In cooperation with the San Antonio Water System

Sources of Groundwater Based on Helium Analyses in and near the Freshwater/Saline-Water Transition Zone of the San Antonio Segment of the Edwards Aquifer, South-Central Texas, 2002–03

Scientific Investigations Report 2010–5030

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

Front cover: Kyle 2 monitoring well, Hays County, Texas.

Back cover: Collecting sample with Kemmerer sampler.

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Conversion Factors, Datums, and Water-Quality Units

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
kilometer (km)	0.6214	mile (mi)
	Volume	
liter (L)	0.2642	gallon (gal)

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

$$°F=(1.8×°C)+32$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Water-Quality Units

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

Concentrations of chemical constituents are given in milligrams per liter (mg/L).

Concentrations of dissolved gases in water are given in microcubic centimeters per kilogram at standard temperature (20 °C) and pressure (1 atmosphere) (µccSTP/kg) and in cubic centimeters per kilogram at standard temperature (20 °C) and pressure (1 atmosphere) (ccSTP/kg).

Concentrations of uranium in soil are given in milligrams per kilogram (mg/kg).

Sources of Groundwater Based on Helium Analyses in and near the Freshwater/Saline-Water Transition Zone of the San Antonio Segment of the Edwards Aquifer, South-Central Texas, 2002–03

By Andrew G. Hunt, Rebecca B. Lambert, and Lynne Fahlquist

Abstract

This report evaluates dissolved noble gas data, specifically helium-3 and helium-4, collected by the U.S. Geological Survey, in cooperation with the San Antonio Water System, during 2002–03. Helium analyses are used to provide insight into the sources of groundwater in the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer. Sixty-nine dissolved gas samples were collected from 19 monitoring wells (categorized as fresh, transitional, or saline on the basis of dissolved solids concentration in samples from the wells or from fluid-profile logging of the boreholes) arranged in five transects, with one exception, across the freshwater/saline-water interface (the 1,000-milligrams-per-liter dissolved solids concentration threshold) of the Edwards aquifer. The concentration of helium-4 (the dominant isotope in atmospheric and terrigenic helium) in samples ranged from 63 microcubic centimeters per kilogram at standard temperature (20 degrees Celsius) and pressure (1 atmosphere) in a well in the East Uvalde transect to 160,587 microcubic centimeters per kilogram at standard temperature and pressure in a well in the Kyle transect. Helium-4 concentrations in the 10 saline wells generally increase from the western transects to the eastern transects. Increasing helium-4 concentrations from southwest to northeast in the transition zone, indicating increasing residence time of groundwater from southwest to northeast, is consistent with the longstanding conceptualization of the Edwards aquifer in which water recharges in the southwest, flows generally northeasterly (including in the transition zone, although more slowly than in the freshwater zone), and discharges at major springs in the northeast. Excess helium-4 was greater than 1,000 percent for 60 of the 69 samples, indicating that terrigenic helium is largely present and that most of the excess helium-4 comes from sources other than the atmosphere. The helium data of this report cannot be used to identify sources of groundwater in and near the transition zone of the Edwards aquifer in terms of specific geologic (stratigraphic) units or hydrogeologic units (aquifers or confining units). However, the data indicate that the source or sources of the helium, and thus the water in which the helium is dissolved, in the transition zone are mostly terrigenic in origin rather than atmospheric. Whether most helium in and near the transition zone of the Edwards aquifer originated either in rocks outside the transition zone and at depth or in the adjacent Trinity aquifer is uncertain; but most of the helium in the transition zone had to enter the transition zone from the Trinity aquifer because the Trinity aquifer is the hydrogeologic unit immediately beneath and laterally adjacent to the transition zone of the Edwards aquifer. Thus the helium data support a hypothesis of sufficient hydraulic connection between the Trinity and Edwards aquifers to allow movement of water from the Trinity aquifer to the transition zone of the Edwards aquifer.

Introduction

The San Antonio segment of the Edwards aquifer, hereinafter the Edwards aquifer, is the primary source of water supply in south-central Texas and one of the most permeable and productive carbonate aquifers in the United States. The Edwards aquifer is about 180 miles long from west to east and ranges from 5 to 40 miles wide from north to south (Maclay, 1995) (fig. 1). The Edwards aquifer consists of regionally extensive, faulted and fractured carbonate rocks of the Georgetown Formation and Edwards Group that dip to the south and southeast. The less permeable and more clay-rich Trinity aquifer, composed primarily of Glen Rose Limestone, underlies and juxtaposes the Edwards aquifer to the north (Barker and Ardis, 1996, plate 3). To the west and east, the aquifer is bounded by groundwater divides and to the south and southeast by a zone of transition from freshwater to saline water.

The freshwater zone of the Edwards aquifer extends north to the northern limit of the aquifer, which coincides with the northern limit of the recharge zone (outcrop) of the aquifer

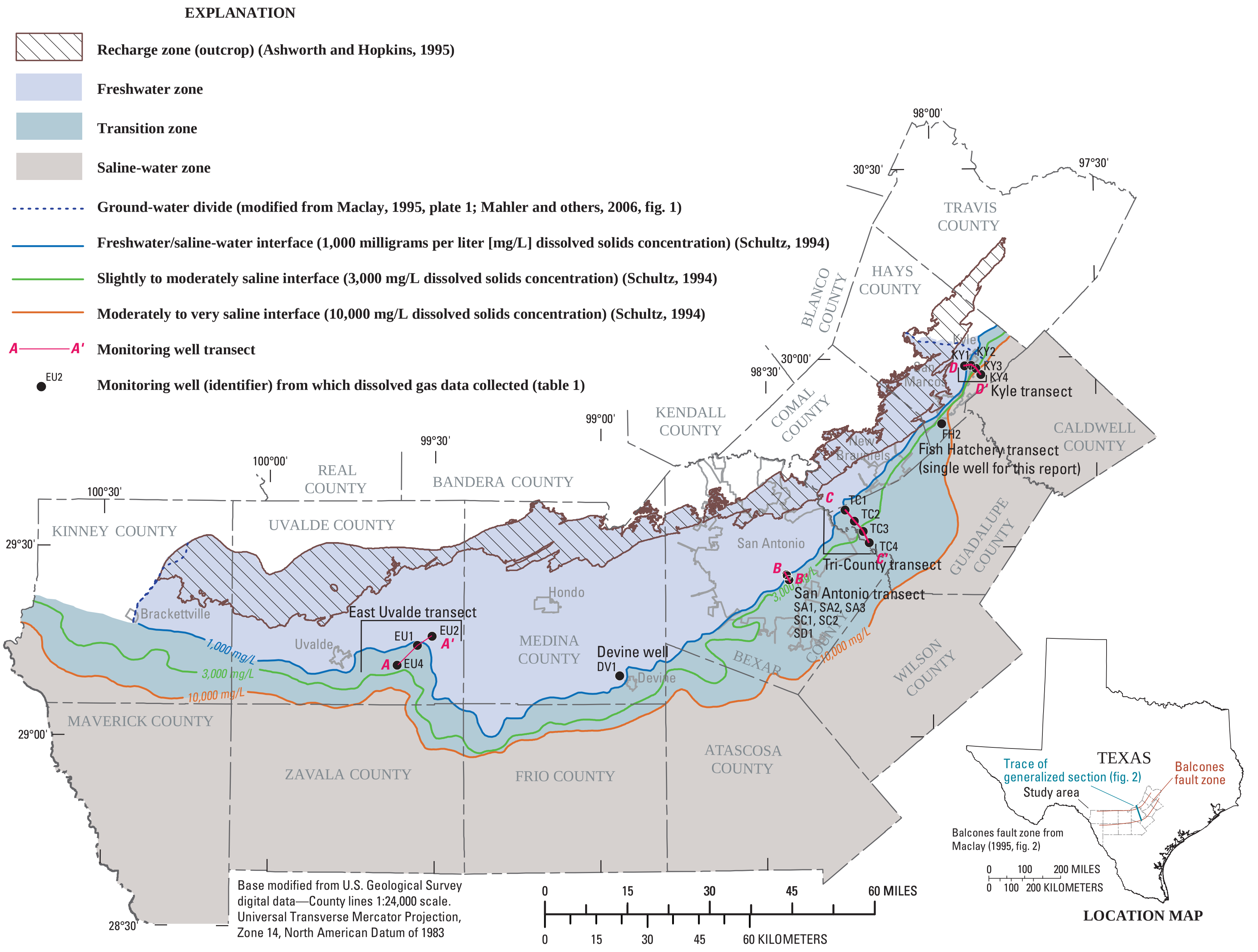

Figure 1. Areal extent of freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, and location of monitoring wells from which dissolved gas data were collected in and near the transition zone, 2002–03 (modified from Lambert and others, 2009, fig. 1).

(fig. 1). Freshwater is defined as water with a dissolved solids concentration of 1,000 milligrams per liter (mg/L) or less; thus the freshwater/saline-water interface is the 1,000-mg/L dissolved solids concentration threshold. The transition zone of the aquifer is defined as the region with dissolved solids concentrations ranging from 1,000 to 10,000 mg/L (Schultz, 1994). Slightly saline water is defined as water with dissolved solids concentrations ranging from 1,000 to 3,000 mg/L; moderately saline is defined as water with dissolved solids concentrations ranging from 3,000 to 10,000 mg/L; and very saline is defined as water with dissolved solids concentrations ranging from 10,000 to 35,000 mg/L (Winslow and Kister, 1956). On the basis of these definitions, the transition zone primarily contains water that is slightly or moderately saline, with very saline water in a few locations.

As the population increases throughout the region (U.S. Census Bureau, 2010), withdrawals from the aquifer likely will increase. Increased withdrawals lower water levels in the aquifer, which increases the potential for encroachment of saline water into the freshwater zone. In 1985, the U.S. Geological Survey (USGS), the San Antonio Water System (SAWS), and other Federal, State, and local agencies began a series of studies to learn more about the interaction between the freshwater and saline-water zones of the Edwards aquifer. The main goal of the studies was to provide better understanding of the potential for movement of saline water into the freshwater zone of the aquifer (Pavlicek and others, 1987; Poteet and others, 1992; Groschen and Buszka, 1997).

The objective of a more recent 9-year (1999–2007) study, done by the USGS in cooperation with SAWS, was to improve understanding of the hydrogeologic, hydraulic, and chemical characteristics of the transition zone of the Edwards aquifer. The study included drilling of additional monitoring wells by SAWS to expand the hydrogeologic and geochemical monitoring network in the aquifer across the freshwater/saline-water transition zone throughout the region. Monitoring wells were drilled or re-completed in and near the transition zone in Uvalde County (East Uvalde transect, four wells), in Medina County (South Medina well and Devine well), in Bexar County (Pitluck transect, three wells; Mission transect, three wells; San Antonio transect, seven wells), in Comal and Guadalupe Counties (Tri-County transect, five wells; New Braunfels transect, six wells), and in Hays County (Fish Hatchery transect, two wells; San Marcos transect, five wells; Kyle transect, four wells) (Lambert and others, 2009, fig. 1). Dissolved constituent and noble (inert) gas data were collected during 2002–03 from 19 of the 41 monitoring wells to further characterize geochemical and hydrologic processes occurring in and near the freshwater/saline-water transition zone.

Purpose and Scope

This report evaluates dissolved noble gas data, specifically helium-3 (^{3}He) and helium-4 (^{4}He), collected by the USGS during 2002–03 as part of the larger, 9-year study of the freshwater/saline-water transition zone of the Edwards aquifer. Helium analyses are used to provide insight into the sources of water in the transition zone. Sixty-nine dissolved gas samples were collected from 19 monitoring wells arranged in five transects, except for the Devine well, across the freshwater/saline-water interface of the Edwards aquifer. Other chemical, hydrologic, and geophysical data collected for the larger study are presented in Lambert and others (2009).

Approach

Water-quality samples and water-quality monitoring data were collected from 19 monitoring wells in and near the freshwater/saline-water transition zone to characterize chemical properties and changes in chemical properties of water over time. The 19 monitoring wells are categorized as fresh, transitional, or saline on the basis of dissolved solids concentration in samples from the wells or from fluid-profile logging of the boreholes (Lambert and others, 2009). The wells were drilled during 1972–2001 by various Federal, State, and local agencies. Most of the wells were constructed with the casing extending from land surface downward into the upper 20 feet of the Edwards aquifer. The remaining vertical extent of each borehole was completed as open hole in the aquifer. Where possible, the open-hole section of each well was drilled through the entire thickness of the aquifer. Some wells do not penetrate the entire thickness because of depth limitations of the drilling rigs. The 19 wells, except the Devine well, are arranged in five transects across the freshwater/saline-water interface; transects are distributed spatially from Uvalde County to Hays County (fig. 1). Three wells are in the East Uvalde transect (*A–A′* in fig. 1); the Devine well is alone; six wells are in the San Antonio transect (*B–B′*); four wells are in the Tri-County transect (*C–C′*); one well is in the Fish Hatchery transect; and four wells are in the Kyle transect (*D–D′*). Descriptive information for wells sampled for dissolved gases is listed in table 1 and in Lambert and others (2009).

Field-property measurement techniques, sample-collection procedures for inorganic and isotopic samples, and results are described in Lambert and others (2009). Field properties (pH, specific conductance, water temperature, depth to water) and samples for dissolved gases were collected at each well. For non-flowing wells in which the borehole was accessible, samples were collected at discrete depths in the uncased borehole using a 6-liter, stainless steel Kemmerer sampling flask attached to a portable cable winch fitted with a digital depth counter. The distances between depth intervals in a borehole water column where discrete samples were collected were based on changes in specific conductance with depth obtained from fluid salinity profiles (Lambert and others, 2009). Fewer samples were collected in water columns of relatively stable specific conductance than in water columns where specific conductance changed appreciably. After being lowered to the selected sampling depth, the Kemmerer flask was closed by

Table 1. Descriptive information for monitoring wells from which dissolved gas data were collected in and near the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, 2002–03 (modified from Lambert and others, 2009, table 1).

[NAD 83, North American Datum of 1983; LSD, land-surface datum; NAVD 88, North American Vertical Datum of 1988. Well descriptor: Fresh, water with dissolved solids concentration less than 1,000 milligrams per liter; Saline, water with dissolved solids concentration greater than 1,000 milligrams per liter; Transitional, freshwater and saline water in stratified lenses]

U.S. Geological Survey site number	State well number	Well name	Well identifier (fig. 1)	Latitude, NAD 83 (decimal degrees)	Longitude, NAD 83 (decimal degrees)	Year drilled	Well depth (feet)	Altitude of LSD (feet above NAVD 88)	Open interval (feet below LSD)	Well descriptor based on water type
291443099325801	YP–69–52–202	East Uvalde 1	EU1	29.245516	99.549772	1998	1,500	874.02	985 to 1,500	Fresh
291612099302001	YP–69–44–902	East Uvalde 2	EU2	29.270237	99.505604	1999	1,560	899.91	1,072 to 1,560	Fresh
291133099363801	YP–69–52–404	East Uvalde 4	EU4	29.192740	99.610885	1999	1,463	867.02	950 to 1,463	Saline
290955098562101	TD–68–49–813	Devine	DV1	29.165778	98.939411	1972	3,200	663.20	2,570 to 3,194	Fresh
292505098254001	AY–68–37–521	San Antonio A1	SA1	29.418289	98.428071	1985	1,275	621.53	1,211 to 1,275	Saline
292505098254002	AY–68–37–522	San Antonio A2	SA2	29.418289	98.428071	1985	1,075	621.53	1,014 to 1,075	Saline
292505098254003	AY–68–37–523	San Antonio A3	SA3	29.418289	98.428071	1985	1,175	621.53	1,113 to 1,175	Saline
292546098260001	AY–68–37–524	San Antonio C1	SC1	29.429677	98.433627	1985	881	626.21	842 to 881	Fresh
292546098260002	AY–68–37–525	San Antonio C2	SC2	29.429677	98.433627	1986	1,150	625.19	1,087 to 1,150	Saline
292556098260701	AY–68–37–526	San Antonio D1	SD1	29.432455	98.435571	1986	1,223	643.60	1,220 to 1,223	Fresh
293610098152701	KX–68–30–314	Tri-County 1	TC1	29.602931	98.257508	1999	920	871.01	385 to 920	Fresh
293424098134701	KX–68–31–403	Tri-County 2	TC2	29.573501	98.229936	1999	1,050	709.08	486 to 1,050	Transitional
293245098121001	KX–68–31–511	Tri-County 3	TC3	29.545969	98.202656	1999	1,222	674.00	656 to 1,222	Saline
293058098110501	KX–68–31–808	Tri-County 4	TC4	29.516217	98.184996	2000	1,562	648.92	1,000 to 1,562	Saline
294946097574501	LR–67–09–401	Fish Hatchery 2	FH2	29.829250	97.962364	2001	1,030	642.51	510 to 1,030	Saline
295853097532901	LR–67–01–311	Kyle 1	KY1	29.981389	97.891389	1997	810	770.52	307 to 810	Fresh
295858097521801	LR–67–02–104	Kyle 2	KY2	29.982995	97.871949	1998	975	674.32	427 to 975	Transitional
295829097512601	LR–67–02–106	Kyle 3	KY3	29.974940	97.857504	1998	1,100	678.28	600 to 1,100	Saline
295730097503201	LR–67–02–105	Kyle 4	KY4	29.958551	97.842504	1998	970	646.70	562 to 970	Saline

a sender weight and retrieved. For flowing wells in which the casing was accessible, a single composite sample was collected from a sampling spigot at the top of the casing after the well was purged and field properties had stabilized.

Dissolved gas samples were collected first to minimize atmospheric contamination; then the other inorganic and isotopic samples were collected. Dissolved gas samples were collected by connecting an approximately 1-foot length of 0.375-inch-diameter copper tubing to Tygon tubing and allowing the water sample to flow from the Kemmerer sampler through the tubing. Once air bubbles were purged from the tubing, the copper tubing was crimped on both ends and sealed with refrigeration clamps. Care was taken to ensure that the samples were bubble-free and did not come into contact with the atmosphere.

Sixty-nine dissolved gas samples were analyzed for helium (He), neon (Ne), argon (Ar), nitrogen (N_2), oxygen (O_2), and methane (CH_4) by the USGS Central Region Isotopic/Geochronology Core Operations Laboratory Support Project (Denver Noble Gas Laboratory) in Denver, Colo. Several wells were sampled at multiple depths. Isotopic ratios of ^3He to ^4He ($^3He/^4He$), neon-20 to neon-22 ($^{20}Ne/^{22}Ne$), argon-40 to argon-36 ($^{40}Ar/^{36}Ar$), and nitrogen to argon concentration (N_2/Ar) also were determined. $^3He/^4He$ in a sample (R), the isotopic composition, is commonly expressed as a multiple of $^3He/^4He$ in the atmosphere (in air) (R_A). Dissolved gas samples were analyzed using procedures documented in Bayer and others (1989) and Solomon and others (1995). The dissolved gases were separated from the formation water in the laboratory and analyzed in an ultra-high vacuum extraction system. Total pressure of the extracted gases was measured on a capacitance manometer, and a split of the gas was run dynamically on a quadrapole mass spectrometer to obtain the concentrations of the major gas components (CH_4, N_2, Ar, O_2). The extracted gases then were separated using an STS–101 separator heated to 300 degrees Celsius, and another split of the gas was analyzed statically on a quadrapole mass spectrometer for isotopic measurements of Ar (^{36}Ar, ^{38}Ar, and ^{40}Ar). He and Ne were further separated from the sample gas using a cryogenic cold trap and then were analyzed for their isotopic composition (^3He, ^4He, ^{20}Ne, ^{21}Ne, and ^{22}Ne) statically on a MAP–215–50 mass spectrometer. The Ne and Ar isotopic ratios are reported as absolute ratios, unlike the He isotope ratios expressed as R/R_A.

No field quality-control dissolved gas samples were collected. For the Denver Noble Gas Laboratory, in-house quality-control standards were used to compute the percentage deviation from known values and to compute laboratory error for dissolved gas analyses. The in-house dissolved gas standards were cross-calibrated with air samples collected from Loveland Pass, Colo., and compared to known dissolved gas and bulk-gas compositions of U.S. Standard Atmosphere 1976 (Weast, 1983). Analytical variation (2-sigma standard deviation) of He gas analyses typically was 1 percent or less of that measured in the samples.

Sources of Groundwater Based on Helium Analyses

General Principles

As water recharges an aquifer, the water that is in equilibrium with the atmosphere commonly is referred to as air-saturated water (ASW). The concentration of a dissolved gas in the water can be altered during recharge by the addition of more gas that is trapped by the recharging waters and forced into solution. This additional component greater than atmospheric solubility is referred to as “excess air” and typically has an air-like composition. Dissolved gas data, including isotopic composition, can be used to determine the amount of excess air measured in water. High concentrations of excess air are common in fractured-rock aquifers, in aquifers that function like fractured rock such as karst, and in aquifers in semiarid areas, such as the Edwards aquifer (Cook and others, 2006).

Most of the He in the atmosphere is ^4He; R_A is 1.384×10^{-6} (Clark and others, 1976; Clark and Fritz, 1997). Although local variation in He concentration (typical atmospheric concentration is 5.24 parts per million [Mamyrin and Tolstikhin, 1984]) and isotopic composition in the atmosphere might occur, the variation is presumed to be negligible. Concentrations of He in groundwater, much like other dissolved gases, initially conform to conditions of atmospheric solubility (recharge temperature, salinity [as indicated by dissolved solids concentration], and altitude) and excess air. Under typical recharge conditions, the atmospheric He component is about 50 to 100 microcubic centimeters per kilogram at standard temperature (20 degrees Celsius) and pressure (1 atmosphere)[1] (μccSTP/kg). The solubility of He at 20 degrees Celsius in freshwater (the ASW value of He) and 1,000 feet elevation is about 43.1 μccSTP/kg (Weiss, 1971), and the isotopic composition is 0.98 R_A (Benson and Krause, 1980). These conditions represent the approximate mean annual air temperature and elevation of the study area, and they also are representative of recharge conditions.

Dissolved He in groundwater is derived from atmospheric and terrigenic (earth) sources. The atmospheric component includes air-soluble He and excess-air He (He derived from excess air) that results from dissolution of air bubbles trapped just below the water table. Another atmospheric source of He (as ^3He) is from decay of tritium in recent (less than 60 years old) recharged water; tritium concentrations in rainfall, some of which became recharge, during the mid-20th century were increased substantially by atmospheric testing of nuclear weapons (Michel, 1989).

Helium also can accumulate in groundwater in excess of the sum of ASW and excess-air concentrations because it is

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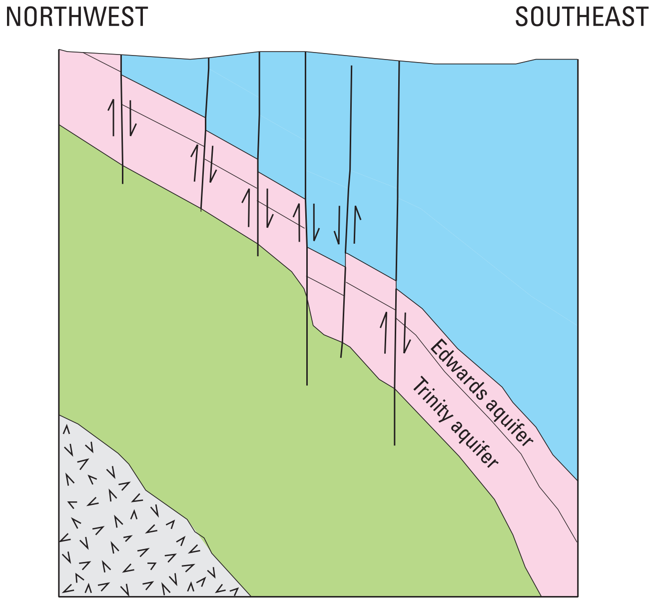
[1] Standard conditions for temperature and pressure per U.S. Environmental Protection Agency (Electronic Code of Federal Regulations, 2009).

produced by the radioactive decay of uranium and thorium in crustal rocks and aquifer solids (crustal He) and from upward diffusion or advection of He from the mantle (mantle He). Together, crustal and mantle He are termed terrigenic He (Solomon, 2000). Likely sources of terrigenic He in the study area include igneous rocks intruded into the Edwards aquifer, oil and gas hydrocarbons that are widely present in Edwards Group rocks downdip from the transition zone of the Edwards aquifer, rocks composing the underlying and adjacent Trinity aquifer, and rocks underlying the Trinity aquifer (fig. 2). Uranium concentrations from selected Edwards aquifer cores collected in the San Antonio area ranged from less than 0.1 to 1.7 milligrams per kilogram (mg/kg), and the median concentration was 0.6 mg/kg (K.M. Conko, U.S. Geological Survey, written commun., 2008), indicating that uranium concentrations in rocks of the Edwards aquifer typically might be relatively low. The concentration of natural uranium in soil is about 2 mg/kg (International Atomic Energy Agency, 2009). Rocks of the Trinity aquifer generally contain more clastic material (conglomerate, sand, silt, clay, shale) than rocks of the Edwards aquifer (Duffin and Musick, 1991), and therefore might contain more radionuclide sources.

Except within active volcanic centers, terrigenic He is essentially all crustal He. Crustal He has a ^{3}He/^{4}He isotopic ratio of 2.77 x 10^{-8} (Mamyrin and Tolstikhin, 1984, p. 273); so as in atmospheric He, the dominant isotope by far in terrigenic He is ^{4}He. Relatively high (greater than 1,000 μccSTP/kg [Solomon, 2000]) terrigenic He concentrations typically are observed in older groundwater with residence times of thousands of years or more because of the relatively slow accumulation rate of crustal He. Terrigenic He concentrations in relatively old water can exceed the atmospheric component by several orders of magnitude (Davis and De Wiest, 1966; Marine, 1979; Stute and others, 1992).



Modified from Barker and Ardis, 1996, fig. 5

Not to scale

EXPLANATION

🟦 **Cenozoic (mostly alluvium) and upper Cretaceous rocks (Edwards aquifer upper confining units)**

🟪 **Lower Cretaceous rocks (Edwards and Trinity aquifers)**

🟩 **Paleozoic rocks**

▨ **Precambrian rocks**

↑↓ **Fault**—Arrows show relative movement

Figure 2. Diagrammatic section showing generalized relation between the Edwards and Trinity aquifers and underlying pre-Cretaceous rocks.

Helium Concentrations

Because of the dominance of ^{4}He in atmospheric and terrigenic sources, helium results will pertain to ^{4}He unless otherwise noted. The concentration of ^{4}He in samples ranged from 63 μccSTP/kg in well EU2 in the East Uvalde transect to 160,587 μccSTP/kg in well KY3 in the Kyle transect (table 2). The lowest ^{4}He concentrations were measured in freshwater wells EU2 and KY1 and are more representative of atmospherically derived He. ^{4}He concentrations in the 10 saline wells generally increase from the western transects to the eastern transects, with the highest (and most variable) ^{4}He concentrations occurring in the Kyle transect. Increasing ^{4}He concentrations from southwest to northeast in the transition zone, indicating increasing residence time of groundwater from southwest to northeast, is consistent with the longstanding conceptualization of the Edwards aquifer: Water recharges in the southwest, flows generally northeasterly (including in the transition zone, although more slowly than in the freshwater zone), and discharges at major springs in the northeast (Lindgren and others, 2004).

In general, ^{4}He concentrations increase as salinity increases (fig. 3). Samples with the lowest salinities show typical ASW values of He coupled with some He from excess air. Because dissolved solids concentration was not measured in all samples, dissolved solids concentration was computed from a linear regression with specific conductance as follows: Dissolved solids = 0.658 x specific conductance, with a coefficient of determination of 0.997, which was determined from existing pairs of dissolved solids concentrations and specific conductance in table 2. Assuming larger ^{4}He concentrations represent older water, the relation between ^{4}He and salinity indicates longer residence time for the more saline water. Water with longer residence time likely contains ^{4}He from crustal or mantle sources.

A relation between ^{4}He concentration and depth might contribute information useful for identifying sources of

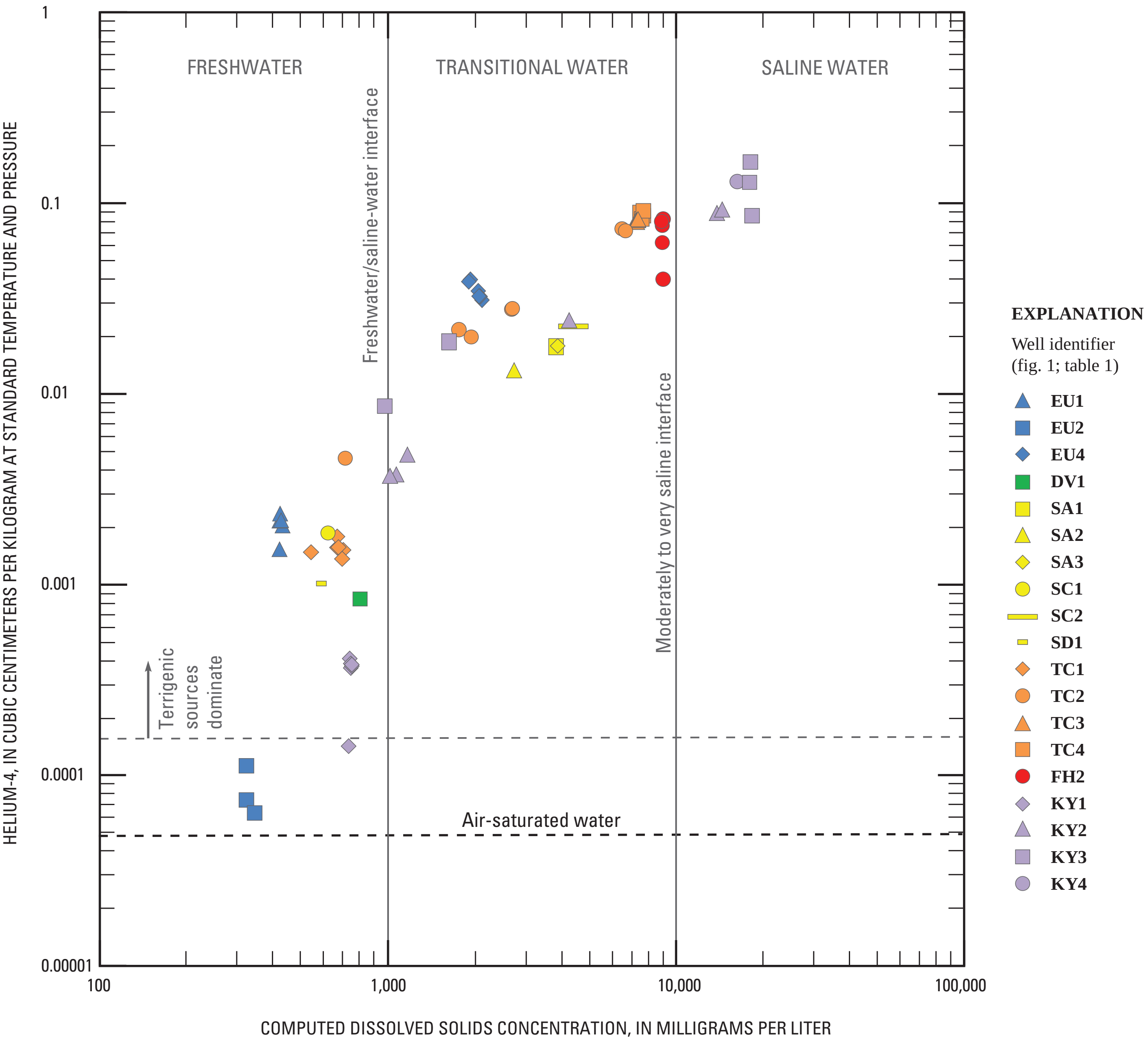


Figure 3. Relation of helium-4 concentration to salinity (computed dissolved solids concentration) in monitoring wells in and near the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, 2002–03.

^{4}He and thus sources of groundwater in the transition zone. However, no discernible relation is apparent (fig. 4). ^{4}He concentrations increase moderately with sample depth in TC2 and KY2, and slightly in KY3, but ^{4}He concentrations generally do not appear to increase with sample depth in most of the wells.

Helium Isotopic Composition

The presence and amount of excess ^{4}He ($^4He_{ex}$) can be useful for identifying possible sources of $^4He_{ex}$. In this report, $^4He_{ex}$ is computed as

$$^4He_{ex} = {}^4He_{measured} - {}^4He_{air\text{-}water\ equilibrium\ (ASW)}, \qquad (1)$$

where

$^4He_{ASW}$ = 43.1 µccSTP/kg;

and the percentage of $^4He_{ex}$ relative to ^{4}He in air at equilibrium with water (Δ^4He_{ex}) is computed as

$$\Delta^4He_{ex} = ({}^4He_{ex} / {}^4He_{ASW}) \times 100. \qquad (2)$$

When Δ^4He_{ex} is near zero, little excess air is present. When Δ^4He_{ex} is greater than about 200 percent, excess Δ^4He_{ex} from

Table 2. Results of analyses of samples for dissolved gases from monitoring wells in and near the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, 2002–03.

[ft, feet; LSD, land-surface datum; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; Computed dissolved solids = 0.658 x specific conductance; µccSTP/kg, microcubic centimeters per kilogram at standard temperature (20 °C) and pressure (1 atmosphere); ccSTP/kg, cubic centimeters per kilogram at standard temperature (20 °C) and pressure (1 atmosphere); R/R_A, (helium-3/helium-4) sample/(helium-3/helium-4) atmosphere; Delta excess helium-4, percentage of excess helium-4 relative to helium-4 in air at equilibrium with water; ASW, air-saturated water; --, not measured; E, estimated; no shade, freshwater well; pink shade, transitional well; gray shade, saline well]

U.S. Geological Survey site number	Well identifier (fig. 1; table 1)	Date sampled	Sample depth (ft below LSD)	Depth to water (ft below LSD)	Specific conductance (µS/cm)	Dissolved solids, residue on evaporation at 180 °C (mg/L)	Dissolved solids, sum of constituents (mg/L)	Computed dissolved solids (mg/L)	Chloride (mg/L)	Helium-4 (µccSTP/kg)	Helium-4 (ccSTP/kg)	R/R_A	Delta excess helium-4 (percent)	Excess helium-4 (µccSTP/kg)	Excess helium-4 (ccSTP/kg)	Helium-3 (µccSTP/kg) (computed from helium-4 measured)	Excess helium-3 (µccSTP/kg) (computed from helium-3 in ASW)	R/R_A of excess helium (computed)
291443099325801	EU1	06/12/2003	1,020	--	658	--	--	433	--	2,028	0.002028	0.18	4,605	1,985	0.001985	0.000491	0.000432	0.16
		06/12/2003	1,140	--	642	395	377	422	33.7	1,511	.001511	.18	3,406	1,468	.001468	.000385	.000325	.16
		06/12/2003	1,250	--	642	--	--	422	--	2,154	.002154	.18	4,898	2,111	.002111	.000543	.000483	.17
		06/13/2003	1,360	--	650	--	--	428	--	2,164	.002164	.17	4,921	2,121	.002121	.000521	.000461	.16
		06/13/2003	1,470	--	645	281	380	424	34.0	2,351	.002351	.18	5,355	2,308	.002308	.000579	.000520	.16
292015099351001	EU2	07/11/2002	1,100	123.67	489	--	263	322	25.0	74	.000074	.89	72	31	.000031	.000091	.000031	.74
		07/11/2002	1,200	123.67	491	--	257	323	24.2	112	.000112	1.09	160	69	.000069	.000169	.000109	1.15
		07/11/2002	1,350	123.67	523	--	258	344	23.6	63	.000063	1.06	46	20	.000020	.000092	.000033	1.19
291133099363801	EU4	06/02/2003	1,000	115.86	3,240	--	--	2,132	--	30,699	.030699	.18	71,127	30,656	.030656	.007563	.007503	.18
		06/02/2003	1,100	115.86	3,190	2,310	2,420	2,099	407	32,014	.032014	.19	74,178	31,971	.031971	.008285	.008226	.19
		06/02/2003	1,160	115.86	3,140	--	--	2,066	--	34,188	.034188	.20	79,223	34,145	.034145	.009227	.009167	.19
		06/02/2003	1,220	115.86	2,940	--	--	1,935	--	39,183	.039183	.18	90,812	39,140	.039140	.009544	.009485	.18
		06/03/2003	1,300	--	3,160	--	--	2,079	--	32,140	.032140	.19	74,471	32,097	.032097	.008452	.008392	.19
		06/03/2003	1,400	--	2,900	1,950	1,885	1,908	431	38,240	.038240	.19	88,624	38,197	.038197	.010003	.009943	.19
290955098562101	DV1	02/27/2003	--	-55.94	1,220	725	E645	803	185	837	.000837	.14	1,842	794	.000794	.000162	.000103	.09
292505098254001	SA1	07/12/2002	--	--	5,850	--	3,941	3,849	848	17,468	.017468	.27	40,429	17,425	.017425	.006407	.006347	.26
292505098254002	SA2	07/12/2002	--	--	4,170	--	2,731	2,744	575	13,052	.013052	.25	30,183	13,009	.013009	.004588	.004529	.25
292505098254003	SA3	07/12/2002	--	--	5,900	--	4,036	3,882	900	17,710	.017710	.26	40,990	17,667	.017667	.006299	.006240	.26
292546098260001	SC1	07/12/2002	--	--	943	--	540	620	71.9	1,843	.001843	.30	4,176	1,800	.001800	.000760	.000700	.28
292546098260002	SC2	07/12/2002	--	--	6,720	--	4,728	4,422	1,096	22,352	.022352	.26	51,761	22,309	.022309	.007888	.007829	.25
292556098260701	SD1	07/12/2002	--	--	854	--	479	562	67.0	1,004	.001004	.29	2,229	961	.000961	.000399	.000339	.26

Table 2. Results of analyses of samples for dissolved gases from monitoring wells in and near the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, 2002–03—Continued.

U.S. Geological Survey site number	Well identifier (fig. 1; table 1)	Date sampled	Sample depth (ft below LSD)	Depth to water (ft below LSD)	Specific conductance (µS/cm)	Dissolved solids, residue on evaporation at 180 °C (mg/L)	Dissolved solids, sum of constituents (mg/L)	Computed dissolved solids (mg/L)	Chloride (mg/L)	Helium-4 (µccSTP/kg)	Helium-4 (ccSTP/kg)	R/R_A	Delta excess helium-4 (percent)	Excess helium-4 (µccSTP/kg)	Excess helium-4 (ccSTP/kg)	Helium-3 (µccSTP/kg) (computed from helium-4 measured)	Excess helium-3 (µccSTP/kg) (computed from helium-3 in ASW)	R/R_A of excess helium (computed)
293610098152701	TC1	02/19/2003	440	193.74	1,060	587	529	697	104	1,518	0.001518	0.25	3,422	1,475	0.001475	0.000521	0.000461	0.23
		02/19/2003	510	193.74	1,050	--	--	691	--	1,364	.001364	.24	3,065	1,321	.001321	.000444	.000384	.21
		02/19/2003	550	193.74	1,010	573	542	665	91.1	1,564	.001564	.25	3,529	1,521	.001521	.000530	.000471	.22
		02/19/2003	650	193.74	820	--	--	540	--	1,478	.001478	.24	3,329	1,435	.001435	.000499	.000439	.22
		02/19/2003	750	193.74	1,010	--	--	665	--	1,784	.001784	.24	4,039	1,741	.001741	.000600	.000540	.22
		02/19/2003	840	193.74	1,020	599	593	671	89.4	1,570	.001570	.25	3,543	1,527	.001527	.000537	.000477	.23
293424098134701	TC2	02/11/2003	520	23.46	1,090	550	--	717	263	4,606	.004606	.21	10,587	4,563	.004563	.001351	.001292	.20
		02/11/2003	575	23.46	2,980	--	--	1,961	--	19,782	.019782	.22	45,798	19,739	.019739	.006023	.005964	.22
		02/12/2003	620	23.46	2,690	1,510	1,440	1,770	691	21,495	.021495	.22	49,772	21,452	.021452	.006604	.006545	.22
		02/12/2003	700	23.46	4,100	--	--	2,698	--	27,527	.027527	.22	63,768	27,484	.027484	.008496	.008436	.22
		02/12/2003	780	23.46	4,150	2,690	2,540	2,731	807	27,726	.027726	.22	64,229	27,683	.027683	.008442	.008382	.22
		02/12/2003	820	23.46	10,000	--	--	6,580	--	72,585	.072585	.21	168,311	72,542	.072542	.021197	.021137	.21
		02/12/2003	900	23.46	10,200	--	--	6,712	--	71,548	.071548	.21	165,905	71,505	.071505	.020993	.020933	.21
		02/12/2003	1,000	23.46	10,200	6,140	6,140	6,712	1,950	71,502	.071502	.22	165,798	71,459	.071459	.021672	.021612	.22
293245098121001	TC3	03/11/2003	700	-2.39	11,000	8,030	7,680	7,238	2,620	78,911	.078911	.22	182,988	78,868	.078868	.024136	.024076	.22
		03/11/2003	800	-2.39	11,100	--	--	7,304	--	77,723	.077723	.22	180,232	77,680	.077680	.023665	.023605	.22
		03/11/2003	900	-2.39	11,100	8,110	7,780	7,304	2,650	79,561	.079561	.23	184,496	79,518	0.079518	.024885	.024826	.23
		03/12/2003	1,000	-2.39	11,200	--	--	7,370	--	79,565	.079565	.22	184,506	79,522	0.079522	.024226	.024166	.22
		03/12/2003	1,140	-2.39	11,200	8,020	7,760	7,370	2,650	80,535	.080535	.22	186,756	80,492	0.080492	.024633	.024573	.22
293058098110501	TC4	05/22/2003	1,050	-6.04	11,700	--	--	7,699	--	84,684	.084684	.22	196,383	84,641	0.084641	.026019	.025959	.22
		05/22/2003	1,150	-6.04	11,600	8,360	7,980	7,633	2,840	83,550	.083550	.22	193,752	83,507	0.083507	.025092	.025033	.22
		05/22/2003	1,250	-6.04	11,600	--	--	7,633	--	83,172	.083172	.22	192,874	83,129	0.083129	.025554	.025495	.22
		05/28/2003	1,350	-6.04	11,700	--	--	7,699	--	89,759	.089759	.23	208,158	89,716	0.089716	.028324	.028264	.23
		05/28/2003	1,450	-6.04	11,400	8,250	8,010	7,501	2,780	87,530	.087530	.23	202,986	87,487	0.087487	.027257	.027197	.22
		05/28/2003	1,525	-6.04	11,600	--	--	7,633	--	81,779	.081779	.22	189,642	81,736	0.081736	.025353	.025293	.22

Table 2. Results of analyses of samples for dissolved gases from monitoring wells in and near the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, 2002–03—Continued.

U.S. Geological Survey site number	Well identifier (fig. 1; table 1)	Date sampled	Sample depth (ft below LSD)	Depth to water (ft below LSD)	Specific conductance (µS/cm)	Dissolved solids, residue on evaporation at 180 °C (mg/L)	Dissolved solids, sum of constituents (mg/L)	Computed dissolved solids (mg/L)	Chloride (mg/L)	Helium-4 (µccSTP/kg)	Helium-4 (ccSTP/kg)	R/R_A	Delta excess helium-4 (percent)	Excess helium-4 (µccSTP/kg)	Excess helium-4 (ccSTP/kg)	Helium-3 (µccSTP/kg) (computed from helium-4 measured)	Excess helium-3 (µccSTP/kg) (computed from helium-3 in ASW)	R/R_A of excess helium (computed)
294946097574501	FH2	01/15/2003	550	--	13,700	9,750	--	9,015	3,330	74,838	0.074838	0.26	173,538	74,795	0.074795	0.027240	0.027181	0.26
		01/15/2003	650	--	13,800	9,620	8,980	9,080	3,310	80,307	.080307	.26	186,227	80,264	.080264	.028342	.028282	.25
		01/15/2003	750	--	13,800	9,670	9,120	9,080	3,340	39,301	.039301	.26	91,086	39,258	.039258	.013870	.013810	.25
		01/22/2003	850	--	13,600	--	--	8,949	--	78,461	.078461	.26	181,944	78,418	.078418	.027908	.027848	.26
		01/22/2003	950	--	13,700	9,580	8,990	9,015	3,290	60,766	.060766	.25	140,888	60,723	.060723	.020605	.020545	.24
295853097532901	KY1	12/12/2002	320	167.88	1,110	432	459	730	10.7	141	.000141	.44	227	98	.000098	.000085	.000026	.19
		12/12/2002	400	167.88	1,120	--	--	737	--	410	.000410	.41	851	367	.000367	.000230	.000171	.34
		12/20/2002	500	167.52	1,140	870	797	750	11.4	374	.000374	.24	768	331	.000331	.000124	.000065	.14
		12/20/2002	600	167.52	1,130	--	--	744	--	386	.000386	.27	796	343	.000343	.000142	.000082	.17
		12/20/2002	700	167.52	1,130	854	771	744	11.9	366	.000366	.26	749	323	.000323	.000132	.000072	.16
		12/20/2002	775	167.52	1,140	797	793	750	11.6	381	.000381	.27	784	338	.000338	.000141	.000081	.17
295858097521801	KY2	05/13/2003	475	106.36	1,630	--	--	1,073	--	3,766	.003766	.14	8,638	3,723	.003723	.000709	.000649	.13
		05/13/2003	530	106.36	1,550	986	--	1,020	206	3,702	.003702	.14	8,489	3,659	.003659	.000717	.000658	.13
		05/13/2003	600	106.36	1,780	--	--	1,171	--	4,779	.004779	.14	10,988	4,736	.004736	.000926	.000866	.13
		05/14/2003	700	106.22	6,480	1,170	1,120	4,264	283	24,106	.024106	.14	55,830	24,063	.024063	.004771	.004711	.14
		05/14/2003	780	106.22	21,100	--	--	13,884	--	87,602	.087602	.15	203,153	87,559	.087559	.017944	.017884	.15
		05/14/2003	900	106.22	22,000	--	--	14,476	6,370	91,354	.091354	.15	211,858	91,311	.091311	.018459	.018400	.15
295829097512601	KY3	01/08/2003	615	88.12	1,490	758	--	980	288	8,494	.008494	.23	19,608	8,451	.008451	.002657	.002597	.22
		01/08/2003	660	88.12	2,480	1,360	1,350	1,632	585	18,359	.018359	.23	42,496	18,316	.018316	.005895	.005835	.23
		01/08/2003	750	88.12	27,600	18,800	17,900	18,161	8,890	126,020	.126020	.23	292,290	125,977	.125977	.039243	.039183	.22
		01/09/2003	950	87.77	27,900	18,500	17,900	18,358	8,860	160,587	.160587	.23	372,492	160,544	.160544	.050896	.050836	.23
		01/09/2003	1,050	87.77	28,100	19,100	18,100	18,490	9,000	84,358	.084358	.23	195,626	84,315	.084315	.026386	.026326	.23
295730097503201	KY4	04/01/2003	575	--	24,900	17,100	16,500	16,384	7,720	127,656	.127656	.24	296,086	127,613	.127613	.042932	.042873	.24

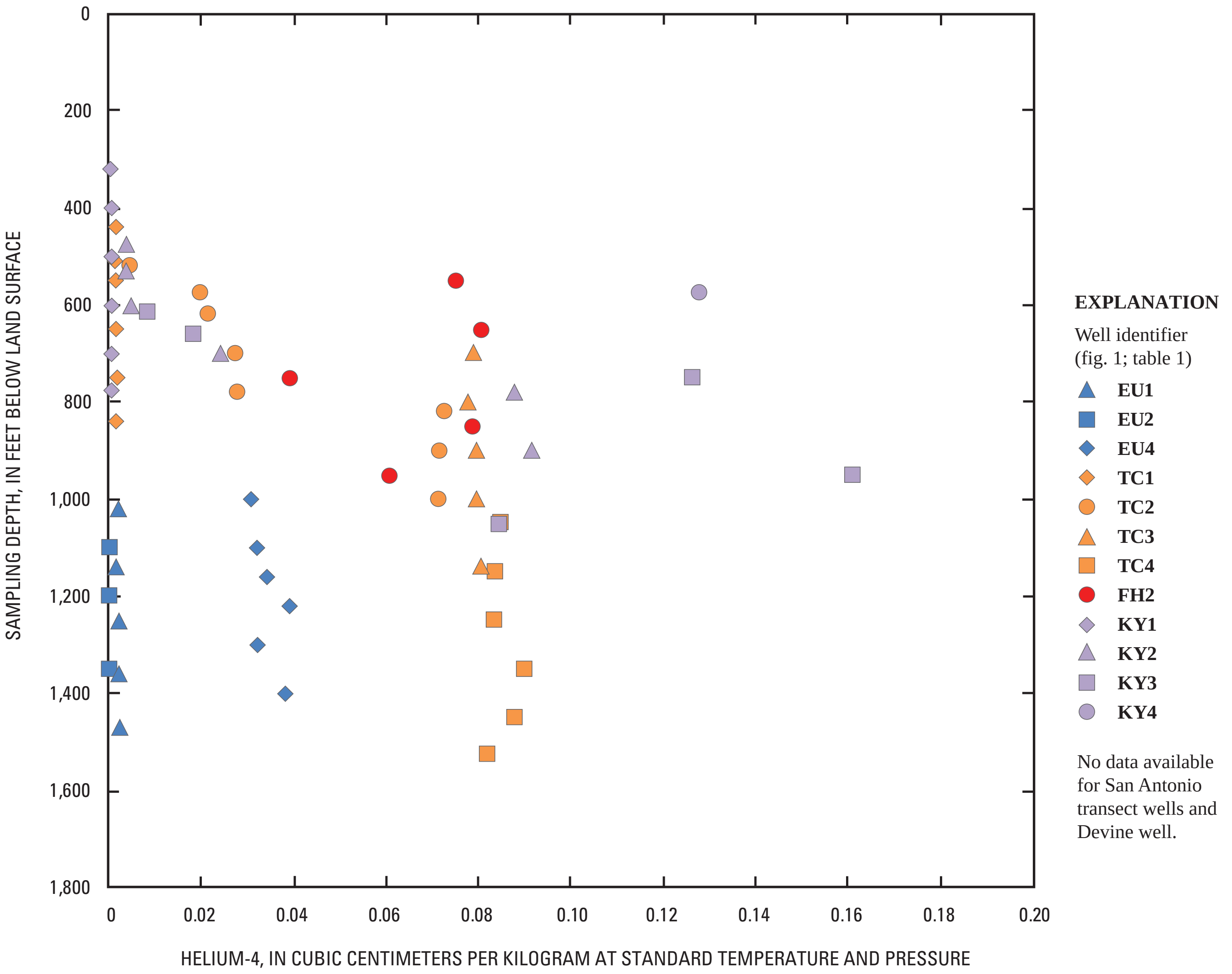


Figure 4. Relation of sampling depth to helium-4 concentration in monitoring wells in and near the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, 2002–03.

terrigenic sources dominates (L.N. Plummer, U.S. Geological Survey, written commun., 2009). Δ^4He_{ex} was greater than 1,000 percent for 60 of the 69 samples (table 2), indicating that terrigenic He is largely present. The nine samples with the lowest Δ^4He_{ex} values (from freshwater wells EU2 and KY1) likely contain mostly atmospherically derived ^4He. The predominance of very large quantities of Δ^4He_{ex}, much greater than could be derived from air-water equilibrium and excess-air sources, indicates that groundwater residence times in the freshwater/saline-water transition zone are relatively long and that most of the Δ^4He_{ex} comes from sources other than the atmosphere.

Excluding three EU2 samples influenced by atmospheric sources (R = 0.89 R_A, 1.09 R_A, and 1.06 R_A [table 2]), the mean isotopic composition for the remaining 66 samples is 0.22 R_A. This relatively uniform isotopic composition might indicate a relatively homogeneous source of He in the freshwater/saline-water transition zone. Homogeneous isotopic composition indicates a uniform source of $^4He_{ex}$ consisting mostly of crustal ^4He, where crustal R is about 0.02 R_A (2.77×10^{-8} [the $^3He/^4He$ ratio of crustal He] and approximately equals 0.02 times 1.384×10^{-6} [the $^3He/^4He$ ratio of atmospheric He]) and possibly includes some mantle ^4He, where R is about 8 R_A (Ozima and Podosek, 2002). Although some in situ production of He might occur in the Edwards aquifer, the Cretaceous carbonates are too young to have produced the large concentrations of ^4He observed. Mantle-derived igneous intrusions are present in and near the Edwards aquifer (Smith and others, 2002) and might be a source of mantle-derived ^4He (Hunt and others, 2005).

The mean R of the 32 samples from the 10 saline wells (0.23 R_A, nearly the same as for the 66 wells noted in the previous paragraph) can be computed as a mixture of about 97 percent crustal ^4He (R equals about 0.02 R_A) and 3 percent mantle (R equals about 8 R_A), assuming the source of the ^{4}He is entirely terrigenic. The source of ^{4}He to the saline water could be migration from deep crustal rocks (fig. 2), by way of faults or fractures, or rocks nearer the Edwards aquifer that contain or radiogenically produce He. Other noble gas (Ne, Ar) data (Lambert and others, 2009) indicate oil and gas hydrocarbons, which are present in relatively deep Edwards Group rocks, are a potential source of $^4He_{ex}$. Those data indicate that there are fractionation pathways (models) between ASW and fluids of varying composition representative of hydrocarbon-bearing rocks (A.G. Hunt, U.S. Geological Survey, written commun., 2009). No noble gas data were collected from the Trinity aquifer for this report, so that potential source could not be evaluated directly. Although Groschen and Buszka (1997) did not identify updip movement of saline water from relatively deep Edwards Group rocks to the shallower transition zone of the Edwards aquifer, a recent study (MaryLynn Musgrove, U.S. Geological Survey, written commun., 2009) indicates that, in localized areas, saline water is mixed with freshwater; and that the likely sources of saline water are relatively deep Edwards Group rocks, or the Trinity aquifer, or both.

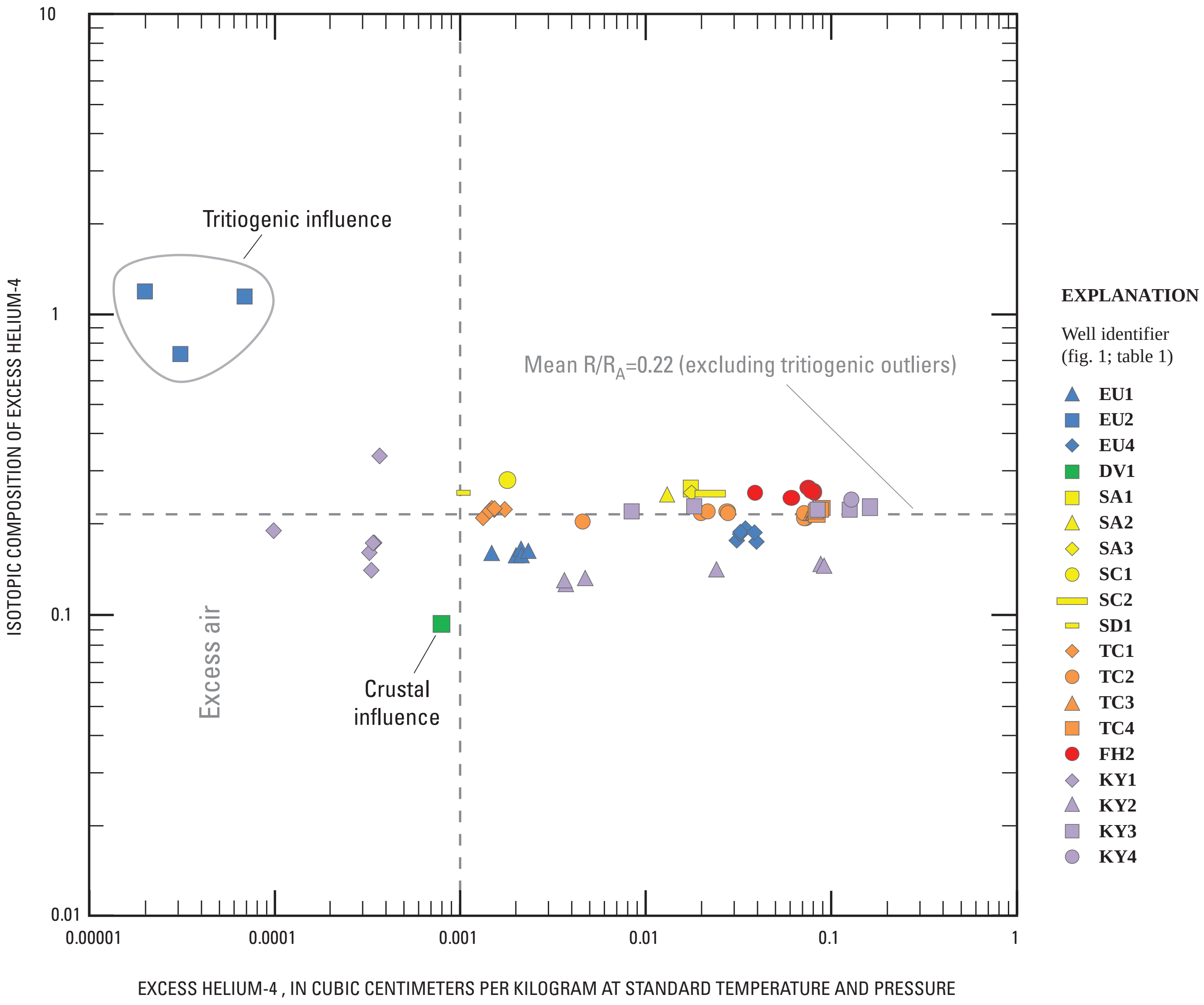


Figure 5. Relation of isotopic composition of excess helium-4 (R/R_A $^4He_{ex}$) to excess helium-4 ($^4He_{ex}$) concentration in monitoring wells in and near the freshwater/saline-water transition zone of the San Antonio segment of the Edwards aquifer, south-central Texas, 2002–03.

A graph of R/R_A of $^4He_{ex}$ (R $^4He_{ex}$ /R_A) relative to the concentration of $^4He_{ex}$ in samples from all wells (fig. 5) might indicate sources of $^4He_{ex}$. R $^4He_{ex}$ /R_A is computed as

$$R\ {}^4He_{ex}/R_A = ({}^3He_{ex}\ /\ {}^4He_{ex})/1.384\text{x}10^{-6}, \qquad (3)$$

where $^3He_{ex}$ is computed as

$$^3He_{ex} = {}^3He - {}^3He_{ASW}\,. \qquad (4)$$

^{3}He in the equation immediately above is computed from R/R_A and ^{4}He (table 2), and $^3He_{ASW}$ is computed as 43.1 µccSTP/kg x 1.384 x 10^{-6}. Excluding five outliers, the R $^4He_{ex}$/R_A values for all samples are between 0.1 and 0.3 for all values of $^4He_{ex}$. Whether the variation in that range among transects or wells within transects is meaningful relative to sources of He is unknown. However, because the ^{4}He concentration in all but the freshest samples is almost entirely excess $^4He_{ex}$, R/R_A of $^4He_{ex}$ is about equal to R/R_A of ^{4}He. As previously noted in this section, relatively uniform isotopic composition might indicate a relatively homogeneous source of He in the freshwater/saline-water transition zone.

As for the outliers, two outliers have R $^4He_{ex}$ values greater than R_A (EU2, R/R_A greater than 1), indicating that ^{3}He dominates the composition; ^{3}He comes from radiogenic decay of tritium in recently recharged water. Two other outliers have R $^4He_{ex}$ values of 0.74 R_A and 0.34 R_A (EU2 and KY1, respectively). These two samples likely are mixtures containing He from recently recharged water and from crustal sources. The fifth outlier, DV1 (R $^4He_{ex}$ = 0.09 R_A), is the lowest value, strongly reflecting the dominance of the crustal component of $^4He_{ex}$ in the sample.

The He data of this report are problematic in that they cannot be used to identify sources of groundwater in and near the transition zone of the Edwards aquifer in terms of specific geologic (stratigraphic) units or hydrogeologic units (aquifers or confining units). However, the data indicate that the source or sources of the He, and thus the water in which it is dissolved, in the transition zone are mostly terrigenic in origin rather than atmospheric, and that the dominant terrigenic source likely is crustal rocks rather than deeper mantle rocks. As previously noted in this section, likely sources of crustal He are oil and gas hydrocarbons that are widely present in Edwards Group rocks downdip from the transition zone of the Edwards aquifer, and potentially rocks composing the underlying and adjacent Trinity aquifer. Whether most He in and near the transition zone of the Edwards aquifer originated either in rocks outside the transition zone and at depth or in the adjacent Trinity aquifer is uncertain; but most of the He in the transition zone had to enter the transition zone from the Trinity aquifer because the Trinity aquifer is the hydrogeologic unit immediately beneath and laterally adjacent to the transition zone of the Edwards aquifer. Thus the He data support a hypothesis of sufficient hydraulic connection between the Trinity and Edwards aquifers to allow movement of water from the Trinity aquifer to the transition zone of the Edwards aquifer.

Summary

This report evaluates dissolved noble gas data, specifically helium-3 (^{3}He) and helium-4 (^{4}He), collected by the U.S. Geological Survey during 2002–03 as part of a larger, 9-year study of the freshwater/saline-water transition zone of the Edwards aquifer done by the U.S. Geological Survey in cooperation with the San Antonio Water System. Helium analyses are used to provide insight into the sources of water in the transition zone. Sixty-nine dissolved gas samples were collected from 19 monitoring wells (categorized as fresh, transitional, or saline on the basis of dissolved solids concentration in samples from the wells or from fluid-profile logging of the boreholes) arranged in five transects, except for the Devine well in Medina County, across the freshwater/saline-water interface (the 1,000-mg/L dissolved solids concentration threshold) of the Edwards aquifer.

Dissolved helium in groundwater is derived from atmospheric and terrigenic (earth) sources. The concentration of helium-4 (the dominant isotope in atmospheric and terrigenic helium) in samples ranged from 63 µccSTP/kg in well EU2 in the East Uvalde transect to 160,587 µccSTP/kg in well KY3 in the Kyle transect. Helium-4 concentrations in the 10 saline wells generally increase from the western transects to the eastern transects, with the highest (and most variable) helium-4 concentrations occurring in the Kyle transect. Increasing helium-4 concentrations from southwest to northeast in the transition zone, indicating increasing residence time of groundwater from southwest to northeast, is consistent with the longstanding conceptualization of the Edwards aquifer: Water recharges in the southwest, flows generally northeasterly (including in the transition zone, although more slowly than in the freshwater zone), and discharges at major springs in the northeast.

When excess helium-4 (the percentage of excess helium-4 [difference between measured helium-4 concentration and helium-4 concentration in air-saturated water]) is greater than about 200 percent, excess helium-4 from terrigenic sources dominates. Excess helium-4 was greater than 1,000 percent for 60 of the 69 samples, indicating that terrigenic helium is largely present and that most of the excess helium-4 comes from sources other than the atmosphere.

The ratio of ^{3}He/^{4}He in a sample (R), the isotopic composition, is commonly expressed as a multiple of the ratio of ^{3}He/^{4}He in the atmosphere (in air) (R_A). The mean R of the 32 samples from the 10 saline wells (0.23 R_A) can be computed as a mixture of about 97-percent crustal helium-4 (R equals about 0.02 R_A) and 3-percent mantle (R equals about 8 R_A), assuming the source of the helium-4 is entirely terrigenic. The source of helium-4 to the saline water could be deep crustal rocks, by way of faults or fractures, or rocks nearer the Edwards aquifer that contain or radiogenically produce helium.

The helium data of this report cannot be used to identify sources of groundwater in and near the transition zone of the Edwards aquifer in terms of specific geologic (stratigraphic) units or hydrogeologic units (aquifers or confining units). However, the data indicate that the source or sources of the helium, and thus the water in which the helium is dissolved, in the transition zone are mostly terrigenic in origin rather than atmospheric, and that the dominant terrigenic source likely is crustal rocks rather than deeper mantle rocks. Likely sources of crustal helium are oil and gas hydrocarbons that are widely present in Edwards Group rocks downdip from the transition zone of the Edwards aquifer, and potentially rocks composing the underlying and adjacent Trinity aquifer. Whether most helium in and near the transition zone of the Edwards aquifer originated either in rocks outside the transition zone and at depth or in the adjacent Trinity aquifer is uncertain; but most of the helium in the transition zone had to enter the transition zone from the Trinity aquifer because the Trinity aquifer is the hydrogeologic unit immediately beneath and laterally adjacent to the transition zone of the Edwards aquifer. Thus the helium data support a hypothesis of sufficient hydraulic connection between the Trinity and Edwards aquifers to allow movement of water from the Trinity aquifer to the transition zone of the Edwards aquifer.

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