Identifying the Origin and Evolution of Groundwater in the Salt River Valley and Applications for Better Water Well Design:

A Stable Isotopic Approach

by

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ABSTRACT

Stable isotopes were measured in the groundwaters of the Salt River Valley basin in central Arizona to explore the utility of stable isotopes for sourcing recharge waters and engineering better well designs. Delta values for the sampled groundwaters range from -7.6‰ to -10‰ in $\delta^{18}O$ and -60‰ to -91‰ in δD and display displacements off the global meteoric water line indicative of surficial evaporation during river transport into the area. Groundwater in the basin is all derived from top-down river recharge; there is no evidence of ancient playa waters even in the playa deposits. The Salt and Verde Rivers are the dominant source of groundwater for the East Salt River valley- the Agua Fria River also contributes significantly to the West Salt River Valley. Groundwater isotopic compositions are generally more depleted in ^{18}O and D with depth, indicating past recharge in cooler climates, and vary within subsurface aquifer layers as sampled during well drilling. When isotopic data were evaluated together with geologic and chemical analyses and compared with data from the final well production water it was often possible to identify: 1) which horizons are the primary producers of groundwater flow and how that might change with time, 2) the chemical exchange of cations and anions via water-rock interaction during top-down mixing of recharge water with older waters, 3) how much well production might be lost if arsenic-contributing horizons were sealed off, and 4) the extent to which replacement wells tap different subsurface water sources. In addition to identifying sources of recharge, stable isotopes offer a new and powerful approach for engineering better and more productive water wells.

DEDICATION

This thesis and anything significant that I have ever done or will do is dedicated to my mom and dad, who never laughed at my ambitions, goals, or dreams, and who attended almost every t-ball, basketball, softball, and volleyball game or any event I was ever involved in. You guys have redefined the words love and support because of how much you've believed in me. Thank you for letting me make my own decisions, but standing by me the whole way. Thank you so much for being my parents!

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INTRODUCTION

This study originated from an aspiration to design and construct improved water production wells using information gained from stable isotopic analysis. Because of the high cost of groundwater pumping facilities, it is imperative to design wells for optimum water quality and quantity. In order to understand the stable isotopic data from specific wells, it is necessary to research the origin of the groundwaters in the study area, the Salt River Valley (SRV) in Central Arizona. Previous studies analyzed only one area of the Valley; more research was needed to confirm this work, expand it, and compare it to the overall regional setting. The opportunity to obtain new information was enhanced by access to new groundwater samples, as well as chemical and well construction data from wells owned and operated by the Salt River Project (SRP). In addition, SRP drilled seven new wells during the time of this project, allowing the opportunity to obtain a unique set of depth specific samples that are available only during well drilling.

This investigation is designed to identify the origin and evolution of the SRV groundwaters and to establish the identity of the various sources of recharge. It compares the results of previous research to new data obtained from sampling SRP wells. These data evaluate the impact of anthropogenic modifications to the natural, pre-development water system. The results are used to evaluate the efficacy of using stable isotopes to distinguish regions of production in a completed well. This, in turn, can identify possible sources of pollution and the potential for successful modification without loss of well production. Furthermore, chemical data are used in concert with the stable isotope results to identify mixing relationships and water-rock exchanges due to diagenetic processes.

This isotopic investigation fuses hydrology, geology, geochemistry, and engineering to improve present and enhance future groundwater well designs. This research is increasingly important in the arid setting of central Arizona because groundwater is a major source of water to the region.

Chapter 2

BACKGROUND

Phoenix, Arizona does not appear to be a typical desert city because lush greenbelts, emerald green golf courses, and agricultural fields dot the landscape. Plentiful water is an anomaly in an arid climate, but to Phoenix residents, it is an expectation. Starting over a hundred years ago, the rivers that once swept through the desert were harnessed behind dams and diverted into canals to control and carefully manage the precious resource. Despite these engineering feats, the water scarcity persists. In Phoenix, an average of fewer than 8.3 inches of rain falls to the ground annually (NCDC 2006). Yet, the population of Phoenix metropolitan area swells; between 2000 and 2007 the Phoenix population grew an astonishing 24.2%, second only to Las Vegas (Woolsey 2007). In 2002, the watersheds of the Salt and Verde Rivers, the major water supply to Phoenix, experienced the 2nd driest year of the 110 year recorded history. In the same year, as a result of a prolonged drought combined storage in the Salt and Verde reservoirs dropped to a 50 year low of only 25.5% capacity (Hubble 2010). In times of such severe drought, large volumes of groundwater from alluvial aquifers are pumped to supplement the surface water supply. With a persistently low annual rainfall and more people needing water, Phoenix-area cities depend on these engineered structures and methods to capture water and deliver it to the tap. This is why it is essential to understand the origins, interaction, and evolution of this precious commodity.

There are obvious signs the first settlers of central Arizona understood the tenuous nature of their water resource. The Hohokam Indians used hand-dug canals to divert water from the Salt River for agriculture between 1 AD and 1450 (Andrews and Bostwick 2000). Some of these canals can still be seen today. Anglo settlers adopted the irrigation concept in the middle 1800's. Many settlers moved to Phoenix to take advantage of the year-round growing season and well-drained soils. Yet, variability in the flood/drought cycles of the Salt River made predicting water availability difficult for farmers. In 1906, the Bureau of Reclamation began construction on Theodore Roosevelt Dam, the first of several eventual diversions on the Salt River. Roosevelt Dam would soon, provide a dependable supply large enough to be regularly diverted into a set of canals for agricultural irrigation. By 1928 dams controlled all of the rivers flowing through the SRV. Today, the surface water systems that enter the valley are completely controlled and delivered; each drop of water accounted.

Groundwater pumping began in the valley in the late 1800's. With fluctuating surface water availability, groundwater became an invaluable water resource. Left unchecked, Phoenix groundwater was mined at a rate faster than it was recharged. Cones of depression and earth fissures developed as water levels plummeted. In 1980, the state legislature passed the Groundwater Management Act, establishing Active Management Areas (AMA) to monitor and regulate over-pumping in areas of concern. Yet even in times of drought, groundwater is still a heavily relied upon resource.

These anthropogenic modifications changed more than simply making water delivery more convenient. They changed the natural groundwater recharge from localized river channels to irrigation recharge ubiquitous throughout the heavily farmed valley. Water once concentrated in channelized river flow now spread into thin pools atop agriculture fields, creating more surface area to evaporate before seeping into the ground. Before the development of the reservoir/canal system, nearly all of the water was recharged from losing stream reaches of the major river systems (Freethey and Anderson 1986). Now, nearly 85% of the groundwater recharge in the valley is delivered through "incidental" recharge (Freihoefer et al. 2009). This water has been spread out and seeped into the ground via such mechanisms as flood irrigation, artificial recharge, golf course irrigation, and retention basins. The water quality from these types of recharge is affected by remnants of fertilizers, pesticides, and metals from storm water. Much interest is directed at detecting the pathways for these contaminants in order to protect the groundwater supply.

The importance of these water resources will only grow for the future population of the Phoenix metropolitan area. For this reason, this study focuses on understanding the SRV groundwater using stable isotopes of oxygen and hydrogen.

Chapter 3

PHYSIOGRAPHIC SETTING

The SRV basin encompasses the greater Phoenix metropolitan area in central Arizona (Figure 1). The SRV is located in the Basin and Range Province where crustal extension nearly 15 million years ago resulted in high-angle block faulting and subsiding basins filled with sediment from adjacent mountain ranges. A north to south divide of semi-impermeable mountain ranges splits the SRV basin. The two sub-basins are the East Salt River Valley (East Valley) and West Salt River Valley (West Valley).

The East Valley covers approximately 1,500 mi^2 (3,885 km^2) and is flanked by Tertiary and Precambrian crystalline mountain ranges (Figure 2): the McDowell Mountains to the north, the Usery and Superstition Mountains to the east, and South Mountain and the Santan Mountains to the south. The lowest elevation in the East Valley is 1,100 ft (335 m) at the southwestern valley floor and the highest elevation occurs in the Superstition Mountains approaching 5,000 ft (1524 m). The East Valley is essentially divided from the West Valley by the Phoenix Mountains, Camelback Mountain, Papago Buttes, and Tempe Butte. A complete hydrogeologic description of the East Valley is given by Laney and Hahn (1986).

The West Valley basin spreads roughly 1,500 mi^2 (3,885 km^2) and surface elevations range from 800 ft (244 m) in the southwest valley floor to 4,500 ft (1,372m) in the Sierra Estrella. The basin boundaries consist of granitic, volcanic, and metamorphic mountain ranges (Figure 2). The Buckeye Hills, South Mountain, and the Sierra Estrella ranges form the southern margin. The White Tank Mountains form the western boundary and the Hieroglyphic Mountains are the northern boundaries of the West Valley sub-basin. A comprehensive review of the hydrogeology of the West Valley is available in Brown and Poole (1989).

River Systems

The main drainages through the study area include the Gila, Salt, Verde, and Agua Fria river systems. The rivers are important to the livelihood and economy of Central Arizona. For this reason these rivers have been dammed and diverted for irrigation use and flood control since the early 20th century.

The Verde River originates in central Arizona along the Transition Zone. The Verde River flows south and drains approximately 6,254 mi^2 (16,198 km^2) of watershed, including Humphrey's Peak at 12,633 ft (3,851 m). Because of the location along the Mogollon Rim, many perennial creeks supply water to the main-stem Verde River. In 1936 the river was dammed at Bartlett Dam forming Bartlett Lake, and then again in 1946 at Horseshoe Dam and Reservoir. The flow of the river is controlled by the Salt River Project (SRP) from these locations. The Verde River joins the Salt River northeast of Phoenix.

The Salt River watershed drains approximately 6,249 mi^2 (16,185 km^2) of east-central Arizona. The Salt River begins at the confluence of the White and Black rivers. These rivers drain the White Mountains where elevations exceed 11,000 ft (3,353 m). The Salt River is fed by a series of perennial streams and flows east to west before reaching a series of four reservoirs and dams operated by SRP. Construction of the first and largest dam, Roosevelt, began in 1906. Below the confluence of the Salt and Verde Rivers, water is diverted by Granite Reef Dam into a system of irrigation canals (Figure 1). The typically dry river channel runs northeast to southwest through the Phoenix metropolitan area and joins the Gila River southwest of Phoenix.

The Gila River is the longest river system in Arizona. The Gila originates in the Mogollon and Mimbres Mountains in New Mexico where elevations exceed 10,000 ft (3,048 m). However, the highest elevation in the Gila drainage in Arizona is only 3,500 ft (1,067 m). The river travels approximately 150 mi (241 km) through the Basin and Range province, and receives no drainage from the Mogollon Rim unlike the other main river drainages. The Gila River is also dammed into reservoirs and an engineered irrigation system. The San Carlos Reservoir is the first impoundment. At Florence, Arizona the river is diverted into a series of irrigation canals. Currently, the Gila River channel through the study area is normally dry until below the confluence with the Salt River southwest of Phoenix.

The Agua Fria River begins in the Bradshaw Mountains and drains south into Lake Pleasant. The highest elevation in the Agua Fria watershed is ~8,000 ft (2,438 m) at Union Peak. The Agua Fria has a few intermittently flowing tributaries. In 1927, the Agua Fria River was dammed (Waddell Dam) to form Lake Pleasant. Most of the water from Lake Pleasant is diverted and combined with Colorado River water by the Central Arizona Project (CAP) canal. Water in the CAP canal flows southeast and delivers water to the Phoenix metropolitan area through the SRP system beginning at Granite Reef Dam (Figure 1). The normally dry Agua Fria River channel runs south through the West Valley to its confluence with the Gila River.

Due to these impoundments of naturally flowing river systems, the sources and quality of water recharged to the SRV has changed. The surface water flow in these systems is highly controlled and regulated by dams, reservoirs, and canal systems. It is possible that remnant groundwater exists that was recharged prior to the construction of impoundments. As explained below, waters unaffected by evaporation and quickly infiltrated into the ground will have an isotopic signature different from that of waters that have been concentrated in reservoirs and canals, and then swept out onto the desert landscape for controlled irrigation. It may be possible to detect any pre-development surface water inputs to the SRV using stable isotope analyses.

Basin Composition

Five hydrogeologic units comprise the East Valley and West Valley sub-basins (Figure 3). The hydrogeologic bedrock unit, the red unit, and the lower, middle, and upper alluvial units are characteristic of the Basin and Range alluvial basins identified in previous studies by Anderson et al. (1992), Robertson (1991), and Oppenheimer (1980). The unit divisions in this study are defined by hydraulic properties, and are described in further detail in the Arizona Department of Water Resources (ADWR) SRV model identified by Corkhill et al. (1993), Corell and Corkhill (1994), and updated by Freihoefer et al. (2009). Figure 3 is a cross section along line A to A’ in Figure 2 that represents the stratigraphic sequences of the two SRV sub-basins.

The Tertiary and Precambrian mountain ranges mentioned previously that form the bottom boundaries of the SRV basin, and are defined as the hydrogeologic bedrock unit. These ranges are composed of crystalline rocks (schist, gneiss, metavolcanics, quartzite, and granite) as well as Tertiary to Quaternary extrusive sequences of rhyolitic to basaltic volcanic flows. Collectively, these rock types form a nearly impermeable boundary to groundwater flow. In the center of the basins, the top of the bedrock is found over 10,000 ft (3,048 m) below ground surface (Oppenheimer 1980; Figure 3).

The red unit occurs in the East Valley. It is above the hydrogeologic bedrock unit, and is formed of Tertiary sedimentary sequences. Radiometric dating indicates the red unit was formed between 17.5 million years to 22 million years ago, prior to high-angle block faulting and basin subsidence (Brown and Pool 1989). The unit is well cemented, but in areas is also highly fractured. As a result the red unit is not a reliable source of water, except in localized areas where it is heavily fractured. Although lithologically the red unit and bedrock unit are very different, their hydraulic characteristics are similar in that they do not readily permit groundwater flow. In this study, these two units are grouped for classification purposes under the category of hydrogeologic bedrock unit.

The lower alluvial unit (LAU Figure 3) or lower unit is a fine-grained basin fill deposit above the hydrogeologic bedrock unit. Radiometric dating indicates the lower unit may be as old as 16.6 million years (Brown and Pool 1989). The lower unit formed during active subsidence of a closed basin. This history is indicated by the increasing thickness and decreasing particle size going upward in the stratigraphic section. Near the basin margins, the lower unit reaches a thickness of approximately 100 ft (30 m) and consists of conglomerate and gravel. Near the center of the basins, the lower unit is several thousand feet thick, and particle sizes grade into gypsiferous and anhydritic mudstone. Previous studies interpret the lower unit as alluvial fan deposits at the basin margins grading into fluvial, playa, and evaporite deposits at the center of the basins (Laney and Hahn 1986). In the West Valley, an evaporite deposit, the Luke Salt Body formed concurrently with the lower unit. The SRV model of the lower unit stops at 3,000 ft (914 m) below ground surface due to lack of deeper drilling data. However, studies indicate that the depth of the lower unit can exceed 11,000 ft (3,353 m) in the center of the West Valley basin (Brown and Pool 1989).

The middle alluvial unit (MAU Figure 3), or the middle unit, is above the lower unit. Like the lower unit, the middle unit is thickest at the center of the basins. This occurs in Gilbert for the East Valley and near Luke Air Force Base in the West Valley. The middle unit consists of clay, mudstone, and interbedded sands and gravels. Near the basin margins, the middle unit thins and consists of mainly sand and gravel, making it nearly indistinguishable from the lower unit. In some areas on the basin margins, the middle unit pinches out and the upper unit directly lies atop the lower unit. Also like the lower unit, this unit formed during a period of basin subsidence in a closed system. It is important to note that the middle unit is the main source of groundwater in present day water wells.

The upper alluvial unit (UAU Figure 3) or upper unit overlies the middle unit and is composed mainly of alluvial deposits of gravel, sand, and silt. The upper unit maintains a consistent thickness of nearly 200 to 300 ft (61-91 m) thick in the East Valley and 300-400 ft (91-122 m) thick in the West Valley. The consistent thickness and grain size suggest that the upper unit was deposited in the final stages of basin development and represents the channel, terrace, floodplain, and fan deposits of the ancestral Salt and Gila

Rivers approximately 3.3 million years ago (Laney and Hahn 1986). The upper unit connects the East Valley and West Valley sub-basins between Papago Buttes and Tempe Butte and between Tempe Butte and South Mountain. This unit historically was the largest groundwater producer, but due to over-pumping of the SRV for agriculture, the horizon is currently dewatered in many areas.

In summary, there are three distinct alluvial fill deposits in the center of the SRV sub-basins. Isotope data in this study are therefore categorized according to the three units defined by ADWR models. However, it is important to note that these units tend to lose their identity near basement highs. When adjacent to bedrock, all three units are coarse grained and almost certainly have enhanced permeability.

The sequence in Figure 3 illustrates the transition from closed basin stream and playa deposits (lower unit and middle unit) to the fluvial deposits from the Salt, Gila, and Agua Fria Rivers. The recharge sources of the groundwaters evolved in turn, from closed basin playa recharge to river water derived from distant, higher elevation terrains. Based on this history it is possible that remnant closed basin and possibly playa water are still found in the lower two units. It is further possible that the relative amounts of the source fluids once present in the East Valley and the West Valley could be distinctly different from one another, recording this historic isolation. Stable isotopes provide an approach for identifying and interpreting these important differences.

Chapter 4

PREVIOUS WORK

SRV Basin Hydrology

In 1977 the Bureau of Reclamation published a report on the hydrogeology of the central Arizona basins for the siting study of the CAP canal. The United States Geological Survey (USGS) soon followed with a Regional Aquifer Systems-Analysis program beginning in 1979 led by T.W. Anderson. In 1986 Laney and Hahn published the first East Valley based hydrogeology report and in 1989 Brown and Pool followed up the counterpart for the West Valley. In 1993 ADWR used these reports as the foundation for the first regional flow model of the SRV. In 2009 ADWR performed a model update. While all of these reports typically settle on the alluvial basin consisting of three different alluvial units, there are some discrepancies among the boundaries of each unit. The USGS unit divisions are based on geologic differences whereas the ADWR divisions are categorized based on hydraulic properties. In most places the Bureau of Reclamation and ADWR reports are in agreement. For the purposes of this study, all alluvial unit boundaries are based upon the depths defined by the current updates to the ADWR SRV model by Freihoefer et al. 2009.

Because of the importance of water to the Phoenix metropolitan area, numerous modeling studies have attempted to quantify the inflows and outflows of groundwater in the SRV. The advent of agriculture and irrigation changed the historical groundwater flows and discharge through numerous water production wells and the redistribution of surface water flow.

Freethey and Anderson (1986) generated a model of pre-development hydrological conditions in the alluvial basins of Southern Arizona. They based the model on wells existing prior to modern development (early 1900’s) and assumed a system in equilibrium (inflows = outflows) where no change in storage occurred. Modern groundwater models operated by the ADWR are based on a system of disequilibrium where discharge from pumping greatly exceeds recharge. Not only did this change the amount of groundwater in storage, but it also modified the overall regional aquifer flow system.

Geochemical and Isotopic Studies

Robertson (1991) published the first water quality analyses of the Basin and Range aquifers. This study evaluated the overall water quality of 72 separate basins to determine the sources of dissolved species in the groundwater. This report serves as the basis for geochemical modeling of the southwest alluvial basins.

Brand (1995) investigated the isotopic evolution of the Salt, Verde, and Gila River systems as they drained from high elevation headwaters into the man-made reservoirs of central Arizona. Brand’s research demonstrated that evaporation plays a significant role in the evolution of surface water. As each river flows from high elevation to the hot, arid conditions of the Sonora Desert, the stable isotopes evolved from that of snow toward isotopic signatures indicative of evaporation. This study also analyzed reservoir stratification and showed that man-made reservoirs enhance the evaporative signature of stable isotopes.

Groundwater contamination from livestock and agricultural industries provoked two studies by the USGS in the West Valley. Gellenbeck (1994) used isotopic compositions of oxygen, hydrogen, nitrogen, sulfur, boron, lithium, and strontium to define a relationship between isotopic composition and sources of nitrate. The oxygen and hydrogen data suggested that these isotopes reflected a geographic grouping due to differences in former Agua Fria/Salt River sources of recharge. The follow-up USGS study by Edmonds and Gellenbeck in 2002 studied the West Valley to evaluate the effects of water use, land use, and hydrogeologic factors on groundwater quality. The wells sampled were separated into five categories based on both the depth of perforations of the well and historic land use. The study concluded that evaporative enrichment of heavy isotopes in wells perforated in the shallower units correlated with irrigation seepage, while deeper units tended to have an isotopic signature similar to that of unevaporated river water.

McLean (2007) investigated flood flows of the Salt and Verde Rivers during a dam release in 2005, and the impact of the flow on the chemical and isotopic composition of Tempe Town Lake, an artificial lake created in the Salt River bed. McLean’s isotopic analysis of the Salt and Verde Rivers demonstrated a striking isotopic difference between the two rivers systems below the dam and reservoir reaches.

The Arizona Department of Environmental Quality (ADEQ) open file report series established ambient water quality conditions in several basin and watershed locations throughout Arizona. Data from Towne (2008) demonstrates the isotopic evolution of the

Agua Fria River as it flows from its headwaters in the Bradshaw Mountains into Lake Pleasant.

Further studies on Arizona rivers include a comprehensive geochemical study of the San Pedro River (Baillie 2005) and of the Verde River headwaters (Zlatos 2008). Knauth and Greenbie (1997) originally investigated the origin of the headwaters of the Verde River and developed a primer explaining how to use stable isotopes in surface water investigations. Other basins have been investigated with respect to geochemical and isotopic compositions by ADEQ. A comprehensive geochemical and isotopic analysis of the San Pedro Basin was developed by Adkins (2008).

Surface water isotopic data from Brand (1995), McLean (2007), and Towne (2008) are given in Figure 4. The figure is a cross plot of the δD and δ^{18}O variations for modern surface waters in the SRV basins. The δD and δ^{18}O represent the relative enrichment or depletion (expressed in per mil ‰) compared to the Standard Mean Ocean Water (SMOW) standard. The Global Meteoric Water Line (GMWL) is a statistical fit to isotopic data for precipitation from samples all over the world. Data from Arizona that plot on this line are for surface waters derived from rain or snow unaffected by evaporation. Data that plot to the right of this line represent surface waters that underwent ^{18}O and deuterium (D) enrichment due to evaporation. Thus, the data shown on the GMWL are for upstream rivers before they run out into the Sonora Desert or into the reservoirs. Those data plotting to the right of the GMWL have undergone evaporation while flowing in the SRV basins. Therefore, isotopic composition data for the groundwater samples can be compared with the surface water data to evaluate the extent of river recharge, and can be used for the engineering applications of this study.

Chapter 5

METHODOLOGY

Sampling Strategy

Data were compiled from previous studies by Brand (1995), Gellenbeck (1994), Edmonds and Gellenbeck (2002), McLean (2007), and Towne (2008) as well as a search of the USGS National Water Information System (NWIS) online database. These data were used to constrain inputs to the groundwater recharge and as a guide for determining further sampling sites.

In considering available isotope data for the Salt River Basin, there was not enough information for East Valley groundwaters to reach conclusions regarding the origin of the groundwaters. Additionally, production wells from Basin and Range aquifers tend to be screened over several tens if not hundreds of feet and therefore across aquifer boundaries. In order to better constrain isotopic variations with depth, zonal samples, as described below, were utilized to fill in the missing information and evaluate the origin and evolution of SRV groundwaters at various depths.

Water quality can be sampled during well installation or during post-well construction testing. During installation of a well it is possible to isolate a specific depth interval for analysis; the water sample comes only from that specific zone. Once the well is cased and screened, it undergoes testing to the extent possible to determine the specific mix of source waters and effects of the cumulative proportions of the various zones sampled. Using these as guidelines, four basic options for well sampling were implemented in this study. These types include: zonal sampling, step tests, constant rate/spinner log, and routine composite. In order to ensure an accurate representation of fresh formation water, attempts were made to purge the well bore by pumping three times its volume prior to sampling. However, due to operation limitations, less purge time was allowed for routine composite samples. Sample locations for 22 different wells in the SRV are shown in Figure 5. The sample sites, all located within the irrigation service territory of SRP, were chosen based on active drilling projects, depth of screen interval, and lateral distribution to obtain the most representative profiles of the two sub-basins. In addition to isotopic sampling, a chemical analysis of the groundwater was also obtained in most cases. Samples for isotope analysis were collect in 125 ml plastic bottles with tight fitting lids. Below is a synopsis of the different types of sampling suites.

During the reverse rotary drilling process of a new production water well, a pilot hole is drilled to total depth. After geophysical logging is completed, the geologist identifies areas of higher porosity to test for water quality. These areas are then discreetly sampled utilizing a process that simulates a mini well (Figure 6). Beginning with the deepest zones a bentonite seal is installed followed by gravel and then a top bentonite seal. A 40 ft (12 m) section of perforated drill pipe acts as the well casing. A small, 20 gallon per minute (gpm; 76 L/min) pump is installed and the zone is purged by pumping for approximately 12 hours before the water quality sample is taken. Normal water quality constituents tested for include metals (aluminum, iron, arsenic, lead, etc.), inorganics (nitrate), solvents, total dissolved solids, and pH. After the samples are obtained, the driller pulls the equipment up to the next desired zone and backfills the previous zone.

This highlights the importance of zonal sampling because it is the one opportunity for discrete sampling of 40 ft (12 m) intervals. A typical new well in the valley is drilled to 1200 ft (366 m), with 6-10 zonal samples.

After the well has been designed and constructed, the geologist performs a series of water quantity tests. The first consists of monitoring the effects of varying pumping rates by increasing the capacity at consecutive time intervals or “steps”. Sometimes, a water quality sample is taken at each step to monitor changes in water quality with increasing discharge (flow rates).

After a step test analysis has suggested an optimum pumping rate, the geologist performs a constant rate test. Usually this is a minimum of 24 hours and aims to monitor the longer term effect of the pumping rate. Many times during this test the geologist will request a spinner log and depth specific sampling. Utilizing an access pipe installed beside the test pump, a spinner log is performed to identify areas that are the largest contributors to the flow during well pumping. After the flow horizons are identified, a bailer is lowered down to a particular flow zone to collect a water sample. Chemical analysis of this water aims to determine the relative contributions of that particular zone to the overall composite water chemistry of the well.

After a new well is put in to service, the well is routinely monitored by SRP for water quality. This is normally performed annually but can also be performed quarterly based on pumping needs and routine maintenance. These samples are a composite of the overall contributions made from the entire screen interval. Attempts are made to purge three times the volume of the well bore, but due to electricity costs and water demand/conservation purposes, the sample is sometimes taken without confirmation of a full purge.

For the purpose of this isotope study, it is important to note that this manner of well construction yields a set of water samples from specific depth intervals before final well construction. Following completion of the well, water is produced from the screened intervals that receive water from multiple depths. Water from the producing well is thus a composite of many depth intervals. As will be shown, comparison of the zonal samples acquired during initial testing with these composite samples derived from the final well can convey extremely useful information regarding the amounts of water ultimately produced from specific depth intervals as well as insights into the source of the aquifer waters.

Laboratory Analysis

Isotopic analysis was performed by the University of Arizona Stable Isotope Laboratory. Both isotopic analysis for oxygen and hydrogen where performed on a Finnigan Delta S gas-source Isotope Ratio Mass Spectrometer (IRMS). Hydrogen analysis involved reduction of water over Cr metal at 750°C (Gehre et al. 1996). Oxygen isotope analysis was performed by CO_2 equilibration at 15°C (Craig 1957). Isotopic data are reported in per mil (‰) notation standardized against Vienna Standard Mean Ocean Water (VSMOW). The analytical precision (1-σ) reported by University of Arizona Stable Isotope Laboratory was 0.9‰ or better for δD and 0.08‰ or better for $\delta^{18}O$ as determined by repeated internal standards. In this study error is reported more conservatively at 2‰ for δD and 0.2‰ for $\delta^{18}O$ based on historical precision between interlaboratory comparisons because several blind duplicates had to be re-analyzed to achieve the lab's normally high precision. Variations in the groundwater samples were large enough to reach conclusions using the bigger error estimates. Data for each sample are presented in Appendix A

When available, standard chemical analyses including pH, total dissolved solids, metals (As, Fe) inorganic constituents (Nitrate), cations (Na^+, Ca^{+2}, Mg^{+2}, K^+) and anions (HCO_3^-, SO_4^{-2}) were conducted by the environmental lab at SRP. Available chemistry data are presented for each sample in Appendix B.

Chapter 6

RESULTS AND DISCUSSION

Data for 102 samples from 22 wells are shown in Figure 7 together with the regional river water data. The well data display a variation of 3.3‰ in δ^{18}O and 31‰ in δD. Most of the data plot in a similar range as river water that has undergone evaporation. They generally fall along the evaporation trajectory (m=4.3) defined by Brand (1995), but some are distinctly different from the river measurements. These latter data plot to the right of the meteoric water line and at more negative δD compositions than the majority of the groundwater samples.

Origin of SRV Groundwater

Previous geologic studies as well as the ADWR SRV model reveal the existence of large evaporite deposits near the center of both sub-basins in the middle unit and lower unit basin fill. Water samples taken from wells in the valley can yield sulfate values near the secondary EPA defined maximum contaminant level of 250 mg/L. From the chemical analysis, it is possible to draw the conclusion that water recharged during playa deposition still exists in the basin today. If so, it should also have an isotopic composition different from that of river water because strong enrichments in ^{18}O and D in playa recharged groundwater should be present if evaporation exceeds inflow.

Isotopic evaporation trajectories are a function of humidity (Gonfiantini 1986). The SRV playas existed in hydrologically closed basins of low elevation prior to the cooler Pleistocene climate therefore source waters derived in this setting would have had δ-values on the GMWL at points higher than the current surface water recharge from distant, high elevation mountain ranges. Therefore, it is possible to infer a starting point on the GMWL several per mil enriched in ^{18}O and D as shown in Figure 8. Assuming a relative humidity between 0-50% (the current summertime humidity of Phoenix is between 12-33%) evaporation trajectories with slopes between 3.9 and 4.3 can be predicted. Using Gonfiantini's humidity and evaporation slope relationships, the inferred playa groundwater values are projected to lie within the orange polygon shown in Figure 8. As shown in the figure, no SRV groundwater data are located within the hypothesized playa polygon; suggesting no playa water is present in the SRV groundwater.

The absence of remnant playa water in the SRV strata may indicate the volume of water carried from high elevation recharge over the last 3.3 million years simply flushed out any ancient playa waters. High sulfate groundwater exists because the river recharged water dissolves gypsum and anhydrite found in the basin fill. This is a chemical reaction, not an indication of the water's origin. This highlights the effectiveness of using stable isotopes for identifying the origin of waters. Stable isotopes are able to measure the water molecules themselves, instead of measuring the chemistry of one species dissolved in another. Although the chemistry and geology indicate a record of playa deposition, the absence of an isotopic evaporation signal indicates that the native water recharged during the time of playa has likely been flushed out.

Another possible explanation of the absence for playa-derived groundwater could be the limited drill depths. In general, most wells are finished in the middle unit because lower yield from the lower unit reduces the economic value of deeper drilling targets. The deepest well sampled was SRP well 05.0E-11.1Nat 1900 ft (579 m). However, the deepest parts of these sedimentary basins exceed 11,000 ft (3353 m; Brown and Pool 1989). Since sedimentary brines are denser than fresh groundwater, playa groundwater may have settled to the deepest parts of these basins where it may reside yet. Deeper drilling may still reveal remnant playa waters if groundwaters are found to have more positive δ^{18}O-values as shown in Figure 8.

Pre-development versus Modern Recharge in the West Valley

There may be several processes, geographic distributions, or depth variations that explain the wide range of isotopes in the SRV groundwater. While not the primary target for their study, Edmonds and Gellenbeck (2002) found data in the West Valley suggested δ–values vary based on land use and screen interval. The sample locations for selected wells from their study and from the West Valley sampling locations from the current study are shown in Figure 9. The data fell into two domains (Figure 10). First, deeper, confined wells and wells with no history of agricultural land use produced water with isotopic compositions close to the GMWL with a wide range of values (labeled "Pre-development Recharge"). Second, wells drilled to the water table and wells with perforations above confining beds and within irrigation districts, returned δ–values off the meteoric water line and enriched in the heavier isotopes (labeled "Modern Recharge"). It should be noted that in general, the deeper well locations were distributed throughout the West Valley east of the Agua Fria River, and the wells that indicated irrigation recharge are located entirely within the southwest part of the West Valley between the White Tank Mountains and the Buckeye Hills along the Gila River (Figure 9).

If the conclusions from Edmonds and Gellenbeck (2002) are correct for all West Valley samples, then the new West Valley data in this study should plot in the domains defined by the USGS data (Figure 10), and variations outside of the data set would require a different explanation. The wells sampled by Edmonds and Gellenbeck (2002) were screened over several units, therefore samples from this study targeted specific 40 ft (12 m) zones to constrain the depth variability. Figure 11 defines the δD versus $\delta^{18}O$ relationships of SRP wells by alluvial unit in reference to the domains defined by the data from Edmonds and Gellenbeck (2002). The upper unit wells from the current study (red triangles) have the shallowest screen interval and receive the most recent recharge. As expected, these data correlate well with the modern recharge domain of the USGS study (Figure 11). In fact, one data point (a in Figure 11) expands the evaporation field, suggesting some areas in the West Valley experience greater degrees of evaporation than defined by the USGS. This data point occurs in well 00.4W-03.3N at the shallowest depth sampled (251 ft (77 m) below ground surface). This well is located east of the USGS wells near the confluence of the Agua Fria and Salt Rivers (Figure 9). The land historically received flood irrigation from both groundwater and surface water for agricultural production, which may be the reason for the enhanced evaporation signal in the isotopic compositions.

Three of the lower unit samples (blue circles) plot within the pre-development boundaries, as expected. However, two of the samples are located on the fringe of the evaporation area (b in Figure 11). These two outlier lower unit samples are from the same well, 12.1E-08.9N (Figure 9). This well is located near the East Valley/West

Valley boundary close to the Grand Canal. Depth to bedrock in this area is relatively shallow, and previous studies indicate the location of this well is on the up-thrown edge of a normal fault (Brown and Pool 1989). Drill cuttings indicate the alluvial units are extremely fined grained and difficult to distinguish. Since the lower unit is relatively shallow in this area at 466 ft (142 m), the isotope samples from the lower unit likely record modern, irrigation recharge.

The middle unit samples are present in both data domains. Several middle unit samples indicate meteoric pre-development origin with the exception of data from two wells. Well 05.1E-16.2N (Figure 9) is located in Peoria, AZ close to the New River channel. The majority of evaporation occurs in the shallower middle unit samples (group c in Figure 11), which is expected due to agricultural recharge percolating quickly through the permeable upper unit. Well 12.1E-08.9N, the outlier in the lower unit analysis, also has an isotopic composition similar to those of the middle unit (d in Figure 11) suggesting isotopic homogeneity along the basin edge.

Five samples contained screen intervals that include two or more units. Well 07.5E-15.2N (Figure 9) is perforated in both the upper unit and middle unit. This sample plots among the most enriched in heavy isotopes and displays a strong evaporation signature (e in Figure 11). Wells 05.0E-11.1N, 07.6E-15.2N, and the composite of 12.1E-08.9N are screened in both the middle unit and the lower units. 12.1E-08.9N (f in Figure 11) and 5.0E-11.1N (g in Figure 11) δ–values are located between the pre-development and modern groups, and are likely a result of mixing between the two groups. Recharge infiltrates vertically through the upper and middle units and eventually reaches the pre-development horizon where the waters mix. Groundwater in the mixing zone would form composition between the two end members in the zone where the data from these two wells is located. Well 07.6E-15.2N (h in Figure 11) plots further down the meteoric water line with the pre-development group, suggesting that the water pumped from this well is older river water. One well, 14.8E-00.7N is screened throughout all three alluvial units. The isotopic composition of this well (i in Figure 11) is located in the evaporated domain suggesting that the contributing volume of groundwater is coming from one or both of the upper and middle alluvial units.

The results of this study indicate that stable isotopes can be used to define a boundary of modern recharge versus pre-development recharge water or river water. Wells that are closer to basin fringes are likely to display isotopic homogeneity while wells at the centers of basins are likely to display larger variations in isotopic composition between horizons.

Deep Groundwater Sources

The variation in the isotopic composition of deep, pre-development water along the GMWL may be indicative of the contributing river system at the time of recharge. Isotopic compositions consistent with modern river water values of the Agua Fria River and Salt Rivers demonstrate a difference likely based on source area elevation (Figure 4). This difference, known as the altitude effect, should also distinguish pre-development surface water between these two river sources. Figure 12 displays the deep, pre-development groundwater isotopic compositions categorized according to their proximity to the modern day Gila, Salt, and northern (Agua Fria and New) river channels. The groundwater samples closest to the Salt River (red in Figure 12) are lower on the meteoric water line. These values shift to more positive δ-values as the well locations progress westward (i.e. in the direction downstream along the river channel), and with distance from the modern channel. This is expected as the modern δ-values of the Salt River reflect similar high elevation source waters and evolve toward more positive δ-values downstream (Brand 1995).

The isotopic data for pre-development groundwater nearest the northern rivers (blue in Figure 12) also begin with ^{18}O and D depleted composition in the northwestern parts of the valley. However, the trend of increasing δ-values downstream is not apparent. The three most negative δ-values are from wells in northwest valley, where the rivers enter the SRV. These are also the deepest samples ("deepest wells" in Figure 12). In top-down recharge, the deeper wells sample older waters. As discussed in a subsequent section the data suggest this is indicative of a cooler climate. This highlights the importance of considering depth variability of groundwater in isotope analysis.

Samples nearest the modern Gila River (green in Figure 12) demonstrate wide isotopic variation overlapping data from wells near the both Salt and the northern rivers. Water from the Gila River wells also exhibits a complex range in isotopic composition based on distance from the river, depth, and progression of the channel from east to west. This is likely due to mixing from the confluence of both the Salt and Agua Fria Rivers in the southwest study area before exiting the SRV. With further zonal analysis and analysis of wells close to each river system, it should be possible to construct contour maps of isotopes based on depth, geographic distance from a river channel, and distance from river source that could identify recharge sources from pre-development times.

It should be noted that while Edmonds and Gellenbeck (2002) concluded that the enrichment in heavy isotopes is due to irrigation seepage (i.e. evaporation), there is another implication of labeling deeper water as “pre-development” groundwater. Since the damming of the major rivers, most recharge in the area comes through “incidental” recharge (recharge from flood irrigation, artificial lakes, domestic water, etc). These are anthropogenic modifications to the natural recharge system. These modifications cause isotope enrichments through a combination of two processes. Surface water diverted by dams and canals enters the East Valley (Figure 1), and evaporates as it travels across the desert; the isotopes become progressively evapoconcentrated as the water reaches the West Valley. Another explanation relates to infiltration rates in valley soil. If infiltration exceeded evaporation, the isotopic composition of the water would be closer to the meteoric water line. If evaporation exceeded infiltration, heavily evapoconcentrated isotopic signatures would dominate the isotopic signal of groundwaters. Increased urban development through construction of parking lots, roadways, etc. increases impervious surfaces therefore causing evaporation to exceed infiltration. This could enhance the evaporative isotopic signal and could be a factor in the modern isotopic composition of shallow groundwaters.

East Valley and West Valley Comparison

The current ADWR hydrologic model discussed previously advocates the genesis of two closed, subsiding basins with little or no hydraulic connectivity until the last 3.3

million years when surface drainages connected the two basins (Figure 3). As concluded from the isotopic data, river recharge drainage has purged any pre-river groundwater signal from the basins. The basins are connected through a relatively thin overlying layer of fluvial deposits (Figure 3). The East Valley basin is closer to the source areas of the Verde, Salt, and Gila Rivers, while the Agua Fria only drained to the West Valley. Groundwater underflow enters the West Valley from more arid areas at lower elevations than the East Valley groundwater underflow. Differences in these two sub-basins may be present based on the elevation differences among the watersheds and drainages that feed the basins. Water from the West Valley may also have isotopic compositions that reflect evapoconcentration due to the increased distance surface water travels across the desert in lined canals.

Figure 13 is a map of the East Valley sampling locations from this study, as well as available well data locations obtained from the USGS NWIS database. Data for these wells, together with those from the West Valley, are shown in Figure 14. The graph illustrates that the isotopic compositions for both basins are similar for the majority of groundwaters, and follow the general Salt and Verde evaporation trend as defined by data from Brand (1995) and McLean (2007;Figure 7). However, the West Valley wells have an enriched D and ^{18}O component that may reflect an evaporated contribution to these samples. The East Valley appears to have samples with much lower δ-values that plot well off the meteoric water line. In general, the data supports the idea that the West Valley is dominated by a lower elevation river source (Agua Fria) than the East Valley;

and that the evaporation of water as it is transported across desert landscape to the West Valley contributes to the enrichment of heavy isotopes in the modern groundwater.

In order to analyze these differences more closely, Figures 15-17 display the isotopic samples grouped by the alluvial unit screened. Only those samples that are screened in one alluvial unit are included, with the exception of the East Valley upper unit. No zonal samples were obtained from the East Valley upper unit. Therefore, three samples screened in both the East Valley upper and middle units were included for consideration. Due to the much higher hydraulic conductivity values of the upper unit (Corkhill et al. 1993), the assumption was made that the upper unit would be the primary water producer where both units are screened.

Figure 15 depicts the lower unit East Valley and West Valley isotopic compositions. There is no significant difference between the data sets; both lower unit data sets show largely unevaporated meteoric source waters. This indicates pre-development waters as described in the previous section.

Unlike the lower unit, the middle unit data show larger variations and a contrast between the East and West Valleys (Figure 16). In general, the East Valley middle unit appears to be slightly more depleted in D than the West Valley middle unit groundwater. Both basins demonstrate some evaporation in the middle unit, although it appears the original sources for these waters were at different elevations due to the ^{18}O and D enriched nature of the West Valley data. This is evidence for the lower elevation recharge from the Agua Fria and possibly for groundwater inflow from the arid Hassayampa Plain dominating the middle unit in the West Valley. Several samples from the East Valley define a unique position in the cross plot, being remarkably depleted in deuterium relative to the other East Valley data. These important samples will be discussed separately in the subsequent section.

Data from the upper unit samples from both basins are displayed in Figure 17. The East Valley upper unit data are from wells screened over both the upper and middle units. These samples display an isotopic composition consistent with evaporated Salt and Verde River water. The upper unit West Valley samples are more depleted in the heavy isotopes than the middle unit West Valley samples in Figure 16; this likely demonstrates the effect of damming and diversion of the Agua Fria River. The Agua Fria is dammed at Lake Pleasant; its water is combined with Colorado River water and diverted to the CAP Canal, which delivers water to the SRP canal system (i.e. Salt and Verde River water) at Granite Reef Dam in the East Valley. The isotopic shift observed in the upper unit West Valley groundwater demonstrates that the majority of source water is now the evaporated Salt and Verde river water delivered through canals, rather than the lower elevation recharge present before the Agua Fria was dammed. This again demonstrates the power of isotopes to identify significant anthropogenic effects due to engineered river systems.

Pleistocene Origin of Bedrock Groundwaters

The most strikingly different groundwater data are for well 22.9E-10.8N in the East Valley (Figure 18). These samples represent the lowest δD values for any of the measured SRV groundwaters (Figure 7) and are located in the fractures of the bedrock unit of well 22.9E-10.8N. Due to its unique source rock, as well as its distinct isotopic signature, it can be inferred that the origin of this groundwater is different from that of the alluvial units throughout the rest of the SRV.

In this top-down recharge setting, groundwater located in deep fractures under the alluvial units is likely much older in age due to it having been trapped in the fractures. Most wells are not drilled to bedrock because too little water is produced. Furthermore the alluvial units above the bedrock are more permeable and therefore focus groundwater flow over the bedrock instead of down into the fractures. These waters are depleted in both D and ^{18}O relative to the other groundwater samples in the SRV. A possible explanation for these data is that they represent water that was originally on the GMWL and evaporated producing the observed δ-values. If so, the isotopic composition of the original water would have to have been much lower on the GMWL because the values are much lower in D than any of the modern evapoconcentrated river waters (Figure 7). In this scenario, an evaporation trajectory with a slope of 4.3 would give an original source water isotopic value of -14.6‰, -107‰. Extremely low values such as these are similar to current snowmelt at the highest elevations on the Verde watershed (Brand 1995). This position of the GMWL suggests that the climate when this water recharged was cooler than it is today. The bedrock fracture groundwater may thus be indicative of Pleistocene Salt River water that descended into the fractures after undergoing significant evapoconcentration along its desert flow path. Although cooler and possibly more humid during the Pleistocene, the SRV was nevertheless a desert climate conducive to evaporation and thus enrichment of the heavy isotopes, so this is a reasonable possible explanation for these unusual fracture-fill waters.

Well 22.9E-10.8N lies within the band of fractured bedrock and close to known thermal wells (Stone, 1980). Isotopic exchange can occur between water and carbonate/silicate at elevated, hydrothermal temperatures. The effect is pronounced in geyser systems, but ground waters heated to higher temperatures could begin to yield observable changes in $\delta^{18}O$. Silicates ($\delta^{18}O> +5$ ‰) and carbonates ($\delta^{18}O>+20$‰) are strongly enriched in ^{18}O relative to meteoric waters, so $\delta^{18}O$ of water can rise to higher values during hydrothermal exchange. Since little hydrogen is in rocks, the δD of the water remains constant. Waters originally on the GMWL thus evolve to more positive $\delta^{18}O$ values during this interaction but δD does not change. This manifests as a horizontal line deviating to the right off the GMWL. Deviations ranging from 1.0‰ to 6.5 ‰ are observed in geyser fields (Craig 1967). If hydrothermal exchange were the reason for the shift off the meteoric water line for the bedrock fracture-fill water here, the original source water would have had an isotopic composition near -12.6‰, -85‰. This is isotopically similar to current surface water in the SRV before it enters the reservoir system (Brand 1995). Elevated well bore temperatures and high silica and sulfate concentrations in the bedrock chemistry analysis (Appendix B) may thus support a hydrothermal alteration explanation for these data. However, the telltale signature of groundwater that has undergone hydrothermal alteration is a data array for several or more samples with constant δD but variable $\delta^{18}O$. Here delta values for the 4 samples from the bedrock fractures fall on a well-defined linear array together with those from the overlying alluvial aquifer units that has large δD variation but little variation in $\delta^{18}O$ (Figure 18).

The lowest δD end member water sample in the bedrock fractures may thus be a single water sample that evolved to high $\delta^{18}O$ via hydrothermal exchange and then mixed with the other and overlying waters. In the absence of the telltale "horizontal" data array in any of the other fracture-fill waters in this unit, it is more likely that the fracture-fill end member value was achieved via the evaporation scenario rather than via hydrothermal alteration. The association of this unusual water with known hydrothermal activity is noteworthy, but the magnitude of ^{18}O enrichment off the GMWL (1.5 ‰) is achieved only in high-temperature geyser fields. Such large enrichments are observed repeatedly in Arizona surface waters, so the evaporation origin for this low δD end-member must be considered the simplest explanation. As the search for hydrothermal resources in Arizona continues, further isotopic analyses of groundwaters in this area might yield interesting surprises.

Mixing Array

The data in Figure 18 are so linear over such a large range of δ-values that mixing between waters with $\delta^{18}O$, δD compositions of -8.7‰ to -10.9‰, and -63‰ to-91‰, respectively, seems certain. Because top-down recharge is common in the SRV, the high δD end member would be expected to be nearest to the surface, and the low δD would be expected to be the deepest groundwater, that has yet to be flushed. Coming down the mixing trend, the data should progress from the shallowest unit (middle alluvial unit here), then lower alluvial unit, and then the bedrock fracture water. Remarkably, the upper end member is actually also from the bedrock fractures and the sequence descends next to lower alluvial unit samples to middle, and then back to bedrock fractures! The sequence is not at all what the simplistic, top-down recharge would yield.

An explanation for this remarkable result relates to the likely nature of recharge in this particular geologic setting. As shown in the geologic cross section (Figure 19), the well is adjacent to a basement high. The basal unit is a section of coarse alluvial fan material extending to the near surface along the surface of the basement high. The middle unit also grades into coarser grained material along the edges of the basin and becomes indistinguishable from the lower unit. However, in this setting a few miles away from the basement outcrop, the middle unit is fine grained, consisting of up to 95% fine silt and clay. The upper unit, consistent with most areas of the valley, is a cobbly coarse grained fluvial deposit. The fine grained nature of the middle unit inhibits the downward infiltration of groundwater through the less permeable silty clay. Areas closer to the bedrock high, along the edges of the basin receive recharge into the coarser grained sediments where it preferentially flows along the basal alluvial fan deposit, and eventually end up circumventing the middle unit. However, over time some water does pass through the middle unit, diluting the original recharge with modern recharge. The isotope data can now be fully understood in terms of this geologic setting that is unusual for most of the SRV groundwaters.

In this explanation, the original deep, low δD water trapped in bedrock fractures once filled the basin at least up to the middle alluvial unit. Recharge to the groundwater evolved to modern day values, and essentially flushed out the signal in the lower unit due to higher permeability and preferential route from the surface. However, since the middle unit is less permeable, it is taking a longer time to flush the middle unit of its original isotopic signature. The result is an intermediate mix between ancient recharge located in the bedrock fractures and recent recharge from the surface that falls along a linear mixing array (Figure 18). This also explains the position of the bedrock sample with the most positive δD (sample 1208). Through a series of interconnected fractures, some recent water has been able to seep down through secondary porosity. This sample is isotopically and chemically most similar to the other lower unit samples, indicating a similar origin, but with a quicker route to the deep subsurface.

This is the only clear mixing trend observed in this study. The stable isotopes have indicated the end-members and the relative proportions of the various mixtures can be readily determined simply from the position of the data in the linear array. For example, a sample lying exactly half way between the two end-members would be a 50/50 mix of the two. A sample lying 25% of the way down from the upper to the lower would indicate 75% of the mixture is composed of the upper end member. Thus, in Figure 18, sample 506 is 37% lower unit (upper end member) and 63% bedrock (lower end member). The other intermediate mixtures may be similarly calculated. In a mixing trend, the chemical constituents of the various mixtures will also vary according to the mixing proportions providing they are not lost to, or leached out of, the aquifer minerals. Cross plots of chemistry versus isotopes can therefore powerfully assess water-rock interactions in mixed samples as explored below.

Water-Rock Interaction

Plots of δ–values versus chemistry can be useful in analyzing water-rock interaction. It is known from the previous isotopic analysis that the isotopic data from well 22.9E-10.8N define a line. This line is interpreted as a mixing line with the lower alluvial unit as the end member enriched in deuterium and bedrock as the end member depleted in deuterium (Figure 18). If chemical constituents are mixing in the same proportions as isotopes, the chemical data should also fall on a mixing line.

Figure 20 is a δD vs. sulfate cross plot of zonal data from 22.9E-10.8N. The data fall on a line with the high sulfate waters from the bedrock and low sulfate waters from the lower unit as end members. The middle unit samples are located on this line between the two end members, indicating the middle unit sulfate composition is a mix between the sulfate compositions of the lower and bedrock units.

This is not the case with all chemical constituents from this well. Figure 21 is a plot of δD vs. calcium for the same well. The bedrock fracture groundwaters have high calcium values, while the modern recharge of the lower unit have the lowest calcium values. Drawing a line defined by the end member values will identify intermediate values of a conservative mix between these two compositions. However, three of the intermediate middle unit data points lie below this inferred mixing line, indicating lower than anticipated calcium values for the middle unit groundwaters. This deviation from the mixing line indicates that approximately 20-40 mg/L of calcium has been lost, likely consumed into the alluvial formation. This could perhaps be the result of calcite precipitation.

Figure 22 illustrates a similar water-rock interaction for magnesium. From the δD vs. magnesium mixing array, it is evident that three of the middle unit samples lie below the mixing line and have therefore lost approximately 15-20 mg/L of magnesium to the formation. Formation of high magnesium calcite and possibly dolomite could consume calcium and magnesium in these water-rock reactions.

The δD vs. arsenic diagram (Figure 23) illustrates a different scenario. In this case, the middle unit data lie above the mixing array defined by the bedrock and lower unit δD values, indicating higher than expected arsenic concentration in the groundwater. Water-rock reactions have mobilized 20-35 μg/L of arsenic in the groundwater. It is common to see groundwaters yielding high arsenic values in the SRV. Arsenic mobility is tied to several different factors including redox potential, dissolved oxygen content, and iron concentration in the groundwater (Robertson 1991).

It is possible that ion exchange reactions within the middle unit clays are playing a dominant role in controlling the water chemistry. It is possible that these ion exchange reactions absorb calcium and magnesium into the rock formation and exchange with arsenic, which is then mobilized to the groundwater. Supporting evidence of this is in Robertson (1991). This study found that ion-exchange reactions dominate basin chemistry and are responsible for magnesium enrichment in the subsurface clays. Clays often found in the formations of the East Valley are dominantly montmorillite, which are high in calcium and magnesium (Robertson 1991).

It is clear that when the water molecules themselves display a robust mixing trend, isotopic cross plots against chemistry can be powerful tools used to evaluate diagenetic water- rock reactions. Stable isotopes make this quantitative analysis possible; it would be near impossible to do this from the chemistry alone.

Utility and Limitations of Zonal Groundwater Isotope Analysis

Zonal sampling during well installation yields a set of water samples from specific depth intervals before final well construction. This type of sampling returns discrete chemical and isotopic analysis for a 40 ft (12 m) depth interval. In this study, zonal analysis has successfully provided the opportunity to expand previous hypotheses as well as indicate the ability to assess mixing relationships and water- rock interaction. Furthermore, zonal sampling highlights distinctive water quality variations with varying stratigraphy within a well, and constitutes vital data when considering the final well design. Following completion of the well, groundwater is produced from the screened intervals that receive water from multiple depths. Water from the producing well is thus a composite of many zonal depth intervals. It is often difficult to identify which horizon is contributing the greatest groundwater flow based on water chemistry alone due to the water-rock interactions discussed in the previous section. Commonly, mechanical methods to determine relative flow contribution to a well are used during a constant rate test. One of these methods, a spinner log, has limitations as it requires testing over the entire screen interval. Often, a pump is set below the top of the screen, or the pumping water level of a well is drawn-down past the top of the screen. Both of these problematic cases restrict access to the uppermost screened area and can therefore result in an incomplete spinner analysis. In a well screened over multiple zones (or hundreds of feet), it is possible that a comparison of stable isotopes analyzed both during zonal sampling and composite sampling may help to identify the zone of greatest contribution. The locations of wells for which zonal samples were taken are indicated in Figures 9 and 13. Well construction diagrams for these wells are available in Appendix C.

Arsenic Mitigation

SRP well 22.9E-10.8N is located in Scottsdale, AZ on the western edge of the East Valley (Figure 13). The well was drilled in 2004 to a total depth of 2010 ft (613 m) and ended in fractured bedrock. Figure 24 shows the δD vs. δ^{18}O plot for this well. The well yielded 14 zonal depth samples, the most of any of the studied wells, and the only well to generate bedrock zonal samples. No upper unit samples were taken. Four samples were taken from the middle unit (circles) as well as four samples from the lower unit (triangles). The six deepest samples were generated from the bedrock unit (squares). The well construction of 22.9E-10.8N includes three screened intervals: from 400-540 ft , 640-760 ft, and 840-1180 ft (122-165 m, 195-2332 m, and 256-360 m respectively).

As discussed previously, the zonal sample data define a mixing line between the lower alluvial and bedrock units. The composite sample of the well once completed should fall on this line in a position relative to the percent of contributions for the zonal sample depths included in the final screened interval. Figure 25 is a δD vs. δ^{18}O cross plot of the zonal samples included in the screen interval and also the composite sample (white diamond) taken after well construction. In a simple mixing scenario between two points, a composite data point will lie somewhere on the line reflecting a contribution from each end member data point. The position of the composite sample is directly proportional to the distance between those two points, analogous to the "lever rule" in petrology. For example, a composite located halfway between two end members reflects a 50/50 mix between those end members. The closer to the end member, the greater the portion that end member contributes. So, an 80% contribution of one end member to a mixture will cause the mixture to plot 20% of the way to the other end member. Analysis with multiple data contributing to the composite, as shown in Figure 25, becomes more complex.

Determining flow contribution is especially important in this well due to the elevated arsenic concentration of the composite sample. The composite arsenic concentration and the middle unit samples (grouped in Figure 25) are high in arsenic. Because of the similarities of elevated arsenic composition in these samples, it has been assumed that the greatest flow contribution is from the middle unit, and that any modifications to the unit to inhibit arsenic production could also result in loss of significant well production. Exploration into this problem via spinner log has been inhibited because the pump is below the top of the perforations and pumping water levels drop below the top of the screen. It is possible that isotopes may help to identify the greatest loss in production that could occur by sealing off the middle unit screen interval to mitigate natural arsenic contamination. The composite in Figure 25 is a mix between two end members. The enriched δD end member is one sample located at 1025 ft (312 m). The depleted δD end member is the sum of the remaining seven samples that plot isotopically more negative than the composite. It would be difficult to determine the proportion of the individual seven low δD samples to the composite without more information. In order to determine the maximum amount that the high arsenic samples contribute to the well, a hypothetical case is calculated where these middle unit, high arsenic samples are the only end member. In this extreme case, which would maximize the contribution of arsenic to the composite, 63% of the composite flow is being contributed by the 1025 sample and 37% of the flow is contributed from the middle unit samples. This is to say if the entire middle unit were to be sealed off from the well, no more than 37% of production from the well would be lost. This is the maximum value of contribution, because the other lower δD samples surely contribute to the mixture. This is likely because the lower alluvial samples at 707 and 926, which lie below the composite, are coarser grained, more permeable units. This suggests it is possible to mitigate the arsenic problem by sealing off the middle unit. This may not result in a significant loss of production, but could increase the overall water quality of this well.

This highly practical result illustrates the significance of isotopes as a tool to determine better well designs, and evaluate well modification challenges. With stable isotopes, it is possible to assess the probability of successful well modification in order to increase composite water quality without sacrificing water quantity.

Identifying Relative Aquifer Contributions and Projecting Aquifer Depletions

SRP well 25.9E-03.9N is located in Tempe, AZ along the Tempe Canal near the Salt River Channel (Figure 13). The well was drilled in 2007 to a depth of 1562 ft (476 m). Eleven zonal samples were generated from the well. Figure 26 is the δD vs. δ^{18}O graph depicting the zonal isotopic data. Seven of these samples were obtained from the middle unit (circles) and four from the lower unit (triangles). The results indicate there are three different horizons of groundwater. The shallowest sample at 290 ft (88 m) is enriched in

^{18}O and plots significantly off of the meteoric water line. This depth likely receives a significant amount of recharge through flood irrigation. The historic land use has been predominantly agriculture, and therefore retains an evaporated isotopic signature. The next 9 samples ranging from depths between 380-1360 ft (116-415 m) plot near or on the meteoric water line within -9.7‰ to -10.3‰ and -70‰ to -73‰. These samples are indicative of modern, meteoric recharge and would be expected from the proximity of the Salt River channel to the well. The deepest sample at 1470 ft (448 m) is the sample most isotopically depleted in the ^{18}O and D, but plots off the meteoric water line at -10.2‰, -79‰. The more depleted in the heavy isotopes yet somewhat evaporated isotopic composition suggests that this water is remnant of a cooler era and has been derived from evaporation of an older, possibly Pleistocene source, much like the bedrock samples from well 22.9E-10.8N.

The composite isotopic sample was taken roughly two months after the zonal sampling, and is shown along with the included zonal samples in the screen interval in Figure 27. The final well design included most of the upper sample zones as the screen was completed from 270 ft (82 m) to 1153 ft (351 m). The composite isotope sample resulted in a value nearly identical to the zonal sample at 290 ft (88 m). A line can be drawn through the data from point 290 and through the composite to the remaining meteoric cluster. Several hypothetical mixing scenarios can then be calculated using this line as a mixing array. Assuming each individual sample within the cluster of samples contributes to the composite in equal amounts, the meteoric group would contribute only 13% of the mix, and the sample 290 would contribute 87%. If any one sample within the cluster of meteoric samples contributes all of the end member contribution, percentages range from 10% (if sample 470 contributes all) to 14% (if 950 contributes all). Each of these scenarios demonstrates that the composite composition is dominated by the horizon around sample 290. In this application, isotopes clearly provide an assessment of where the main contributing unit is located.

The sample at 290 ft is located in a shallow, unconfined unit. Over-pumping groundwater at a rate faster than can be naturally recharged to these units leads to dewatering. If the composite of this well drifts with time down the mixing line toward the cluster of meteoric samples, it would suggest that the horizon at 290 is contributing less water, possibly as a result of dewatering the unit. Monitoring this well for changes in the composite isotopic composition may potentially reveal an isotopic application to project the rate of depletion from a contributing unit, and could potentially influence the designed pumping rate to be modified for a more sustainable discharge rate.

Isotopic Measurements Varying Flow Rate Contributions

SRP well 31.1E-02.1S is located near the center of the East Valley basin in the southeast valley (Figure 13). The well was drilled in 2007 to a total depth of 1059 ft (323 m). All 6 zonal samples are located in the middle unit. Figure 28 is the δD vs. $\delta^{18}O$ graph depicting zonal isotopic data. Four of the samples plot close to the meteoric water line, including the shallowest sample. However, the next two shallowest samples 510 and 620 are enriched in ^{18}O. This suggests evaporation and possibly a different source of recharge from the shallowest sample. This could perhaps be the result of a change of land use in the area from agriculture to domestic use.

Three composite samples were taken at three different flow rates, 800, 1200, and 2000 gpm (3082, 4543, 7570 L/m) to determine if the isotopic composition of the composite is dependent upon discharge flow rate (Figure 29). Discharge samples at 800 gpm (3082 L/m) and 2000 gpm (7570 L/m) were taken during a step rate test, while the discharge rate of 1200 gpm (4542 L/m) reflected the final constant rate test. The composite isotope results (Figure 29) demonstrate variability and suggest that at a lower pumping rate, more evapoconcentrated water is being captured. At higher pumping rates, more meteoric water is captured. All pumping rates suggest the interval at 510 ft (155 m) plays a significant role in flow contribution.

Limitations of Isotopic Analysis to Well Evaluations

SRP well 00.4W-03.3N is located in the southwest valley near the confluence of the Gila and Agua Fria rivers in the West Valley (Figure 9). The well was drilled in 2008 to a total depth of 995 ft (303 m). The well yielded 9 zonal depth samples at 8 different depths (1 duplicate). Figure 30 is a δD vs. $\delta^{18}O$ plot of the zonal samples. Seven of these samples were located in the upper unit (x) with depths between 144 -326 ft (44-99 m) below ground surface. Most of the upper unit samples cluster in a domain between -8.5‰ and -8.8‰ in $\delta^{18}O$ and -65‰ to -68‰ in δD. One outlier at 251 ft (77 m) appears more evaporated and is farther off of the meteoric water line than the other upper unit samples. Two of the samples from the middle unit (circles) at depths of 371 ft (113 m) and 416 ft (127 m) below ground surface are closer to the meteoric water line and are more ^{18}O depleted than the upper unit samples. These sample values range from -9.5‰ to -9.9‰ in $\delta^{18}O$ and -70‰ to -72‰ in δD. Sampling did not occur in the lower unit. The composite sample was taken roughly one month later after casing was installed with a screen interval of 365-435 ft (111-133 m).

Figure 31 illustrates the composite sample (diamond) with the zonal sampling data included in the screen interval. The composite is not clearly located on a line between the two remaining zonal samples. There are two possible explanations. The composite sample data point lies above the middle unit samples, but within error of δD from sample 371. This near identical relationship suggests that the sample 416 contributes almost nothing to the composite. The isotopic composite value could signify additional water contribution after construction. The upper unit samples were isotopically more enriched in the heavy isotopes than the middle unit samples and could be mixing with the middle unit samples. If so, it could indicate that the bentonite seal above the perforations is partially ineffective and allows upper unit groundwater to circumvent or seep through the seal. With future, regular, composite analysis this possibility could be monitored and evaluated.

The error bars on sample 371 and the composite overlap and may indicate overwhelming contributions from sample 371 to the composite. All these data are so isotopically similar that interpretation is very difficult. In cases where variations of δ-values are small for different zones, isotopes are of little utility.

SRP well 05.1E-16.2N is located near the end of the Arizona Canal in Peoria, AZ (Figure 9). This well was drilled in 2008 to a total depth of 1739 ft (530 m). The well generated 12 zonal depth samples at 11 different depths (1 duplicate). Figure 32 is the δD vs. δ^{18}O plot of zonal samples from well 05.1E-16.2N. Sampling did not occur from the upper unit. Nine of the samples were generated from the middle unit (circles). The four shallowest samples suggest minimal evaporation (with one exception) and are enriched in the heavy isotopes to the right of the GMWL. These ^{18}O values range from -8.1‰ to -8.4‰ and δD values of -63‰ to -65‰. The deeper middle unit samples are enriched in the heavy isotopes but lie near the meteoric water line ranging between δ^{18}O values of -8.3‰ to -8.5‰ and δD values -61‰ to 62‰. There is one middle unit sample at 517 ft (158 m), which plots close to meteoric water line but is more depleted in the heavy isotopes than the samples immediately above or below it stratigraphically. This could be the result of a slug of older flood water from the nearby New River. The lower unit samples (triangles) at depths 1435, 1550, and 1705 ft (437, 472, and 520 m respectively) are more depleted in ^{18}O and D and close to the GMWL. The two deepest samples are the most depleted in the heavy isotopes.

The composite sample was taken from a casing design with two sections of screen. One section is screened from 560-920 ft (171-280 m), the other from 1020-1250 ft (311-381 m). The composite isotopic water quality (diamond) and zonal samples included in the screen interval are shown in Figure 33. The composite likely receives nearly all its contributions from the samples that are near identical and within error, which are samples 920, 1078, and 1245.

Here again, the composite sample is indistinguishable in isotopic composition from an end member of a zonal sample array signifying dominant water contribution from those end members. Precise evaluation is not possible from samples displaying limited isotopic variations.

SRP well 12.1E-08.9N is the closest West Valley well to the East Valley divide (Figure 9). The well is located in Phoenix, AZ and was drilled to a total depth of 709 ft (216 m) in 2007. The well yielded 6 zonal samples. Four of these samples are located in the middle unit (circles), while two are located in the lower unit (triangles). No samples were obtained from the upper unit. The δD vs. $\delta^{18}O$ results are shown in Figure 34. The $\delta^{18}O$ values vary between -8.5‰ and -9.0‰. The δD values range between -63‰ to -67‰. The lower unit samples are slightly more depleted in D, but within error of the middle unit sample values. Regardless of the depth sampled, the samples cluster in one general area, suggesting a homogeneous mix of source waters. As discussed previously, this is likely due to basin edge geology and the relatively shallow depth to basement and subsequent thinning of alluvial layers.

The composite (diamond) of this well is shown in Figure 35 and illustrates an isotopic composition more enriched in ^{18}O than the zonal samples but within the error of sample 280 ft (85 m). The composite sample does not lie within or between the zonal data, and therefore suggests the well is not a mix of the zonal samples. The composite is likely identical to the sample 280, and in fact the error bars overlap. It is improbable that the composite is a result of mixing with an unidentified horizon because most of the saturated depth of the well was sampled during zonal testing.

This investigation of zonal sampling comparisons with composite samples is useful in evaluating the relative flow contributions from a given stratigraphic horizon as well as establishing a baseline of composite isotopes to monitor for the future. By instituting routine annual isotopic analysis, the composite isotopic composition may reveal changing conditions of the aquifer including dewatering, over pumping, changing flow contribution, effectiveness of bentonite seals, and changing sources of recharge. These can suggest the need for a change in the way wells are operated in order to maintain production from desired units.

One common trend that became apparent in this investigation is that isotopic data returned progressively more negative δ-values with increased depth. As previously discussed, this can be explained through 'pre-development recharge", but also may be indicative of cooler source climates such as the bedrock data in 22.9E-10.8N. The study also demonstrates the need for more precise isotopic measurements in order to more certainly identify the greatest flow contribution. Multiple analyses of isotopic samples can shrink the error bars and more clearly define mixing arrays. For future studies additional zonal sampling at shallower depths may identify composite end members.

Old versus New Wells

Wells deteriorate with age, and over the history of the SRV several wells have needed to be replaced. As a general rule, WWII era and older wells were drilled to shallower depths with a cable tool drilling method. Advanced drilling techniques and further exploration has made it possible to drill deeper down, into the middle and lower alluvial units. In general, when a well is replaced, the water quality increases as waters from deeper, pre-development eras are tapped. In the design and construction of new wells, it is helpful in determining if the water is indeed significantly different between the old and new replacement wells. This is important when considering pathways for surface pollutants such as nitrate from agriculture or heavy metals from urban storm drainage.

At times this is difficult to determine based solely on water quality. As already shown, stable isotopes have provided helpful analysis in determining the differences between SRV recharge sources and variations with well depth. Therefore, it is possible that stable isotopes may also confirm the success of tapping a different groundwater source. Figures 36-39 illustrate the δD versus $\delta^{18}O$ graph of four separate replacement well pairs. Well constructions are available in Appendix C.

Figure 36 compares the isotopic composition of a pair of northwest valley wells. The older well, 07.5E-15.2N had a screen interval of 320-685 ft (98-201 m) while the replacement well 07.6E-15.2N is screened in two areas from 655-975 ft (200-297 m) and 1125-1560 ft (343-475 m). The results indicate that even though there is a small section of overlapping screen, the older replacement well is indeed tapping a different horizon of the aquifer than the older well.

Figure 37 compares the isotopic results of the replacement well 25.9E-03.9N, which was a zonally tested well in the previous section, with the older well 26.0E-03.9N, which was screened over 80-362ft (25-110 m). Again, the results show that even though there is some screen overlap between the old and new wells, the source of groundwater contributing to these screen intervals is significantly different.

Figure 38 illustrates the isotopic differences between an old well 33.0E-03.0S, which has a screen interval of 174-434 ft (53-132 m) and the replacement well 32.9-02.1S with a screen interval of 560-820 ft (171-250 m). The results of this data comparison indicate that the waters between the two are slightly different, but that despite the separation of screen intervals and no overlap, there may not be a major difference between the sources of recharge for that area.

The final comparison of wells 23.0E-10.8N and 22.9E-10.8N (Figure 39) demonstrate that both wells have similar isotopic composition. This is expected as the screen designs of both wells overlap for the majority of the casing construction. This illustrates that both wells tap the same aquifer and any water quality problems from the old well will likely be seen in the new well without modifications.

This result indicates that stable isotopes can be used to confirm the effectiveness of replacement wells. If the isotopic data for the old and the new wells do not overlap, it suggests that the wells have tapped different groundwater horizons. In the wells that do have overlapping isotopic data, the implication is that the source of water is the same. This is important when dealing with replacement wells for water quality. Overlapping wells from the same source could obviously experience the same water quality problems. It is also possible that with time and continue monitoring, communication between the old and the new could be discovered by tracking any convergence of the composite δ-values.

Chapter 7

CONCLUSION

This investigation yielded interpretations regarding the origin and the anthropogenic evolution of groundwater in the SRV. There is no indication of remnant playa water in the SRV groundwaters. The sources of groundwater recharge to the SRV are river systems. The anthropogenic alteration of these river systems shows up in the isotopic record as more evapoconcentrated waters produced during irrigation.

This study also confirmed, expanded, and compared the existing research of the local West Salt River Valley isotopic variations to the East Salt River Valley groundwaters. The East and the West Valley sub-basin isotopic composition originally differ due to the difference in elevation of source areas, but now are strikingly similar because of the engineering diversion of the lower elevation source surface water to the East Valley.

Stable isotopes in conjunction with geophysical, geologic, and chemical data are powerful tools to explain complex hydrology problems. Isotopes successfully uncover mixing arrays, which, in conjunction with geophysical and geological data, can decipher anomalous groundwater flow paths. Furthermore, isotopes can be used distinctively with chemical data to indicate and quantify water-rock interactions in the subsurface.

Zonal isotopic sampling is a powerful tool that can be used for multiple investigations such as contaminant mitigation, determining mixing ratios and stratigraphic flow contributions, monitoring depletion of groundwater resources over time, and assessing contribution variations with changing flow rates, and verification of replacement well design. The utility of isotopes is certainly apparent in identifying sources of groundwater recharge and can therefore be implemented for industrial applications such as well design, well modification, contamination remediation, and sustainable pump designs.

This study is only the beginning of the practical use of isotopes. By obtaining unique depth specific zonal sampling and comparing these data to the final composite well samples, this investigation has created a baseline against which to monitor these wells in the future. The comparison of the initial and future data will identify changes in the groundwater contribution for these wells, and provide a database of the evolution of the aquifer.

Isotopic investigation is not without limitations. Although the utility of isotopes are apparent in datasets with a wide range of δ-values, they are of little significance for data containing small variations. With increased precision, even small variations in data sets may be decipherable and used in these noteworthy engineering and operational applications.

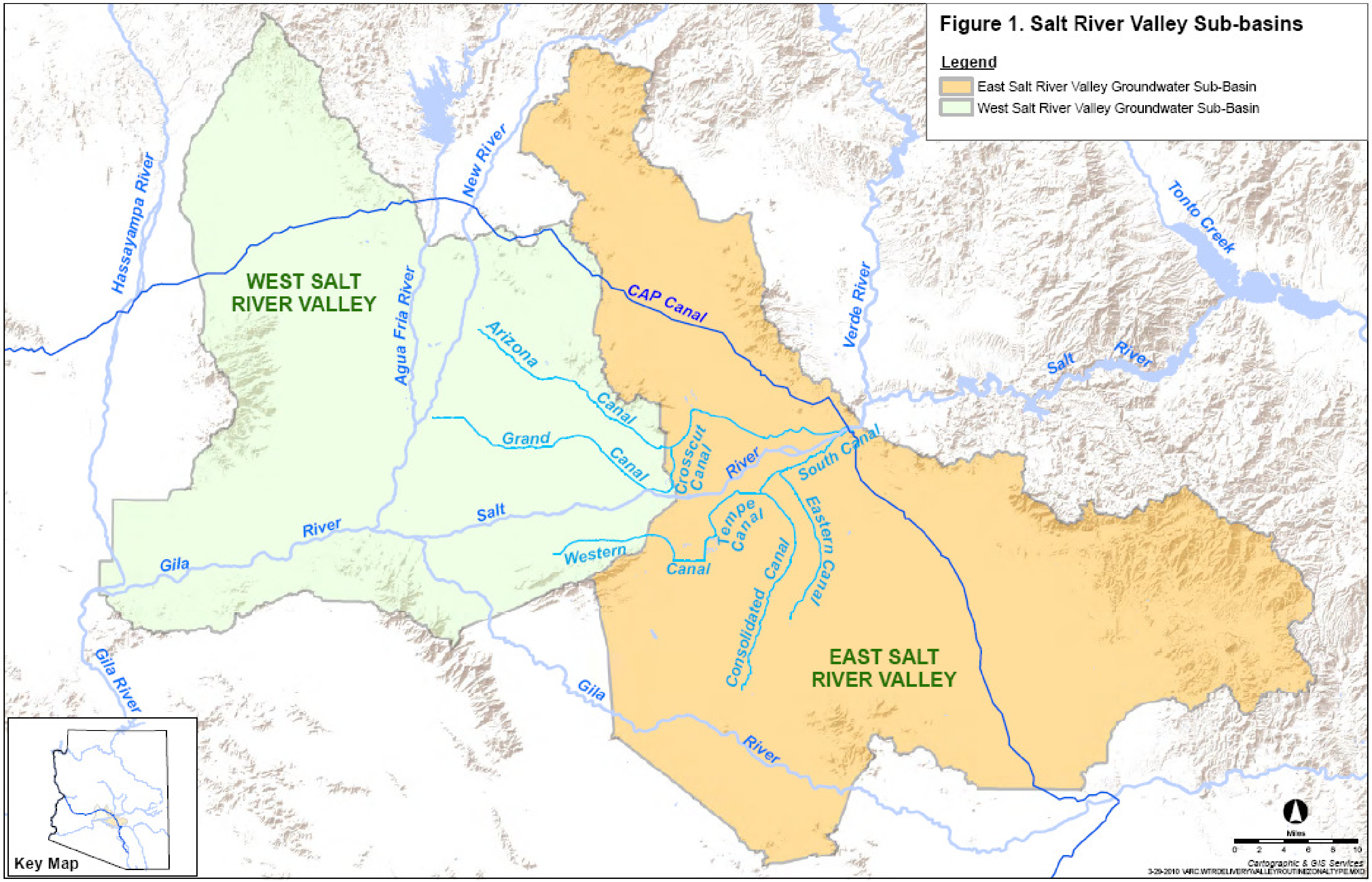

Figure 1. Salt River Valley Sub-basins

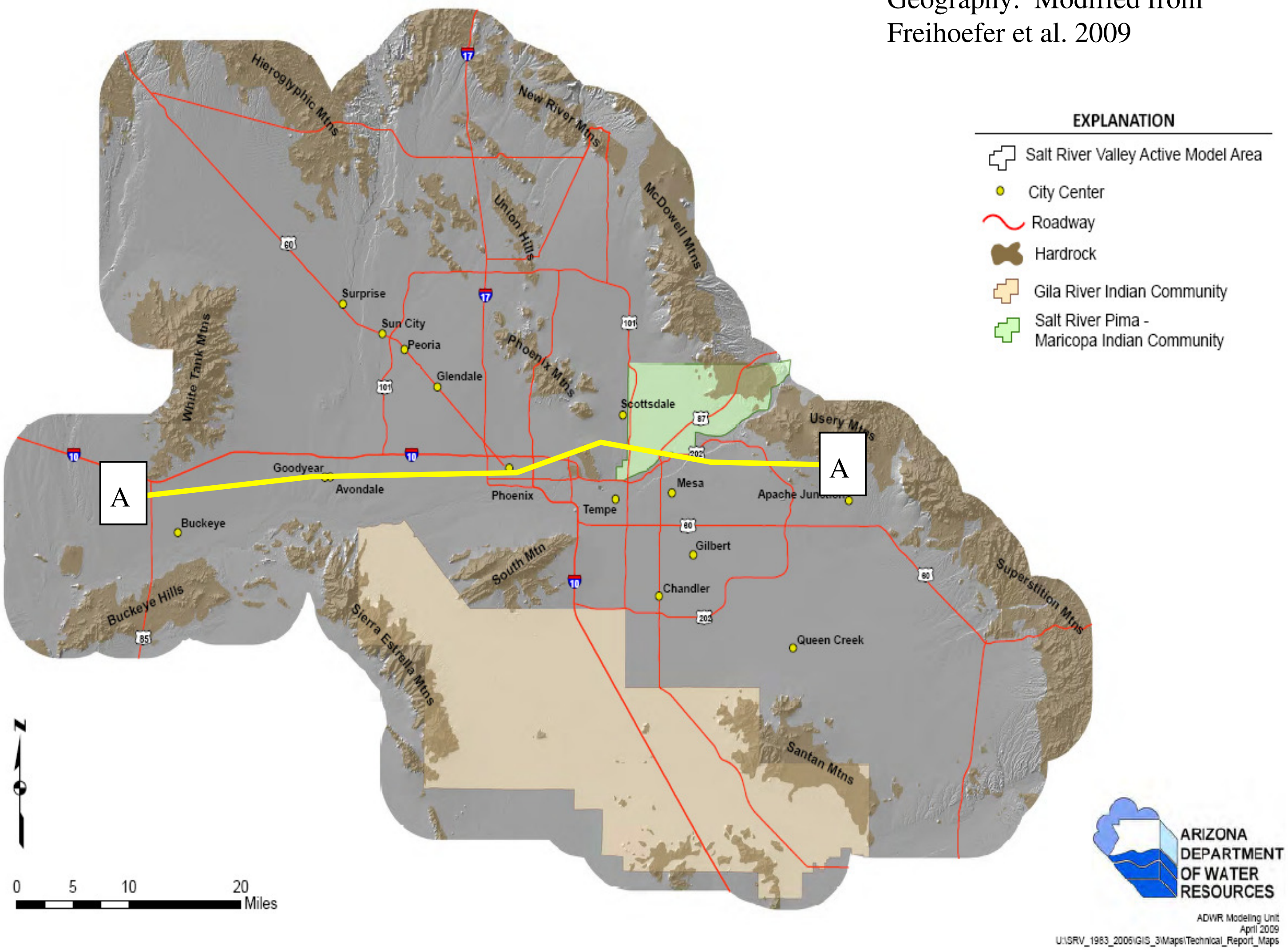

Figure 2. Salt River Valley Basin Geography. Modified from Freihoefer et al. 2009

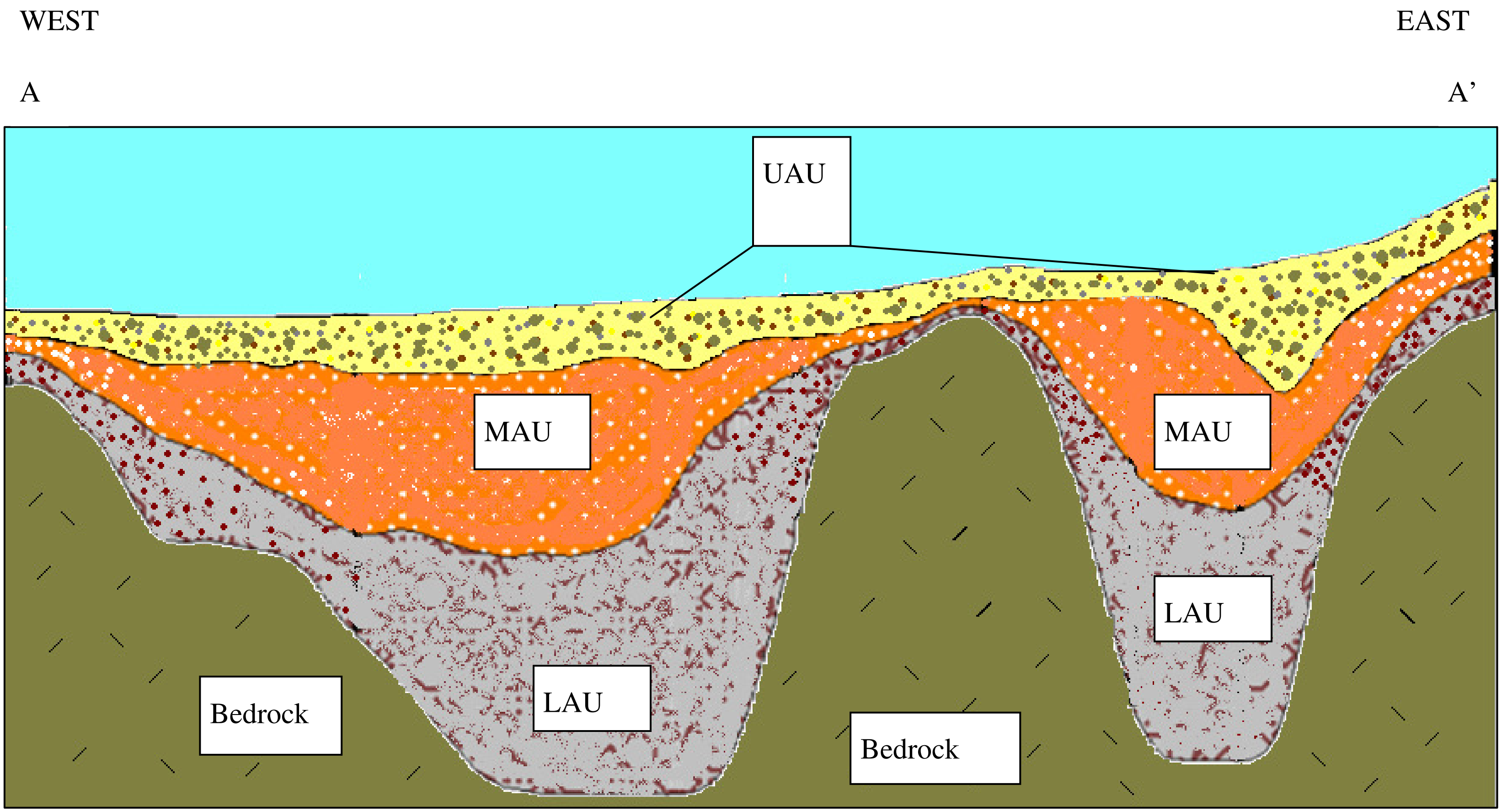

Figure 3. Vertically exaggerated and schematic cross section of Salt River Valley alluvial units. Modified from Freihoefer et al. 2009

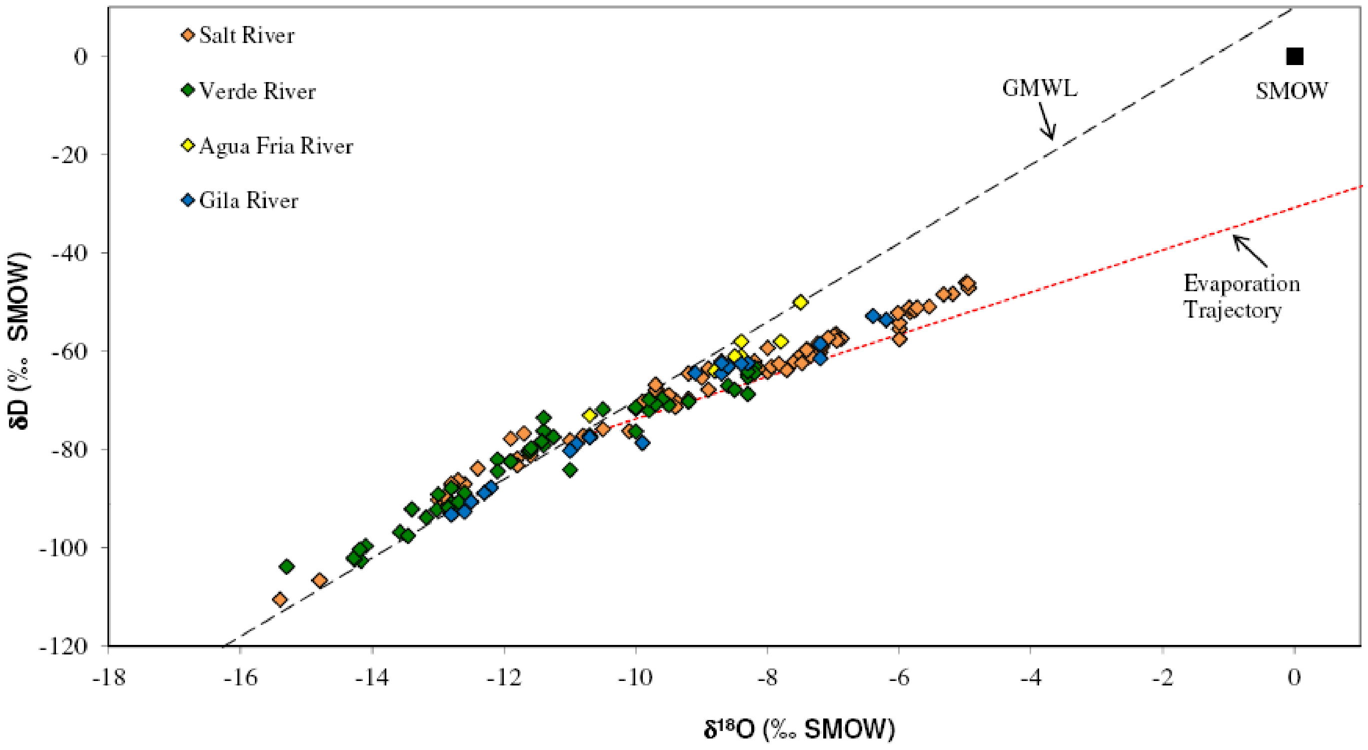

Figure 4. Isotopic composition (δD vs. δ^{18}O) of the major river systems in the Salt River Valley. Salt, Verde, and Gila River data are taken from Brand (1995) and McLean (2007). Agua Fria data are from Towne (2008). Evaporation trajectory of 4.3 is based on Brand (1995) summer Salt River evaporation.

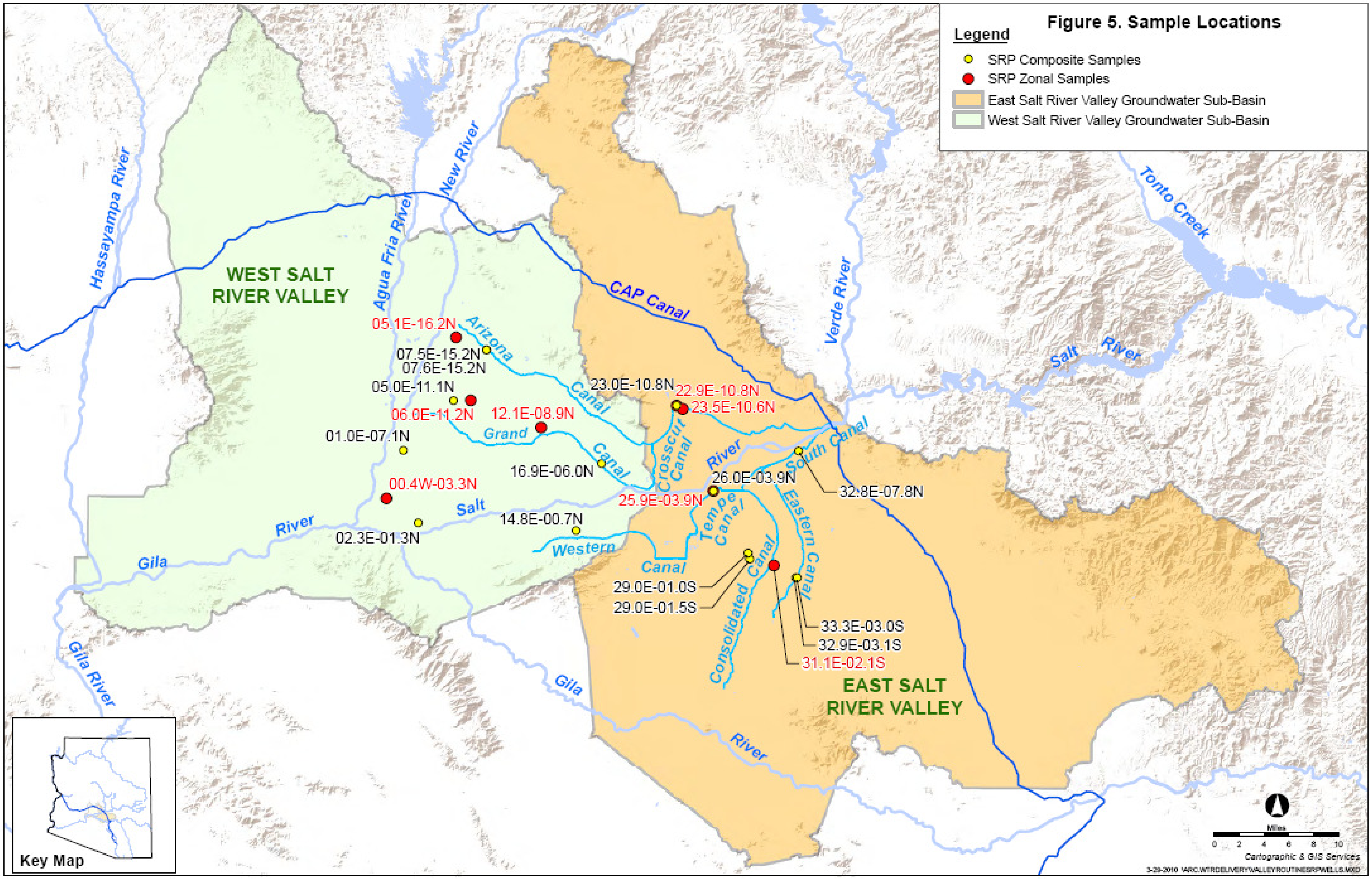

Figure 5. Sample Locations

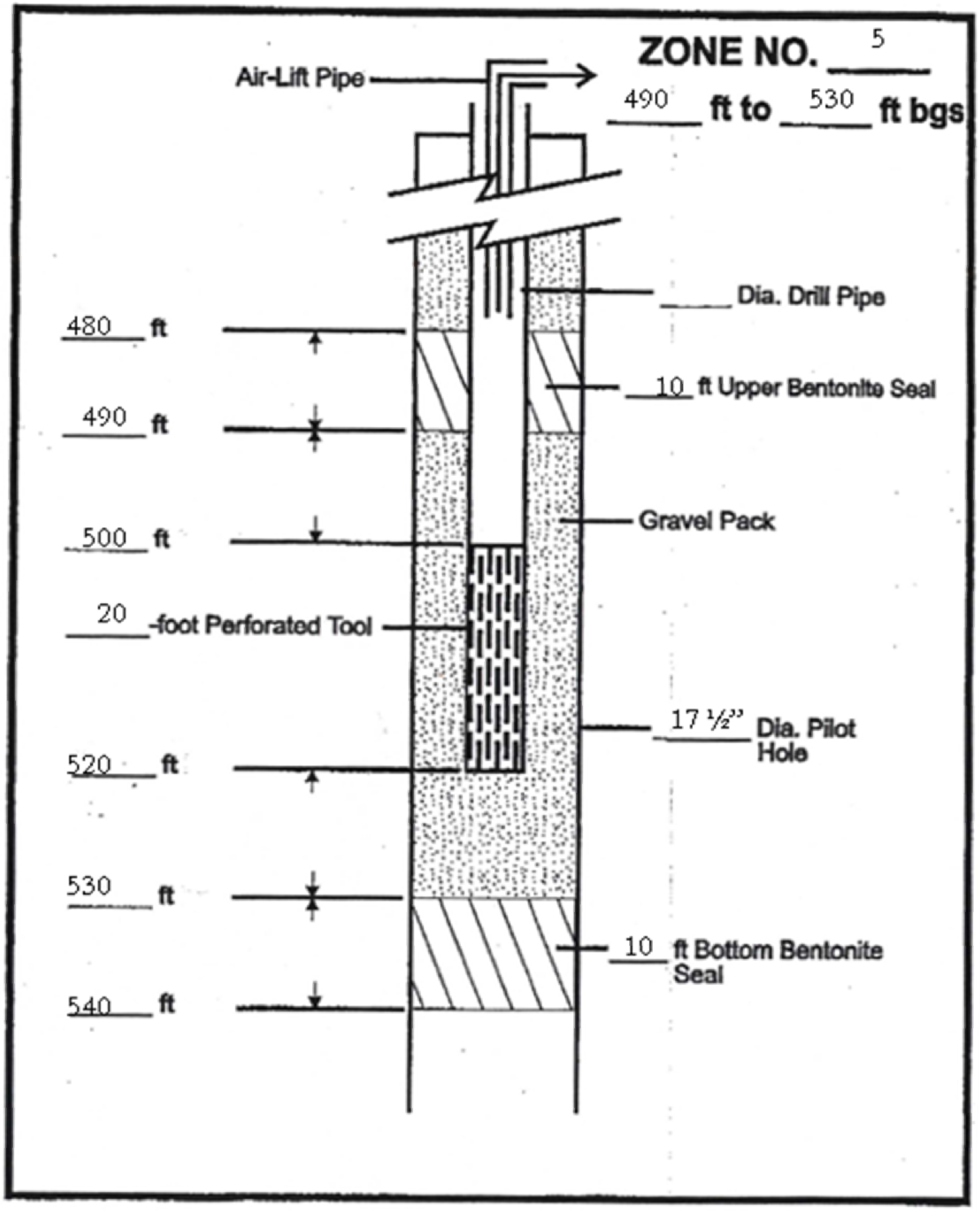

Figure 6. Example of a zonal sampling design. Units are in feet below ground surface (bgs).

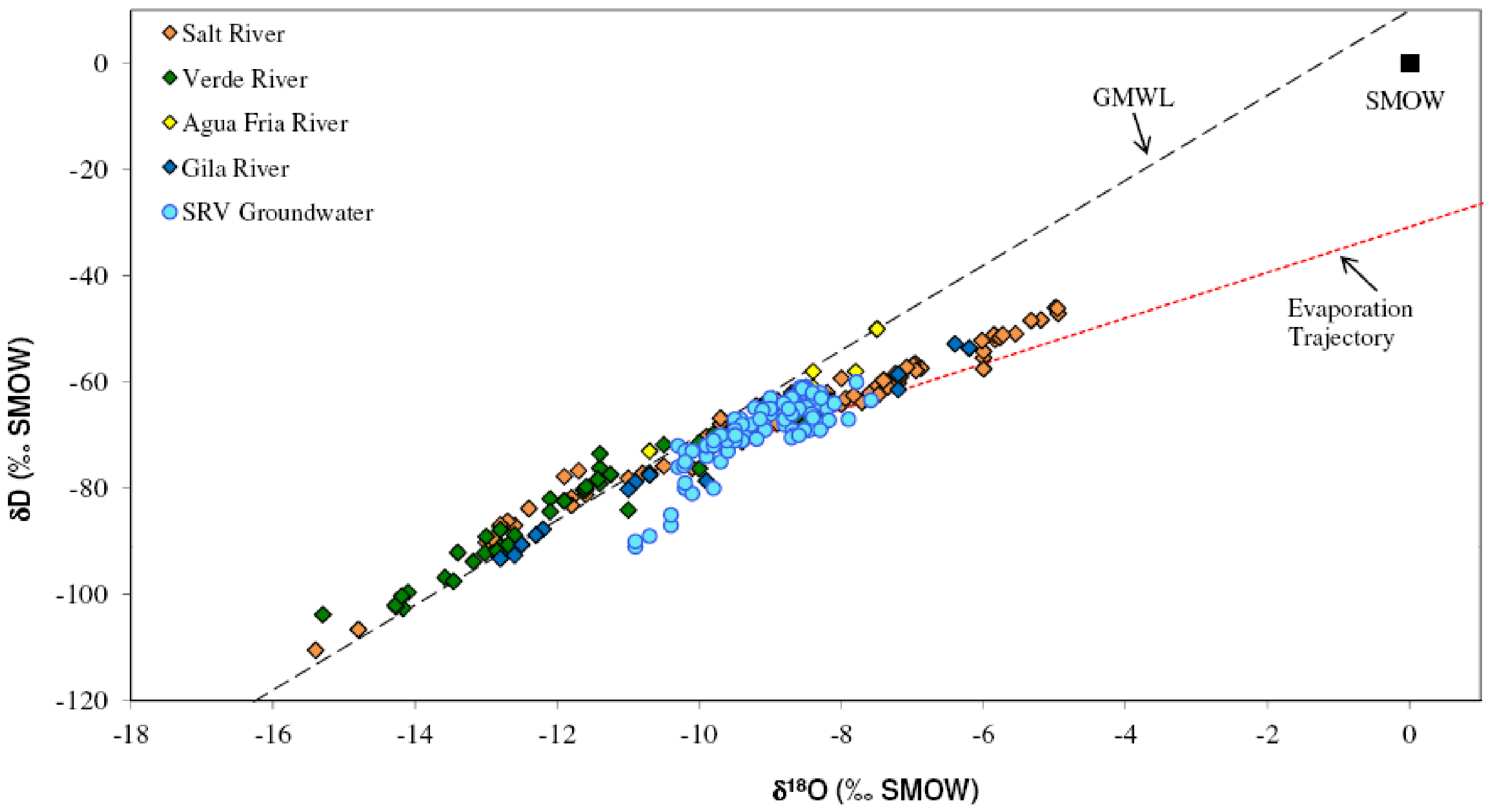

Figure 7. Isotopic composition (δD vs. $\delta^{18}O$) of the major river systems and sampled groundwater in the Salt River Valley.

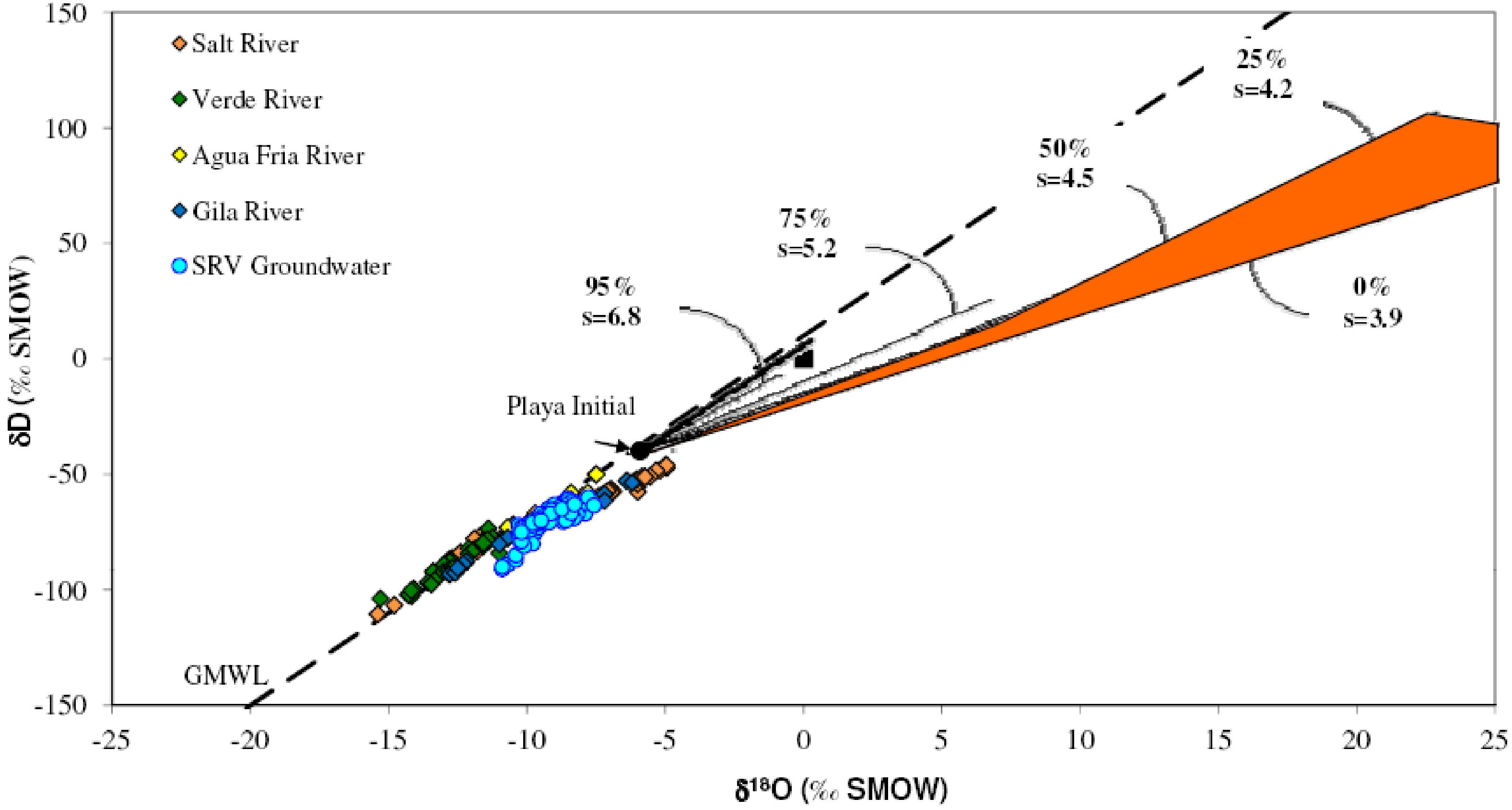

Figure 8. Estimated playa-recharged groundwater isotopic composition. Figure modified from Gonfiantini (1986).

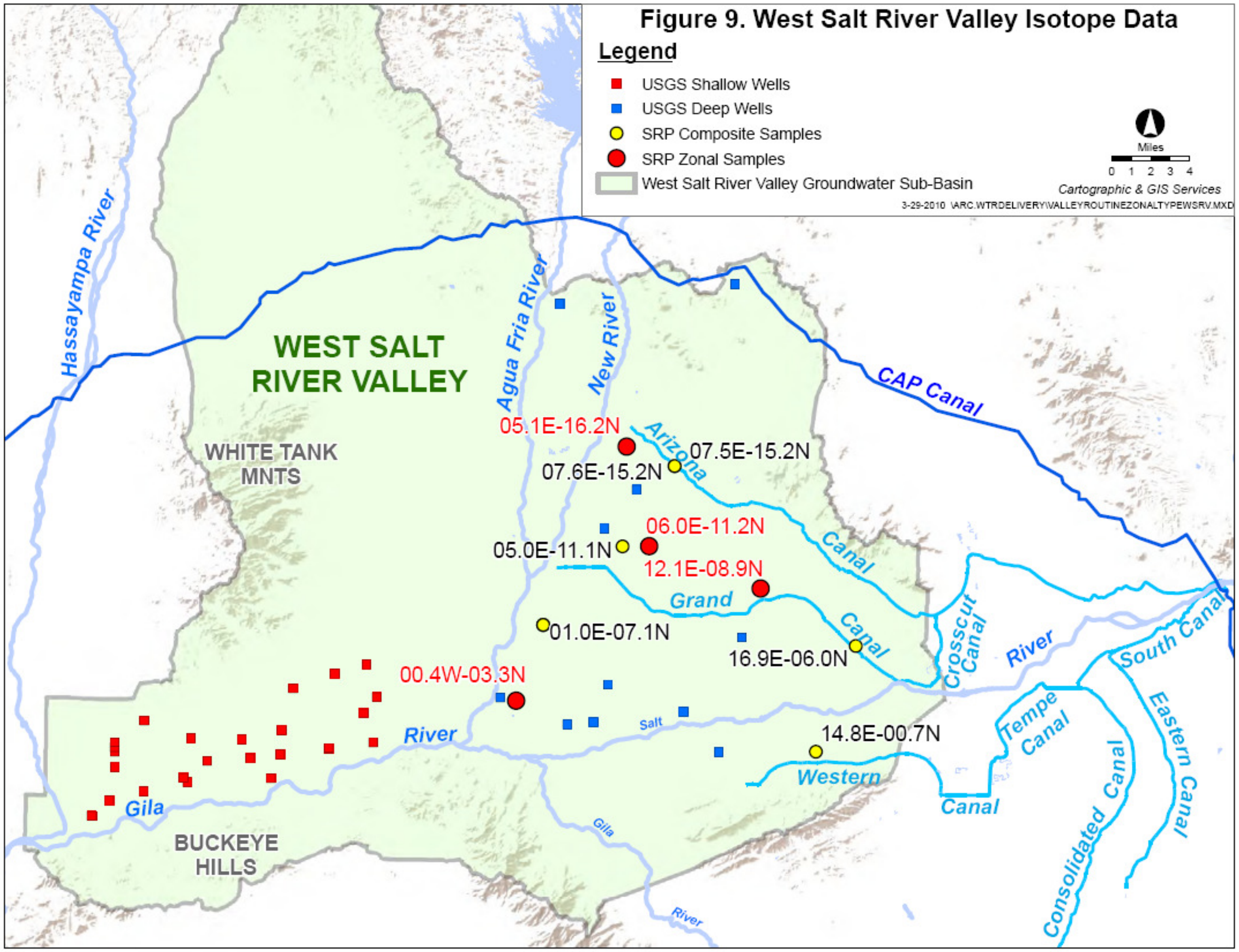

Figure 9. West Salt River Valley Isotope Data

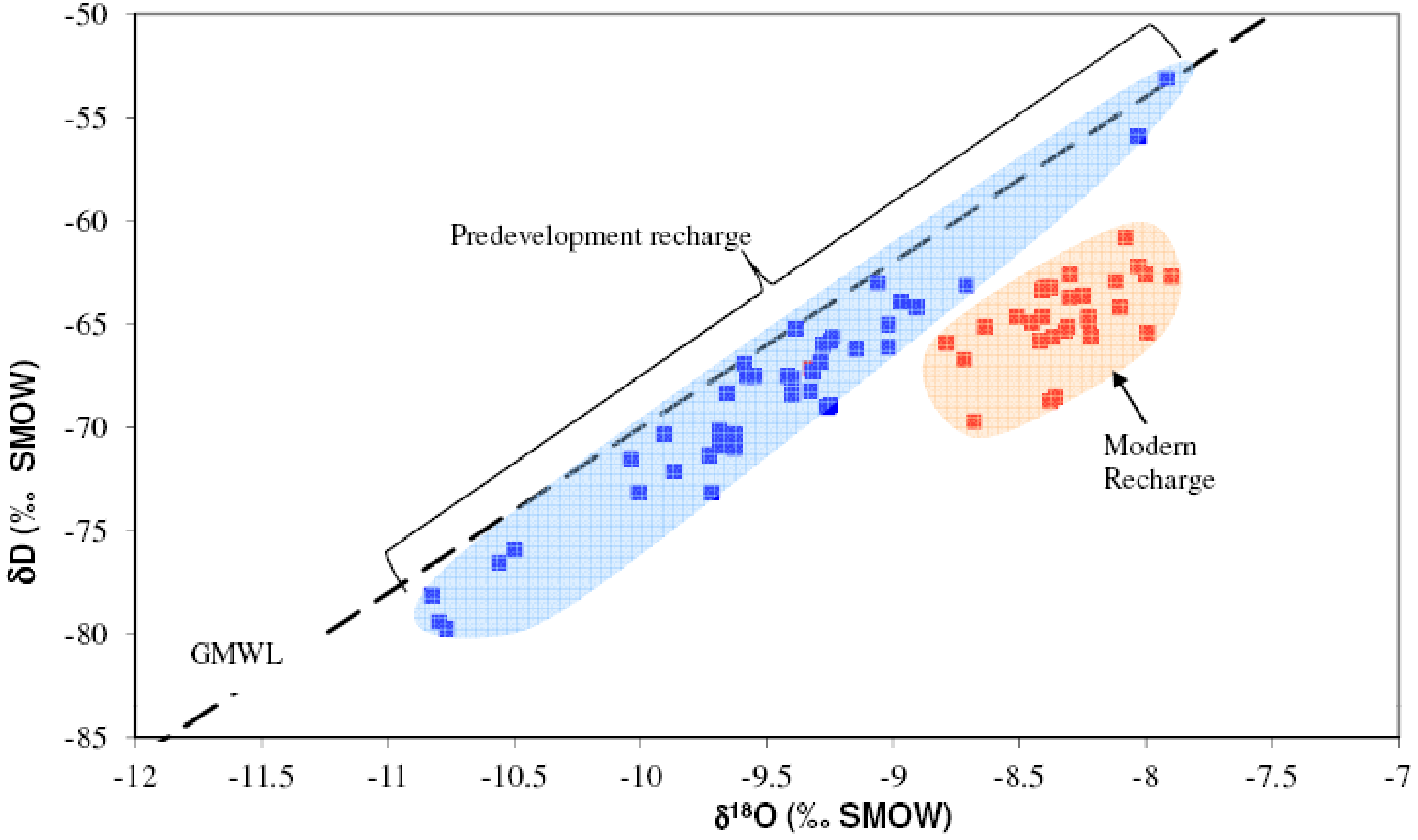

Figure 10. West Valley predevelopment recharge and modern recharge. USGS data from Edmonds and Gellenbeck (2002).

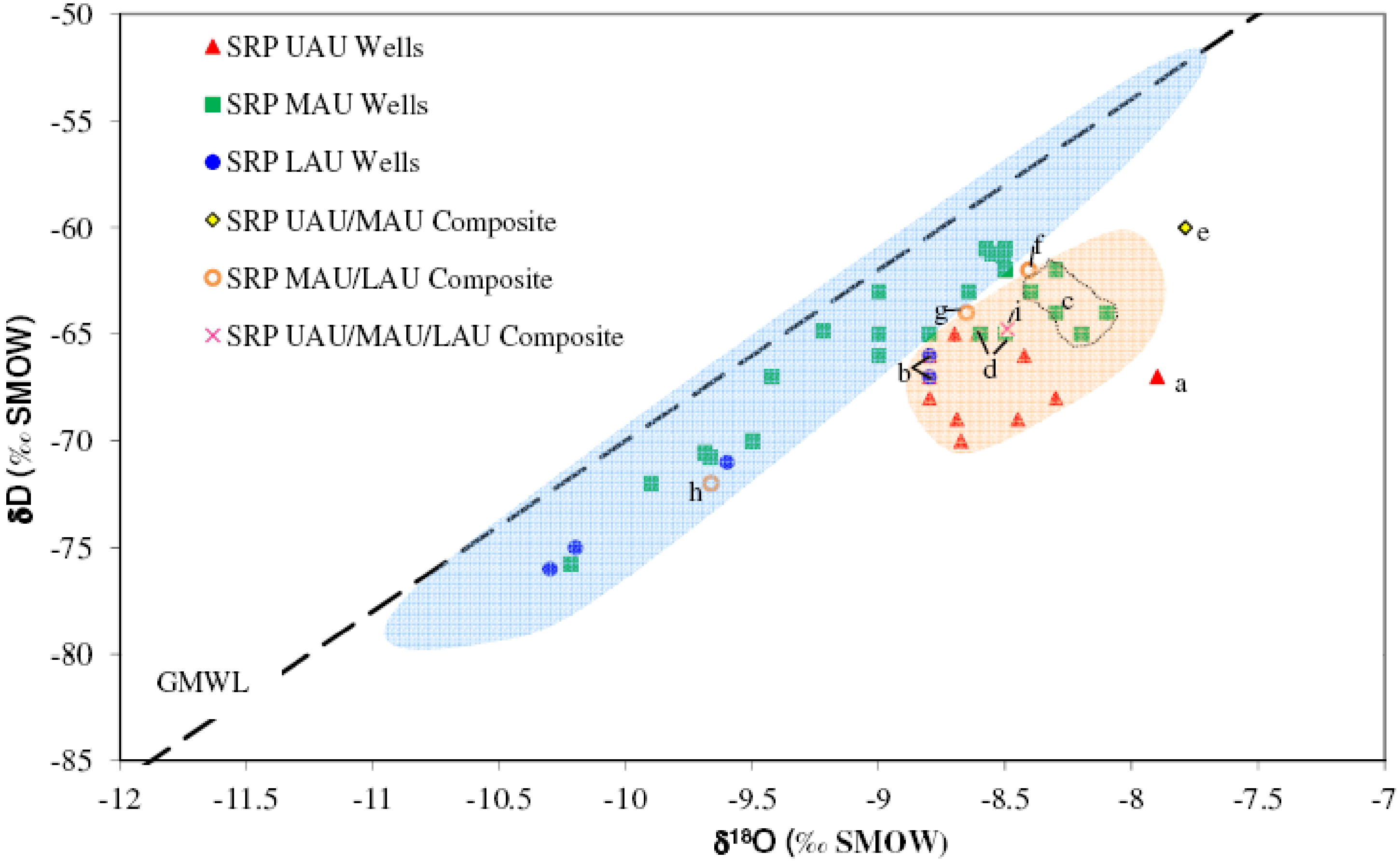

Figure 11. Isotopic composition (δD vs. δ^{18}O) for samples collected in the West Valley. Upper alluvial unit =uau, middle alluvial unit = mau, lower alluvial unit =lau. Letters indicate discussion in text.

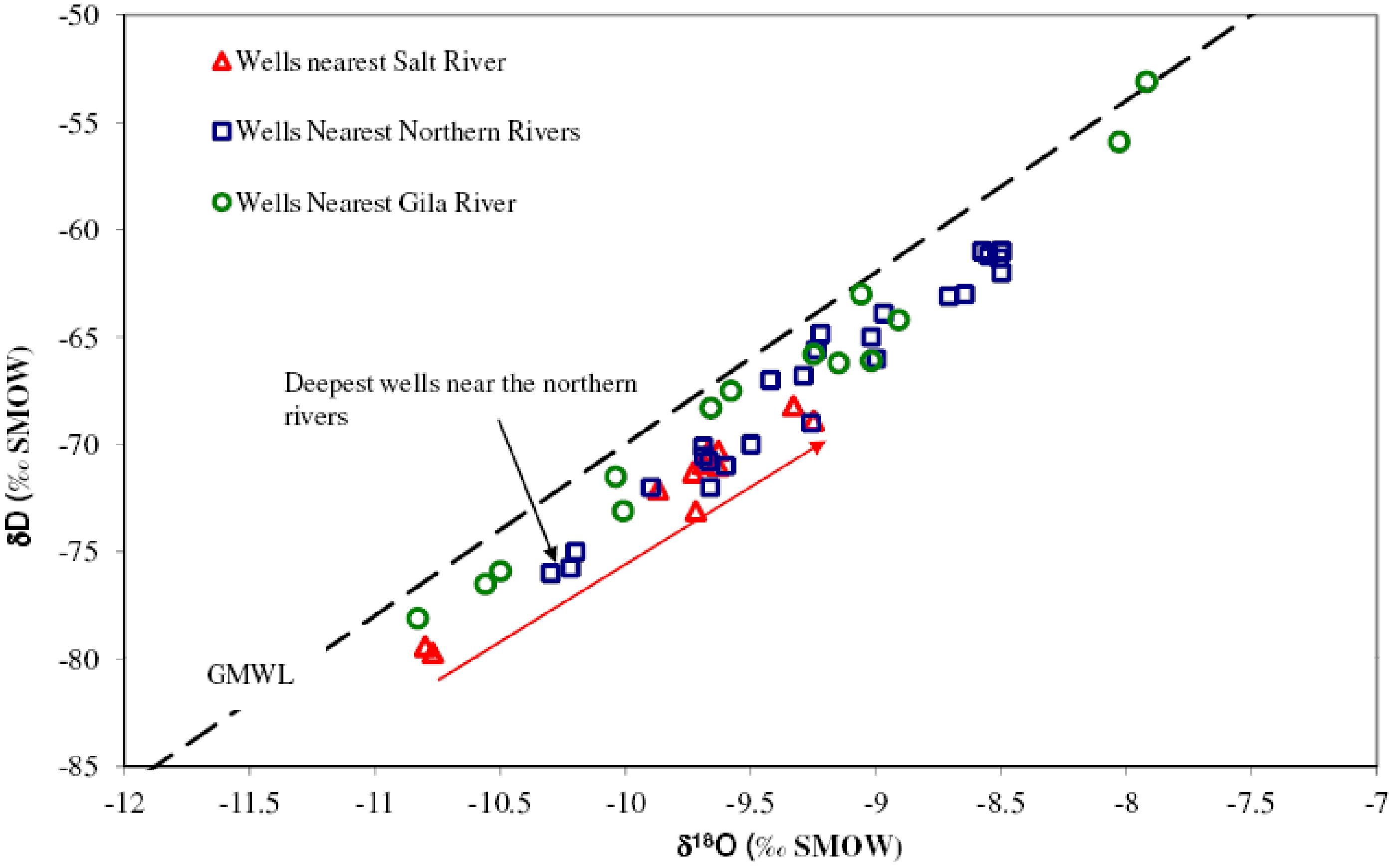

Figure 12. Deep, confined groundwater data from current study and Edmonds and Gellenbeck (2002). Wells represent predevelopment recharge contributions from closest river flow. Red arrow indicates Groundwater near the Salt River channel isotopic enrichment downstream.

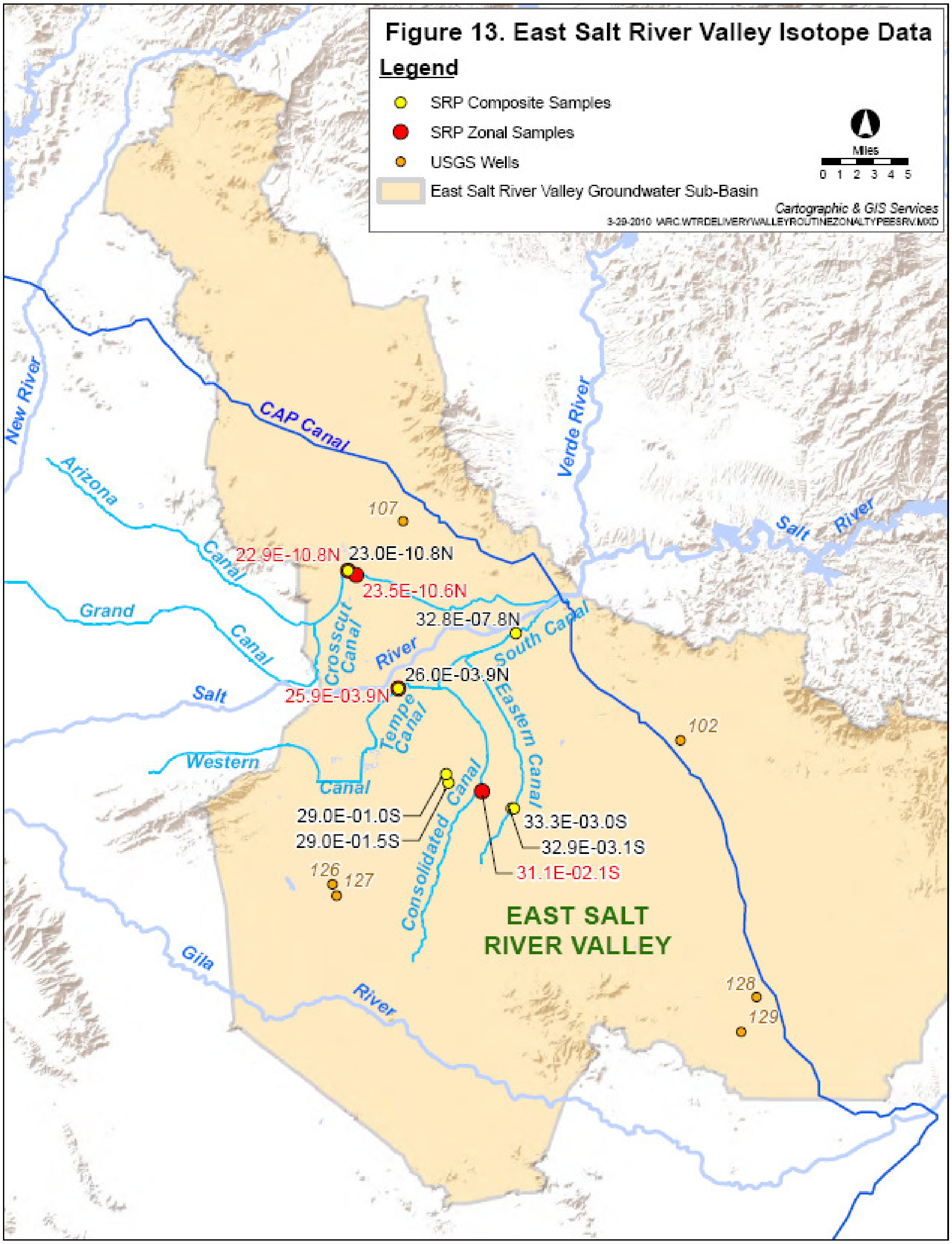

Figure 13. East Salt River Valley Isotope Data

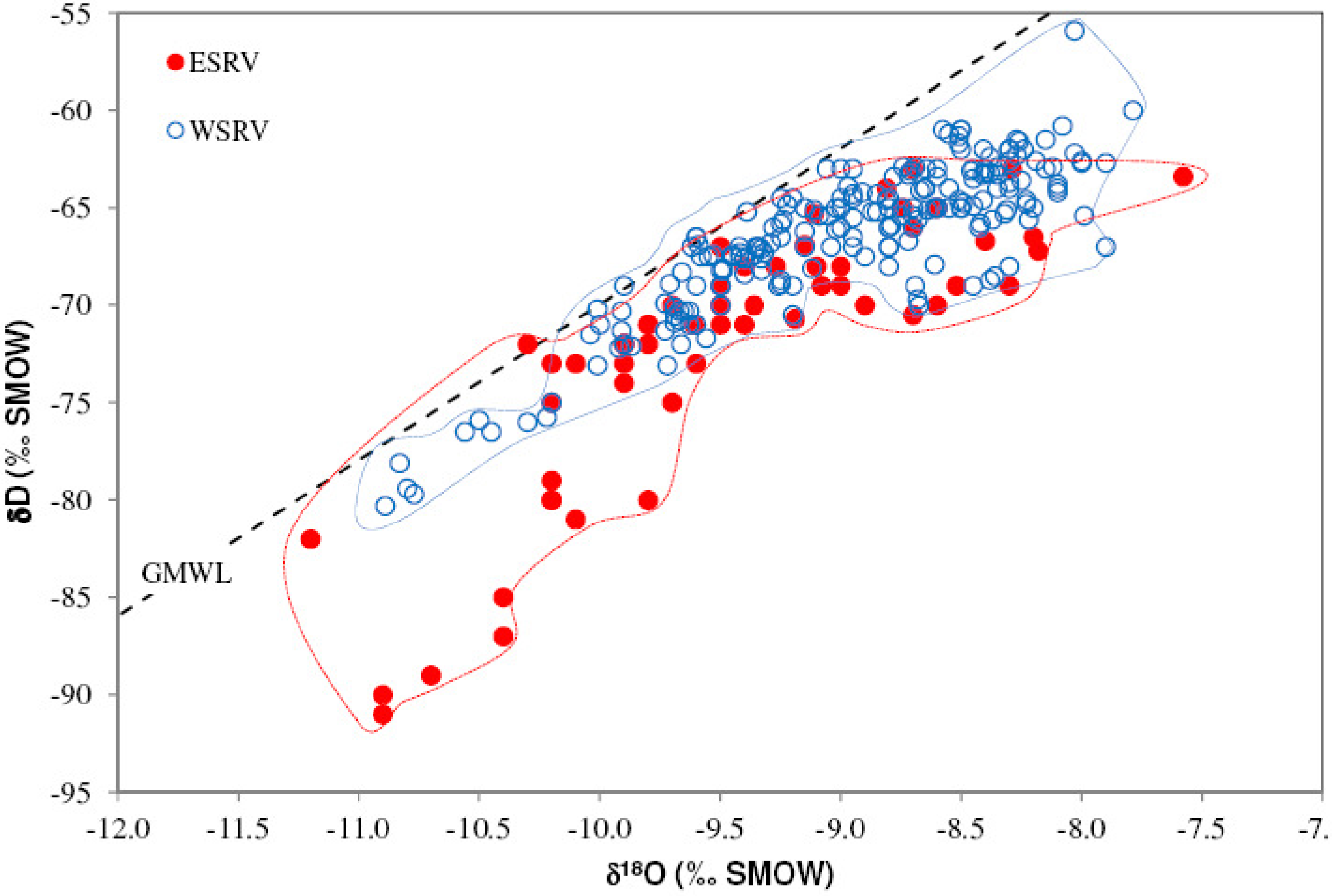

Figure 14. Isotopic composition (δD vs. $\delta^{18}O$) of samples from the East and West Valley. Data from Gellenbeck (1994), Edmonds and Gellenbeck (2002), the USGS NWIS database, and results from this study for both the East and West Valleys.

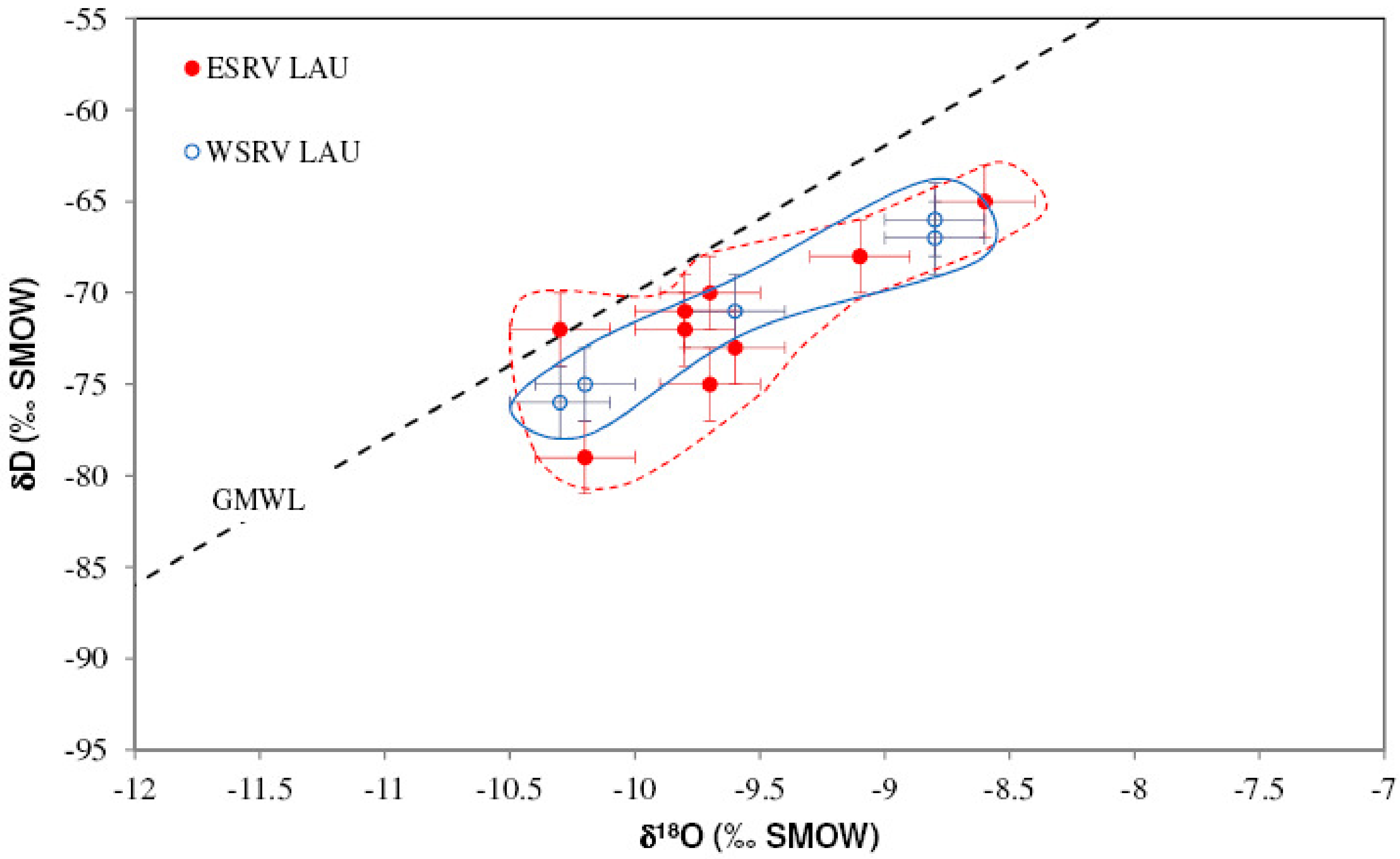

Figure 15. Isotopic composition (δD vs. δ^{18}O) of samples from the East and West Valley lower alluvial units.

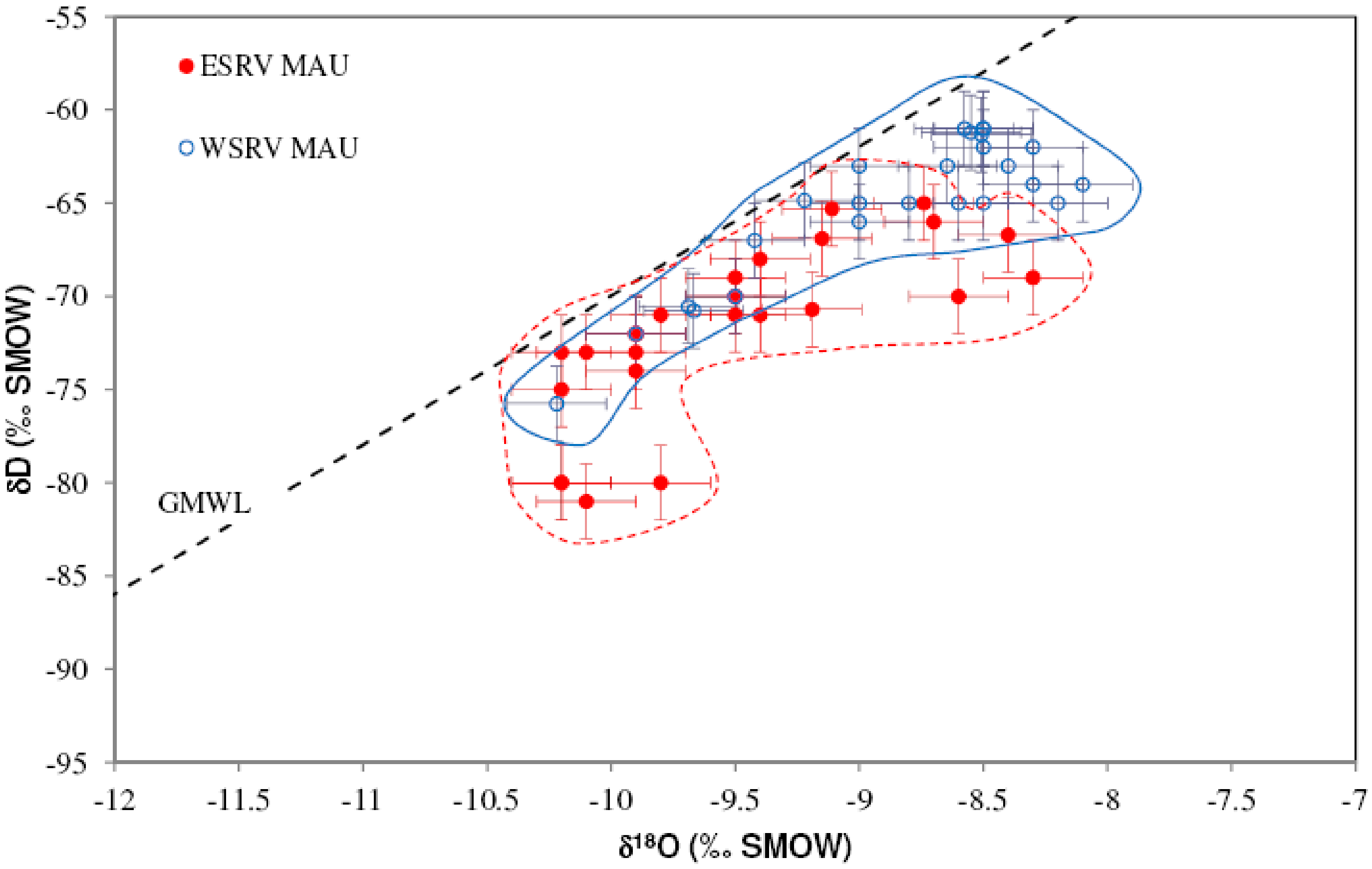

Figure 16. Isotopic composition (δD vs. $\delta^{18}O$) of samples from the East and West middle alluvial units.

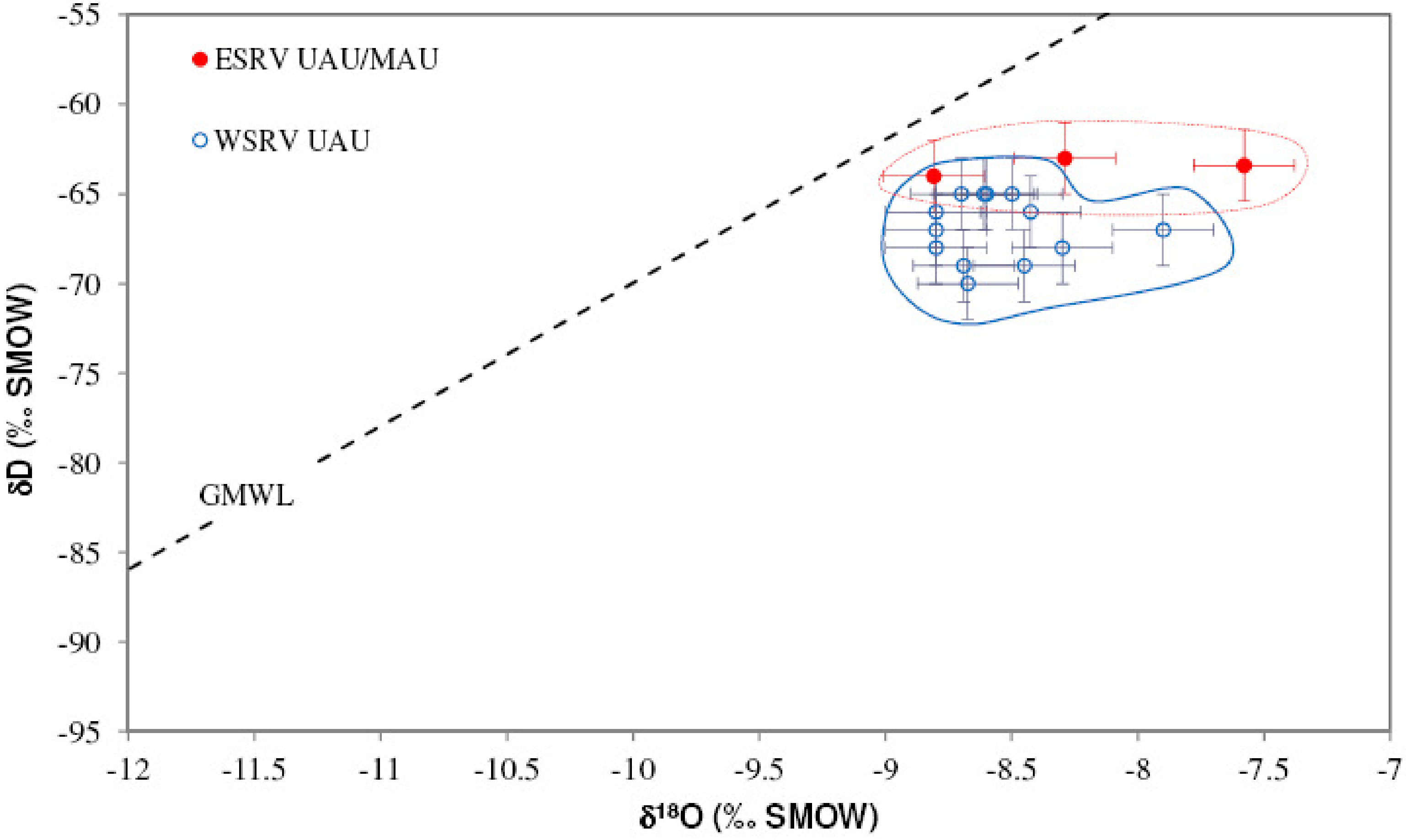

Figure 17. Isotopic composition (δD vs. $\delta^{18}O$) of samples from the East and West Valley upper alluvial units.

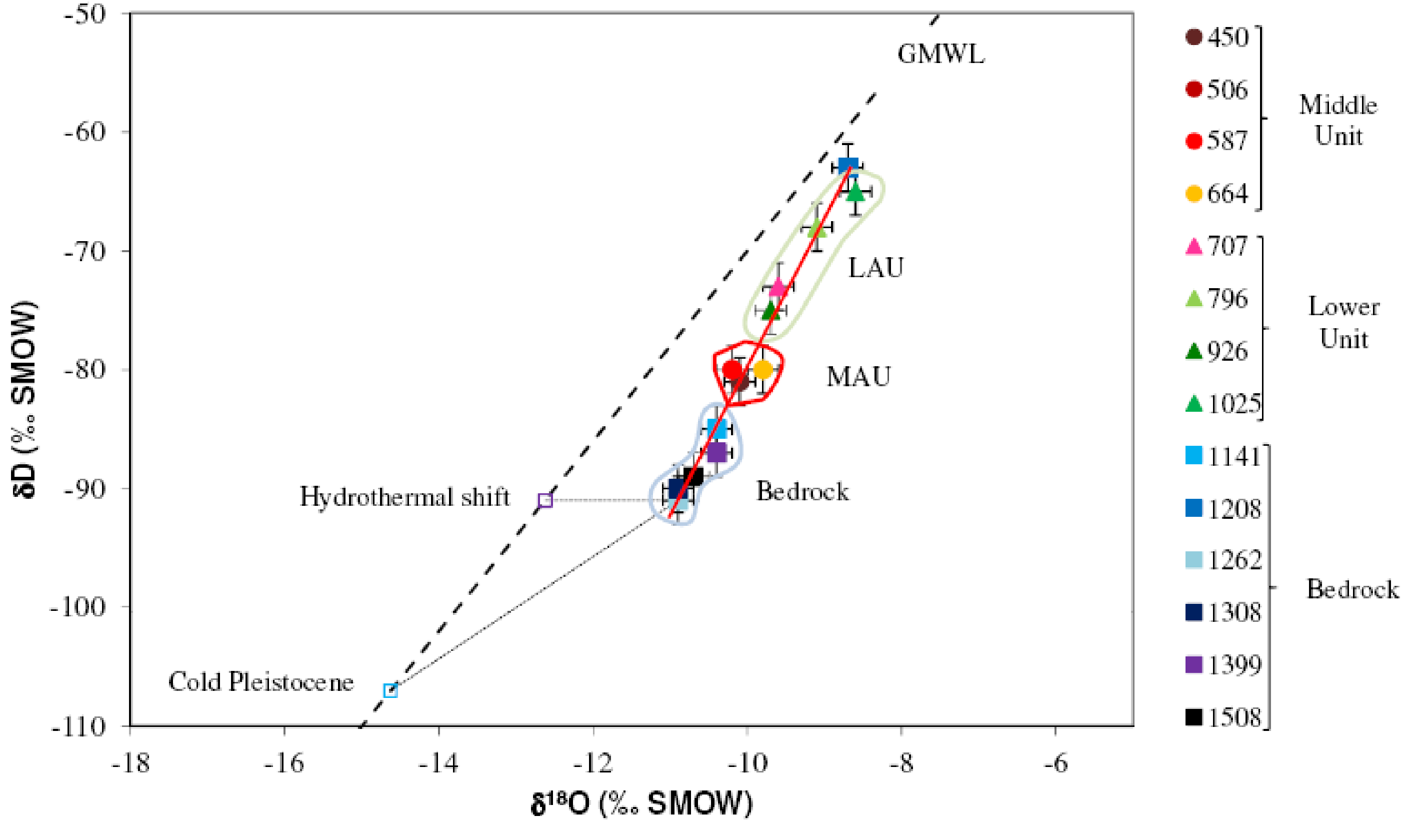

Figure 18. Isotopic composition of zonal samples from well 22.9E-10.8N. Mixing array shown as a red line. Two possible original compositions of bedrock groundwater are traced along dotted lines. Sample keys are recorded in feet below ground surface.

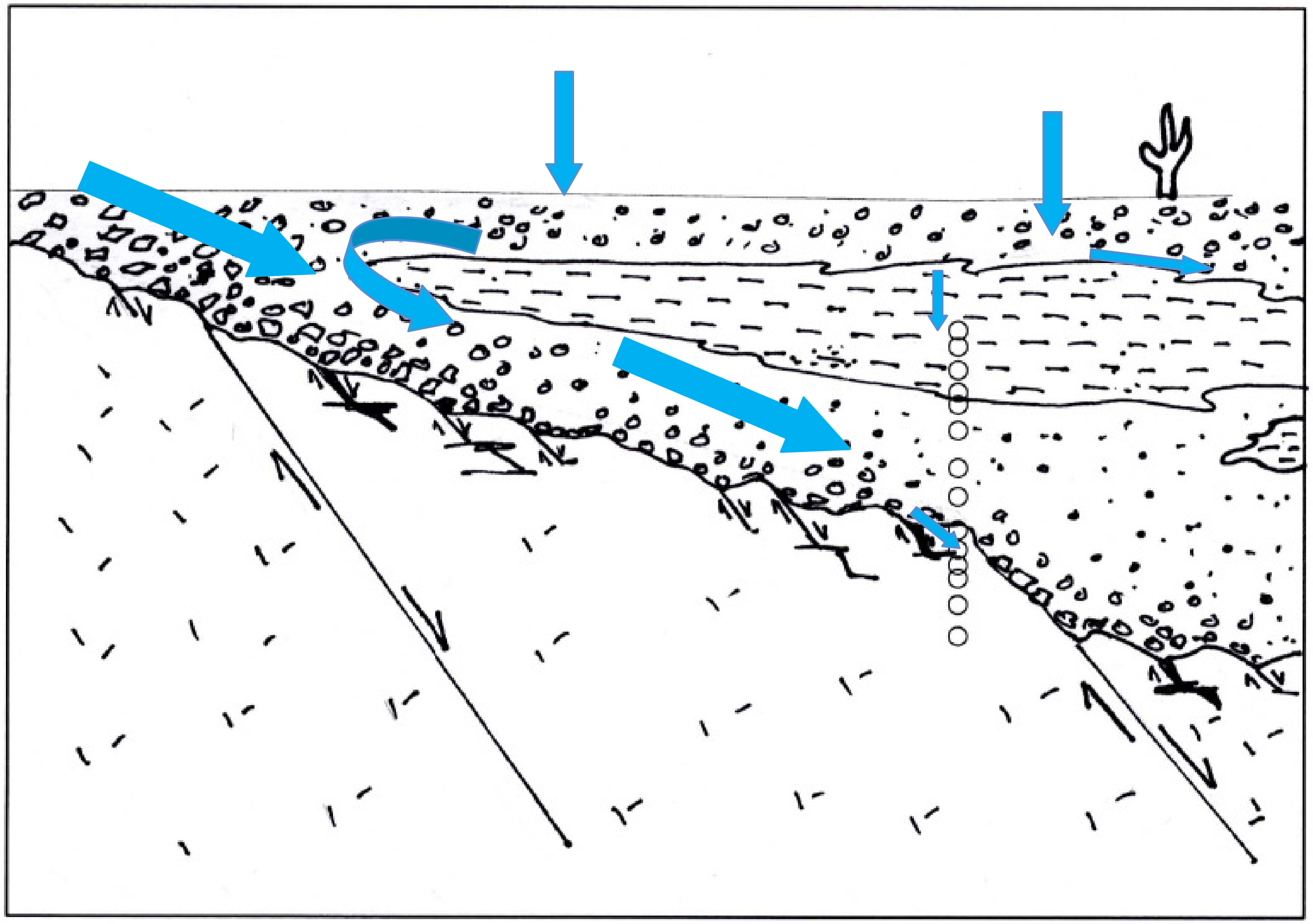

Figure 19. Schematic cross section of lithology near well 22.9E-10.8N. Open circles represent zonal depth samples. Blue arrows indicate recharge pathways. The largest arrows flow easily through coarse alluvial fill, the small arrow through the clay indicates less permeability, and longer travel time.

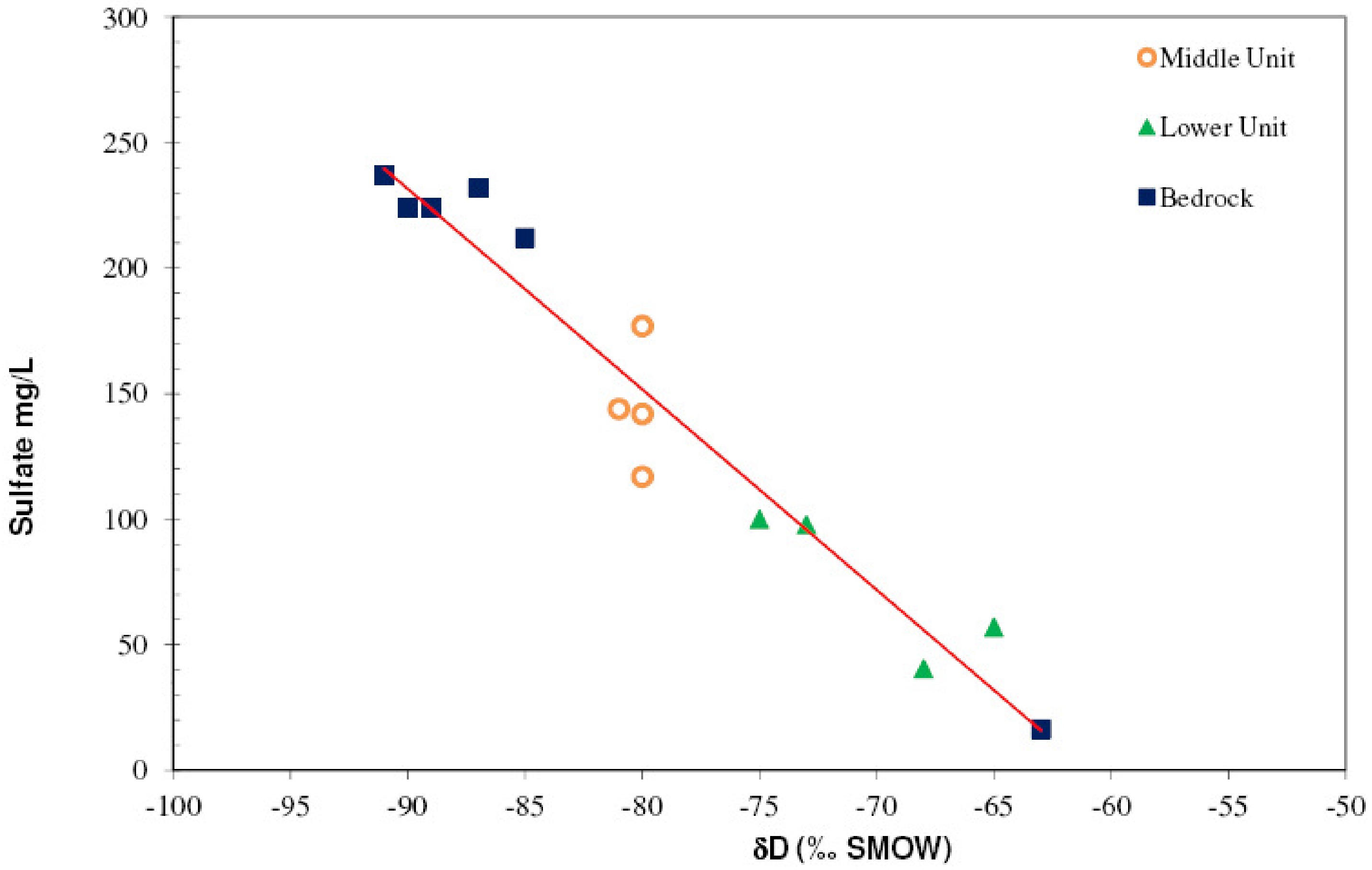

Figure 20. Sulfate vs. δD compositions of zonal samples from well 22.9E-10.8N. The red line indicates mixing.

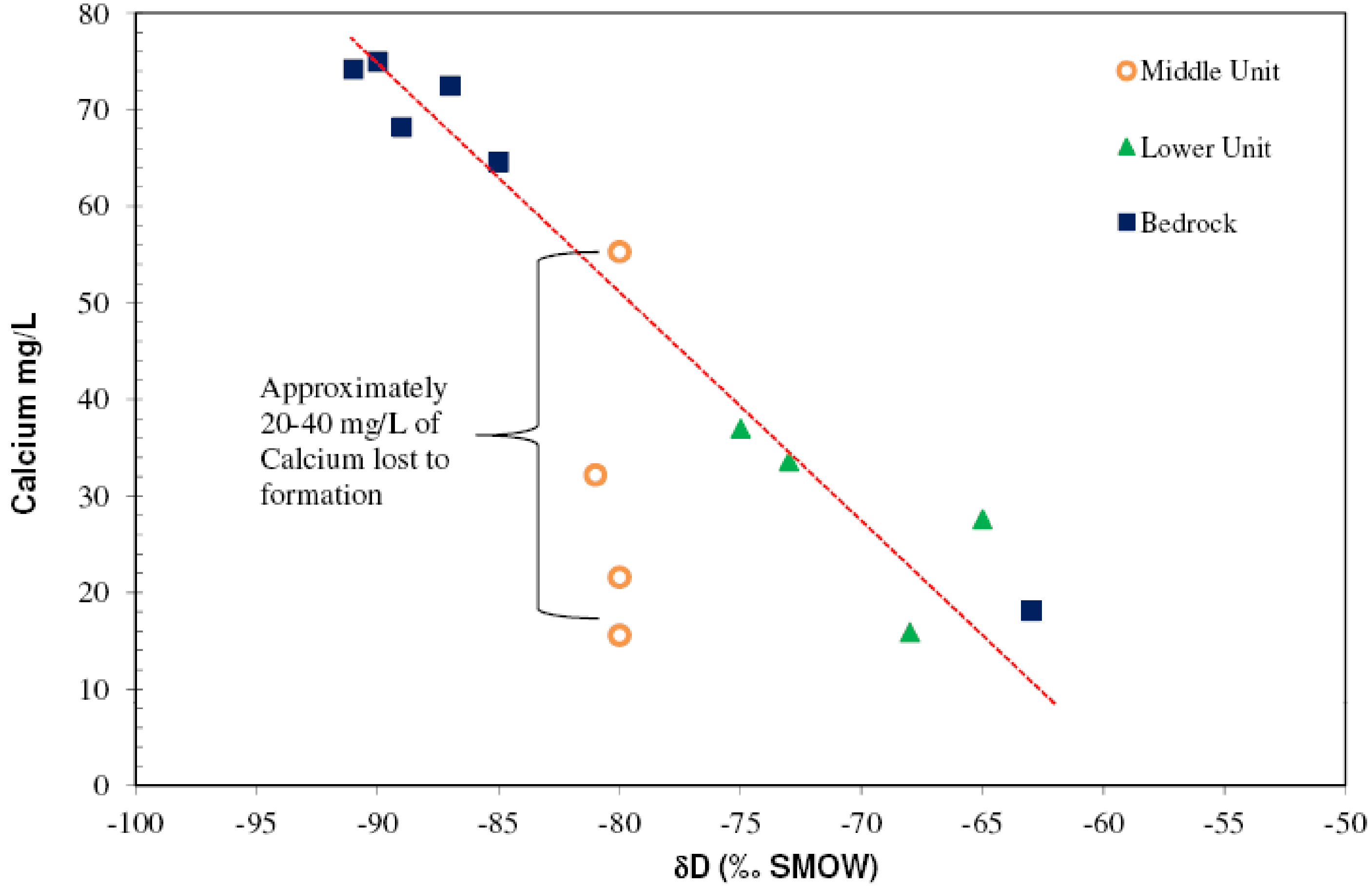

Figure 21. Calcium vs. δD compositions of zonal samples from well 22.9E-10.8N. The red line indicates end member mixing.

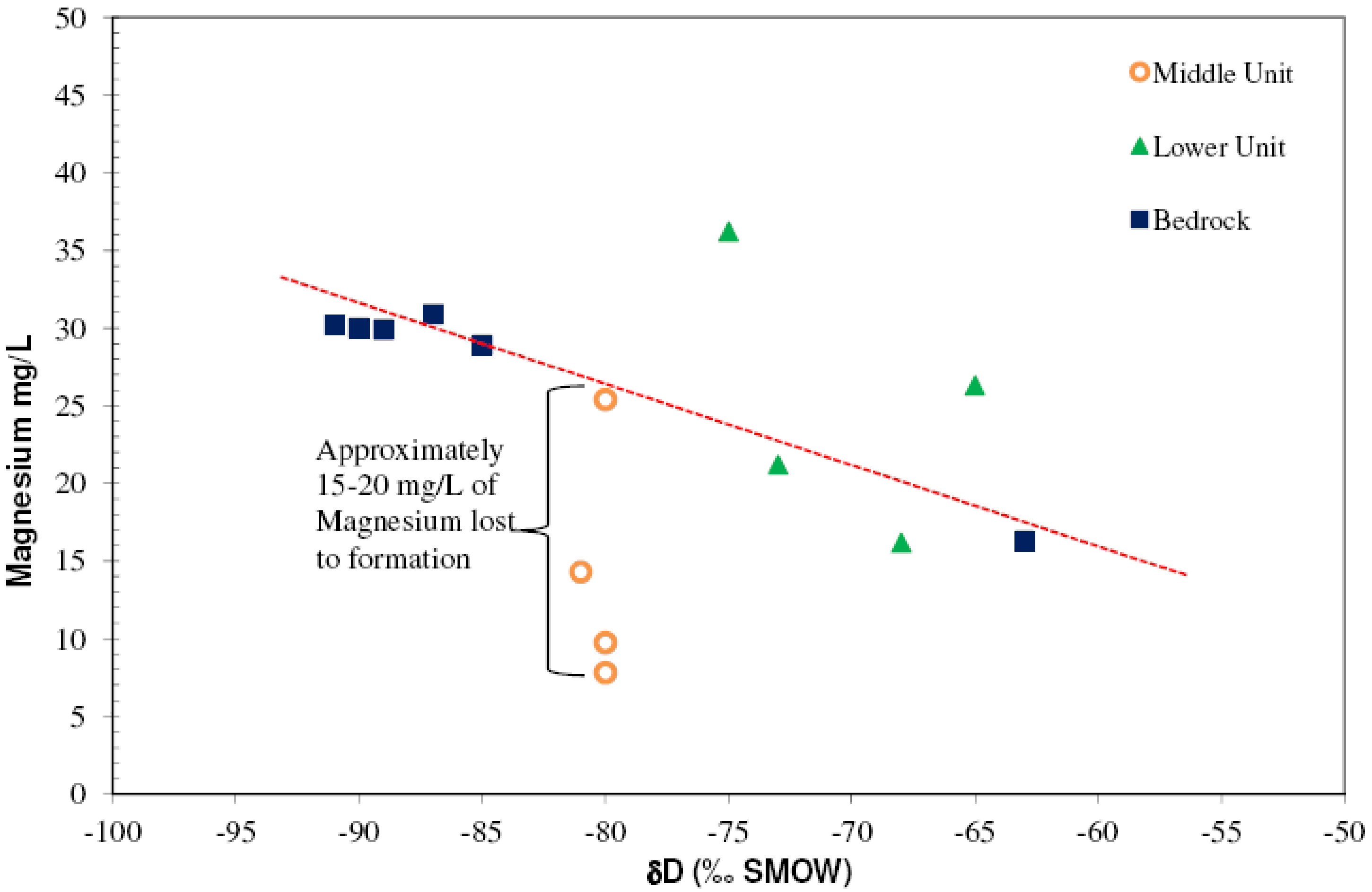

Figure 22. Magnesium vs. δD compositions of zonal samples from well 22.9E-10.8N. The red line indicates end member mixing.

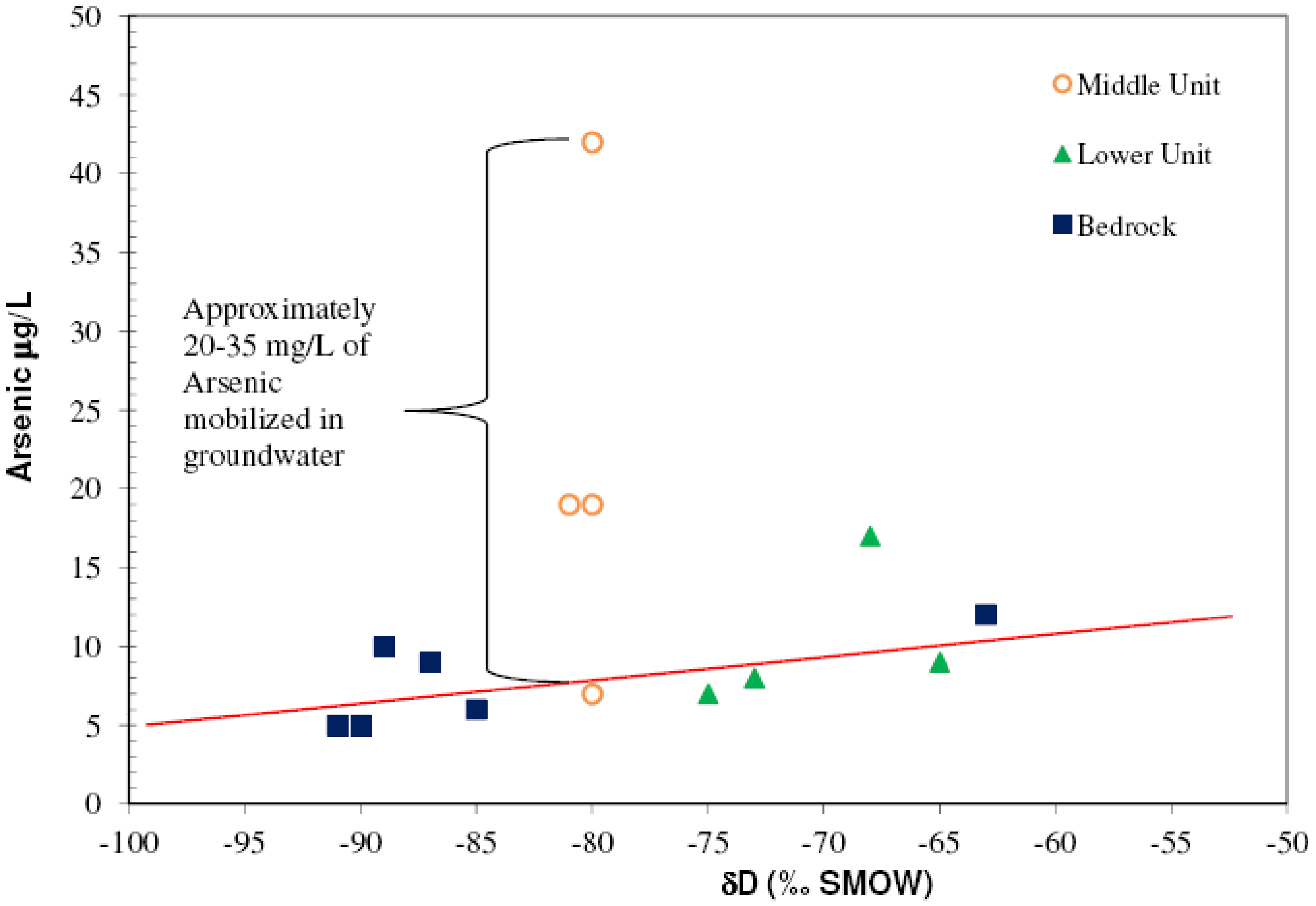

Figure 23. Arsenic vs. δD compositions of zonal samples from well 22.9E-10.8N. The red line indicates end member mixing.

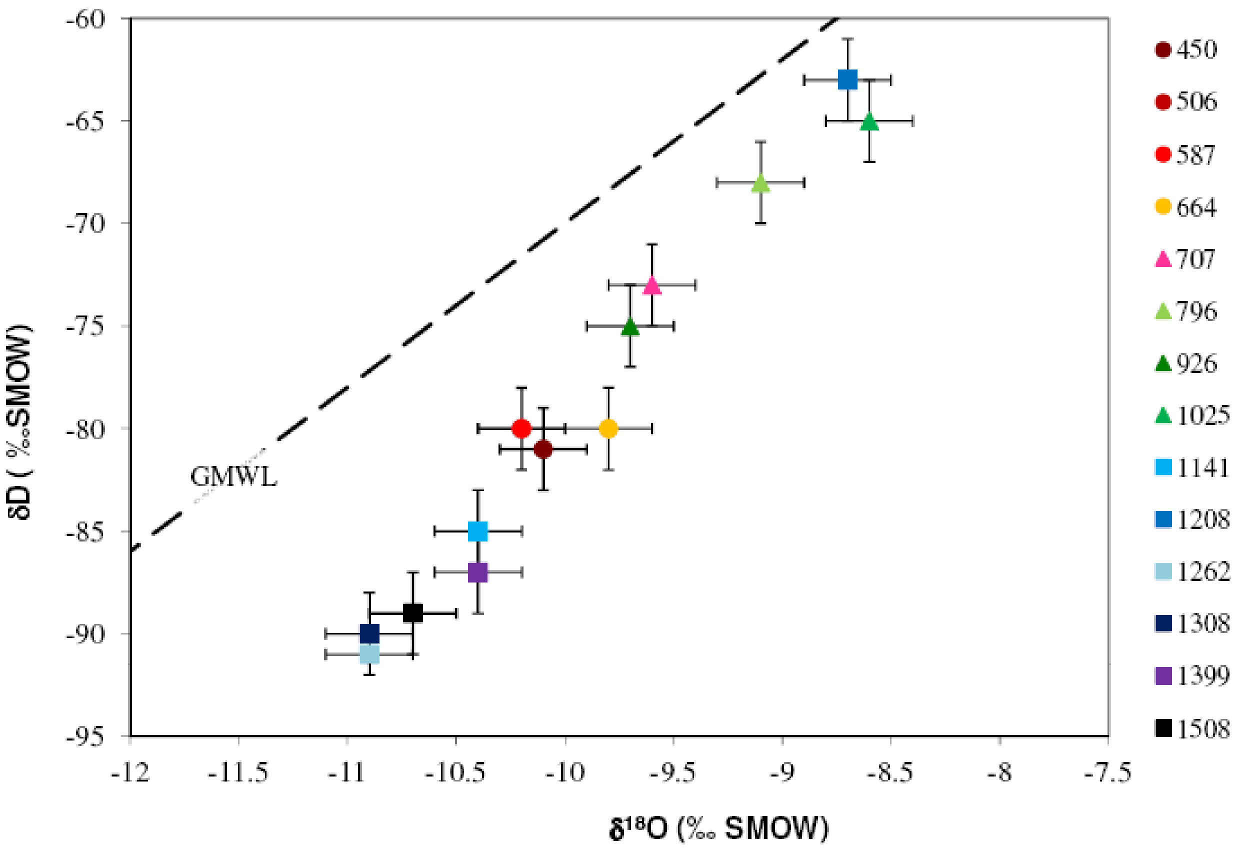

Figure 24. Isotopic composition (δD vs. δ^{18}O) of zonal samples from well 22.9E-10.8N. Stratigraphic units are represented as: circles= middle unit, triangles=lower unit, squares=bedrock. Sample keys are recorded in feet below ground surface.

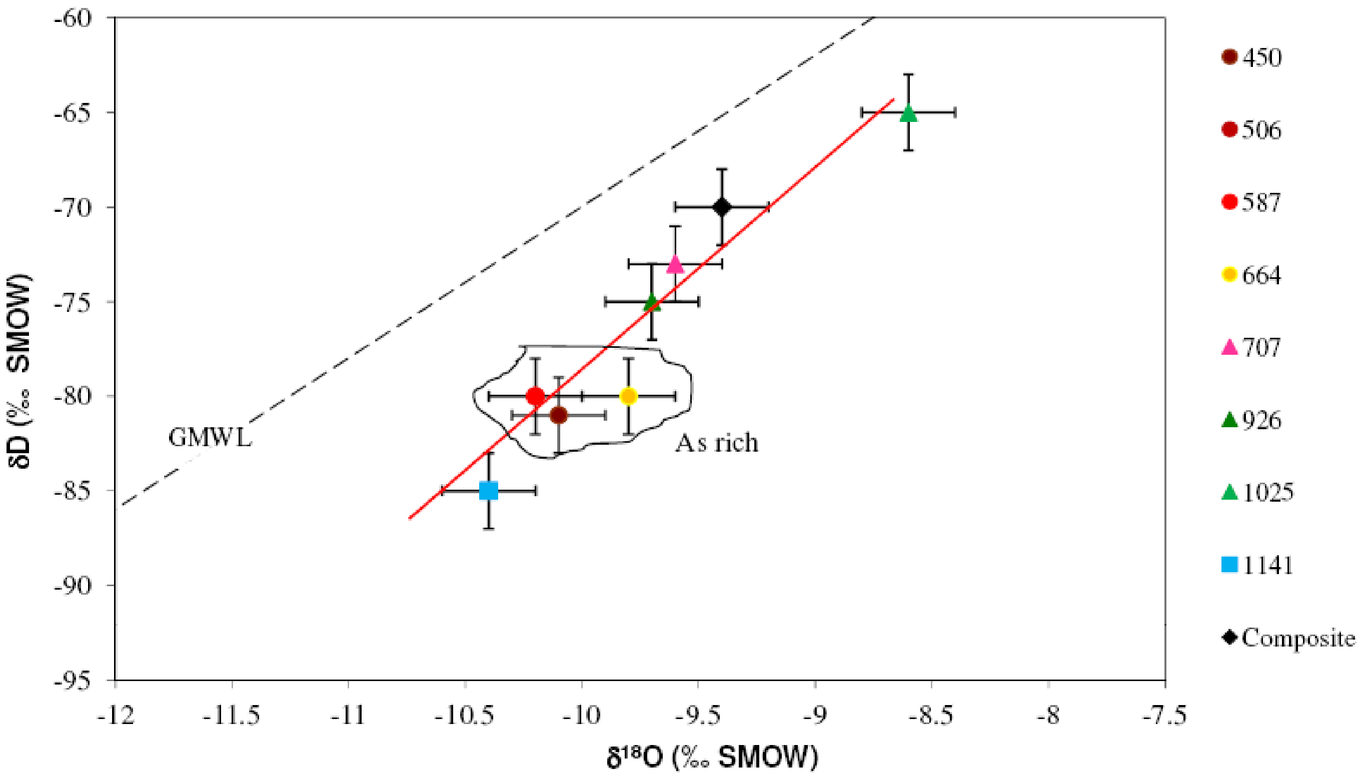

Figure 25. Isotopic composition (δD vs. $\delta^{18}O$) of zonal samples included in the screen interval and the composite sample (black diamond) of completed well 22.9E-10.8N . The red line represents a mixing array. The middle unit groundwater samples are represented by circles; the lower unit-triangles and the bedrock unit- squares. Sample keys are recorded in feet below ground surface.

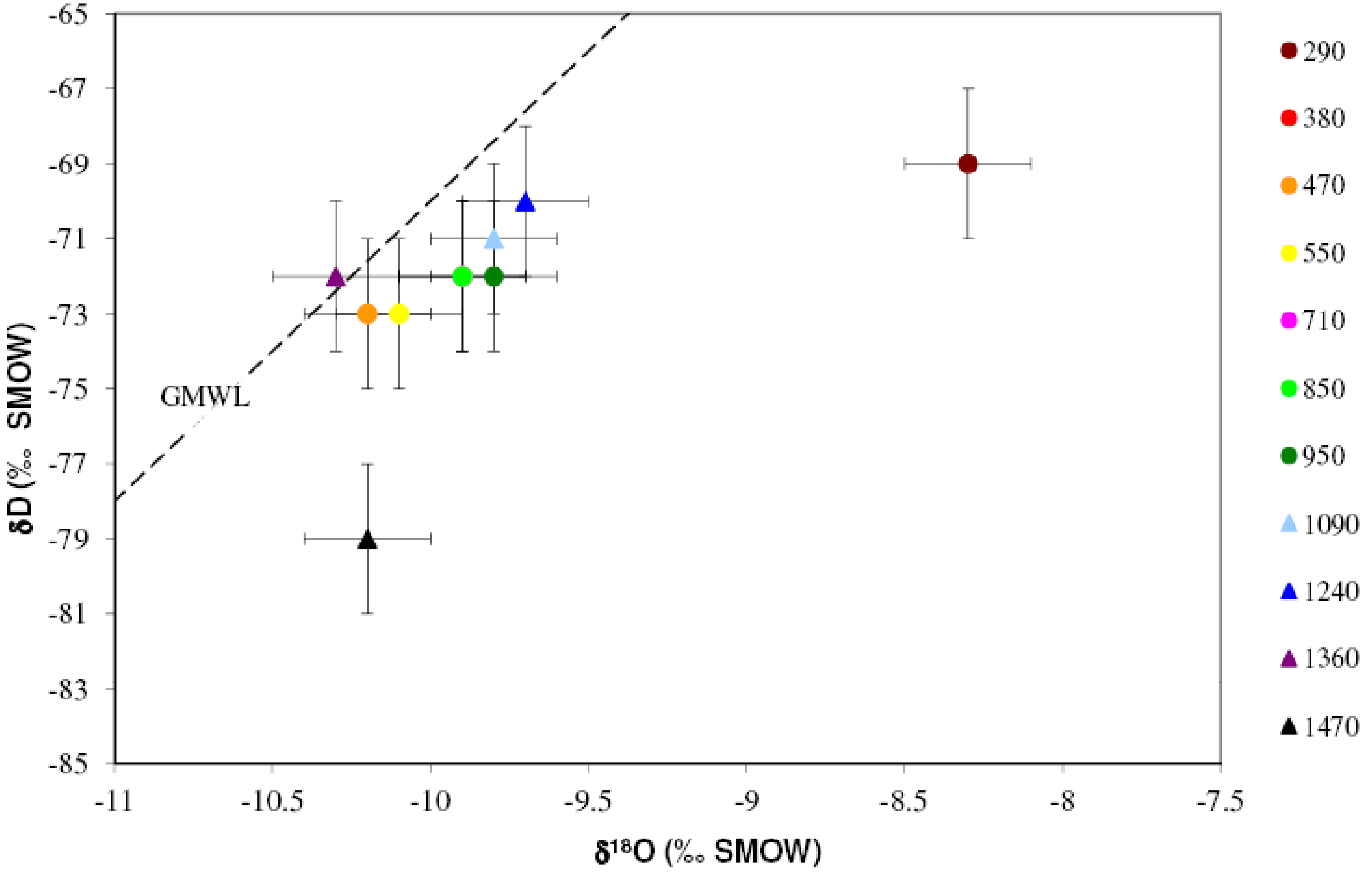

Figure 26. Isotopic composition (δD vs. $\delta^{18}O$) of zonal samples from well 25.9E-03.9N. Stratigraphic units are represented by: circles= middle unit, triangles=lower unit. Sample keys are recorded in feet below ground surface.

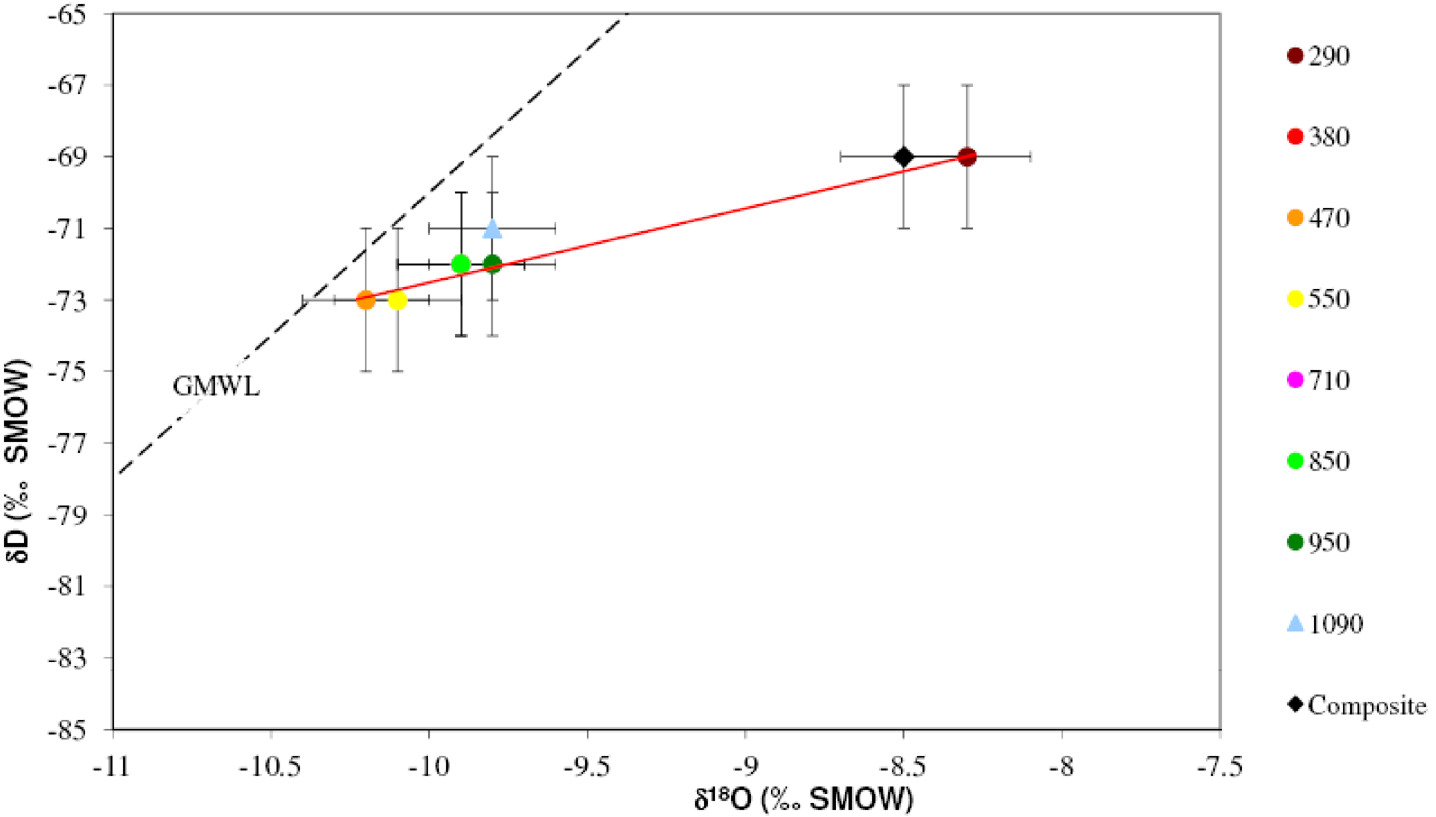

Figure 27. Isotopic composition (δD vs. $\delta^{18}O$) of zonal samples included in the screen interval and the composite sample (black diamond) of completed well 25.9E-03.9N . The red line represents a mixing array. The middle unit groundwater samples are represented by circles; the lower unit-triangles. Sample keys are recorded in feet below ground surface.

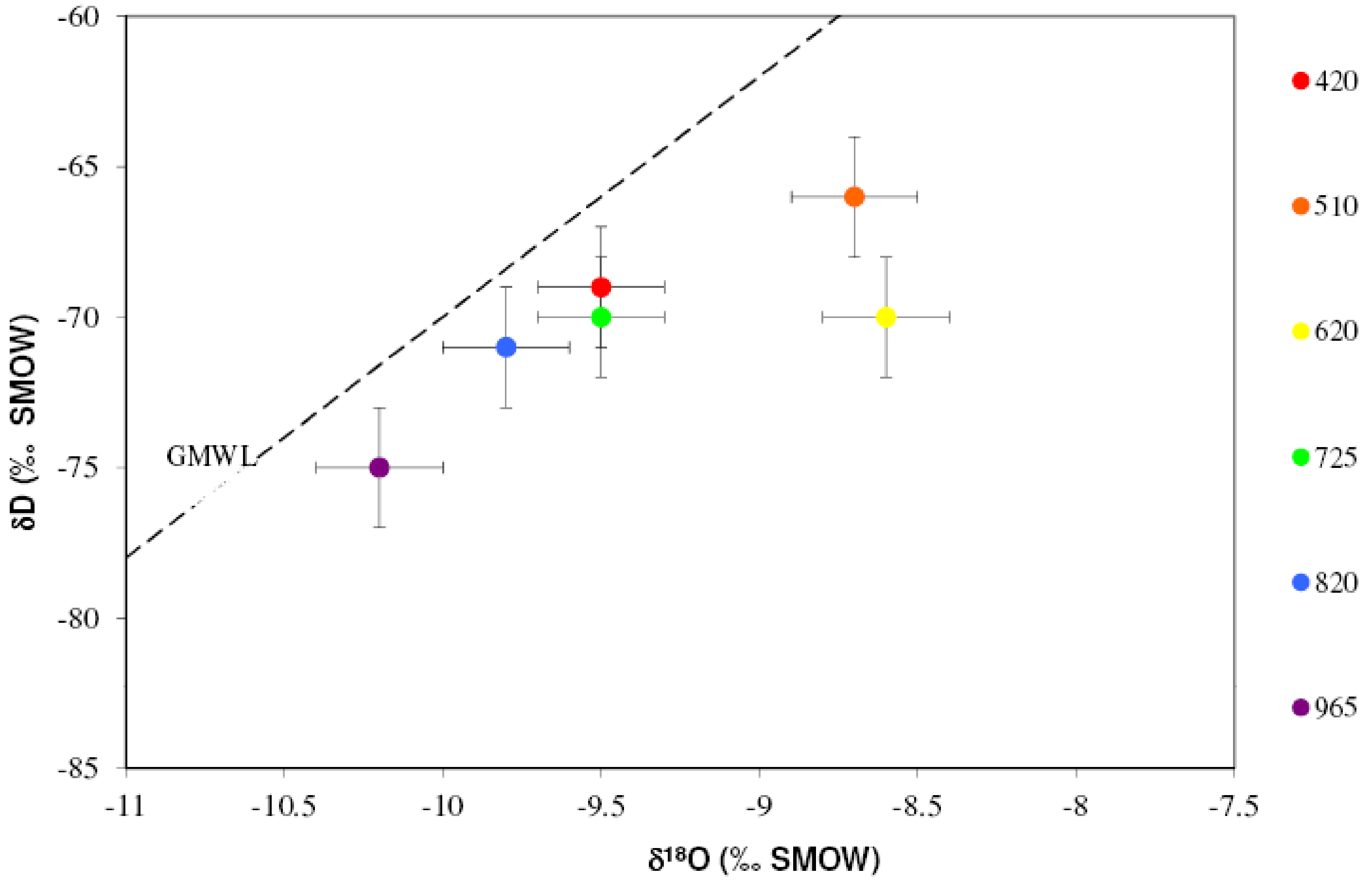

Figure 28. Isotopic composition (δD vs. $\delta^{18}O$) of zonal samples from well 31.1E-02.1S. Sample keys are recorded in feet below ground surface.

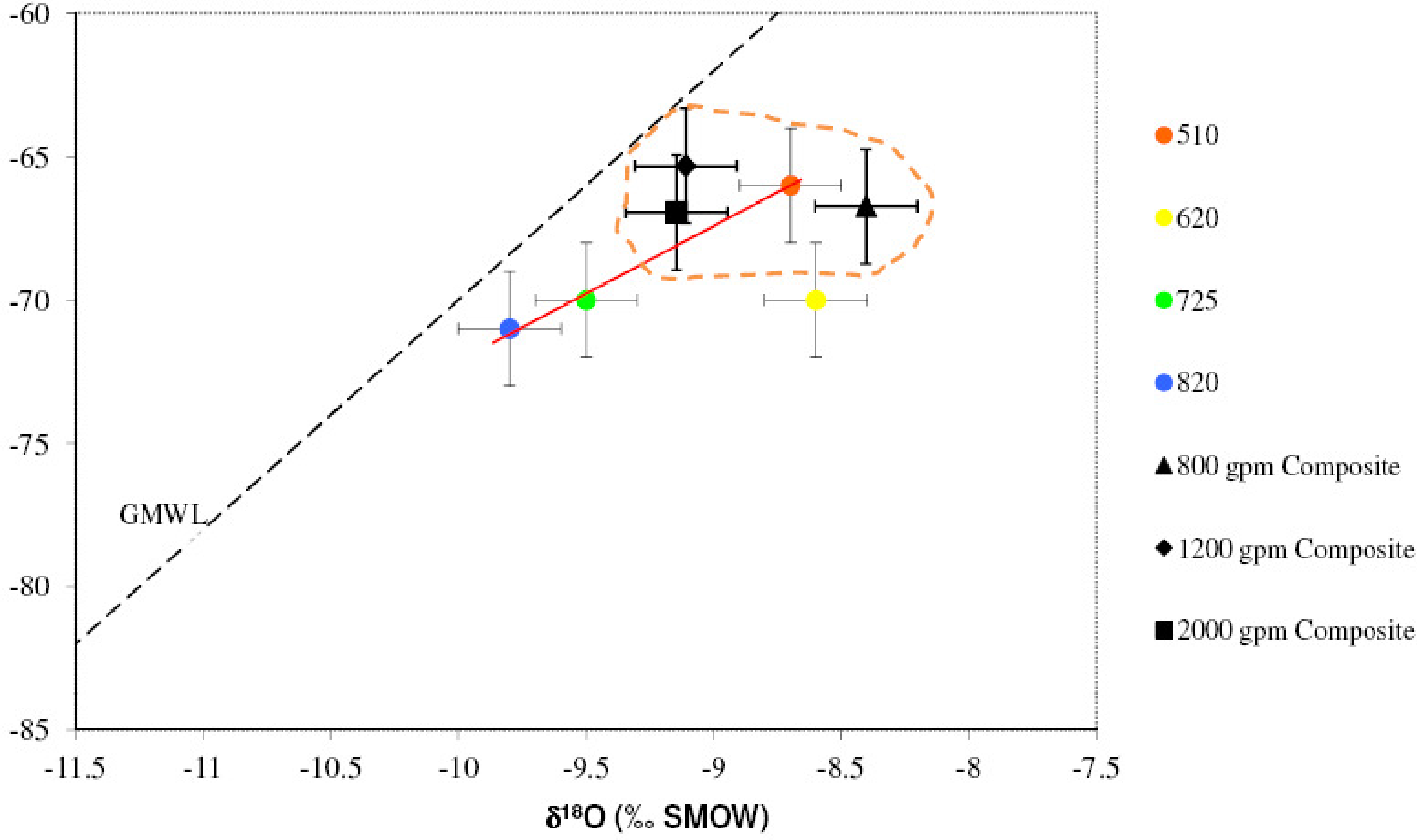

Figure 29. Isotopic composition (δD vs. $\delta^{18}O$) of zonal samples included in the screen interval and the composite samples (in black) of completed well 31.1E-02.1S. The red line represents a mixing array. Sample keys are recorded in feet below ground surface.

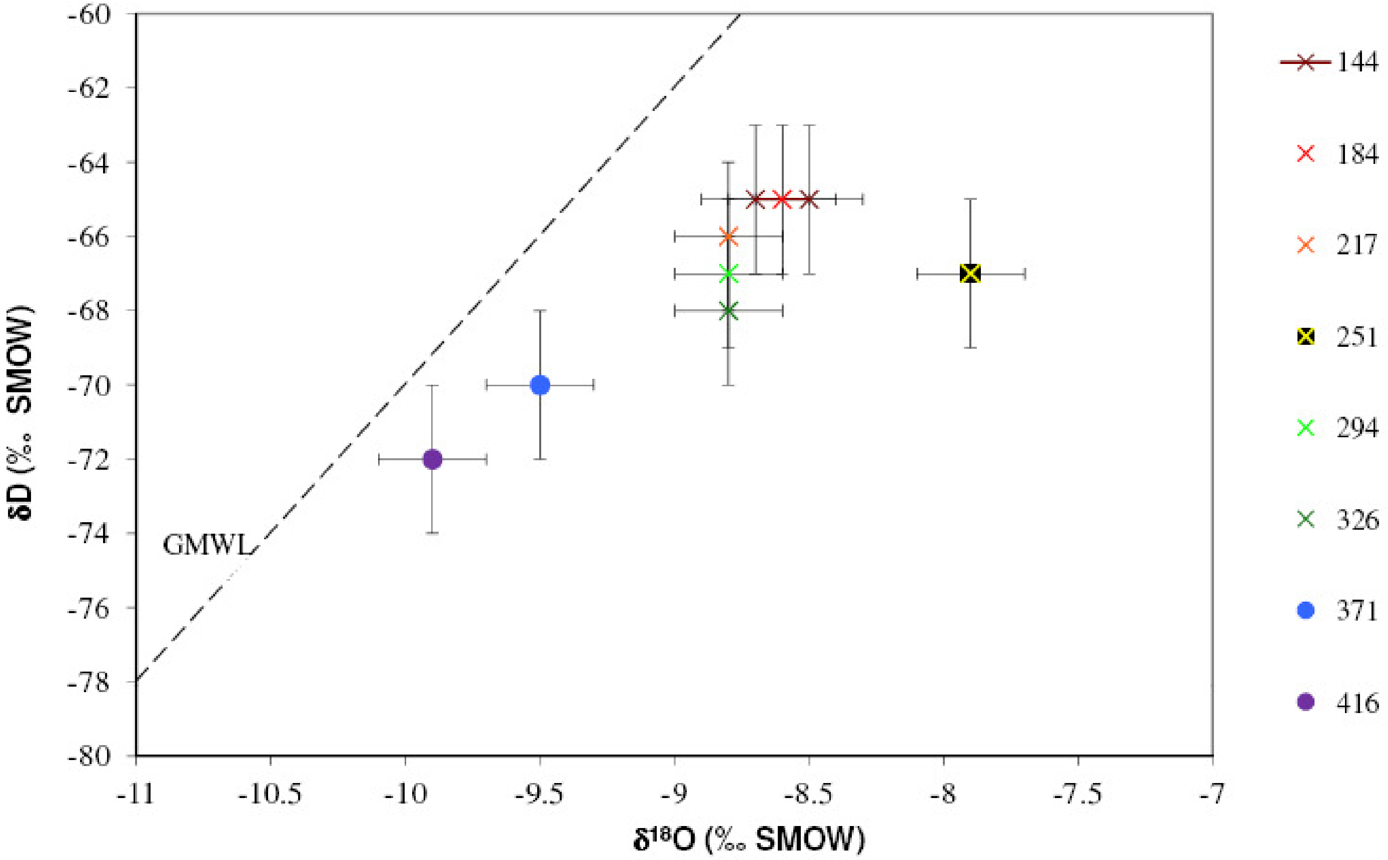

Figure 30. Isotopic composition (δD vs. $\delta^{18}O$) of zonal samples from well 00.4W-03.3N. Stratigraphic units are represented by: x= upper unit, circles=middle unit. Sample keys are recorded in feet below ground surface. A tie-line indicates a duplicate sample at 144.

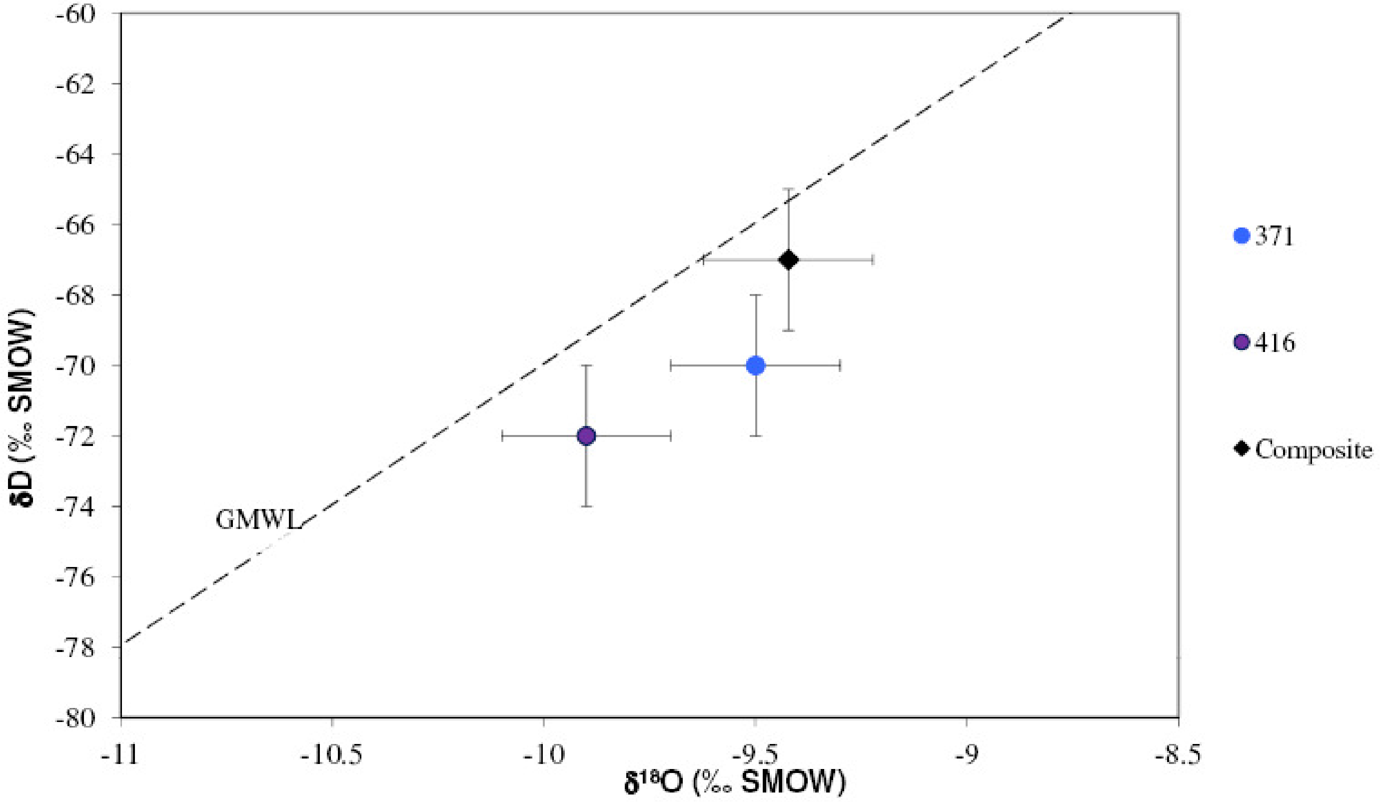

Figure 31. Isotopic composition (δD vs. $\delta^{18}O$) of zonal samples included in the screen interval and the composite sample (black diamond) of completed well 00.4W-03.3N . Sample keys are recorded in feet below ground surface.

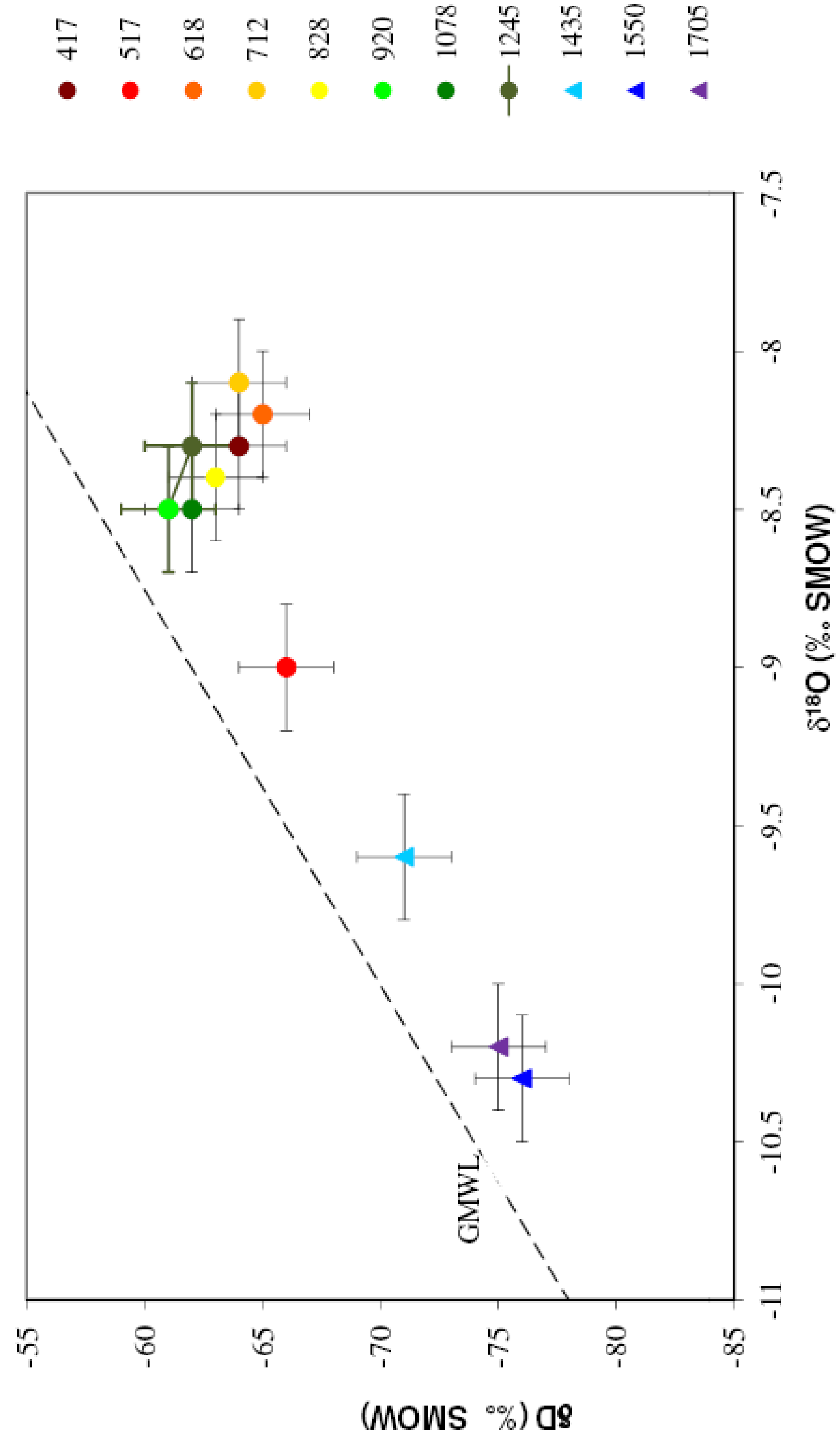

Figure 32. Isotopic composition (δD vs. $\delta^{18}O$) of zonal samples from well 05.1E-16.2N. Stratigraphic units are represented by; circles=middle unit, triangles = lower unit. Sample keys are recorded in feet below ground surface. The tie-line at 1245 indicates a duplicate sample.

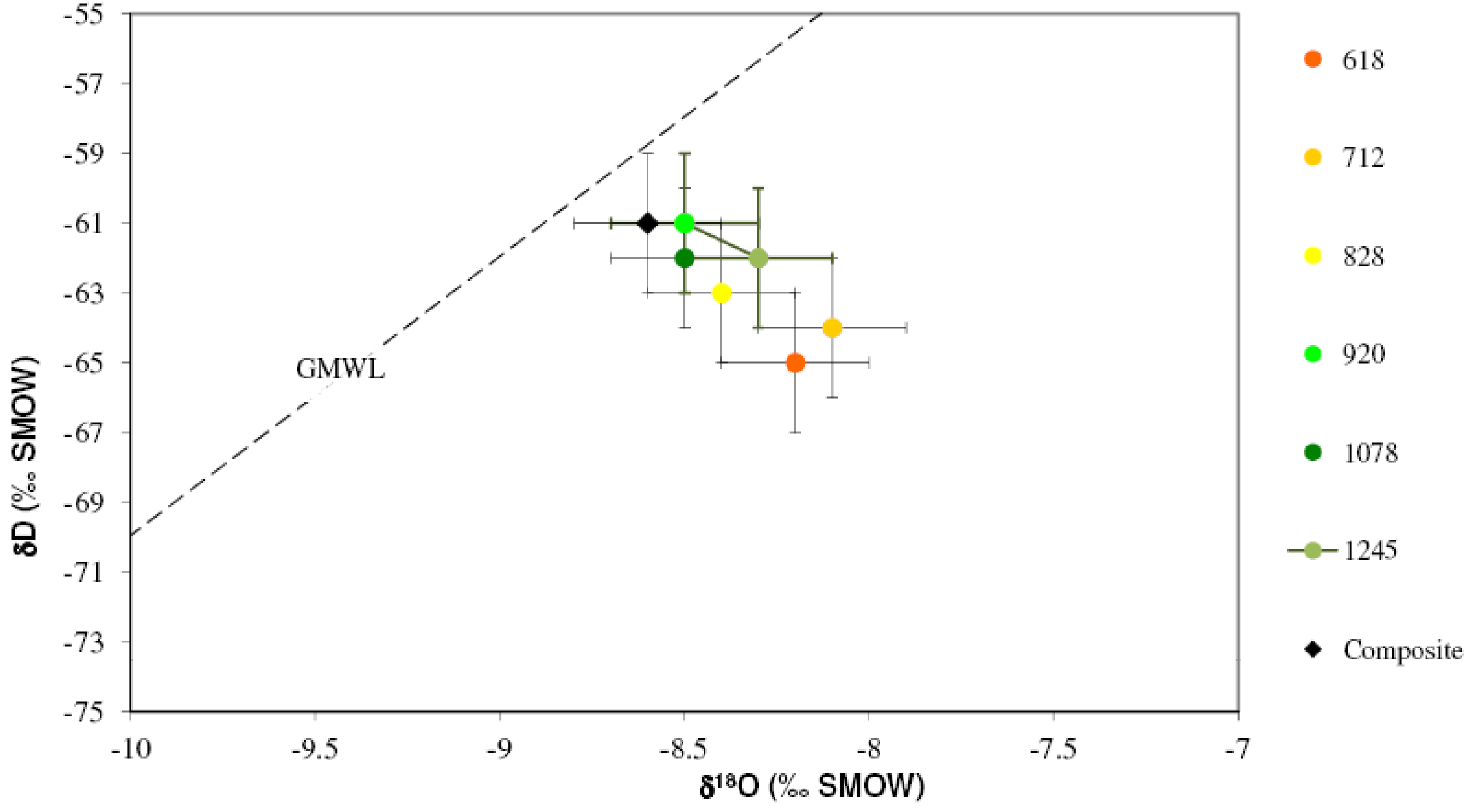

Figure 33. Isotopic composition (δD vs. $\delta^{18}O$) of zonal samples included in the screen interval and the composite sample (black diamond) of completed well 05.1E-16.2N. Sample keys are recorded in feet below ground surface. A tie- line indicates a duplicate sample at 1245.

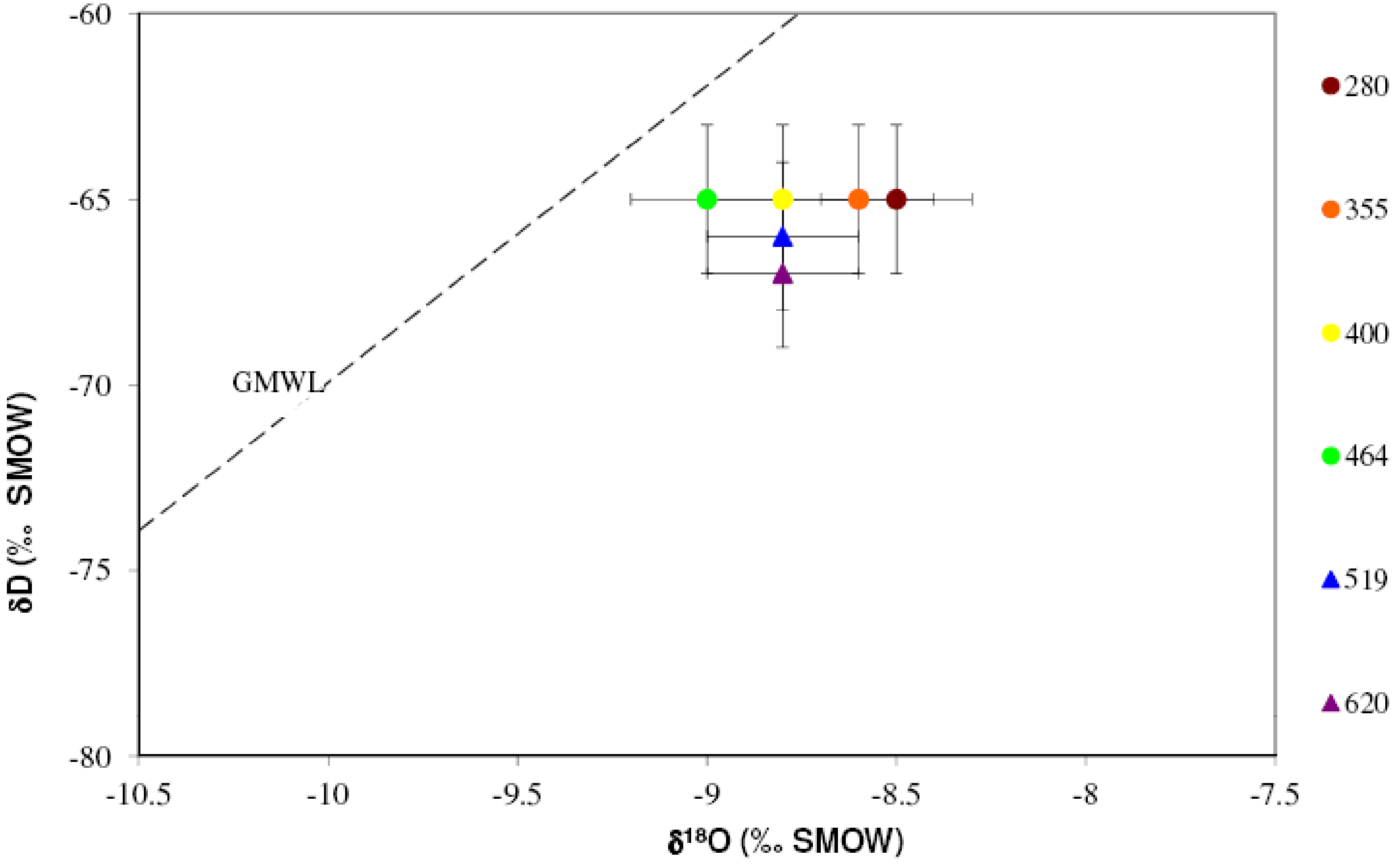

Figure 34. Isotopic composition (δD vs. $\delta^{18}O$) of zonal samples from well 12.1E-08.9N. Stratigraphic units are represented as: circles= middle unit, triangles=lower unit. Sample keys are recorded in feet below ground surface.

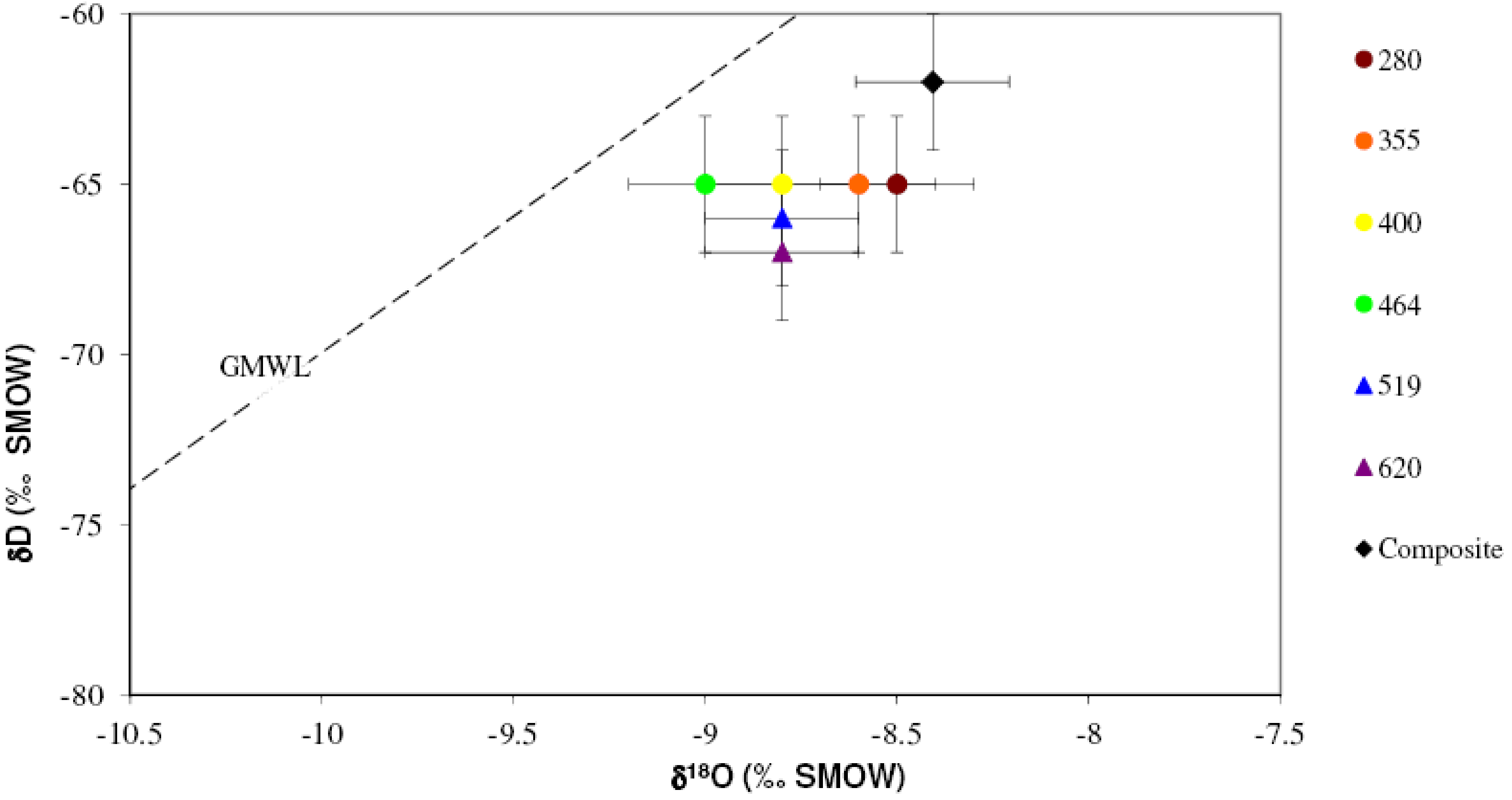

Figure 35. Isotopic composition (δD vs. δ18O) of zonal samples included in the screen interval and the composite sample (black diamond) of completed well 12.1E-08.9N. Sample keys are recorded in feet below ground surface.

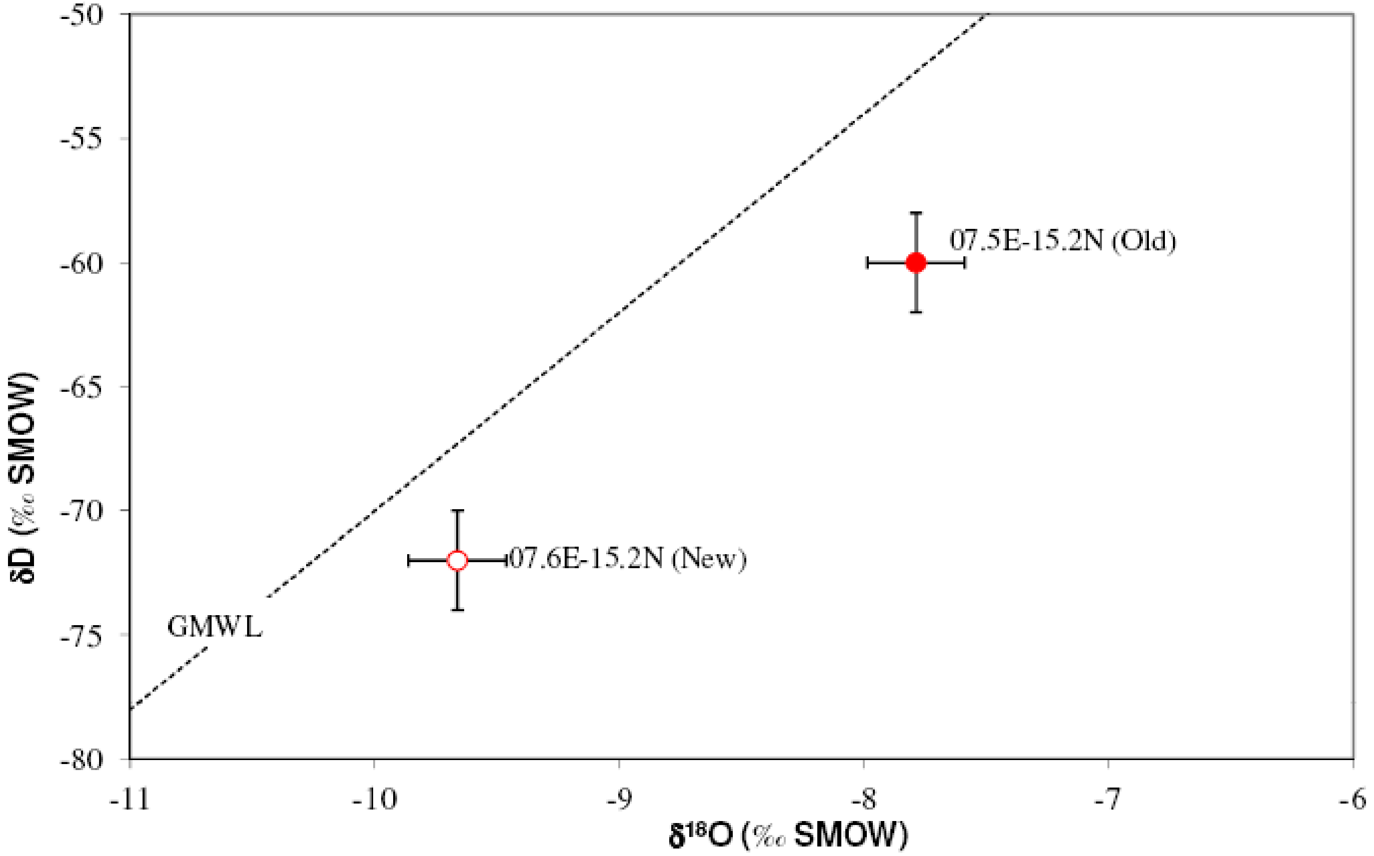

Figure 36. Replacement well 07.6E-15.2N (open circle) isotopic composition compared to the old well 07.5E15.2N (filled circle).

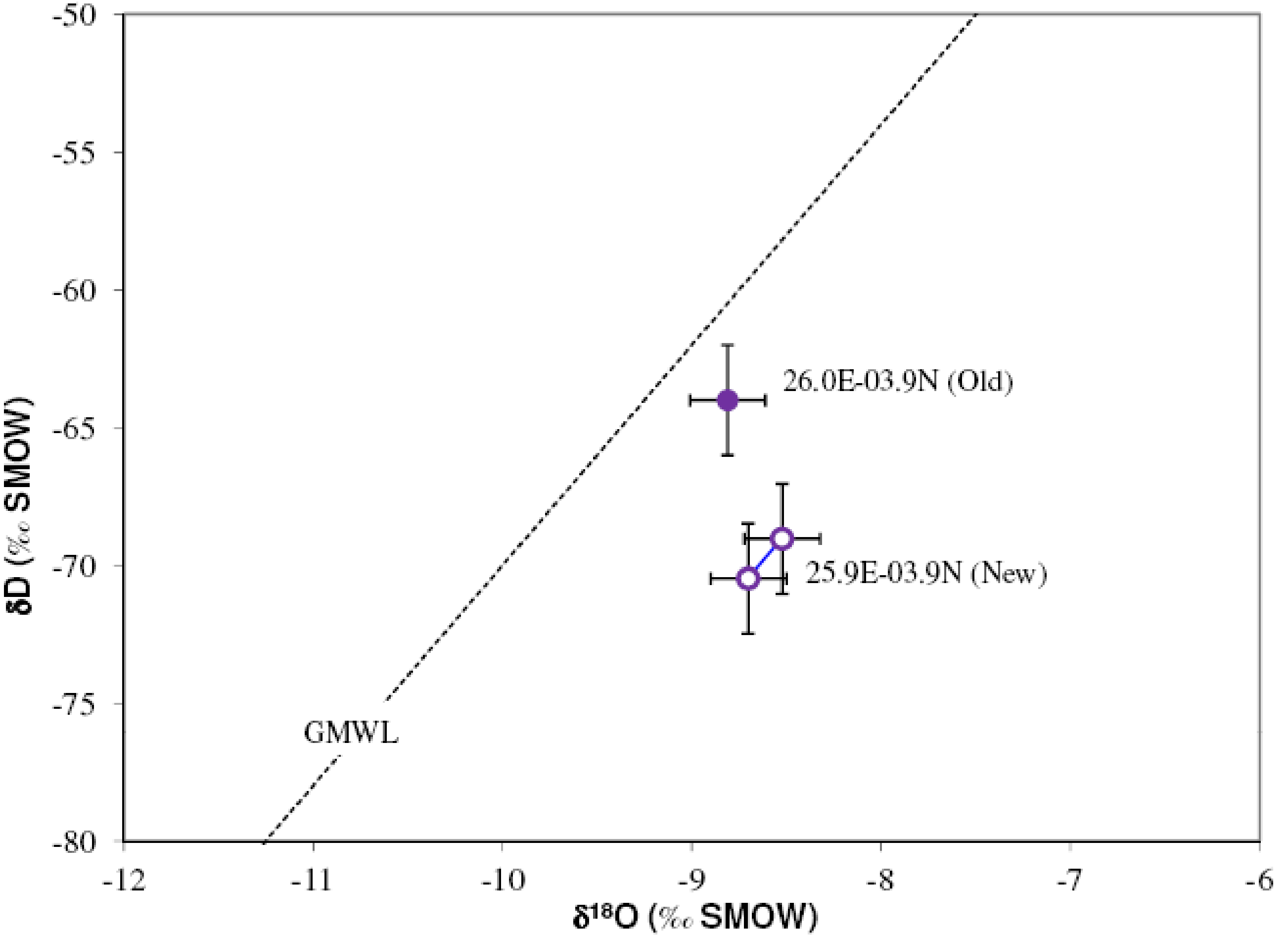

Figure 37. Replacement well 25.9E-03.9N (open circle) isotopic composition compared to the old well 26.0E-03.9N (filled circle).

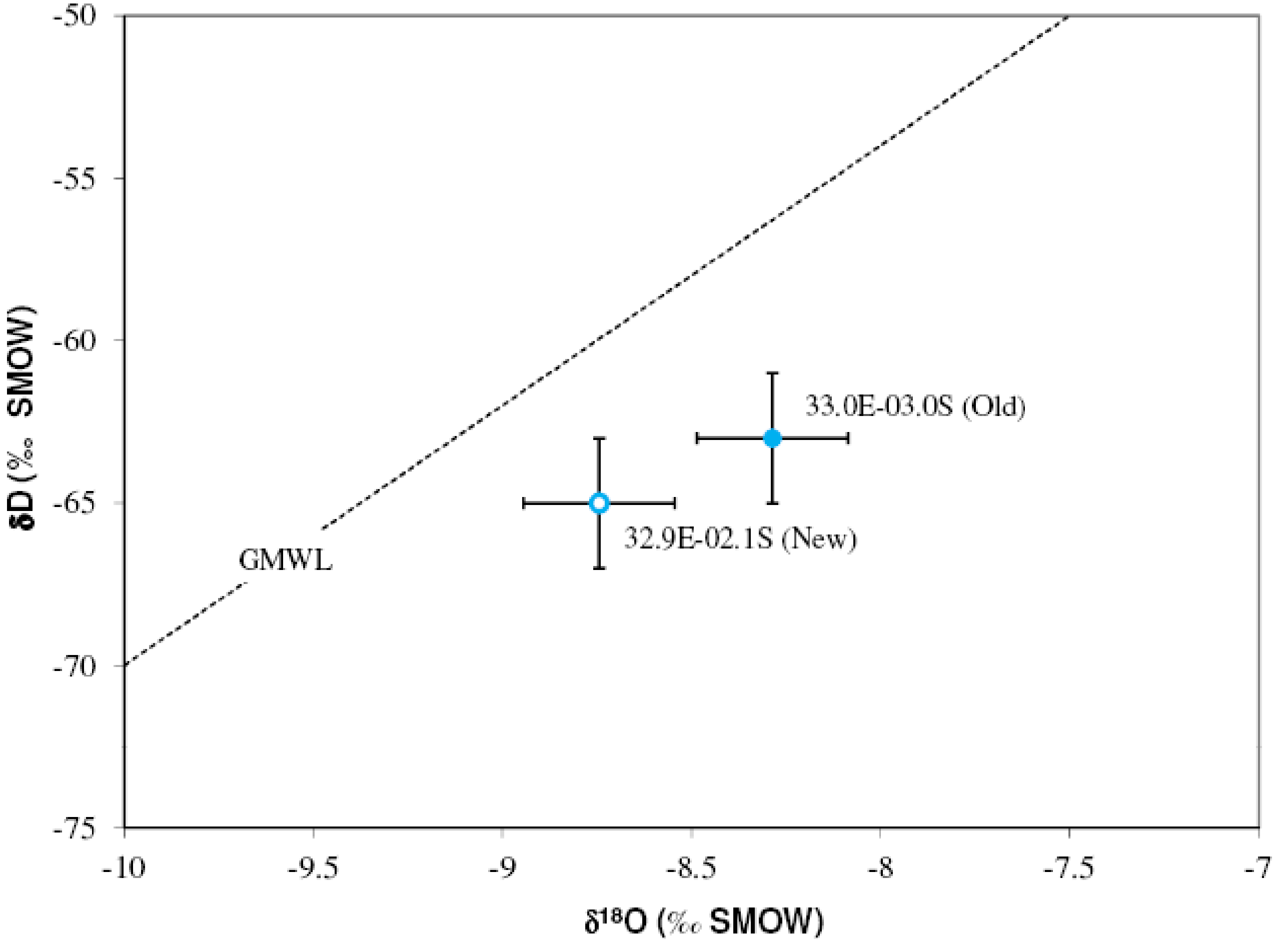

Figure 38. Replacement well 32.9E-03.1S (open circle) isotopic composition compared to the old well 33.0E-03.0S (filled circle).

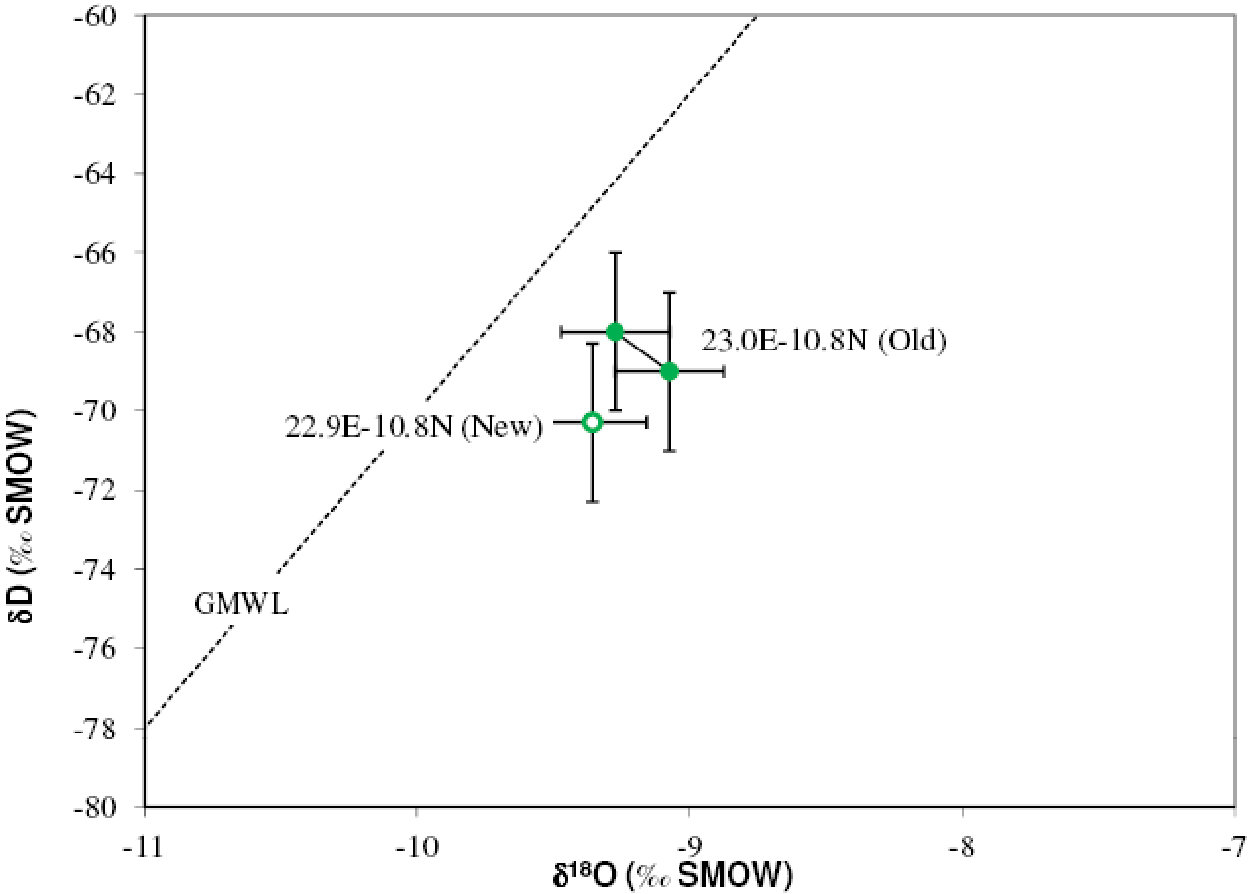

Figure 39. The replacement well 22.9E-10.8N (open circle) is not isotopically distinguishable from the old well, 23E-10.8N (filled circle).

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APPENDIX A

ISOTOPIC RESULTS OF SAMPLED WELLS

West Salt River Valley

Thesis Sample ID	δ18O ‰	δD ‰	Well Coordinate	Sample Qualifier	Screened Interval Depth (feet below ground surface)	ADWR Alluvial Unit
8/26/08-00.4W-03.3N-134-154*	-8.5	-65	00.4W-03.3N	144	134-154	UAU
8/26/08-00.4W-03.3N-134-154*	-8.7	-65	00.4W-03.3N	144	134-154	UAU
8/25/08-00.4W-03.3N-174-194	-8.6	-65	00.4W-03.3N	184	174-194	UAU
8/25/08-00.4W-03.3N-207-227	-8.8	-66	00.4W-03.3N	217	207-227	UAU
8/24/08-00.4W-03.3N-241-261	-7.9	-67	00.4W-03.3N	251	241-261	UAU
8/23/08-00.4W-03.3N-284-304	-8.8	-67	00.4W-03.3N	294	284-304	UAU
8/22/08-00.4W-03.3N-316-336	-8.8	-68	00.4W-03.3N	326	316-336	UAU
8/21/08-00.4W-03.3N-361-381	-9.5	-70	00.4W-03.3N	371	361-381	MAU
8/20/08-00.4W-03.3N-406-426	-9.9	-72	00.4W-03.3N	416	406-426	MAU
10/9/08-00.4W-03.3N-Comp	-9.4	-67	00.4W-03.3N	Composite	365-430	MAU
12/7/07-01.0E-07.1N-Comp	-8.6	-63	01.0E-07.1N	Composite	460-670	MAU
2/28/08-02.3E-01.3N-Comp*	-8.7	-69	02.3E-01.3N	Composite	120-170	UAU
2/28/08-02.3E-01.3N-Comp*	-8.7	-70	02.3E-01.3N	Composite	120-170	UAU
7/17/07-02.3E-01.3N-Comp	-8.3	-68	02.3E-01.3N	Composite	120-170	UAU
7/30/08-02.3E-01.3N-Comp	-8.5	-69	02.3E-01.3N	Composite	120-170	UAU
1/27/09-05.0E-11.1N-Comp	-8.7	-64	05.0E-11.1N	Composite	1000-1500; 1540-1900	MAU/LAU
6/7/08-05.1E-16.2N-407-427	-8.3	-64	05.1E-16.2N	417	407-427	MAU
6/6/08-05.1E-16.2N-507-527	-9.0	-66	05.1E-16.2N	517	507-527	MAU
6/5/08-05.1E-16.2N-608-628	-8.2	-65	05.1E-16.2N	618	608-628	MAU
6/5/08-05.1E-16.2N-702-722	-8.1	-64	05.1E-16.2N	712	702-722	MAU
6/4/08-05.1E-16.2N-818-838	-8.4	-63	05.1E-16.2N	828	818-838	MAU
6/3/08-05.1E-16.2N-910-930	-8.5	-61	05.1E-16.2N	920	910-930	MAU
6/2/08-05.1E-16.2N-1068-1088	-8.5	-62	05.1E-16.2N	1078	1068-1088	MAU
6/1/08-05.1E-16.2N-1235-1255	-8.3	-62	05.1E-16.2N	1245	1235-1255	MAU
5/31/08-05.1E-16.2N-1415-1435	-9.6	-71	05.1E-16.2N	1435	1415-1435	LAU
5/30/08-05.1E-16.2N-1540-1560	-10.3	-76	05.1E-16.2N	1550	1540-1560	LAU
5/30/08-05.1E-16.2N-1695-1715	-10.2	-75	05.1E-16.2N	1705	1695-1715	LAU
6/1/08-05.1E-16.2N-1235-1255	-8.5	-61	05.1E-16.2N	1245	1235-1255	MAU
9/10/08-05.1E-16.2N-Composite	-8.6	-61	05.1E-16.2N	Composite	560-920; 1020-1250	MAU
9/11/09-06.0E-11.3N-344	-8.6	-65	06.0E-11.2N	344		UAU
9/11/09-06.0E-11.3N-415	-8.5	-61	06.0E-11.2N	415		MAU
9/11/09-06.0E-11.3N-446	-8.6	-61	06.0E-11.2N	446		MAU
9/11/09-06.0E-11.3N-509	-9.2	-65	06.0E-11.2N	509		MAU
9/11/09-06.0E-11.3N-557	-9.7	-71	06.0E-11.2N	557		MAU
9/11/09-06.0E-11.3N-588	-9.7	-71	06.0E-11.2N	588		MAU
9/11/09-06.0E-11.3N-872	-10.2	-76	06.0E-11.2N	872		MAU
8/21/07-07.5E-15.2N-Comp	-7.8	-60	07.5E-15.2N	Composite	320-685	UAU/MAU
4/29/09-07.6E-15.2N-Comp	-9.7	-72	07.6E-15.2N	Composite	647-967; 1117-1560	UAU/MAU/LAU
5/21/07-12.1E-08.9N-240	-9.0	-63	12.1E-08.9N	240	230-250	MAU
5/20/07-12.1E-08.9N-270-290	-8.5	-65	12.1E-08.9N	280	270-290	MAU
5/20/07-12.1E-08.9N-345-365	-8.6	-65	12.1E-08.9N	355	345-365	MAU
5/19/07-12.1E-08.9N-390-410	-8.8	-65	12.1E-08.9N	400	390-410	MAU
5/18/07-12.1E-08.9N-454-474	-9.0	-65	12.1E-08.9N	464	454-474	MAU
5/17/07-12.1E-08.9N-509-529	-8.8	-66	12.1E-08.9N	519	509-529	LAU
5/16/07-12.1E-08.9N-620	-8.8	-67	12.1E-08.9N	620	610-630	LAU
7/17/07-12.1E-08.9N-Comp	-8.4	-62	12.1E-08.9N	Composite	260-350; 370-630	MAU/LAU
7/30/08-14.8E-00.7N-Composite	-8.5	-65	14.8E-00.7N	Composite	171-411	UAU/MAU/LAU
7/31/08-16.9E-06.0N-Comp	-8.4	-66	16.9E-06.0N	Composite	90-212	UAU
* Indicates duplicate sample						

East Salt River Valley

Thesis Sample ID	δ18O ‰	δD ‰	Well Coordinate	Sample Qualifier	Screened Interval Depth (feet below ground surface)	ADWR Alluvial Unit
4/13/04-22.9E-10.8N-450	-10.10	-81	22.9E-10.8N	450	441-472	MAU
4/12/04-22.9E-10.8N-506	-10.20	-80	22.9E-10.8N	506	486-528	MAU
4/10/04-22.9E-10.8N-587	-10.20	-80	22.9E-10.8N	587	577-617	MAU
4/9/04-22.9E-10.8N-664	-9.80	-80	22.9E-10.8N	664	656-690	MAU
4/8/04-22.9E-10.8N-707	-9.60	-73	22.9E-10.8N	707	700-737	LAU
4/6/04-22.9E-10.8N-796	-9.10	-68	22.9E-10.8N	796	786-826	LAU
4/5/04-22.9E-10.8N-926	-9.70	-75	22.9E-10.8N	926	910-950	LAU
4/3/04-22.9E-10.8N-1025	-8.60	-65	22.9E-10.8N	1025	1018-1051	LAU
4/1/04-22.9E-10.8N-1141	-10.40	-85	22.9E-10.8N	1141	1132-1166	Bedrock
3/30/04-22.9E-10.8N-1208	-8.70	-63	22.9E-10.8N	1208	1195-1232	Bedrock
3/29/04-22.9E-10.8N-1262	-10.90	-91	22.9E-10.8N	1262	1250-1293	Bedrock
3/27/04-22.9E-10.8N-1308	-10.90	-90	22.9E-10.8N	1308	1299-1340	Bedrock
3/26/04-22.9E-10.8N-1399	-10.40	-87	22.9E-10.8N	1399	1399-1434	Bedrock
3/24/04-22.9E-10.8N-1508	-10.70	-89	22.9E-10.8N	1508	1500-1538	Bedrock
12/8/08-22.9E-10.8N-Comp*	-9.50	-67	22.9E-10.8N	Composite	400-540; 640-760; 840-1180	MAU/LAU/BR
12/8/08-22.9E-10.8N-Comp*	-9.36	-70	22.9E-10.8N	Composite	400-540; 640-760; 840-1180	MAU/LAU/BR
5/14/08-23.0E-10.8N-Comp*	-9.08	-69	23.0E-10.8N	Composite	400-785	MAU/LAU
5/14/08-23.0E-10.8N-Comp*	-9.27	-68	23.0E-10.8N	Composite	400-785	MAU/LAU
8/30/07-23.0E-10.8N-Comp	-8.18	-67	23.0E-10.8N	Composite	400-785	MAU/LAU
10/17/07-23.5E-10.6N-302	-9.40	-68	23.5E-10.6N	302	292-312	MAU
10/16/07-23.5E-10.6N-390	-9.90	-72	23.5E-10.6N	390	380-400	MAU
10/15/07-23.5E-10.6N-509	-9.90	-73	23.5E-10.6N	509	499-519	MAU
10/15/07-23.5E-10.6N-509*	-9.90	-74	23.5E-10.6N	509	499-519	MAU
12/26/07-23.5E-10.6N-SP560	-9.40	-71	23.5E-10.6N	Spinner 560	380-630; 730-980	
12/26/07-23.5E-10.6N-SP680	-9.50	-71	23.5E-10.6N	Spinner 680	380-630; 730-980	
12/21/07-23.5E-10.6N-Comp	-9.61	-71	23.5E-10.6N	Composite	380-630; 730-980	MAU/LAU
6/21/07-25.9E-03.9N-280-300	-8.30	-69	25.9E-03.9N	290	280-300	MAU
6/21/07-25.9E-03.9N-370-390	-9.90	-72	25.9E-03.9N	380	370-390	MAU
6/20/07-25.9E-03.9N-460-480	-10.20	-73	25.9E-03.9N	470	460-480	MAU
6/19/07-25.9E-03.9N-540-560	-10.10	-73	25.9E-03.9N	550	540-560	MAU
6/18/07-25.9E-03.9N-700-720	-9.90	-72	25.9E-03.9N	710	700-720	MAU
6/17/07-25.9E-03.9N-840-860	-9.90	-72	25.9E-03.9N	850	840-860	MAU
6/16/07-25.9E-03.9N-940-960	-9.80	-72	25.9E-03.9N	950	940-960	LAU
6/15/07-25.9E-03.9N-1080-1100	-9.80	-71	25.9E-03.9N	1090	1080-1100	LAU
6/14/07-25.9E-03.9N-1230-1250	-9.70	-70	25.9E-03.9N	1240	1230-1250	LAU
6/13/07-25.9E-03.9N-1350-1370	-10.30	-72	25.9E-03.9N	1360	1350-1370	LAU
6/12/07-25.9E-03.9N-1460-1480	-10.20	-79	25.9E-03.9N	1470	1460-1480	LAU
8/16/07-25.9E-03.9N-Comp	-8.70	-71	25.9E-03.9N	Composite	270-415; 435-1153	MAU/LAU
8/16/07-25.9E-03.9N-Comp*	-8.52	-69	25.9E-03.9N	Composite	270-415; 435-1153	MAU/LAU
6/10/08-26.0E-03.9N-Comp	-8.81	-64	26.0E-03.9N	Composite	80-362	UAU/MAU
8/19/08-29.0E-01.0S-Comp	-9.19	-71	29.0E-01.0S	Composite	570-950	MAU
9/17/07-29.0E-01.5S-Comp	-7.58	-63	29.0E-01.5S	Composite	210-580	UAU/MAU
4/24/07-31.1E-02.1S-420	-9.50	-69	31.1E-02.1S	420	410-430	MAU
4/23/07-31.1E-02.1S-510	-8.70	-66	31.1E-02.1S	510	500-520	MAU
4/22/07-31.1E-02.1S-620	-8.60	-70	31.1E-02.1S	620	610-630	MAU
4/21/07-31.1E-02.1S-725	-9.50	-70	31.1E-02.1S	725	715-735	MAU
4/20/07-31.1E-02.1S-820	-9.80	-71	31.1E-02.1S	820	810-830	MAU
4/20/07-31.1E-02.1S-965	-10.20	-75	31.1E-02.1S	965	955-975	MAU
6/8/07-31.1E-02.1S-800gpm	-8.40	-67	31.1E-02.1S	800gpm	430-460; 500-520; 560-840	MAU
6/12/07-31.1E-02.1S-1200gpm	-9.11	-65	31.1E-02.1S	1200gpm	430-460; 500-520; 560-840	MAU
6/8/07-31.1E-02.1S-2000gpm	-9.15	-67	31.1E-02.1S	2000gpm	430-460; 500-520; 560-840	MAU
10/22/07-32.8E-07.2N-Comp	-9.50	-70	32.8E-07.0N	Composite	310-470	MAU
1/28/09-32.9E-03.1S-Comp	-8.74	-65	32.9E-03.1S	Composite	560-800	MAU
8/20/08-33.3E-03.0S-Comp	-8.29	-63	33.3E-03.0S	Composite	175-434	UAU/MAU
* Indicates duplicate sample						

APPENDIX B

AVAILABLE CHEMICAL DATA FROM SAMPLED WELLS

West Salt River Valley

Thesis Sample ID	TDS Method 2540C mg/L	pH	Arsenic µg/L	Iron µg/L	Bicarbonate mg/L	Fluoride mg/L	Chloride mg/L
8/26/08-00.4W-03.3N-134-154*	1800	7.8	3	438	346	0.13	592.0
8/25/08-00.4W-03.3N-174-194	2000	7.8	6	3420	344	0.16	668.0
8/25/08-00.4W-03.3N-207-227	2100	7.7	2	315	355	0.13	733.0
8/24/08-00.4W-03.3N-241-261	2300	7.7	2	848	273	0.14	735.0
8/23/08-00.4W-03.3N-284-304	2600	7.3	2	457	273	0.16	882.0
8/22/08-00.4W-03.3N-316-336	2500	7.2	1	215	239	0.18	956.0
8/21/08-00.4W-03.3N-361-381	1600	7.7	4	809	121	0.11	677.0
8/20/08-00.4W-03.3N-406-426	1000	8.5	8	1100	98	0.24	251.0
10/9/08-00.4W-03.3N-Comp	1300**	8.1	4	159	114	0.15	602.0
12/7/07-01.0E-07.1N-Comp	705**	7.8	3	83	121	0.14	267.0
2/28/08-02.3E-01.3N-Comp*	1270**	7.2	8	BRL	324	0.46	426.0
7/17/07-02.3E-01.3N-Comp	NA	NA	NA	NA	NA	NA	NA
7/30/08-02.3E-01.3N-Comp	NA	NA	NA	NA	NA	NA	NA
1/27/09-05.0E-11.1N-Comp	624**	7.7	2	42	111	0.29	246.0
6/7/08-05.1E-16.2N-407-427	850	8.6	3	673	173	0.22	292.0
6/6/08-05.1E-16.2N-507-527	310	8.1	4	289	124	0.16	89.2
6/5/08-05.1E-16.2N-608-628	190	8.1	6	265	138	0.22	23.5
6/5/08-05.1E-16.2N-702-722	210	8.1	6	419	148	0.20	24.3
6/4/08-05.1E-16.2N-818-838	190	8.2	7	471	157	0.27	24.1
6/3/08-05.1E-16.2N-910-930	200	8.3	8	289	168	0.44	27.2
6/2/08-05.1E-16.2N-1068-1088	280	8.4	16	1260	174	0.80	33.3
6/1/08-05.1E-16.2N-1235-1255*	560	8.9	22	11300	467	1.22	47.7
5/31/08-05.1E-16.2N-1415-1435	460	8.6	121	462	88	2.49	121.0
5/30/08-05.1E-16.2N-1540-1560	630	8.9	97	183	49	2.67	211.0
5/30/08-05.1E-16.2N-1695-1715	630	8.8	131	467	46	4.77	217.0
9/10/08-05.1E-16.2N-Aquifer Test	220	8.3	7	58	154	0.41	26.9
9/11/09-06.0E-11.2N-344	330	8.2	3	283	139	0.45	81.1
9/11/09-06.0E-11.2N-415	1300	7.8	2	314	96	0.37	390.0
9/11/09-06.0E-11.2N-446	300	8.3	4	215	148	0.47	67.4
9/11/09-06.0E-11.2N-509	260	8.4	4	254	138	0.46	75.2
9/11/09-06.0E-11.2N-557	230	8.7	11	2000	165	0.5	18.6
9/11/09-06.0E-11.2N-588	250	8.7	12	2330	176	0.48	21.7
9/11/09-06.0E-11.2N-872	440	8.8	139	5420	240	1.52	34.3
8/21/07-07.5E-15.2N-Comp	NA	NA	NA	NA	NA	NA	NA
4/29/09-07.6E-15.2N-Comp	590**	7.7	5	105	111	0.44	200.0
5/21/07-12.1E-08.9N-240	400	8.1	7	483	135	0.5	94.6
5/20/07-12.1E-08.9N-270-290	230	8.1	7	68	144	0.52	41.6
5/20/07-12.1E-08.9N-345-365	480	7.8	BRL	578	127	0.37	148.0
5/19/07-12.1E-08.9N-390-410	560	7.7	BRL	421	127	0.34	184.0
5/18/07-12.1E-08.9N-454-474	380	7.8	6	844	143	0.40	119.0
5/17/07-12.1E-08.9N-509-529	260	7.9	6	317	143	0.46	68.9
5/16/07-12.1E-08.9N-620	300	7.9	6	724	133	0.47	85.2
7/17/07-12.1E-08.9N-Comp	320	8.2	7	67	140	0.46	64.7
7/30/08-14.8E-00.7N-Comp	NA	NA	NA	NA	NA	NA	NA
7/31/08-16.9E-06.0N-Comp	NA	NA	NA	NA	NA	NA	NA

* Indicates duplicate sample ** indicates tds calc method

West Salt River Valley

Thesis Sample ID	Bromide mg/L	Sulfate mg/L	Calcium mg/L	Magnesium mg/L	Sodium mg/L	Potassium mg/L	Boron µg/L
8/26/08-00.4W-03.3N-134-154*	0.65	330.0	147.0	66.10	359.0	3.9	0.811
8/25/08-00.4W-03.3N-174-194	0.71	342.0	131.0	77.80	439.0	6.8	0.926
8/25/08-00.4W-03.3N-207-227	0.75	345.0	154.0	95.50	379.0	6.4	0.872
8/24/08-00.4W-03.3N-241-261	0.73	300.0	185.0	120.00	260.0	6.5	0.568
8/23/08-00.4W-03.3N-284-304	0.79	374.0	212.0	146.00	304.0	7.7	0.695
8/22/08-00.4W-03.3N-316-336	0.81	399.0	231.0	162.00	291.0	8.0	0.674
8/21/08-00.4W-03.3N-361-381	0.56	217.0	129.0	83.40	241.0	5.8	0.301
8/20/08-00.4W-03.3N-406-426	0.21	210.0	16.8	5.48	248.0	2.7	0.491
10/9/08-00.4W-03.3N-Comp	0.49	203.0	109.0	69.90	242.0	4.6	0.362
12/7/07-01.0E-07.1N-Comp	0.45	93.5	56.9	43.70	124.0	4.6	0.149
2/28/08-02.3E-01.3N-Comp*	0.33	224.0	76.7	32.00	339.0	4.7	0.669
7/17/07-02.3E-01.3N-Comp	NA	NA	NA	NA	NA	NA	0.749
7/30/08-02.3E-01.3N-Comp	NA	NA	NA	NA	NA	NA	0.710
1/27/09-05.0E-11.1N-Comp	0.52	60.3	68.0	46.20	86.2	4.9	0.090
6/7/08-05.1E-16.2N-407-427	0.29	97.7	103.0	51.20	105.0	6.1	0.061
6/6/08-05.1E-16.2N-507-527	0.22	26.5	33.4	17.70	56.1	3.7	0.039
6/5/08-05.1E-16.2N-608-628	0.11	28.5	17.0	9.26	46.9	3.0	0.045
6/5/08-05.1E-16.2N-702-722	0.11	29.0	14.9	7.57	57.3	2.9	0.057
6/4/08-05.1E-16.2N-818-838	0.10	29.1	13.0	6.82	67.7	3.4	0.087
6/3/08-05.1E-16.2N-910-930	BRL	30.0	11.7	5.77	78.4	3.1	0.109
6/2/08-05.1E-16.2N-1068-1088	BRL	36.1	11.5	4.61	92.8	3.0	0.249
6/1/08-05.1E-16.2N-1235-1255*	0.10	48.6	153.0	14.30	164.0	4.4	0.330
5/31/08-05.1E-16.2N-1415-1435	0.11	117.0	10.6	1.45	158.0	2.6	0.693
5/30/08-05.1E-16.2N-1540-1560	0.11	180.0	16.5	1.18	212.0	3.4	0.657
5/30/08-05.1E-16.2N-1695-1715	0.12	170.0	21.2	1.33	204.0	3.3	0.704
9/10/08-05.1E-16.2N-Aquifer Test	0.11	29.4	13.8	6.91	62.5	2.8	0.119
9/11/09-06.0E-11.2N-344	0.33	17.3	24.0	17.00	62.0	3.6	0.080
9/11/09-06.0E-11.2N-415	0.72	120.0	114.0	72.00	77.0	6.2	0.068
9/11/09-06.0E-11.2N-446	0.26	19.3	21.0	14.00	65.0	3.6	0.084
9/11/09-06.0E-11.2N-509	0.28	22.4	18.0	11.00	74.0	3.2	0.090
9/11/09-06.0E-11.2N-557	BRL	17.1	8.8	4.00	71.0	2.4	0.095
9/11/09-06.0E-11.2N-588	BRL	17.2	8.9	4.19	78.1	2.2	0.101
9/11/09-06.0E-11.2N-872	0.12	22.2	10.5	5.97	114.0	2.8	0.238
8/21/07-07.5E-15.2N-Comp	NA	NA	NA	NA	NA	NA	NA
4/29/09-07.6E-15.2N-Comp	0.30	110.0	61.4	39.90	85.3	5.4	0.362
5/21/07-12.1E-08.9N-240	0.23	11.1	30.9	19.30	65.6	3.2	0.061
5/20/07-12.1E-08.9N-270-290	BRL	11.6	17.5	11.90	48.4	2.6	0.054
5/20/07-12.1E-08.9N-345-365	0.22	30.2	41.0	27.70	66.8	4.3	0.087
5/19/07-12.1E-08.9N-390-410	0.31	48.9	51.8	36.40	79.5	4.4	0.145
5/18/07-12.1E-08.9N-454-474	0.18	29.7	34.9	23.50	73.5	3.7	0.088
5/17/07-12.1E-08.9N-509-529	BRL	13.8	23.5	13.90	53.0	2.7	0.063
5/16/07-12.1E-08.9N-620	0.11	21.3	23.4	12.40	66.1	3.2	0.078
7/17/07-12.1E-08.9N-Comp	0.11	15.1	22.5	15.50	53.7	3.4	0.067
7/30/08-14.8E-00.7N-Comp	NA	NA	NA	NA	NA	NA	0.789
7/31/08-16.9E-06.0N-Comp	NA	NA	NA	NA	NA	NA	4.680

* Indicates duplicate sample

West Salt River Valley

Thesis Sample ID	Silica mg/L	Nitrate (as N) mg/L
8/26/08-00.4W-03.3N-134-154*	30.3	18.90
8/25/08-00.4W-03.3N-174-194	55.2	18.20
8/25/08-00.4W-03.3N-207-227	29.8	18.30
8/24/08-00.4W-03.3N-241-261	34.6	15.60
8/23/08-00.4W-03.3N-284-304	29.3	14.20
8/22/08-00.4W-03.3N-316-336	24.1	13.30
8/21/08-00.4W-03.3N-361-381	24.3	8.90
8/20/08-00.4W-03.3N-406-426	23.5	3.16
10/9/08-00.4W-03.3N-Comp	17.4	7.91
12/7/07-01.0E-07.1N-Comp	18.2	12.70
2/28/08-02.3E-01.3N-Comp*	33.9	2.33
7/17/07-02.3E-01.3N-Comp	NA	NA
7/30/08-02.3E-01.3N-Comp	NA	NA
1/27/09-05.0E-11.1N-Comp	21.3	13.00
6/7/08-05.1E-16.2N-407-427	25.7	12.70
6/6/08-05.1E-16.2N-507-527	21.6	5.20
6/5/08-05.1E-16.2N-608-628	21.5	1.09
6/5/08-05.1E-16.2N-702-722	22.2	1.06
6/4/08-05.1E-16.2N-818-838	21.3	1.08
6/3/08-05.1E-16.2N-910-930	20.7	0.96
6/2/08-05.1E-16.2N-1068-1088	28.9	0.72
6/1/08-05.1E-16.2N-1235-1255*	34.2	0.56
5/31/08-05.1E-16.2N-1415-1435	28.1	0.50
5/30/08-05.1E-16.2N-1540-1560	24.7	0.11
5/30/08-05.1E-16.2N-1695-1715	26.8	BRL
9/10/08-05.1E-16.2N-Aquifer Test	22.3	1.18
9/11/09-06.0E-11.2N-344	NA	38.6
9/11/09-06.0E-11.2N-415	NA	78.7
9/11/09-06.0E-11.2N-446	NA	30.80
9/11/09-06.0E-11.2N-509	NA	42.00
9/11/09-06.0E-11.2N-557	NA	5.32
9/11/09-06.0E-11.2N-588	34.8	5.59
9/11/09-06.0E-11.2N-872	69.6	1.61
8/21/07-07.5E-15.2N-Comp	NA	16.58
4/29/09-07.6E-15.2N-Comp	28.2	7.37
5/21/07-12.1E-08.9N-240	20.5	6.01
5/20/07-12.1E-08.9N-270-290	19.1	3.25
5/20/07-12.1E-08.9N-345-365	21.7	5.70
5/19/07-12.1E-08.9N-390-410	21.4	8.20
5/18/07-12.1E-08.9N-454-474	22.5	4.66
5/17/07-12.1E-08.9N-509-529	22.0	2.94
5/16/07-12.1E-08.9N-620	21.3	2.98
7/17/07-12.1E-08.9N-Comp	21.1	3.82
7/30/08-14.8E-00.7N-Comp	NA	NA
7/31/08-16.9E-06.0N-Comp	NA	NA

* Indicates duplicate sample

East Salt River Valley

Thesis Sample ID	TDS Method 2540C mg/L	pH	Arsenic µg/L	Iron µg/L	Bicarbonate mg/L	Fluoride mg/L	Chloride mg/L
4/13/04-22.9E-10.8N-450	475	8.6	19	3100	183	0.72	82.3
4/12/04-22.9E-10.8N-506	462	8.7	19	50	172	0.61	72.0
4/10/04-22.9E-10.8N-587	437	8.7	42	120	196	0.98	55.2
4/9/04-22.9E-10.8N-664	531	8.4	7	590	200	0.41	77.8
4/8/04-22.9E-10.8N-707	399	8.3	8	150	195	0.49	56.4
4/6/04-22.9E-10.8N-796	294	8.4	17	44	204	0.66	39.8
4/5/04-22.9E-10.8N-926	479	8.1	7	120	164	0.41	122.0
4/3/04-22.9E-10.8N-1025	330	8.1	9	110	211	0.46	40.8
4/1/04-22.9E-10.8N-1141	585	8.2	6	810	183	0.40	83.8
3/30/04-22.9E-10.8N-1208	237	8.0	12	89	201	0.45	17.0
3/29/04-22.9E-10.8N-1262	644	8.2	5	1600	167	0.39	90.5
3/27/04-22.9E-10.8N-1308	633	8.5	5	2000	173	0.41	98.6
3/26/04-22.9E-10.8N-1399	643	8.4	9	16000	167	0.41	126.0
3/24/04-22.9E-10.8N-1508	654	8.1	10	32000	160	0.44	128.0
12/8/08-22.9E-10.8N-Comp*	494**	8.6	27	389	167	0.52	140.0
5/14/08-23.0E-10.8N-Comp	NA	NA	14	NA	NA	NA	NA
5/14/08-23.0E-10.8N-Comp*	NA	NA	14	NA	NA	NA	NA
10/17/07-23.5E-10.6N-302	560	8.5	13	102	137	0.68	204.0
10/16/07-23.5E-10.6N-390	600	8.8	52	81	187	1.39	194.0
10/15/07-23.5E-10.6N-509*	660	8.9	66	148	217	1.33	151.0
12/21/07-23.5E-10.6N-Comp	550	8.9	28	220	159	1.02	201.0
6/21/07-25.9E-03.9N-280-300	520	8.4	51	277	212	0.21	162.0
6/21/07-25.9E-03.9N-370-390	610	7.8	BRL	563	171	0.14	252.0
6/20/07-25.9E-03.9N-460-480	690	7.9	3	65	168	0.12	262.0
6/19/07-25.9E-03.9N-540-560	750	7.7	4	109	162	0.12	255.0
6/18/07-25.9E-03.9N-700-720	640	7.9	5	188	145	0.16	277.0
6/17/07-25.9E-03.9N-840-860	620	8.2	12	568	130	0.76	275.0
6/16/07-25.9E-03.9N-940-960	640	8.2	11	170	122	0.86	281.0
6/15/07-25.9E-03.9N-1080-1100	620	8.2	12	203	116	0.83	286.0
6/14/07-25.9E-03.9N-1230-1250	630	8.5	33	229	117	0.89	294.0
6/13/07-25.9E-03.9N-1350-1370	580	8.6	44	207	157	1.66	231.0
6/12/07-25.9E-03.9N-1460-1480	1300	8.5	36	687	102	2.26	110.0
8/16/07-25.9E-03.9N-Comp*	620	7.9	4	26	198	0.26	237.0
6/10/08-26.0E-03.9N-Comp	NA	NA	NA	NA	NA	NA	NA
8/19/08-29.0E-01.0S-Comp	NA	8.0	9	55	145	0.93	362.0
9/17/07-29.0E-01.5S-Comp	NA	NA	NA	NA	NA	NA	NA
4/24/07-31.1E-02.1S-420	600	8.1	BRL	145	76	0.65	261.0
4/23/07-31.1E-02.1S-510	1300	7.6	BRL	415	165	0.24	465.0
4/22/07-31.1E-02.1S-620	1000	8.3	BRL	468	57	0.60	460.0
4/21/07-31.1E-02.1S-725	1200	8.2	7	728	51	0.98	558.0
4/20/07-31.1E-02.1S-820	910	8.6	24	914	61	2.17	453.0
4/20/07-31.1E-02.1S-965	1500	8.4	69	847	74	5.95	737.0
6/8/07-31.1E-02.1S-800gpm	NA	NA	NA	NA	NA	NA	NA
6/12/07-31.1E-02.1S-1200gpm	830	8.0	1	85	140	0.44	362.0
6/8/07-31.1E-02.1S-2000gpm	NA	NA	NA	NA	NA	NA	NA
10/22/07-32.8E-07.2N-Comp	NA	NA	NA	NA	NA	NA	NA
1/28/09-32.9E-03.1S-Comp	866**	7.9	6	30	77	0.58	363.0
8/20/08-33.3E-03.0S-Comp	1600**	7.1	2	230	193	0.17	686.0

* Indicates duplicate sample ** indicates tds calc method

East Salt River Valley

Thesis Sample ID	Bromide mg/L	Sulfate mg/L	Calcium mg/L	Magnesium mg/L	Sodium mg/L	Potassium mg/L	Boron µg/L
4/13/04-22.9E-10.8N-450	BRL	144.0	32.2	14.3	135.0	4.0	0.151
4/12/04-22.9E-10.8N-506	BRL	142.0	21.6	9.8	128.0	2.3	0.125
4/10/04-22.9E-10.8N-587	BRL	117.0	15.6	7.8	141.0	BRL	0.210
4/9/04-22.9E-10.8N-664	BRL	177.0	55.3	25.4	75.8	2.7	0.095
4/8/04-22.9E-10.8N-707	BRL	97.8	33.6	21.2	66.2	2.6	0.065
4/6/04-22.9E-10.8N-796	0.17	40.5	15.9	16.2	77.3	BRL	0.067
4/5/04-22.9E-10.8N-926	0.21	100.0	37.0	36.2	59.3	2.6	0.059
4/3/04-22.9E-10.8N-1025	BRL	57.0	27.6	26.3	46.1	2.2	0.050
4/1/04-22.9E-10.8N-1141	BRL	212.0	64.6	28.9	92.8	3.2	0.110
3/30/04-22.9E-10.8N-1208	BRL	16.4	18.1	16.3	41.3	2.0	0.043
3/29/04-22.9E-10.8N-1262	BRL	237.0	74.2	30.2	109.0	3.3	0.114
3/27/04-22.9E-10.8N-1308	BRL	224.0	75.0	30.0	115.0	3.4	0.156
3/26/04-22.9E-10.8N-1399	BRL	232.0	72.5	30.9	154.0	5.4	0.163
3/24/04-22.9E-10.8N-1508	BRL	224.0	68.2	29.9	144.0	5.9	0.113
12/8/08-22.9E-10.8N-Comp*	0.23	60.0	9.6	4.7	174.0	2.3	0.157
5/14/08-23.0E-10.8N-Comp	NA	NA	NA	NA	NA	NA	NA
5/14/08-23.0E-10.8N-Comp*	NA	NA	NA	NA	NA	NA	NA
10/17/07-23.5E-10.6N-302	0.16	55.8	11.5	6.5	168.0	BRL	0.156
10/16/07-23.5E-10.6N-390	0.15	38.0	3.8	BRL	198.0	BRL	0.221
10/15/07-23.5E-10.6N-509*	0.16	36.2	2.6	BRL	185.0	BRL	0.212
12/21/07-23.5E-10.6N-Comp	0.12	35.6	4.0	1.3	203.0	BRL	0.172
6/21/07-25.9E-03.9N-280-300	0.11	54.2	40.0	14.7	137.0	3.2	0.117
6/21/07-25.9E-03.9N-370-390	0.11	44.8	38.8	14.3	134.0	3.0	0.108
6/20/07-25.9E-03.9N-460-480	0.12	44.4	67.1	27.6	111.0	3.4	0.118
6/19/07-25.9E-03.9N-540-560	0.11	42.0	73.6	28.3	95.2	3.3	0.119
6/18/07-25.9E-03.9N-700-720	0.11	45.2	64.9	20.7	118.0	3.7	0.107
6/17/07-25.9E-03.9N-840-860	0.11	43.7	36.5	11.9	164.0	3.8	0.116
6/16/07-25.9E-03.9N-940-960	0.11	43.8	31.2	10.6	161.0	3.3	0.108
6/15/07-25.9E-03.9N-1080-1100	0.11	42.7	30.5	10.8	168.0	3.4	0.109
6/14/07-25.9E-03.9N-1230-1250	0.12	43.5	14.3	4.8	194.0	2.6	0.117
6/13/07-25.9E-03.9N-1350-1370	0.11	113.0	12.0	2.9	210.0	3.0	0.740
6/12/07-25.9E-03.9N-1460-1480	0.11	807.0	47.9	5.8	398.0	4.1	1.590
8/16/07-25.9E-03.9N-Comp*	0.12	54.8	56.9	22.7	127.0	3.4	0.131
6/10/08-26.0E-03.9N-Comp	NA	NA	NA	NA	NA	NA	NA
8/19/08-29.0E-01.0S-Comp	0.20	78.5	50.3	19.2	204.0	4.6	0.261
9/17/07-29.0E-01.5S-Comp	NA	NA	NA	NA	NA	NA	0.765
4/24/07-31.1E-02.1S-420	0.26	63.0	52.3	5.6	161.0	4.5	0.167
4/23/07-31.1E-02.1S-510	0.58	156.0	146.0	13.4	287.0	5.2	0.804
4/22/07-31.1E-02.1S-620	0.31	94.2	52.1	9.7	268.0	3.8	0.159
4/21/07-31.1E-02.1S-725	0.41	143.0	66.1	11.4	338.0	4.1	0.278
4/20/07-31.1E-02.1S-820	0.11	100.0	28.3	2.3	320.0	2.8	0.236
4/20/07-31.1E-02.1S-965	0.12	215.0	41.9	3.1	502.0	3.8	0.565
6/8/07-31.1E-02.1S-800gpm	NA	NA	NA	NA	NA	NA	NA
6/12/07-31.1E-02.1S-1200gpm	0.37	112.0	84.7	8.9	215.0	4.7	0.551
6/8/07-31.1E-02.1S-2000gpm	NA	NA	NA	NA	NA	NA	NA
10/22/07-32.8E-07.2N-Comp	NA	NA	NA	NA	NA	NA	NA
1/28/09-32.9E-03.1S-Comp	0.53	118.0	92.0	22.3	192.0	5.0	0.174
8/20/08-33.3E-03.0S-Comp	1.21	234.0	315.0	81.3	86.6	4.2	0.538

* Indicates duplicate sample

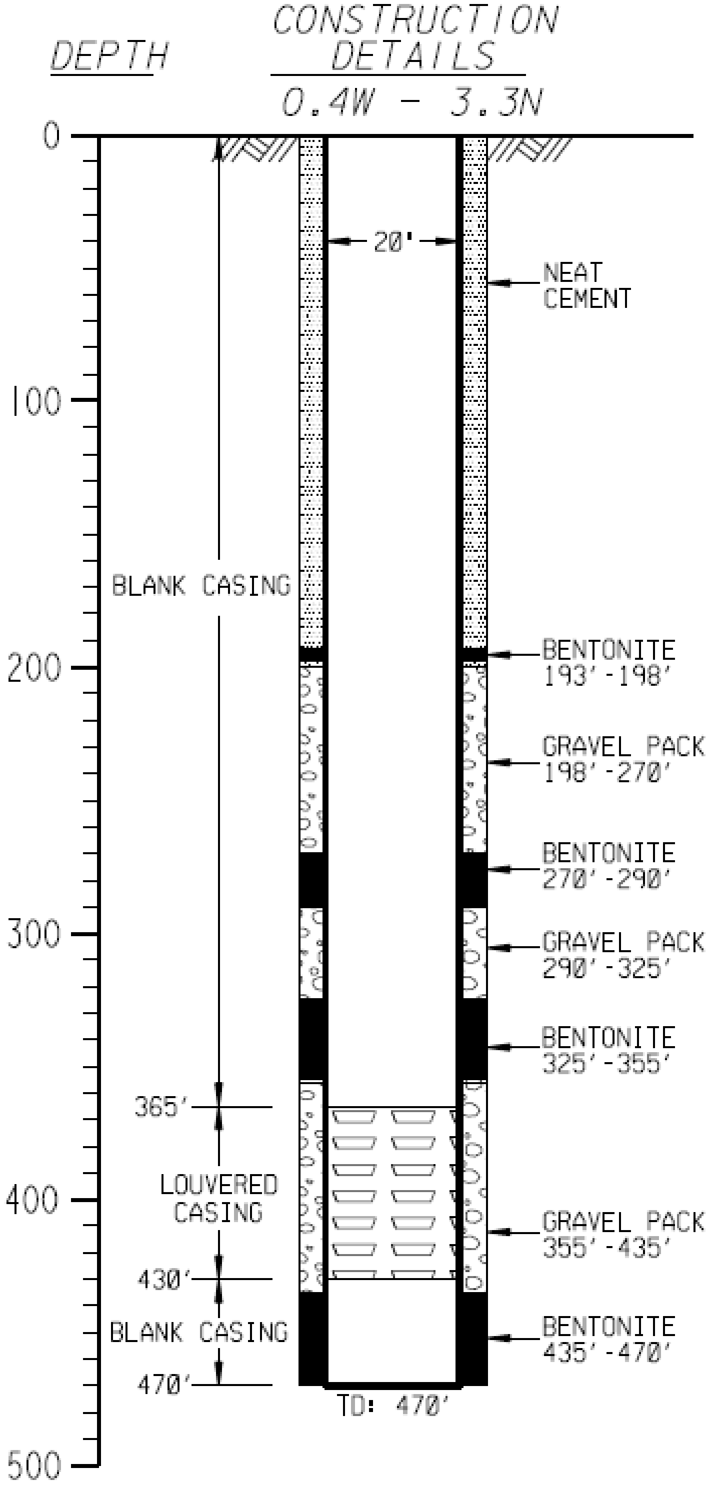
East Salt River Valley

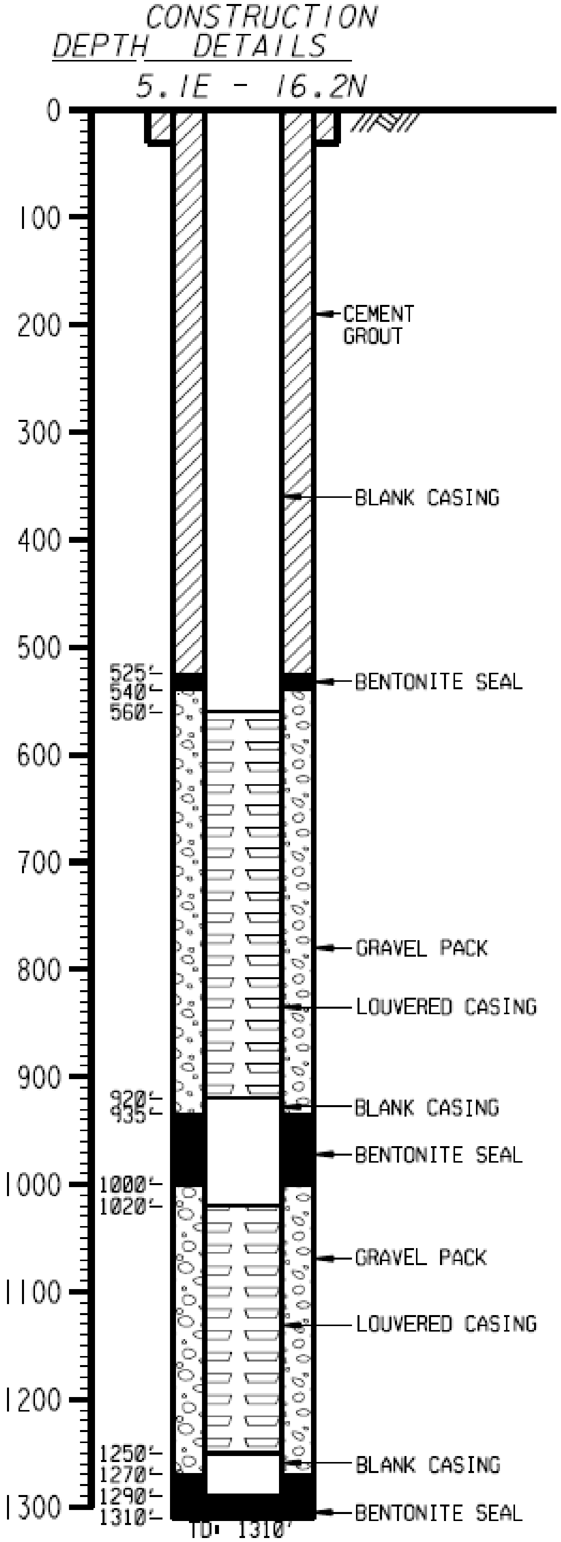
Thesis Sample ID	Silica mg/L	Nitrate (as N) mg/L
4/13/04-22.9E-10.8N-450	42.7	0.79
4/12/04-22.9E-10.8N-506	14.5	0.50
4/10/04-22.9E-10.8N-587	17.0	0.40
4/9/04-22.9E-10.8N-664	13.7	0.21
4/8/04-22.9E-10.8N-707	17.8	1.03
4/6/04-22.9E-10.8N-796	22.9	1.90
4/5/04-22.9E-10.8N-926	21.0	2.62
4/3/04-22.9E-10.8N-1025	24.1	0.99
4/1/04-22.9E-10.8N-1141	17.0	0.35
3/30/04-22.9E-10.8N-1208	27.1	1.55
3/29/04-22.9E-10.8N-1262	20.2	0.27
3/27/04-22.9E-10.8N-1308	36.3	0.29
3/26/04-22.9E-10.8N-1399	73.3	0.27
3/24/04-22.9E-10.8N-1508	68.0	0.26
12/8/08-22.9E-10.8N-Comp*	19.8	4.63
5/14/08-23.0E-10.8N-Comp	NA	NA
5/14/08-23.0E-10.8N-Comp*	NA	NA
10/17/07-23.5E-10.6N-302	15.4	3.12
10/16/07-23.5E-10.6N-390	17.1	2.40
10/15/07-23.5E-10.6N-509*	16.4	2.96
12/21/07-23.5E-10.6N-Comp	18.0	1.37
6/21/07-25.9E-03.9N-280-300	28.4	2.06
6/21/07-25.9E-03.9N-370-390	26.5	0.84
6/20/07-25.9E-03.9N-460-480	26.8	1.27
6/19/07-25.9E-03.9N-540-560	28.5	0.38
6/18/07-25.9E-03.9N-700-720	29.6	0.31
6/17/07-25.9E-03.9N-840-860	29.6	0.31
6/16/07-25.9E-03.9N-940-960	25.6	0.30
6/15/07-25.9E-03.9N-1080-1100	23.7	0.31
6/14/07-25.9E-03.9N-1230-1250	17.2	0.30
6/13/07-25.9E-03.9N-1350-1370	22.1	0.50
6/12/07-25.9E-03.9N-1460-1480	20.5	1.18
8/16/07-25.9E-03.9N-Comp*	26.4	1.74
6/10/08-26.0E-03.9N-Comp	NA	NA
8/19/08-29.0E-01.0S-Comp	27.9	2.42
9/17/07-29.0E-01.5S-Comp	NA	NA
4/24/07-31.1E-02.1S-420	30.9	4.11
4/23/07-31.1E-02.1S-510	31.1	9.21
4/22/07-31.1E-02.1S-620	20.2	3.82
4/21/07-31.1E-02.1S-725	22.9	6.12
4/20/07-31.1E-02.1S-820	21.7	0.48
4/20/07-31.1E-02.1S-965	23.9	0.32
6/8/07-31.1E-02.1S-800gpm	NA	NA
6/12/07-31.1E-02.1S-1200gpm	30.6	6.67
6/8/07-31.1E-02.1S-2000gpm	NA	NA
10/22/07-32.8E-07.2N-Comp	NA	NA
1/28/09-32.9E-03.1S-Comp	24.0	7.93
8/20/08-33.3E-03.0S-Comp	62.3	21.70

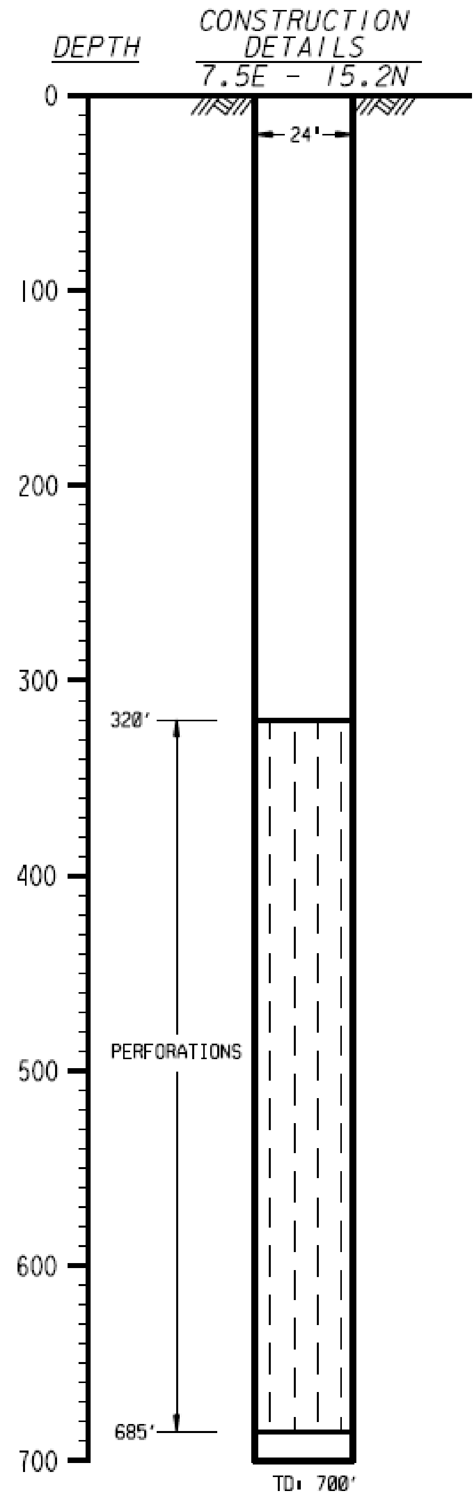
* Indicates duplicate sample

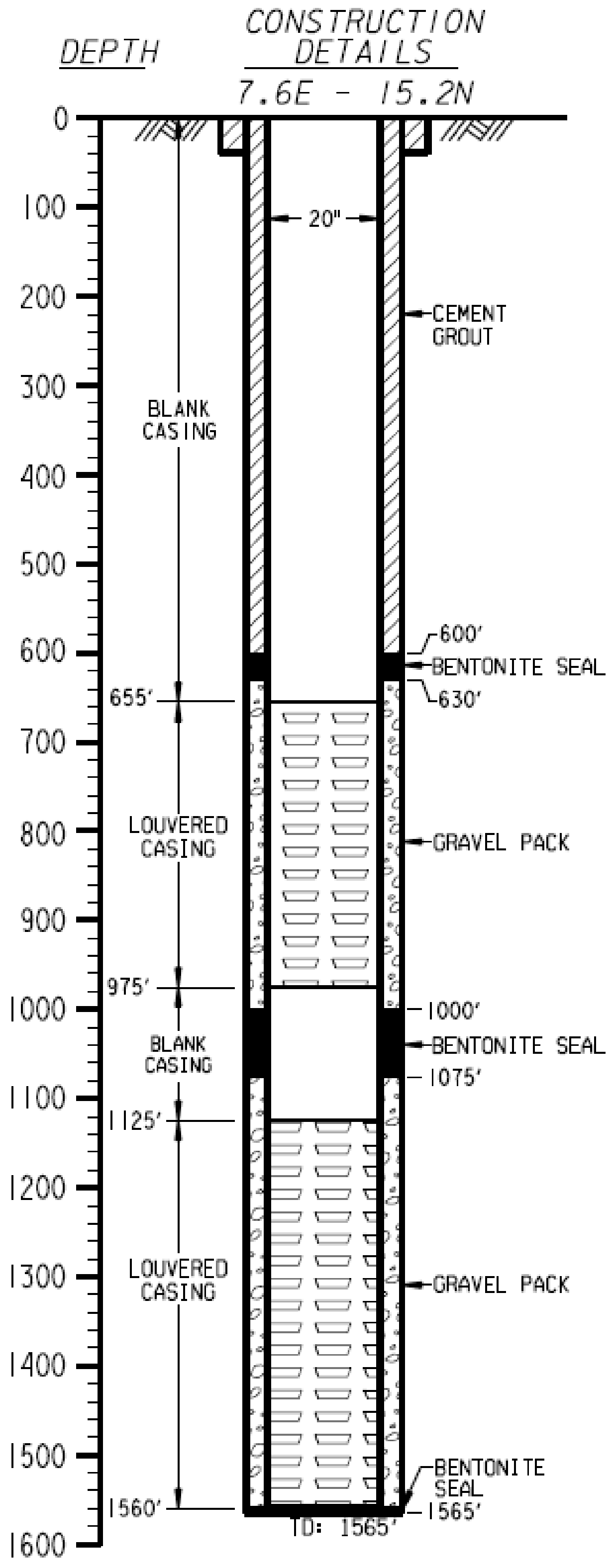
APPENDIX C

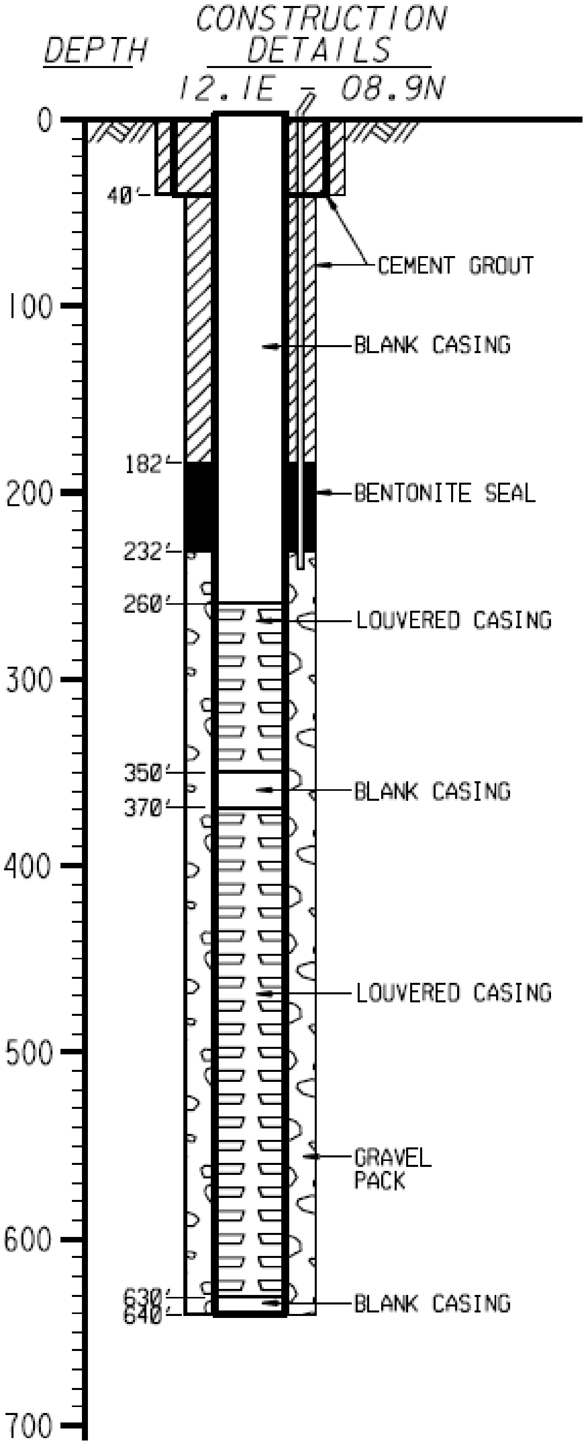
WELL CONSTRUCTION DIAGRAMS

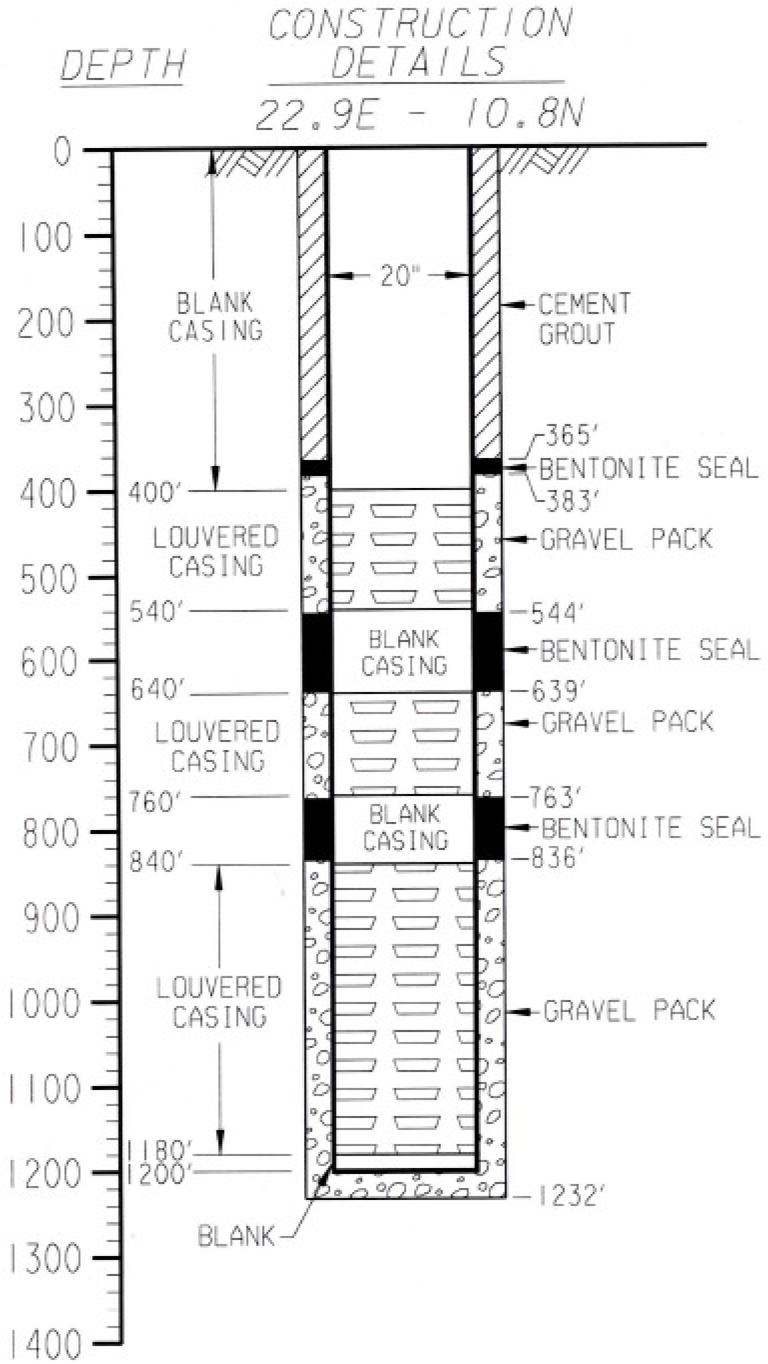

DEPTH
CONSTRUCTION DETAILS
0.4W - 3.3N
0
100
200
300
400
500
20'
NEAT CEMENT
BLANK CASING
BENTONITE 193'-198'
GRAVEL PACK 198'-270'
BENTONITE 270'-290'
GRAVEL PACK 290'-325'
BENTONITE 325'-355'
365'
LOUVERED CASING
GRAVEL PACK 355'-435'
430'
BLANK CASING
BENTONITE 435'-470'
470'
TD: 470'

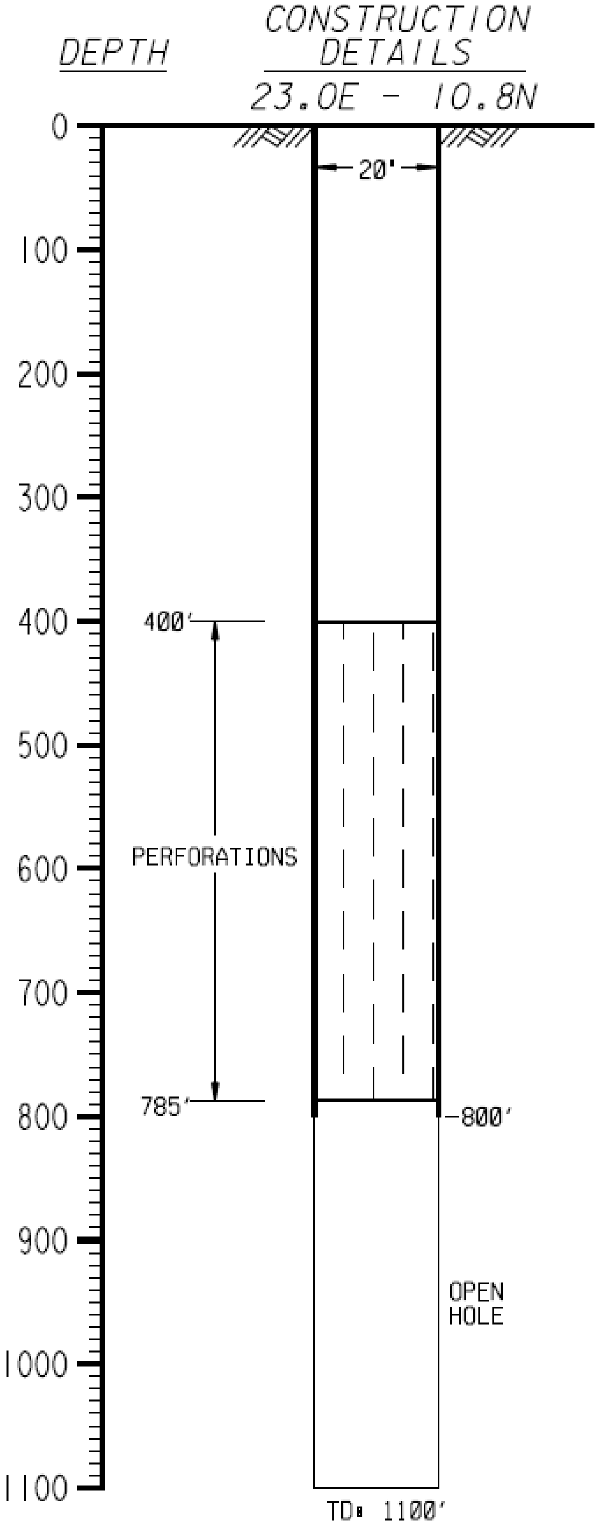

CONSTRUCTION
DEPTH DETAILS
5.1E - 16.2N
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
525'
540'
560'
920'
935'
1000'
1020'
1250'
1270'
1290'
1310'
TD: 1310'
CEMENT GROUT
BLANK CASING
BENTONITE SEAL
GRAVEL PACK
LOUVERED CASING
BLANK CASING
BENTONITE SEAL
GRAVEL PACK
LOUVERED CASING
BLANK CASING
BENTONITE SEAL

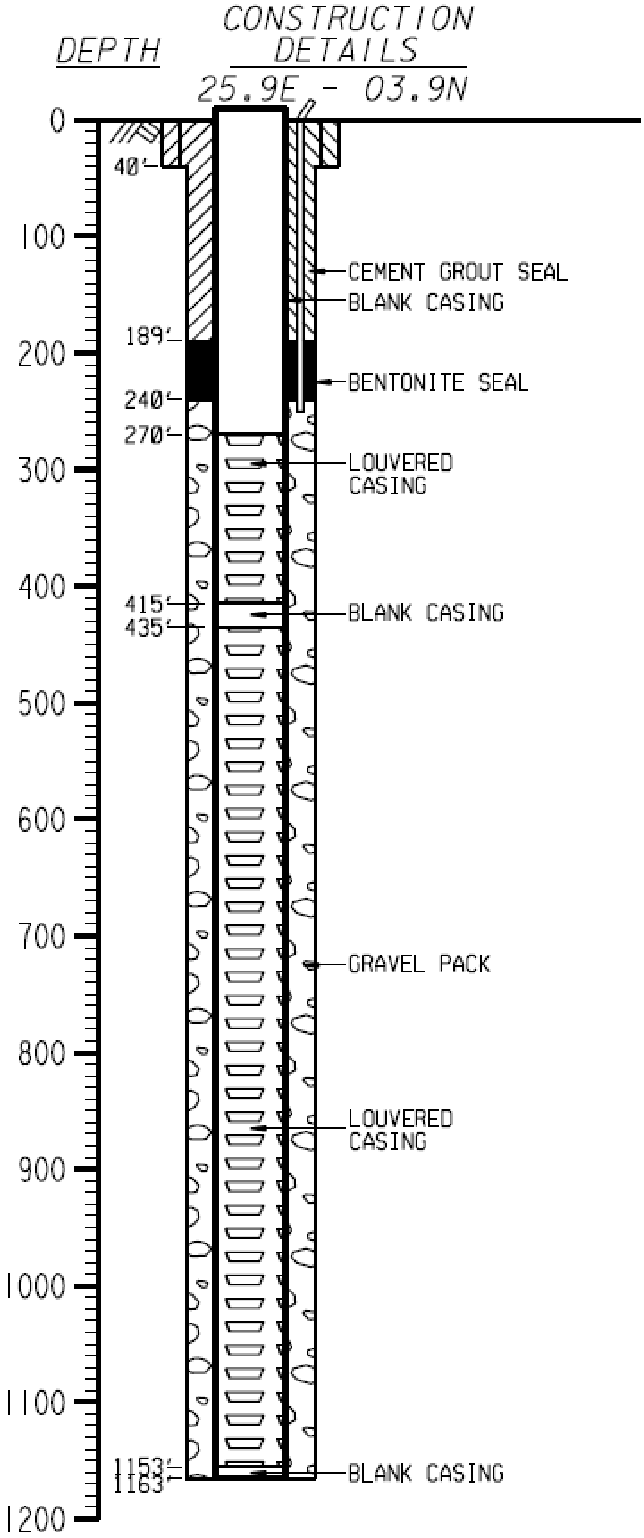

DEPTH
CONSTRUCTION DETAILS
7.5E - 15.2N
0
100
200
300
400
500
600
700
24'
320'
PERFORATIONS
685'
TD: 700'

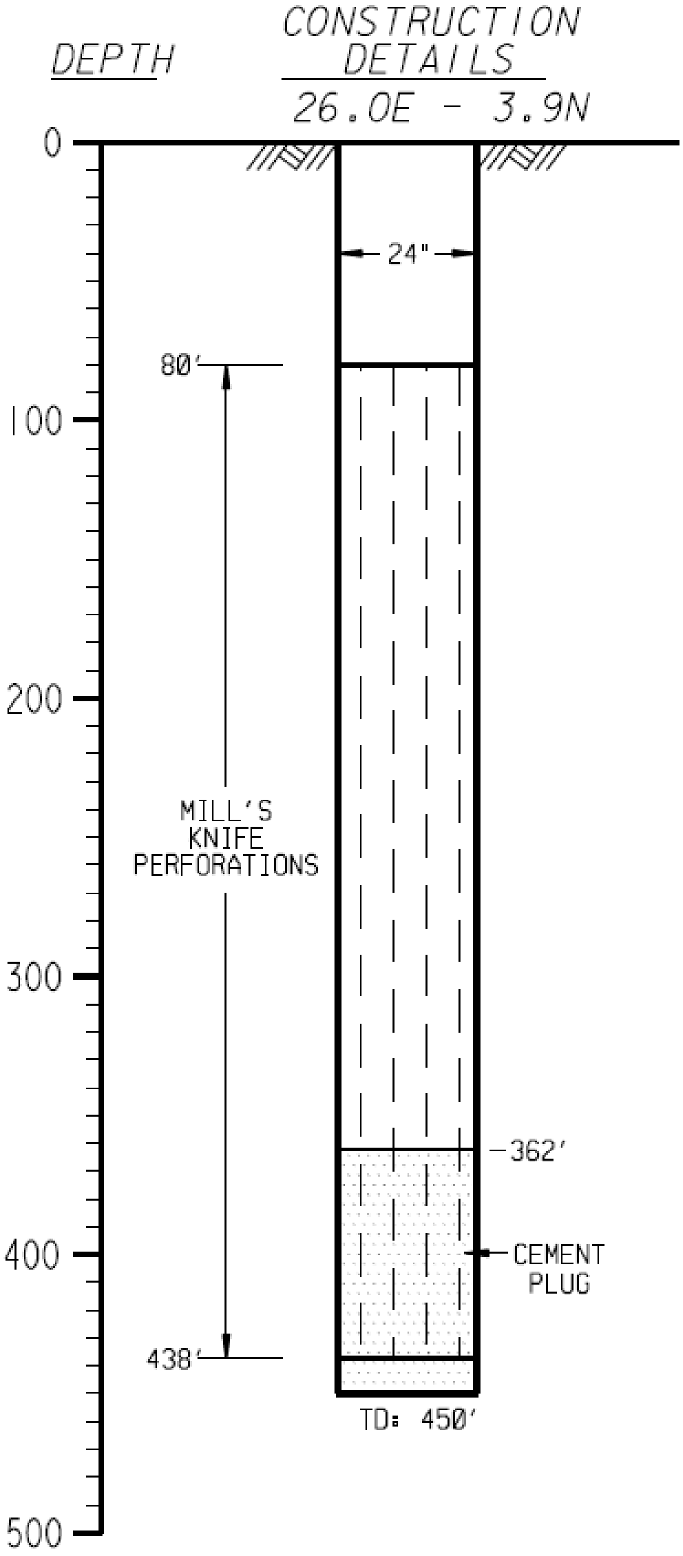

DEPTH
CONSTRUCTION DETAILS
7.6E - 15.2N
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
20"
CEMENT GROUT
BLANK CASING
600'
BENTONITE SEAL
630'
655'
LOUVERED CASING
GRAVEL PACK
975'
1000'
BLANK CASING
BENTONITE SEAL
1075'
1125'
LOUVERED CASING
GRAVEL PACK
BENTONITE SEAL
1560'
1565'
TD: 1565'

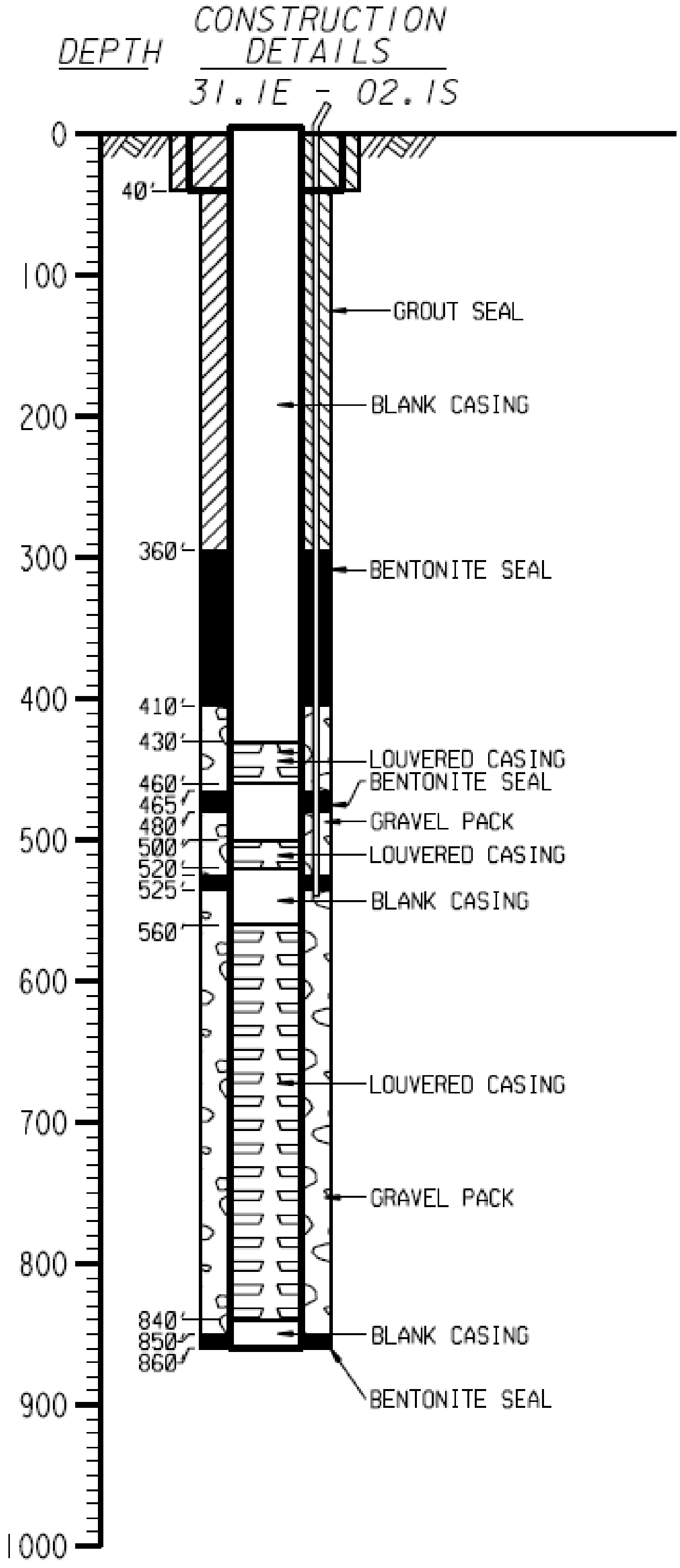

DEPTH
CONSTRUCTION DETAILS
12.1E - 08.9N
0
40'
CEMENT GROUT
100
BLANK CASING
182'
200
BENTONITE SEAL
232'
260'
LOUVERED CASING
300
350'
BLANK CASING
370'
400
LOUVERED CASING
500
GRAVEL PACK
600
630'
640'
BLANK CASING
700

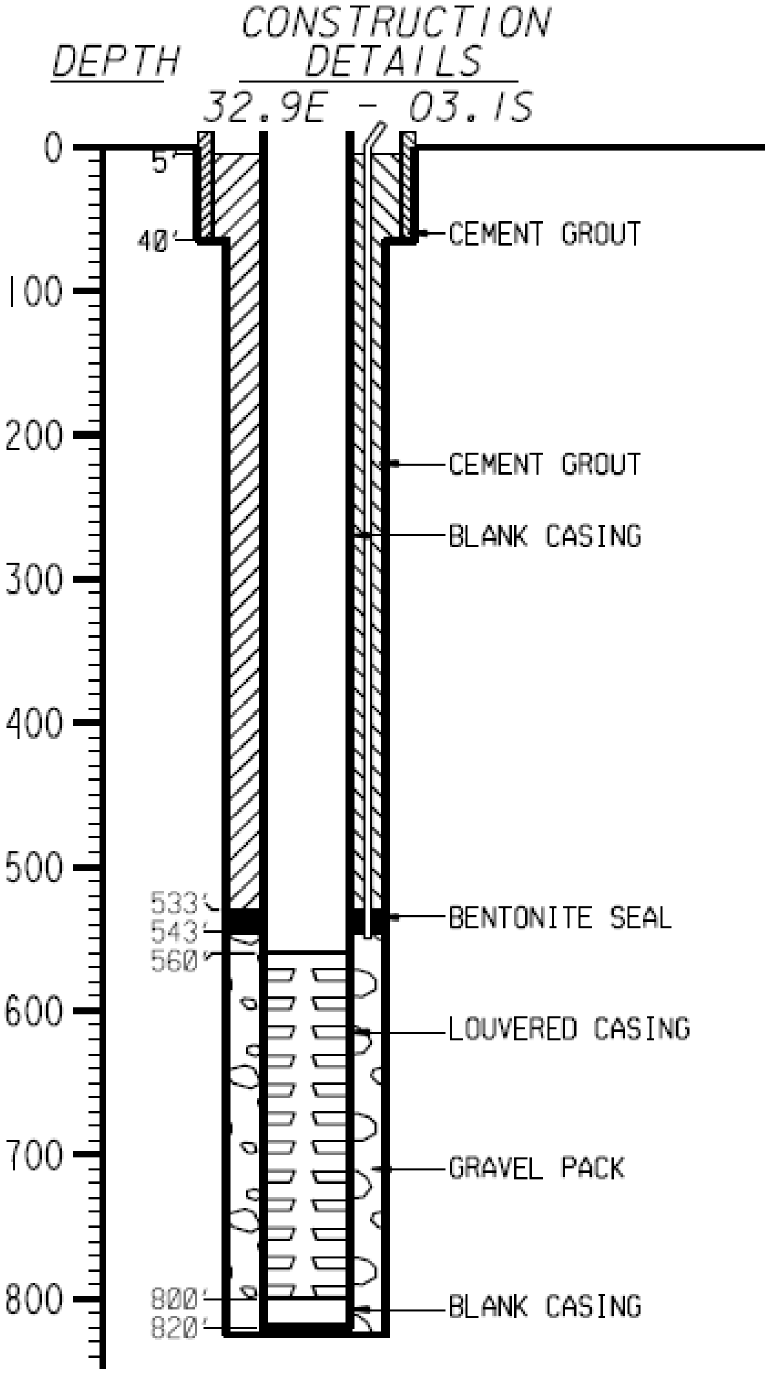

DEPTH
CONSTRUCTION DETAILS
22.9E - 10.8N
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
BLANK CASING
20"
CEMENT GROUT
365'
BENTONITE SEAL
383'
400'
LOUVERED CASING
GRAVEL PACK
540'
544'
BLANK CASING
BENTONITE SEAL
640'
639'
LOUVERED CASING
GRAVEL PACK
760'
763'
BLANK CASING
BENTONITE SEAL
840'
836'
LOUVERED CASING
GRAVEL PACK
1180'
1200'
1232'
BLANK

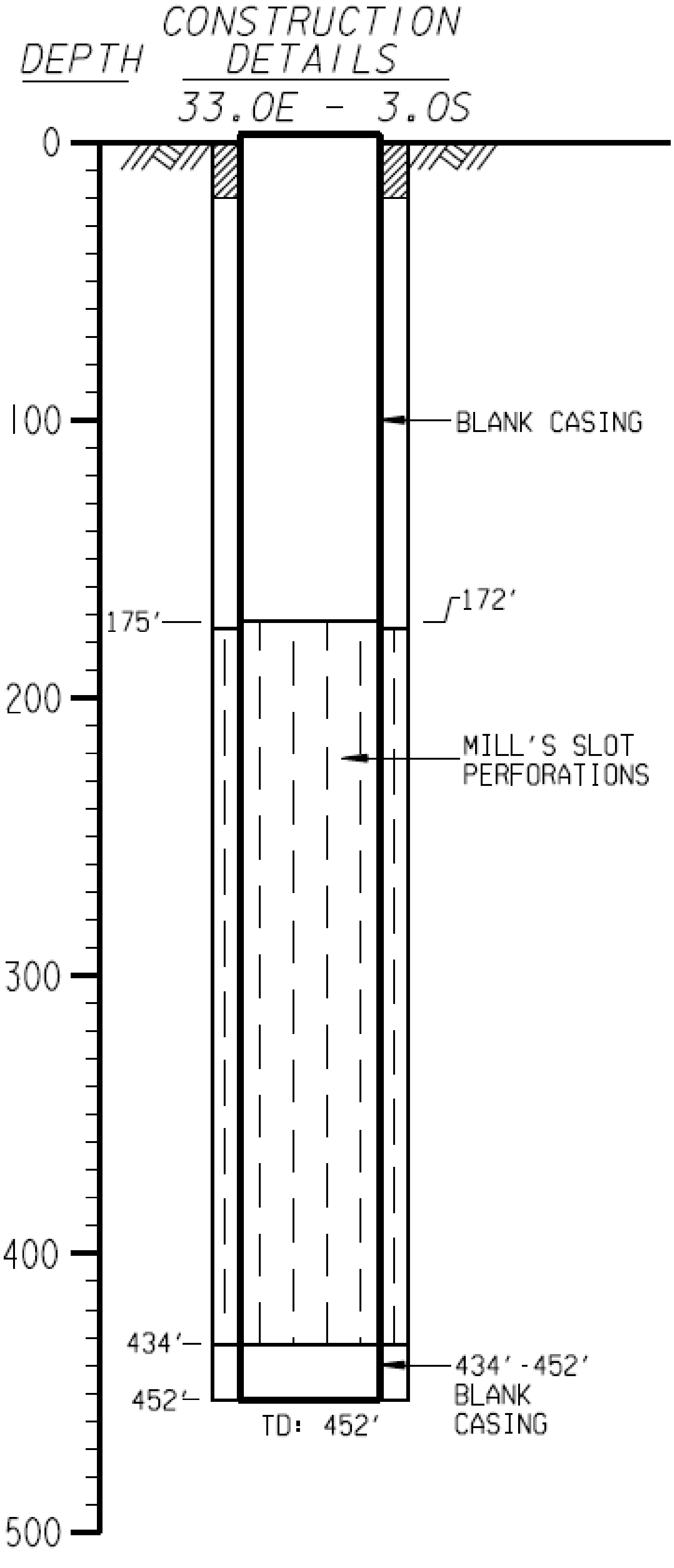

DEPTH
CONSTRUCTION DETAILS
23.0E - 10.8N
0
100
200
300
400
500
600
700
800
900
1000
1100
20'
400'
PERFORATIONS
785'
-800'
OPEN HOLE
TD= 1100'


DEPTH
CONSTRUCTION DETAILS
25.9E - 03.9N
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
40'
189'
240'
270'
415'
435'
1153'
1163'
CEMENT GROUT SEAL
BLANK CASING
BENTONITE SEAL
LOUVERED CASING
BLANK CASING
GRAVEL PACK
LOUVERED CASING
BLANK CASING


DEPTH
CONSTRUCTION DETAILS
26.0E - 3.9N
0
100
200
300
400
500
24"
80'
MILL'S KNIFE PERFORATIONS
362'
CEMENT PLUG
438'
TD: 450'


DEPTH
CONSTRUCTION DETAILS
31.1E - 02.1S
0
100
200
300
400
500
600
700
800
900
1000
40'
360'
410'
430'
460'
465'
480'
500'
520'
525'
560'
840'
850'
860'
GROUT SEAL
BLANK CASING
BENTONITE SEAL
LOUVERED CASING
BENTONITE SEAL
GRAVEL PACK
LOUVERED CASING
BLANK CASING
LOUVERED CASING
GRAVEL PACK
BLANK CASING
BENTONITE SEAL


DEPTH
CONSTRUCTION DETAILS
32.9E - 03.1S
0
100
200
300
400
500
600
700
800
5'
40'
533'
543'
560'
800'
820'
CEMENT GROUT
CEMENT GROUT
BLANK CASING
BENTONITE SEAL
LOUVERED CASING
GRAVEL PACK
BLANK CASING


DEPTH
CONSTRUCTION DETAILS
33.0E - 3.0S
0
100
BLANK CASING
175'
172'
200
MILL'S SLOT PERFORATIONS
300
400
434'
452'
434'-452' BLANK CASING
TD: 452'
500