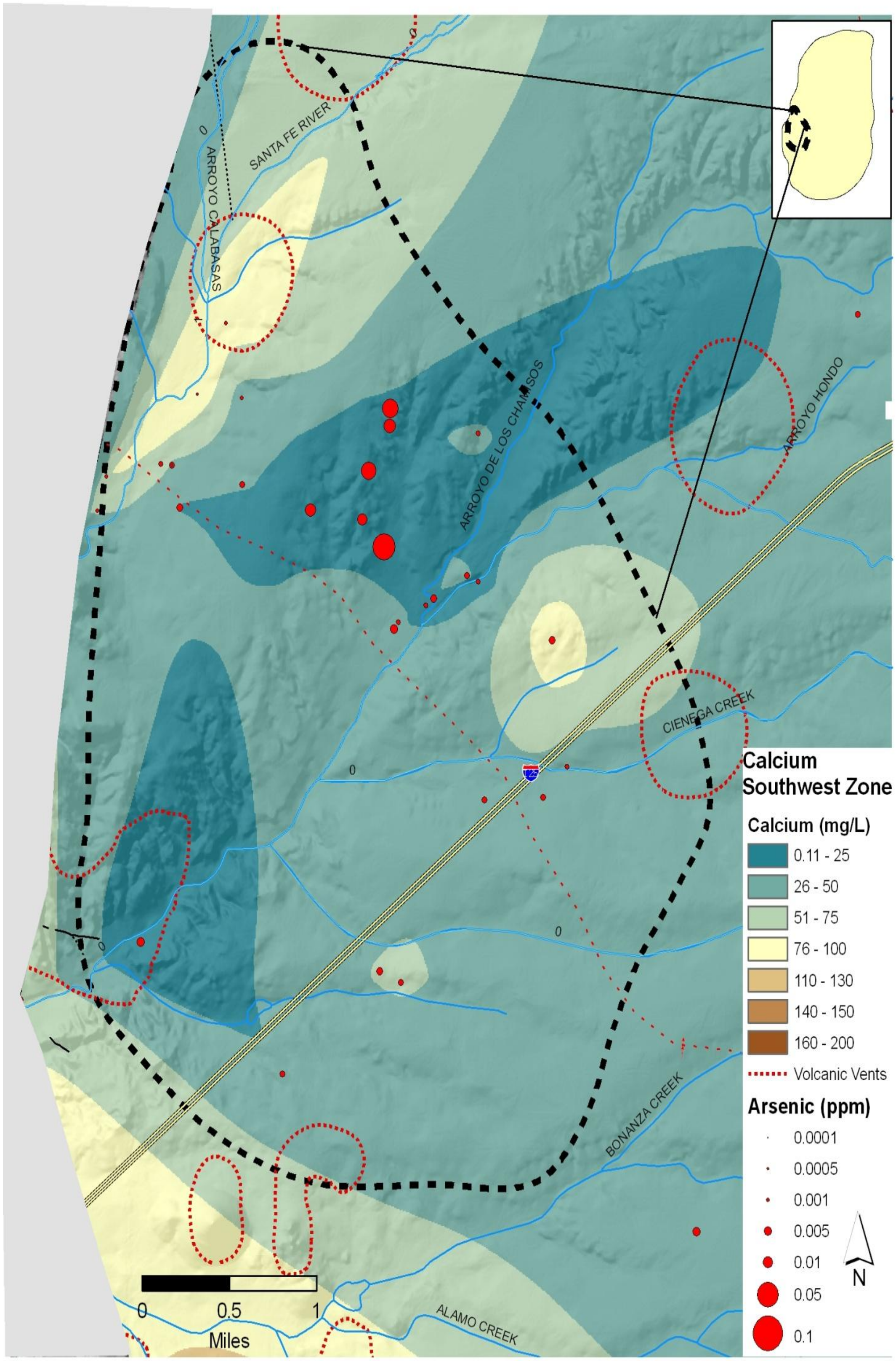


Figure 39: Calcium Concentration Map of the Southwest Zone.

Study Results

Comparison between zones

Geology

In the Mountain Front, South and Southwest Zones elevated arsenic occurs either outside or barely within the Rancho Viejo Hinge Zone. Several structural features in the basin have brought pre-rift sediments close enough to the surface to be economically viable aquifers. In the Southwest zone the Cerrillos Uplift and in the South zone the Santa Fe Platform are structural highs, which influence the depth of the Espinaso Formation. In the Mountain Front zone the saturated Espinaso Formation is present outside of the Santa Fe Platform and the Rancho Viejo Hinge Zone where the greatest arsenic concentrations within the study area are located. In the Northwest Zone wells with elevated arsenic are located near the hinge of the Barrancos monocline and west of the Agua Fria fault zone.

Hydrology

In the Mountain Front, South and Southwest Zones elevated arsenic is associated with the volcaniclastics of the Espinaso Formation either directly as the aquifer or by the reworking of this unit in the overlying Lithosome E of the Tesuque Formation. In the Northwest Zone the relationship of arsenic concentrations to Lithosome S of the Tesuque Formation is not as well defined but the upward hydraulic gradient and the clustering of wells with elevated arsenic near the hinge of the monocline provides a mechanism for the upwelling of older water into this zone.

Spatial Analysis

The broad ranges of values for sulfate, alkalinity, TDS and calcium spatially coincident to wells with elevated arsenic were put in the table below.

	Sulfate	**HCO_3**	**TDS**	**Calcium**
Mountain Front Zone As = 1 to 94 µg/L	6 and 10 mg/L	100 to 200 mg/L	300 – 400 mg/L	0 – 25 mg/L
Northwest Zone As = 0 to 23 µg/L	6 and 10 mg/L	100 to 200 mg/L	300 – 400 mg/L	0 – 25 mg/L
South Zone As = 1 to 25µg/L	6 to 20 mg/L	50 to150 mg/L	200 to 400 mg/L	0.1 and 25 mg/L
Southwest Zone As = 0 to 52 µg/L.	0 – 10 mg/L	100 to 200 mg/L	200 and 300 mg/L	0 – 25 mg/L

The overall trend between the separate zones is very similar for elevated arsenic but this analysis was useful in spatially correlating areas of high or low levels of for sulfate, alkalinity, TDS and calcium with geologic features. The influence of faults, surface water and igneous rocks is prominent within the study area.

Piper

Based on piper diagrams of the four zones groundwater appears to be a mixture of sodium and calcium carbonate within all the zones. The Mountain Front and Northwest zones a have very similar anion distribution of low chloride and high carbonate. Cation distribution has similar trends for the Southwest and Northwest Zones where the water in more calcium rich.

Spring water in the Southwest Zone did not standout as having distinct properties and are very similar to the low arsenic wells dominated by calcium carbonate water.

Correlation to Arsenic

All groundwater in the study have a high (r^2 value > 0.8) positive correlated with selenium, copper, sodium and uranium. (

Figure 40) The north zone has a poor correlation to iron and TDS but highly correlated to SO_4 relative to the other zones. The Mountain Front Zone is poorly correlated to calcium, fluoride and magnesium with a. The south zone also has a high correlation to TDS and chloride with weaker correlations with aluminum and iron. In the Southwest zone iron has the highest correlation to arsenic.

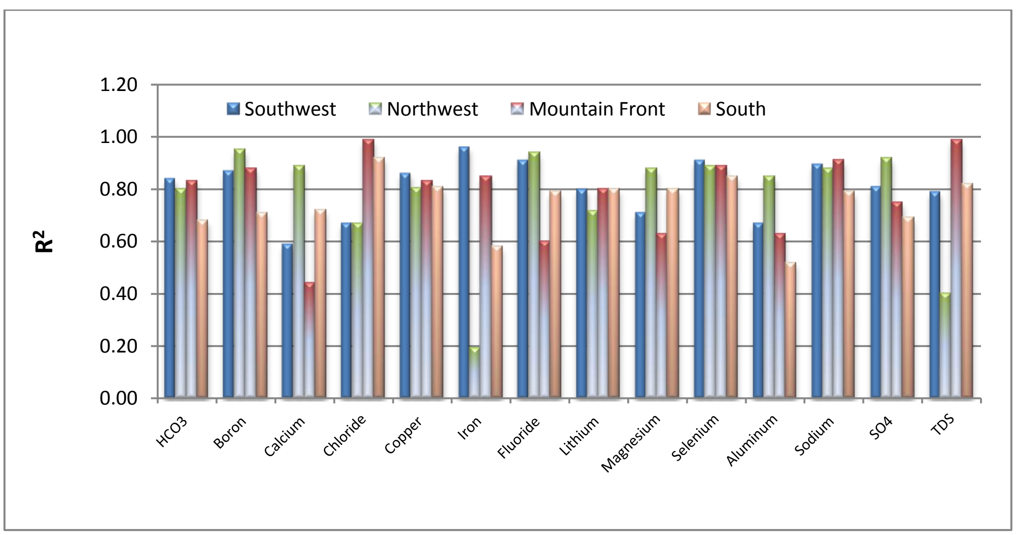


Figure 40: Correlation of Arsenic with HCO_3, B, Ca, Cl, Cu, Fe, Fl, Li, Mg, Se, SO_4, Al, Na, TDS and U in all zones

Saturated Indices

The primary reactive minerals found in the study are barite, calcite, dolomite and ferrihydrite. The percentage of samples that are near equilibrium with respect to these mineral is tabulated by zone in Table 2.

Table 2: Saturation Indices for barite, calcite, dolomite and ferrihydrite for each zone.

	Barite	**Calcite**	**Dolomite**	**Ferrihydrite**
Mountain Front Zone As = 1 to 94 µg/L	66%	77%	75%	0
Northwest Zone As = 0 to 23 µg/L	89%	92%	52%	0
South Zone As = 1 to 25µg/L	76%	68%	52%	0
Southwest Zone As = 0 to 52 µg/L.	79%	83%	43%	4%

Relative to the other zones the Mountain Front zone has a small percentage of wells with barite is near equilibrium but the percentages of calcite and dolomite are similar. The South zone also has similar percentages for calcite and dolomite but the Southwest and North zones has twice as many wells with calcite near equilibrium. As discussed previously, in natural water dolomite occurs as an alteration product of calcite or aragonite but rarely at low temperatures. The conversion of calcite to dolomite is impacted by the absence of SO_4 which speeds up the reaction (Drever 2002).

The Mountain Front and the South Zone have the highest average value for sulfate in the study area. Based on Drever groundwater temperatures greater than 25°C may have existed in these zones.

Comparison to other studies and data

Major anions, cations and HCO_3 have very similar values to water quality found within the Middle Rio Grande Valley along the mountain front of the Sandias and northwest of the confluence of the Jemez River and the Rio Grande. (Bexfield 2002) The reported source of arsenic is upwelling of mineralized water and local desorption for the mountain front. In the northwest area the source of arsenic is attributed to geothermally altered rocks in the recharge zone and desorption. Comparing the arsenic and iron concentrations from the Northwest Zone of this study to the one in the Middle Rio Grande the water quality northwest of the Jemez River and the Rio Grande is most similar.

Bexfield positively correlated elevated arsenic with boron, chloride and sodium near the Sandia Mountains. Similar correlations exist within the Mountain Front Zone of this study. High chloride levels near the Sandia Mountains are associated with older more mineralized water mixing with low arsenic water associated with recharge. (Bexfield 2002) Just west toward the Rio Grande there is a weaker correlation between chloride and a positive correlation with fluoride, boron, sodium and lithium. The Northwest Zone in this study has chemistry similar to the west area of the Bexfield study.

Spatial maps of sulfate and HCO_3 from the Johnson (2008) study were compared to maps made for this study. An effort was made to symbolize data from this study with the same quantity intervals as the 2008 study but the maps are not easy to compare to each other. Using georeferenced well locations with chemistry data obtained from NMBGMR concentrations of arsenic in the 2005 study are plotted on the regional geology map with the wells in this study (Figure 41). Data from this study expands the information on groundwater chemistry in the Eldorado and La Cienega areas. Arsenic levels in both of these areas are elevated but not interpreted as an increase with time but an artifact of an expanded dataset.

Johnson (2008) identified an area with arsenic concentrations up to 50 ppb, located on the west side of figure 41 near the axis of the Santa Fe Embayment syncline, within a monitoring well #1 at the Caja del Rio Landfill. Water quality data for this monitoring well from 1999 to 2011 was obtained from the Santa Fe Solid Waste Management Agency and reviewed for arsenic concentration trends through time. At this location arsenic concentrations have declined from 90 ppb to 12 ppb in this 12 year period along with lower iron and pH values . Monitoring well # 1 is 335 feet deep with a reported depth to water of 304 feet (Johnson 2008) and is representative of the shallow aquifer in this area.

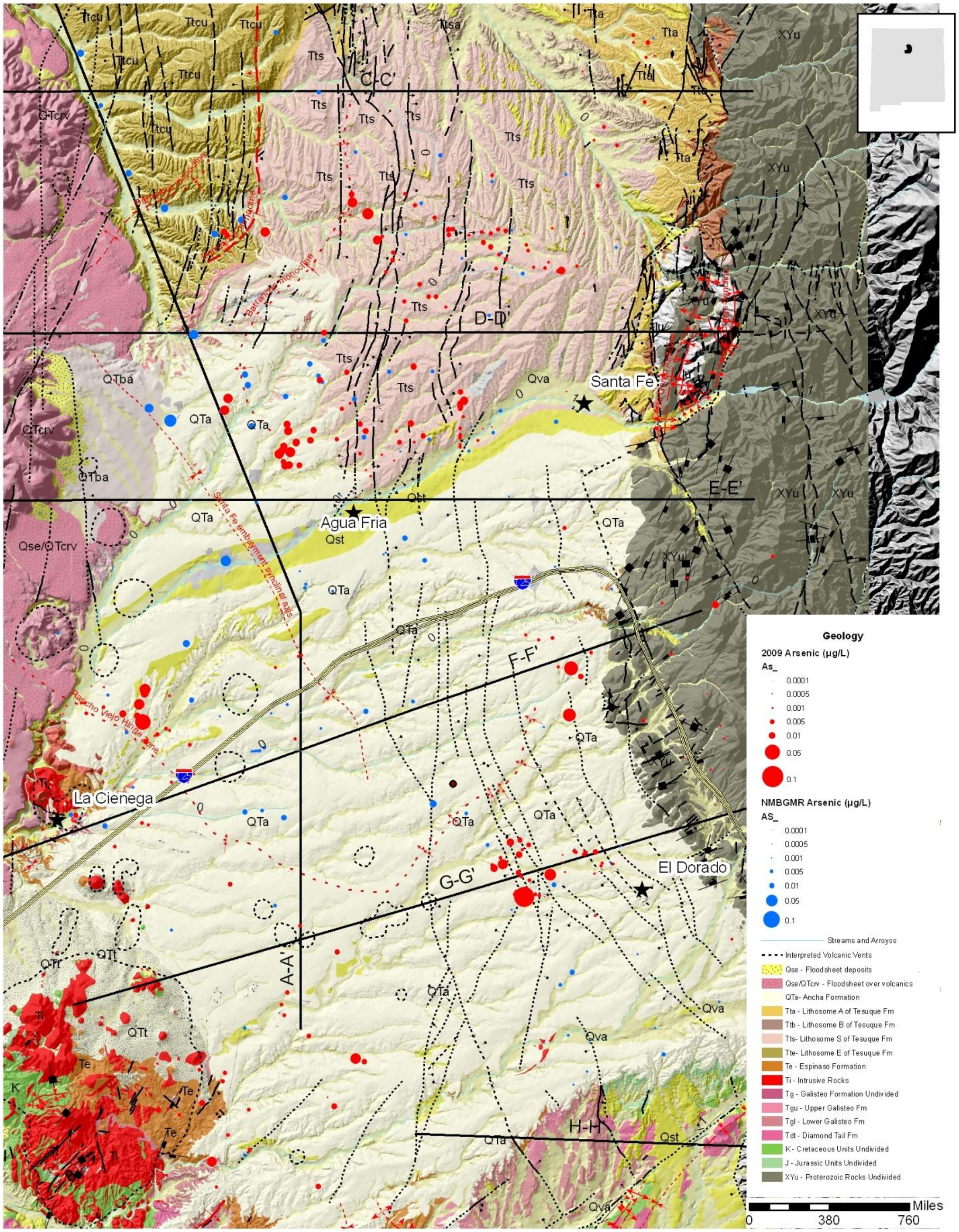


Figure 41: 2005 NMBGMR and 2009 Arsenic Concentrations

Conclusions

Groundwater with elevated arsenic within the Mountain Front, South and Southwest Zones are either in direct contact or influenced by the volcaniclastic of the Tertiary Espinaso Formation. The highest concentrations, located in the Mountain Front Zone, are outside the structural highs in the region and within the Agua Fria Fault Zone. The Northwest Zone, composed of Lithosome S of the Tesuque Formation, does not have the same connection to the Espinaso Formation but elevated arsenic is noted near the hinge of the Barrancos monocline, especially where it is transected by a fault. In addition to volcanics associated with the Espinaso Formation the data from this study indicates the location of faults plays a role in elevated arsenic. No clear connection to interrupted volcanic vents and elevated arsenic was made but the potential influence on groundwater chemistry should not be dismissed.

Comparing geochemical, geological and hydrological attributes of the Northwest Zone to the Bexfield (2002) study data may provide some insight. In the Middle Rio Grande Valley, the most similar groundwater to the Northwest is located near the confluence of the Jemez River and the Rio Grande. Bexfield describes the primary arsenic source and controls as contact with geothermally altered rocks and desorption. There is no evidence that groundwater in the Northwest Zone comes in contact with hydrothermally altered rocks.

Arsenic ions can be strongly sorbed onto metal oxides, especially iron and aluminum at pH values between 7.0 to 8.0. (Bexler 2002) Stanton (2002) demonstrated a strong correlation between iron and arsenic and suggests iron oxides as the source and sink of arsenic within the Santa Fe Group. The correlation between arsenic and pH in the Northwest Zone is not strong (R^2 value of 0.71) and very low for iron ($R^2 = 0.2$).

The analysis performed by LANL (citation) posed desorption of arsenic from oxides along with upwelling of deeper groundwater. The magnitude of faulting within and proximal to the Northwest allows a mechanism for up-welling of deeper older, isotopically depleted water. The Middle Rio Grande study found high levels of chloride in water with elevated arsenic and posed chloride as evidence of upwelling of older water. Low chloride levels in the Northwest zone do not support the level of upwelling or connection to deep water as observed in the Middle Rio Grande. One area in the Northwest Zone has higher alkalinity and TDS than the surrounding area and is near the intersection of the Barrancos monocline and the downthrown side of a fault. This may indicate upwelling of older water but more investigation is required.

Based on the structural geology of the Northwest Zone connection to deeper water cannot be ignored. Combination of both up-welling of deeper water and desorption, most likely from metal oxides, are proposed as controls for arsenic concentrations in Lithosome S of the Tesuque Formation within the Santa Fe Embayment of the Espanola Basin.

Recommendation of Future Studies

Within the Northwest Zone a better understanding of the relationship of metal oxide sorption and desorption as a control for arsenic concentrations is recommended. Though no clear spatial relationship was found between interpreted volcanic vents in the Southwest zone and elevated arsenic further geochemical investigation may help decide if the presence of these vents should be ignored as a source of arsenic,

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