the study area based on both aerial photographs and outcrop data shows large variation in both the orientation of prominent fractures and the fracture density (Hurlow, 1998, pl. 6). In general, the aerial photograph data and the outcrop data indicate prominent fracturing in the north-south orientation between Anderson Junction and the Gunlock Fault (Hurlow, 1998, p. 27). However, some rose-diagram plots of data from Anderson Junction, Sandstone Mountain, Washington Hollow, and the Red Mountains show an additional east-west to northwest trending set of fractures (Hurlow, 1998, pl. 6). Rose diagrams from aerial photographs depicting joint frequency weighted by fracture length emphasize the orientation of the longer joints and joint zones. Rose diagrams from outcrop data are not weighted toward the longer joints and thus may be less meaningful with regard to the regional movement of ground water. In addition, the outcrop data contain an inherent sampling bias because more resistant, less fractured outcrop locations provide the best surfaces for conducting the surveys. This is likely a problem along the Santa Clara River west of the Gunlock Fault, where outcrop data show the main fracture orientation to be east-northeast, whereas aerial photographs (Cordova, 1978) and field observations indicate predominant north-south trending fractures. The recent study by Hurlow (1998) suggests that no correlation exists between outcrop fracture density and aerial-photograph-determined fracture density. Generalized conclusions based on aerial photograph data indicate that fracture density generally is high at Snow Canyon, Anderson Junction, Sandstone Mountain, and near the Gunlock Fault zone; contrarily, fracture density from aerial photographs is relatively low near Mill Creek and Sand Mountain (Hurlow, 1998).

About 25 percent of the outcrop surface of the Navajo Sandstone and Kayenta Formation is covered by sand dunes, alluvial deposits, and basalt flows (pl. 1). Sand dunes and alluvial deposits generally are less than 150 ft thick (Hurlow, 1998, pl. 4). However, two areas of the Navajo Sandstone outcrop are overlain by thicker wedges of alluvial deposits at Anderson Junction (more than 350 ft thick) and south of Hurricane near Gould Wash and Frog Hollow Wash (pl. 1). The thickness of basalt covering the Navajo Sandstone outcrop generally is less than 100 ft (Hugh Hurlow, Utah Geological Survey, oral commun., 1998).

HYDROCHEMICAL CHARACTERISTICS

Knowledge of the role of ground water in the hydrochemical framework of a ground-water system is as important as knowledge of how aquifers fit into the geologic framework of an area. To investigate ground-water direction and rate of movement within the Navajo and Kayenta aquifers and the Ash Creek drainage basin, chemical and isotopic data from water samples were collected or compiled from previous investigations (Wilkowske and others, 1998, tables 4 and 5). CFC, dissolved gas, general chemistry, and stable isotope data were used to evaluate potential sources of recharge to the aquifers and average residence times within the aquifers, both of which aid in determining possible ground-water flow directions.

Methods and Limitations

Chlorofluorocarbon Collection Methods

Concentrations of chlorofluorocarbons (CFCs) in the modern atmosphere are greater than in older ground water that entered the water table in the past, so care must be taken to avoid sample contamination via contact with modern air. Two methods have been developed to collect water samples for CFC analysis that prevent atmospheric contamination—the copper-tube method and the glass-ampoule method.

The copper-tube collection method requires that CFC samples be collected in sealed 3/8-in.-diameter copper tubes approximately 30 in. long (about a 30-mL sample). Prior to sampling, the tubes were annealed in an argon atmosphere at 600 °C, which cleaned the tubes and made them easier to seal. Rubber and plastic gaskets can absorb CFCs and be a source of contamination; therefore, the tubes were connected directly to well heads using all metal connections. For the collection of spring and surface-water samples, the copper tubes were placed directly in a flowing spring or stream. A 2-ft piece of Tygon tubing with a plastic pinch valve was connected to the downstream end of the tube to prevent any back diffusion of atmospheric CFCs into the sampler. The tubes were then flushed with at least 10 sample volumes of ambient water. While water was flowing through the sampler, the copper tube was crimped off using a hand-held crimping tool. This seal holds best under a vacuum, so prior to sampling, a 1-to 2-in. section of the copper tube was flattened using pliers to reduce the volume of the sampler. After crimping the

ends of the tube, the flattened part was re-rounded, creating a negative pressure inside the tube. If a good seal is made, a water hammer will make a clicking noise when the tube is moved in a rapid up and down motion. Copper-tube samples were analyzed for CFCs at the University of Utah with a gas chromatograph within 1 month after collection to ensure sample integrity. Sample blanks were run with each batch of copper-tube samples to ensure that no CFC contamination was introduced by the copper tubing or the hand-crimping tool.

The glass-ampoule method for collecting CFC samples is described by Busenberg and Plummer (1992). Replicate samples were collected in sealed borosilicate glass ampoules for comparison with samples collected in copper tubes. These samples were analyzed by both the University of Utah Department of Geology and Geophysics and the U.S. Geological Survey (USGS), Eastern Region Office of Hydrologic Research in Reston, Virginia. Because the University of Utah lab primarily analyzes water collected in copper tubes and the USGS primarily analyzes water collected in glass ampoules, a comparison was made between CFC-11 and CFC-12 concentrations from water collected in copper tubes and analyzed at the University of Utah versus water collected in glass ampoules and analyzed at the USGS (fig. 4) (table 3). Mean apparent recharge ages of water calculated from CFC-12 samples collected in copper tubes and analyzed at the University of Utah were within about 2 years of ages calculated from samples collected in glass ampoules and analyzed at the USGS. Comparison of CFC-11-determined ages did not correlate as closely. Mean apparent ages calculated from CFC-11 samples collected in copper tubes and analyzed at the University of Utah were about 4 years different than ages calculated from samples collected in glass ampoules and analyzed at the USGS. On the basis of this comparison and other published information, only CFC-12 concentration was used for determination of apparent ages reported in this study.

Limitations of Chlorofluorocarbon Age Dating

The calculated equivalent-air concentration of CFCs assumes that concentrations in the unsaturated zone are the same as those in the atmosphere. Generally, this is the case in aquifers with shallow unsaturated zones (Cook and Solomon, 1995). However, depth to the water table in the central Virgin River basin varies from just below land surface to more than 800 ft

Table 3. Chlorofluorocarbon concentration measured from samples from the central Virgin River basin collected by copper-tube versus glass-ampoule method

[U of U, University of Utah; pmole/kg, picomoles per kilogram; USGS, U.S. Geological Survey]

Location	Sample type	Sample number[1]	Sample date	CFC-11				CFC-12			
				U of U glass-ampoule method average concentration and standard deviation (pmole/kg)	U of U copper-tube method average concentration and standard deviation (pmole/kg)	USGS glass-ampoule method average concentration and standard deviation (pmole/kg)	U of U glass-ampoule method average concentration and standard deviation (pmole/kg)	U of U copper-tube method average concentration and standard deviation (pmole/kg)	USGS glass-ampoule method average concentration and standard deviation (pmole/kg)
(C-41-17)8abc	Stream	9	6-04-97	2.85 ± 0.31	3.32 ±± 0.07	3.87 ±± 0.10	2.21 ± 0.22	2.07 ±± 0.4	2.5 ±.26
(C-38-13)35aba	Well	15	6-05-97	2.03 ±.01	2.27±.04	2.72 ±.01	1.37 ±.04	1.42 ±±.23	1.53 ±±.02
(C-41-17)8bad-1	Well	27	6-05-97	1.34 ±.04	1.43±.03	1.78± ±.01	1.23 ±.08	1.11 ±±.09	1.30±±.03
(C-41-17)8cda-2	Well	28	6-05-97	.65 ±.06	.78 ±.03	.79 ±±.03	1.11 ±.08	1.15 ±.12	1.09±±.04
(C-41-17)8dba-1	Well	29	6-06-97	.01 ±.0003	.06 ±.03	.01 ±± .0004	.00 ± 0	.02 ±.03	.00±±.003
(C-41-17)17bdb-1	Well	30	6-06-97	.19 ±.02	.29±.09	.20± ±.001	.47 ±.08	.56 ±±.21	.46 ±±.03

[1]Sample numbers correspond to CFC data in table 4.

(Wilkowske and others, 1998, table 1). Where depth to the water table is more than a few tens of feet, the movement of water through the unsaturated zone could effectively lower or raise its CFC concentration as a result of interaction with unsaturated zone pore air not in equilibrium with the atmosphere. Cook and Solomon (1995) indicated that unsaturated-zone pore air is typically lower in CFCs than recharging pore water. However, in some geologic environments such as fractured basalt, pore air may move more quickly to depth and be a source of higher CFC concentration for water moving through the unsaturated zone (D.K. Solomon, University of Utah, oral commun., 1998). Other factors, such as anaerobic microbial degradation, contamination by the atmosphere during sampling, contamination from sampling equipment such as submersible pumps containing plastic or rubber, CFC enrichment from dry organic matter in the vadose zone, or incorporation of excess air in the recharge water also can affect the measured CFC concentrations in ground water and result in an inaccurate age determination (Plummer and others, 1993; Russell and Thompson, 1983). Additionally, ground water often is stratified with depth, so that younger ground water is found at shallower depths. In this study, most of the wells are constructed with open intervals over hundreds of vertical feet. Because horizontally stratified flow paths converge at the well bore, the apparent CFC age may be an average of ground waters with varying ages. Similarly, springs may be points of convergence for ground-water flow paths with different aquifer residence times (D.K. Solomon, University of Utah, oral commun., 1998). Because ages determined for a particular site may not represent the actual recharge age of the water sampled, ages in this report are shown as apparent rather than actual. Although aquifer residence times based on these CFC data should be considered approximate, the presence of CFCs in wells and springs indicates that some fraction of recently recharged water is traveling to these discharge points, showing the importance of protecting recharge zones.

Age-Dating of Ground Water with Chlorofluorocarbons

CFC samples were collected at 36 ground- and surface-water sites to investigate sources of recharge and ground-water residence times (fig. 6; table 4). CFCs are anthropogenic compounds that were first released into the atmosphere in the 1930s (Lovelock, 1971). They have since been used as refrigerants, blow-ing agents for expanded foams, and propellants in spray cans. Because CFCs are man-made substances, their concentration in the atmosphere is a function of their rate of production (Rowland and Molina, 1975). The steady growth of CFC-12 (CCl_2F_2) in the atmosphere during the last 50 years (Busenberg and Plummer, 1992; Elkins and others, 1993) is shown in figure 7. CFCs are water soluble and can therefore enter ground water by dissolving in rainwater that enters the water table as recharge. Because the total concentration of CFCs released to the atmosphere is a function of time, the amount of CFCs dissolved in ground water at equilibrium conditions is a function of age and solubility. Therefore, by measuring the CFC concentration in water, an equivalent air concentration of CFCs can be calculated by assuming a temperature and elevation of water recharging the aquifer. This concentration is then compared to the atmospheric CFC concentration (fig. 7) to estimate the recharge age of the ground water.

Because CFC solubility in water is temperature dependent, the age of ground water determined from CFC concentration depends on the water temperature as it enters the water table, known as the recharge temperature. In areas where the water table is more than 10 ft below land surface, including most of the CFC-sampling sites in the study area, the recharge temperature generally corresponds to the mean annual temperature of the recharge location (Plummer and others, 1993, p. 271). The recharge temperature, however, can be lower than the mean annual temperature in late winter and early spring when most recharge is likely to occur.

To determine recharge temperature, six samples (fig. 6; table 4) were collected for analysis of a suite of dissolved gases including nitrogen and argon (Wilkowske and others, 1998, table 5). Dissolved concentrations of these gases is a function of the air temperature at the point where the ground water enters the water table. Therefore, by measuring the dissolved concentration of these gases in ground water and knowing their solubilities, the recharge temperature can be calculated. Calculated recharge temperatures for the six dissolved-gas samples range from 6.1 to 12.6°C (table 4). Dissolved-gas samples from LDS Church Well B ((C-38-13)35aba-1) had the lowest calculated recharge temperature of 6.1°C, probably because it receives most of its recharge from higher (thus colder) altitudes in the Pine Valley Mountains. Dissolved-gas samples from Newell Matheson's well ((C-40-13)22dcd-1) had the highest calculated recharge temperature of 12.6°C, consistent with the oxygen and hydrogen isotope data
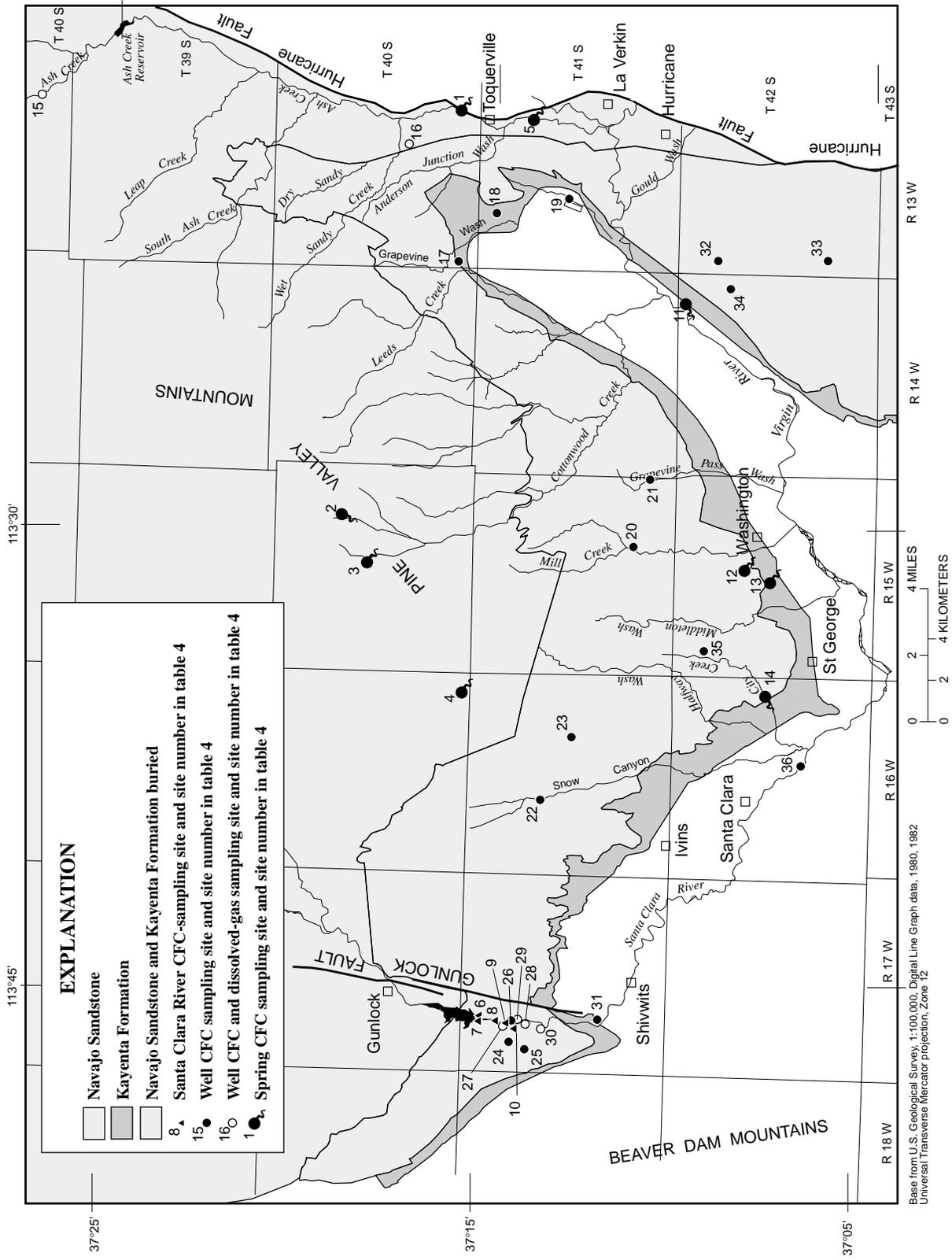
Figure 6. Location of CFC- and dissolved-gas sampling sites, central Virgin River basin study area, Utah. (Data are contained in table 4.)
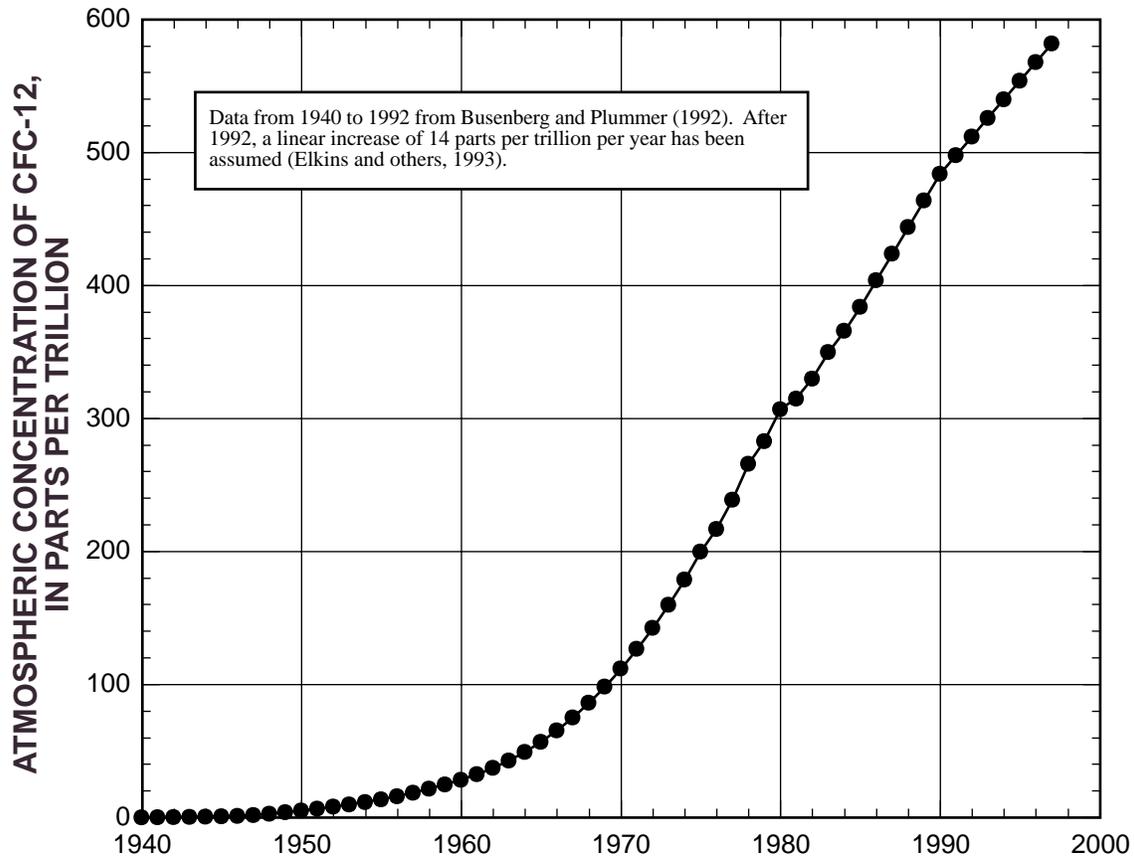
Figure 7. Global atmospheric concentration of CFC-12 as a function of time.

Data from 1940 to 1992 from Busenberg and Plummer (1992). After 1992, a linear increase of 14 parts per trillion per year has been assumed (Elkins and others, 1993).

that indicated lower-altitude recharge. The recharge temperatures for the other ground-water sites were estimated on the basis of their proximity to the six dissolved-gas sample sites and to St. George, where the average annual air temperature is 16 $^{\circ}$C.

Use of Age-Dating to Investigate Sources of Recharge to the Main Part of the Navajo and Kayenta Aquifers

Ten wells and 4 springs in the main part (between the Gunlock and Hurricane Faults) of the Navajo and Kayenta aquifers were sampled for CFCs (fig. 8, wells and springs with formation type "Jn" or "Jk" in table 4). Apparent ground-water recharge years range from pre-1950 to the late 1970s (fig. 8).

Water discharging from wells and springs with a ground-water recharge year in or prior to the 1950s had a very low or no CFC concentration, generally indicating long, deep flow paths with little local recharge or a very thick unsaturated zone. The oldest water sample

collected from the main part of the Navajo and Kayenta aquifers was from Winchester Hills Well 1 ((C-41-16)23bba-2), where the water table is more than 700 ft deep (Wilkowske and others, 1998, table 1). The low CFC concentrations from this well are within the error of analysis, indicating an apparent ground-water recharge age during or prior to the 1950s. The St. George City Mill Creek Well 2 ((C-41-15)27dda-1), the St. George City Creek Well 2 ((C-42-15)6dcd-1), West City Spring ((C-42-16)13dcb-S1), and the Washington City Grapevine Pass Well ((C-41-15)36aad-1), all had apparent recharge ages in the mid-to-late 1950s. Their CFC concentrations are just above the error of analysis and may indicate mixing of older, deeper ground water with a small amount of younger, shallower water. These wells and springs are mostly in the central part of the Navajo and Kayenta aquifers north of St. George and Washington, and may receive recharge from higher-altitude parts of the outcrop near the base of the Pine Valley mountains (table 4, fig. 6).

Table 4. Average chlorofluorocarbon-12 concentration and estimated recharge year for selected springs, surface-water sites,

[NA, not applicable; vmoles/kg, picomoles per kilogram]

Site no.: See figure 8 for map location

Location: See "numbering system" at beginning of report for an explanation of the numbering system used for hydrologic data sites in Utah.

Owner (Well name): WCWCD, Washington County Water Conservancy District; Well name given in parentheses.

Formation: Qtb, Quaternary and Tertiary basalt; Tvip, Pine Valley quartz monzonite; Ks, undifferentiated Cretaceous sedimentary
the Moenave Formation; Trcs, Shinarump Member of the Chinle Formation.

Casing Finish: P, perforated; X, open hole; S, screened; —, no information.

Recharge temperature: Estimated temperature of water as it entered the aquifer as recharge; e, estimated recharge temperature; m, measured

Average CFC concentration, water: Average concentration of CFC-12 in water in replicate samples measured at the University of

Standard deviation: Standard deviation of replicate samples.

CFC concentration, air equivalent: ppt, parts per trillion; Calculated atmospheric concentration of CFC-12 in equilibrium with sample

Apparent recharge year: Apparent year that water entered the ground-water flow system as recharge based on CFC-12

Site no.	Location	Owner (Well name)	Formation	Altitude of land surface (feet)	Approximate depth to water below land surface (feet)	Casing finish below land surface (feet)	
Springs and surface-water sites							
1	(C-40-13)35acd-S1	Toquerville Spring	QTb	3,440	NA	NA	
2	(C-40-15)14bab-S1	Cottonwood (Main) Spring	Tvip	7,800	NA	NA	
3	(C-40-15)15cbd-S1	West Fork Spring	Tvip	6,900	NA	NA	
4	(C-40-16)36cda-S1	Diamond Valley Spring	Ks	4,780	NA	NA	
5	(C-41-13)11cad-S1	Ash Creek Spring	QTb	3,200	NA	NA	
6	(C-41-17) 5acd	Santa Clara River at hydro plant	NA	3,540	NA	NA	
7	(C-41-17) 5acd-S1	Seep below Gunlock dam	NA	3,540	NA	NA	
8	(C-41-17) 5dcc	Santa Clara River (1,500 feet from dam)	NA	3,520	NA	NA	
9	(C-41-17) 8abc	Santa Clara River (2,250 feet from dam)	NA	3,510	NA	NA	
10	(C-41-17) 8bdc	Santa Clara River (3,000 feet from dam)	NA	3,500	NA	NA	
11	(C-42-14) 1bcb-S1	Berry Springs	QTb/Jn	2,860	NA	NA	
12	(C-42-15)15bbd-S1	Green Spring	Jn	2,880	NA	NA	
13	(C-42-15)16ddd-S1	Huntington Spring	Jk	2,880	NA	NA	
14	(C-42-16)13dcb-S1	West City Spring	Jn	2,960	NA	NA	
Wells							
15	(C-38-13)35aba- 1	LDS Church (Well B)	Tvip	5,010	59	P	220-620
16	(C-40-13)22dcd- 1	Newell Matheson	Qs	3,830	220	P	320-340
17	(C-40-13)31bcc- 1	Leeds Domestic (Well #1)	Jk	3,980	204	X	69-400
18	(C-41-13) 5dba- 2	Alan Howard	Jn/Jk	3,600	21	X	83-97
19	(C-41-13)16bcd- 1	Sullivan Flowing Well	Jmss	3,240	—	—	—
20	(C-41-15)27dda- 1	St. George (Mill Creek Well #2)	Jn	3,325	249	P, S	330-768
21	(C-41-15)36aad- 1	Washington (Grapevine Pass Well)	Jn	3,490	347	S	496-900
22	(C-41-16)16bbd- 1	St. George (Snow Canyon Well #2)	Jn	3,460	301	S	350-830
23	(C-41-16)23bba- 2	Winchester Hills (Well #1)	Jn	3,840	722	P	740-940
24	(C-41-17) 7ada-2	St. George (Gunlock Well #6)	Jn	3,598	246	S	123-573
25	(C-41-17) 7ddb-1	St. George (Gunlock Well #2)	Jn	3,570	227	P	176-466
26	(C-41-17) 8acc-1	St. George (Gunlock Well #7)	Jn	3,485	74	S	200-800
27	(C-41-17) 8bad-1	St. George (Gunlock Well #5)	Jn	3,443	24	P	100-384

and wells within the central Virgin River basin study area, Utah

rocks; Jn, Navajo Sandstone; Jk, Kayenta Formation; Qs, Quaternary sediments; Jmss, Springdale Sandstone Member of

temperature of the water sample; c, recharge temperature calculated from dissolved gas concentrations; ^{o}C, degrees Celsius. Utah; pmoles/kg, picomoles per kilogram.

water at recharge temperature.
concentration.

Site no.	Location	Recharge temperature (^{o}C)		Sampling date	Number of replicates	Average CFC concentration, water (pmoles/kg)	Standard deviation (pmoles/kg)	CFC concentration, air equivalent (ppt)	Standard deviation (ppt)	Estimated recharge year	Standard deviation (years)
Springs and surface-water sites										
1	(C-40-13)35acd-S1	12.0	e	10-27-96	3	1.39	0.18	331	43.4	1982	3
		12.0	e	06-04-97	4	1.43	.15	339	36.0	1982	2
2	(C-40-15)14bab-S1	6.0	e	10-23-96	3	2.42	.22	426	39.4	1987	2
3	(C-40-15)15cbd-S1	6.0	e	10-23-96	3	1.70	.18	299	32.2	1980	2
4	(C-40-16)36cda-S1	8.0	e	10-26-96	2	.00	NA	0	NA	pre-1950	NA
5	(C-41-13)11cad-S1	12.0	e	10-25-96	3	1.84	.45	436	107	1987	5
6	(C-41-17) 5acd	19.0	m	10-07-97	3	1.57	.08	354	26.3	1983	2
7	(C-41-17) 5acd-S1	12.5	m	06-04-97	4	.310	.02	74.6	5.29	1967	1
8	(C-41-17) 5dcc	19.0	m	10-07-97	3	1.41	.26	393	22.7	1985	1
9	(C-41-17) 8abc	12.5	m	06-04-97	4	2.07	.04	497	8.75	1991	1
		19.0	m	10-07-97	3	1.25	.04	389	11.2	1985	1
10	(C-41-17) 8bdc	19.0	m	10-07-97	3	1.19	.06	368	17.8	1984	1
11	(C-42-14) 1bcb-S1	12.0	e	10-26-96	3	1.42	.32	338	76.6	1982	4
12	(C-42-15)15bbd-S1	12.0	e	10-22-96	3	.34	.16	79.9	37.2	1966	4
13	(C-42-15)16ddd-S1	12.0	e	10-25-96	2	.93	.13	222	31.7	1976	2
14	(C-42-16)13dcb-S1	12.0	e	10-25-96	3	.04	.04	10.3	8.94	1953	5
Wells										
15	(C-38-13)35aba- 1	6.1	c	10-28-96	4	1.82	.22	321	39.2	1981	3
		6.1	e	06-05-97	4	1.42	.23	250	41.2	1977	2
16	(C-40-13)22dcd- 1	12.6	c	10-30-96	3	1.12	.22	273	54.1	1979	3
17	(C-40-13)31bcc- 1	12.0	e	10-26-96	2	.23	.22	52.8	51.6	1962	8
18	(C-41-13) 5dba- 2	12.0	e	10-30-96	3	.67	.24	158	57.8	1972	3
19	(C-41-13)16bcd- 1	12.0	e	10-26-96	3	.72	.22	170.7	52.2	1973	3
20	(C-41-15)27dda- 1	12.0	e	10-23-96	3	.07	.08	15.9	18.2	1953	7
21	(C-41-15)36aad- 1	12.0	e	10-26-96	1	.09	NA	21.1	NA	1957	NA
22	(C-41-16)16bbd- 1	11.0	e	10-24-96	2	.52	.11	119	24.7	1970	1
23	(C-41-16)23bba- 2	10.0	e	10-24-96	3	0	NA	0	NA	pre-1950	NA
24	(C-41-17) 7ada-2	10.0	e	02-24-97	3	.04	.00	8.99	0.520	1952	0
25	(C-41-17) 7ddb-1	10.0	e	02-24-97	3	.42	.21	87.7	43.6	1967	5
26	(C-41-17) 8acc-1	10.0	e	02-24-97	3	.11	.07	24.2	14.9	1957	4
27	(C-41-17) 8bad-1	10.8	c	02-28-97	3	1.14	.29	246	62.3	1977	3
		10.8	e	06-05-97	4	1.11	.09	239	20.2	1977	1

Table 4. Average chlorofluorocarbon-12 concentration and estimated recharge year for selected springs, surface-water sites,

Site no.	Location	Owner (Well name)	Formation	Altitude of land surface (feet)	Approximate depth to water below land surface (feet)	Casing finish below land surface (feet)	
			Wells—Continued				
28	(C-41-17) 8cda-2	St. George (Gunlock New Well #4)	Jn	3,445	94	S	123-573
29	(C-41-17) 8dba-1	St. George (Gunlock Well #8)	Jn	3,454	47	S	200-800
30	(C-41-17)17bdb-1	St. George (Gunlock Original Well #3)	Jn	3,444	115	X	9-626
31	(C-41-17)29aba-1	BIA (Shivwits Flowing Well)	Trcs	3,240	—	P	100-700
32	(C-42-13) 7bba-3	Winding Rivers	Jn	2,960	51	X	50-705
33	(C-42-13)30bdc-1	WCWCD (Sky Ranch Well)	Jn	3,040	131	X	52-590
34	(C-42-14)12ddb-3	Winding Rivers	Jn	2,920	60	S	140-503
35	(C-42-15) 6dcd-1	St. George (City Creek Well #2)	Jn	3,308	279	P	260-660
36	(C-42-16)22cdd-1	St. George (Sunbrook Golf Course Well)	Trcs	2,660	130	P	260-580

Wells and springs with apparent recharge ages in the 1960s and 1970s probably receive a greater component of younger recharge than those in the central part of the aquifers. These apparent recharge ages indicate younger, more localized recharge which may be entering the water table more rapidly through fracture zones or along ephemeral stream channels. Two Winding Rivers wells ((C-42-13)7bba-3 and (C-42-14)12dbb-3), Leeds Domestic Well (C-40-13)31bcc-1, along with Green Spring ((C-42-15)15bba-S1), have apparent ages in the 1960s. Alan Howard's Well ((C-41-13)5dba-2), St. George City Snow Canyon Well 2 ((C-41-16)16bbd-1), the Sky Ranch Well ((C-42-13)30bdc-1), and Huntington Spring ((C-42-15)16ddd-S1), all have apparent ages in the early-to-mid-1970s (table 4).

The highest measured CFC concentrations from the Navajo and Kayenta aquifers are from Berry Springs ((C-42-14)1bcb-S1), indicating an apparent recharge age of early 1980s. Berry Springs emerge at the contact of basalt with the underlying Kayenta Formation. Ground water moving through basalt aquifers within the study area typically has relatively high (36-44 mg/L) silica concentrations. Berry Springs, however, had a silica concentration of 26 mg/L on February 24, 1986 (Wilkowske and others, 1998, table 4), similar to the lower silica concentrations found in the Navajo and Kayenta aquifers. Thus the young apparent recharge age, in combination with the lower silica concentration, may indicate a mixing of waters from both the basalt and Kayenta aquifers.

In summary, age-dating with CFCs indicate that residence times for the main part of the Navajo and Kayenta aquifers range from more than 50 years to less than 20 years. These ages are likely dependent on both the lateral length of the flow path from point of recharge to point of discharge, as well as vertical stratification of the aquifer such that shallower ground water has been recharged more recently from local infiltration than deeper ground water. However, the relatively small number of sampling sites (14), the vertical averaging because of large perforated borehole intervals, and the inability of CFC techniques to age date water older than the 1950s all indicate the need for a more comprehensive age-dating study, in combination with particle-tracking computer analysis, before this information can be readily incorporated into the hydrologic conceptualization of ground-water flow within the main part of the Navajo and Kayenta aquifers.

Comparison of Apparent Ages Calculated from Chlorofluorocarbon Concentration to Radio-Isotope Age-Dating Methods

Tritium (^{3}H) is a radioactive or unstable isotope of hydrogen that decays with a half-life of about 12.3 years. Tritium occurs naturally in the atmosphere, but the largest source has been atmospheric nuclear testing between 1952 and 1969. The natural level for tritium prior to atmospheric nuclear testing ranged from 2 to 8 tritium units (TU). Large scale testing during 1962-63 raised tritium levels to more than three orders of magnitude larger than natural concentrations (Plummer and

Site no.	Location	Re-charge temper-ature (°C)		Sam-pling date	Number of rep-licates	Average CFC concen-tration, water (pmoles/kg)	Stan-dard devia-tion (pmoles/kg)	CFC concen-tration, air equivalent (ppt)	Stan-dard devia-tion (ppt)	Esti-mated re-charge year	Stan-dard devia-tion (years)
				Wells—Continued							
28	(C-41-17) 8cda-2	10.4	c	02-24-97	3	.42	.08	89.5	16.1	1968	1
		10.4	e	06-05-97	4	1.15	.12	242	25.0	1976	1
29	(C-41-17) 8dba-1	9.9	c	10-24-96	3	0	NA	0	NA	pre-1950	NA
		9.9	e	06-06-97	4	.2	.03	5.08	7.05	pre-1950	NA
30	(C-41-17)17bdb-1	9.7	c	02-28-97	2	.35	.31	73.0	64.2	1965	8
		10.2	e	06-06-97	4	.56	.21	118	44	1970	3
31	(C-41-17)29aba-1	10.0	e	10-23-96	3	0	NA	0	NA	pre-1950	NA
32	(C-42-13) 7bba-3	12.0	e	10-24-96	3	.17	.03	39.2	6.30	1962	1
33	(C-42-13)30bdc-1	12.0	e	10-30-96	2	.56	.01	133.2	3.47	1971	0
34	(C-42-14)12ddb-3	12.0	e	10-25-96	3	.37	.12	87.0	27.4	1967	3
35	(C-42-15) 6dcd-1	12.0	e	10-25-96	3	.10	.06	22.8	14.4	1957	4
36	(C-42-16)22cdd-1	12.0	e	10-24-96	4	.03	.03	6.06	7.07	1950	5

others, 1993, p. 258). In 1998, while still above pre-nuclear testing values, atmospheric tritium concentrations have decreased back down to a range of about 10 to 30 TUs as a result of radioactive decay and the cessation of most atmospheric testing (D.K. Solomon, Univ. of Utah, oral commun., 1999).

Two wells were sampled for tritium analysis (Wilkowske and others, 1998, table 5) to compare estimated recharge ages with those determined by CFC sampling. Tritium concentrations were less than the detection limit at both the St. George City Gunlock Well #8 ((C-41-17)8dba-1) and the Sky Ranch well ((C-42-13)30bdc-1) (Wilkowske and others, 1998, table 5), indicating that water recharging these wells entered the aquifers prior to 1953. This is consistent with the pre-1950s apparent recharge age estimates at the St. George Gunlock Well #8 (water table at 47 ft), which are based on CFC sampling (table 4). Apparent recharge age is the estimated year when water enters the water table. However, apparent recharge age estimated on the basis of CFC sampling at Sky Ranch well #1 (water table at 131 ft), indicated that water recharging this well entered the aquifer in the early 1970s. One possibility for this discrepancy is that CFC enrichment may occur by exchange with unsaturated-zone pore air above the water table. Vertical sampling done at other study sites with thick unsaturated zones has determined the tritium peak to be in the unsaturated zone; samples at the water table have had detectable CFC concentrations.

Differences in apparent recharge ages between the tritium and CFC samples may be explained by differences in the way the two are transported through the unsaturated zone. Transport of tritium is primarily by water, whereas CFCs diffuse between air and water and can be transported to the water table by both phases (D.K. Solomon, oral commun., 1998). Thus, as discussed in the "Methods and Limitations" section, the presence of CFCs in ground water beneath thick unsaturated zones may falsely give a more recent apparent recharge age where pore-gas transport of CFCs reaches the water tables sooner than pore water transport of CFCs. However, other wells with similar depths to water (St. George City Sunbrook Golf Course well), or shallower depths to water (St. George City Gunlock well 8) had no detectable CFC-12, arguing against the mechanism of pore-gas transport of CFCs (table 4).

Another possible reason for the discrepancy in apparent recharge year at the Sky Ranch well is that the CFC sampling method had a higher level of accuracy than the selected tritium analysis method, which had a detection limit of 2.5 TUs. The apparent CFC recharge year of 1971 could result from the mixing of a small fraction of younger, shallow ground water with a large fraction of older, deep ground water. If one assumes a two-member mixing model with young and old waters such that 30 percent of the water is young (1984) water with a CFC-12 concentration of 1.5 pmoles/kg and 15.0 TU initial tritium concentration. The 1997 tritium concentration after one half life (10.7 yr) of decay would be

APPARENT GROUND-WATER RECHARGE YEAR DETERMINED FROM CFC-12 CONCENTRATION

EXPLANATION

● 34 — Well sample and site number; additional information in table 4, location shown in figure 6

● 13 — Spring sample and site number; additional information in table 4, location shown in figure 6

├─┤ Standard deviation of replicate samples where greater than 1

→ Pre-1950 samples have measured CFC-12 concentrations within the error of analysis and may be much older as indicated by arrows

Figure 8. Apparent ground-water recharge year determined from CFC-12 concentration for selected wells and springs in the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

7.5 TUs. The other 70 percent is old (pre-1950) water with a CFC concentration of 0 pmole/kg and 0 TU's. The resulting CFC-12 and tritium concentrations would be about 0.5 pmoles/kg and 2.5 TUs, respectively. The 0.5 pmoles/kg CFC-12 concentration (the value measured at Sky Ranch Well #1) is within detection limits, but the tritium concentration is right at the detection limit. Similar to Sky Ranch Well #1, most of the wells sampled for CFCs had large screened intervals. Thus, it is likely that many of the 1960s through 1980s apparent CFC recharge ages reflect a mixture of a large fraction of old (pre-1950s) water with a small fraction of younger water. The possibility of young, recent precipitation rapidly reaching the aquifer highlights the need for adequate protection of the aquifer's recharge zones.

Four wells and one spring also were sampled for chlorine-36 (^{36}Cl) as part of a broad regional study of its distribution in ground water across the United States (S. Davis, written commun., 1997). Low concentrations of chlorine-36 are produced naturally in the atmosphere by cosmic radiation interacting with argon, but the largest source has been testing of thermonuclear devices from 1952 to 1958. These tests produced atmospheric ^{36}Cl concentrations that remain 100 times higher than pre-bomb concentrations (Lehmann and others, 1993). Three St. George wells finished in the Navajo Sandstone (Gunlock Well #6, Gunlock Well #8, and Mill Creek Well #2) and the Bureau of Indian Affairs Shivwits flowing well finished in the Shinarump conglomerate of the Chinle Formation ((C-41-17)29aba-1) all had reported (^{36}Cl)/(^{35}Cl x10^{15}) ratios of less than 400, indicating apparent recharge ages of pre-1952 (S. Davis, written commun, 1997). These ages generally are consistent with ages determined from CFC sampling (table 4). A higher (^{36}Cl)/(^{35}Cl x10^{15}) ratio of about 780 from water sampled at Toquerville Springs ((C-40-13)35acd-S1), which emanates from an outcrop of Quaternary-Tertiary fractured basalt along Ash Creek, indicates more recent recharge. This is consistent with an early 1980s apparent recharge age determined from CFC-12 data (table 4). In summary, CFC age dating from four of the five ground-water sites, which were compared with other age-dating methods, yielded similar ages. Although the apparent recharge year determined by both the CFC method and the tritium method were not the same for the fifth site (Sky Ranch Well #1), this can be explained by the lack of accuracy in the chosen tritium age-dating method.

Use of Other Geochemical Data to Investigate Sources of Ground-Water Recharge

The chemistry of water changes as it moves from land surface, through the unsaturated zone, into and through an aquifer, and finally back to land surface. Water dissolves some minerals that it contacts and retains certain isotopic species during its journey. Dissolved chemicals in the ground water also may react with minerals in the aquifer material, further altering water chemistry. Knowledge of water chemistry at various points along a flow path can be a valuable aid to understanding the workings of an entire hydrologic system.

Navajo and Kayenta Aquifers

Dissolved-solids concentration of ground-water samples from wells and springs in the Navajo and Kayenta aquifers ranged from 110 to 1,310 mg/L (Wilkowske and others, 1998) at 73 sample sites. Ground water from most of the Navajo and Kayenta aquifers was low in dissolved minerals, with an average dissolved-solids concentration of about 300 mg/L in water from 54 well and spring samples. However, there were two distinct areas with dissolved-solids concentrations greater than 500 mg/L: a large area north of St. George and a smaller area a few miles west of Hurricane (fig. 9). Nineteen wells and springs from these areas had an average dissolved-solids concentration of about 1,020 mg/l.

Cordova (1978, p. 38) stated that the "Navajo Sandstone is mineralogically a relatively pure lithologic unit composed mostly of silica and other low-solubility substances. The water that flows through such a lithologic medium would expectably dissolve relatively small amounts of minerals even if the water was in contact with them for a long time." The Kayenta Formation is finer grained and contains more clays and feldspar than the Navajo Sandstone, but also generally consists of minerals that do not dissolve easily. Therefore, there is likely an external source for the higher salinity water moving into the Navajo and Kayenta aquifers at the two higher salinity zones, either from overlying or underlying formations.

Both overlying Upper Jurassic and Cretaceous and underlying Lower Jurassic, Triassic, and Permian formations contain alternating layers of conglomerate, sandstone, siltstone, shale, limestone, and evaporite beds that contain gypsum, mirabilite, and other easily
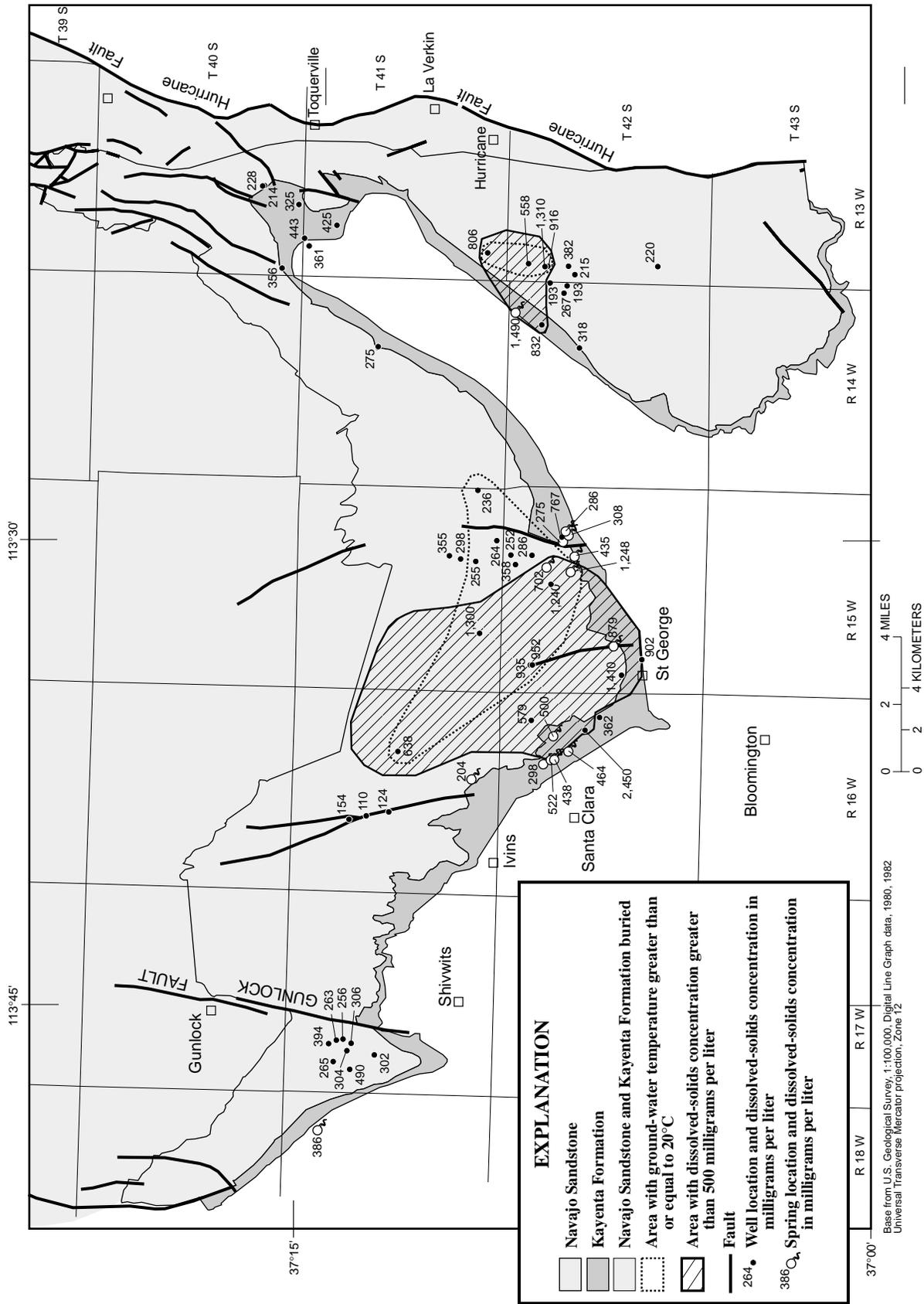
Figure 9. Areas of dissolved-solids concentration greater than 500 mg/L and temperatures greater than 20°C from wells and springs in the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

dissolved minerals (Cook, 1957). Therefore, no conclusive determination about the source of higher salinity water can be made on the basis of lithology of overlying versus underlying formations. Thus, further geochemical investigation was necessary to determine the probable source.

One relation that can be seen in figure 9 is that two zones of warmer water (20.0 to 35.5°C) partially overlap the higher salinity zones. This indicates that the source of higher salinity water entering the Navajo aquifer is the underlying formations, possibly from the hydrothermally induced upward vertical flow along fractures. The zone north of St. George corresponds with a low-temperature geothermal area identified by the Utah Geological Survey (UGS) as the "central St. George Basin"; the zone west of Hurricane corresponds to the "southeast St. George Basin" (Budding and Sommer, 1986, fig. 3). The larger area north of St. George is considered by the UGS to have geothermal development potential. Budding and Sumner (1986) stated that the location of several low-temperature geothermal areas in the St. George basin probably are related to three major fault zones: the Hurricane, Gunlock, and Washington Faults. The UGS report indicates that fault zones provide conduits for the upward movement of geothermal waters. The low-temperature geothermal area north of St. George is located as much as 3 mi west of the Washington Fault; the area west of Hurricane City is located up to 5 mi west of the Hurricane Fault (Budding & Sommer, 1986, p. 15-16, fig. 3). Budding and Sumner (1986) suggested that lateral movement of ground water away from the faults may be responsible for the higher temperature zones; however, an alternative is that the zones correspond to increased vertical permeability associated with fracturing adjacent to the faults.

General Chemistry

The samples with low dissolved-solids concentration (less than 500 mg/L) and high dissolved-solids concentration (greater than 500 mg/L) from the Navajo aquifer have distinctive geochemical signatures when displayed on a trilinear diagram (fig. 10). The low dissolved-solids waters generally are a calcium-carbonate type; the higher dissolved-solids ground waters generally are a calcium-sodium-sulfate type.

The relation of samples with higher dissolved-solids concentration from the Navajo and Kayenta aquifers to the chemical composition of water samples from overlying and underlying formations is shown in figure

11. The samples with higher dissolved-solids concentration are geochemically more similar to water from the underlying formations than they are to the overlying formations.

Oxygen and Hydrogen Isotopes

The stable isotopes of oxygen (^{18}O and ^{16}O) and hydrogen (^{2}H, or deuterium, and ^{1}H) in water provide a useful geochemical tool to determine sources of recharge to an aquifer. The ratios of these isotopes vary in precipitation primarily from changes in topography, air temperature, and distance from water bodies (Mazor, 1991). Because these stable isotopes generally are conservative in ground-water systems, water recharging the aquifer has an isotopic signature that indicates the relative altitude at which it fell as precipitation. The oxygen isotopic ratio ($^{18}O/^{16}O$) and the hydrogen isotopic ratio ($^{2}H/^{1}H$) in a water sample are reported in delta (d) units per mil (parts per thousand) deviation from a reference standard called Standard Mean Ocean Water (SMOW) (Craig, 1961). These delta values are determined from the following equation:

$$\delta R = \left[\frac{(R_{sample} - R_{standard})}{R_{standard}} \right] \times 1,000 \qquad (1)$$

where

$\delta R = \delta^{2}H$ or $\delta^{18}O$ in the water sample,

R_{sample} = ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in the water sample, and

$R_{standard}$ = ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in the reference standard.

Waters that have not undergone evaporation generally plot along a meteoric water line (fig. 12) where the heavier isotopes of oxygen and hydrogen condense first and fall as precipitation at lower altitudes. Subsequent precipitation at higher altitudes is depleted in the heavier isotopic species. The isotopic composition of 17 ground-water samples from the main part of the Navajo and Kayenta aquifers (between the Gunlock and Hurricane Faults) was compared with the North American (Craig, 1961) and arid-zone (Welch and Preissler, 1986) meteoric water lines (fig. 12). All of the Navajo and Kayenta aquifer water samples plot between the two meteoric water lines, indicating that little or no evaporation occurs before infiltration and recharge. Although no precipitation samples were collected during this study, two composite snow samples from the Abajo Mountains about 200 mi to the east of the study area in Utah and an average of eight snow samples from
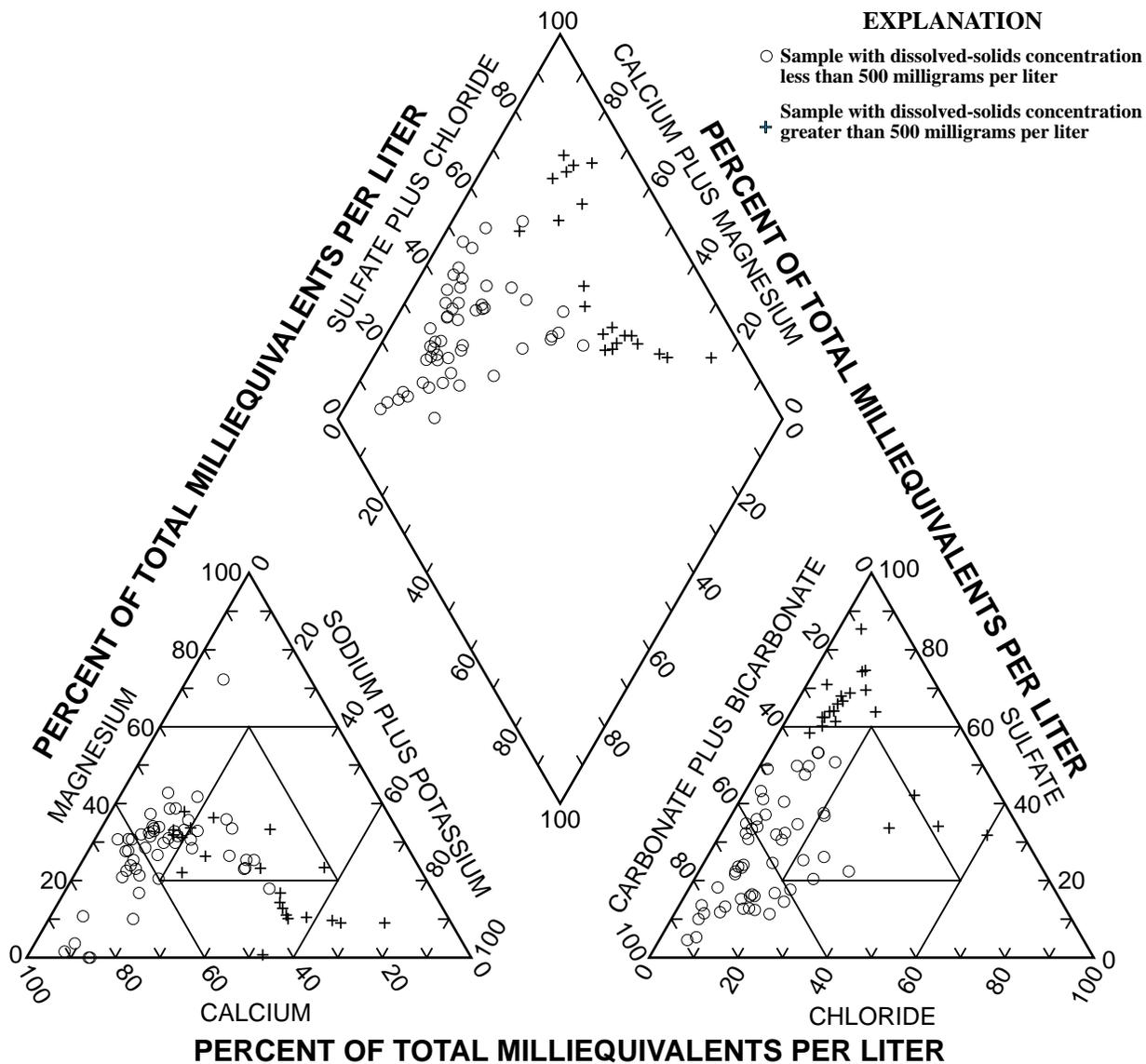
Figure 10. Chemical composition of 73 water samples collected from the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

the Spring Mountains near Las Vegas, Nevada, are plotted to show nearby isotopic signatures of high-altitude precipitation.

The data plotted in figure 12 indicate that groundwater samples from the main part of the Navajo and Kayenta aquifers with heavier isotopic signatures (less negative values) also had dissolved-solids concentrations less than 500 mg/L. In contrast, samples with lighter isotopic signatures generally have elevated dissolved-solids concentrations. One possible explanation for this is that recharge along the outcrop from local lower-elevation precipitation (either diffuse or along stream channels) is only in contact with the Navajo Sandstone (fairly clean quartz sand). Conversely,

streams originating higher in the Pine Valley Mountains from higher-elevation precipitation must first cross the highly soluble evaporite deposits of the Carmel and other overlying formations. During low-flow conditions, the dissolved-solids concentrations of this surface water may be elevated by dissolution of these minerals, as was found at site (C-41-15)12baa along Bitter Creek (Wilkowske and others, 1994, table 4) just upstream of the Navajo Sandstone outcrop. Thus, recharge from streams carrying this isotopically light precipitation could also have an elevated dissolved-solids concentration.

Another possible explanation for the relation between lighter isotopic species and higher dissolved-
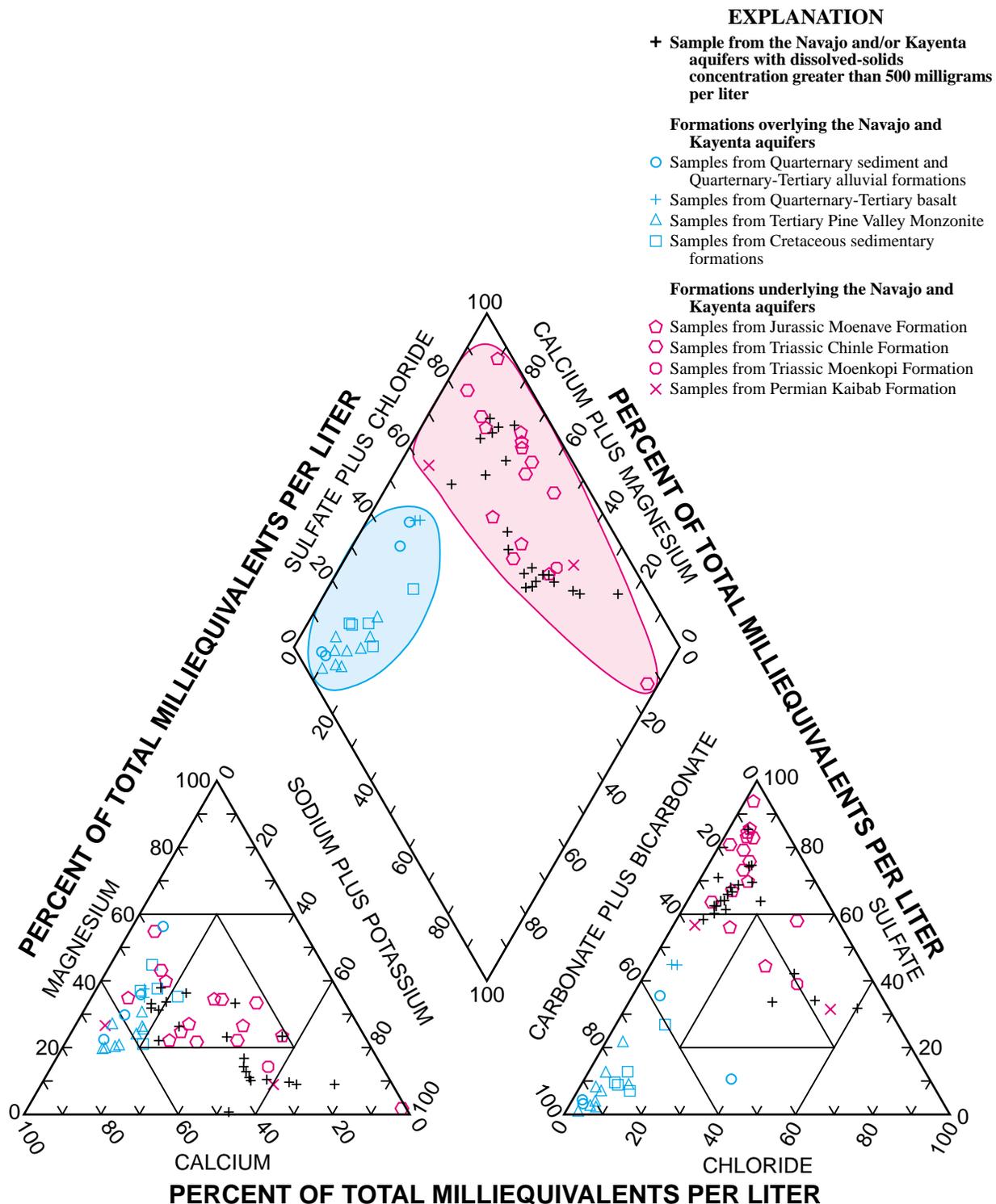
Figure 11. Relation of Navajo and Kayenta aquifer samples with high dissolved-solids concentration to the chemical composition of samples collected from overlying and underlying formations within the central Virgin River basin study area, Utah.
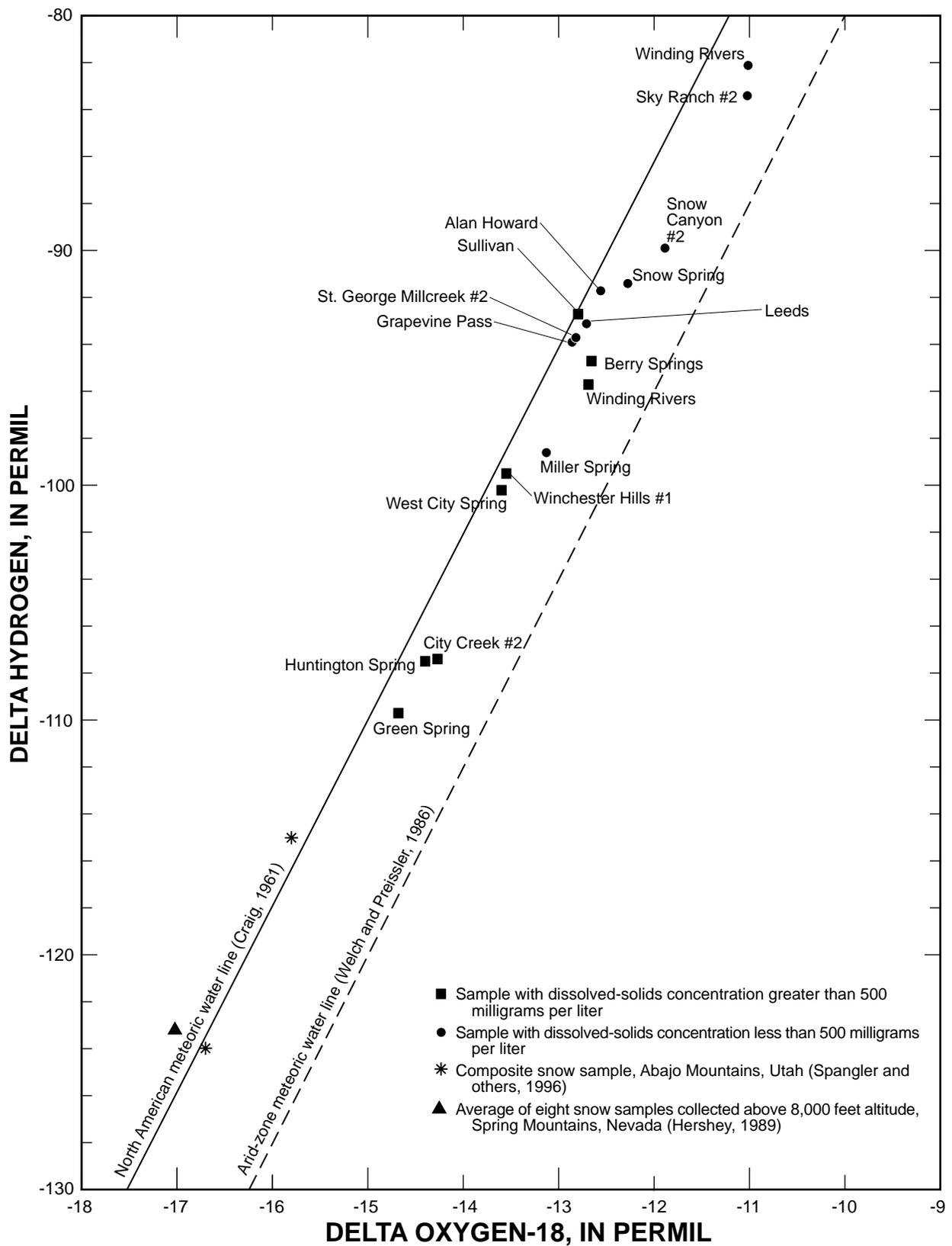
Figure 12. Stable-isotope ratios of hydrogen versus oxygen from ground water in the main part of the Navajo and Kayenta aquifers within the central Virgin River basin study area, Utah.

solids concentrations is mixing of recharge from precipitation from the higher-elevation Pine Valley Mountains with higher dissolved-solids hydrothermal water migrating upward along fractures into the Navajo and Kayenta aquifers (discussed in more detail in the "Recharge from overlying and underlying formations" section). This hypothesis requires that recharge from streams carrying isotopically light precipitation generally occurs higher along the outcrop, creating deeper and longer flow paths that would mix more with upwardly migrating hydrothermal water deeper in the aquifer than the shallow and shorter flow paths associated with precipitation that falls locally on the outcrop. One advantage of this explanation is that it also explains the elevated temperatures (greater than 20°C) related to the higher dissolved-solids concentrations. Further investigation, including the determination of ground-water recharge temperatures from dissolved noble gases to augment the stable-isotope and general-chemistry data of sampling sites shown in figure 12, is necessary to more conclusively determine ground-water flow paths within the Navajo and Kayenta aquifers.

Possible Sources of Ash Creek and Toquerville Springs

The hydrology of the Ash Creek drainage below Ash Creek Reservoir is of particular interest to local water management agencies in Washington County, especially with respect to possible sources for Toquerville and Ash Creek Springs. These springs, with a combined flow of about 28 ft^3/s (Wilkowske and others, 1998, table 3), are likely the principal source of discharge from the lower Ash Creek drainage ground-water system. Wells along the Ash Creek drainage below the reservoir also discharge small amounts of water from the aquifer. Ground water also may migrate from the lower Ash Creek drainage ground-water system into the Navajo aquifer where it is buried between Pintura and Toquerville.

Ash Creek is ephemeral just upstream of the reservoir, which is often empty. However, when the reservoir is full, water rapidly flows out through fractures in the basalt outcrop near the dam abutment. Although the amount and fate of this water is unknown, it is likely only a small component of overall recharge to the lower Ash Creek drainage ground-water system. Several other potential sources recharge the ground-water system. One possible source is seepage of surface water from Kanarra, Spring, Camp, and Taylor Creeks (pl. 1).

These creeks generally dry up as they flow west across the Hurricane Fault, indicating recharge to the alluvial deposits north of Ash Creek Reservoir. A part of this ground water likely migrates southward through boulder conglomerate and fractured basalt along the Ash Creek drainage (Hurlow, 1998). The Pine Valley monzonite aquifer, part of the undifferentiated Tertiary igneous and sedimentary rocks (labeled "Tsi" on fig. 13), also may provide a source of recharge where it contacts the fractured basalt between Ash Creek Reservoir and Pintura. Similarly, the Navajo Sandstone (labeled "Jn" on fig. 13) may provide recharge where it contacts with the basalt between Anderson Junction and Ash Creek Springs. Finally, seepage studies along South Ash Creek indicate that water seeps from the stream into coarse boulder conglomerate (labeled "Qs" on fig. 13) that overlies the fractured basalt of the Ash Creek drainage (Dale Wilberg, U.S. Geological Survey, oral commun., 1998) and is likely an additional source of recharge to the lower Ash Creek drainage ground-water system.

Water-chemistry data from Toquerville and Ash Creek Springs, along with nine other ground- and surface-water sampling sites along the Ash Creek drainage, were compiled and analyzed to investigate possible sources to the springs. The chemical composition of water from these sites is shown in figure 14. Dissolved-solids concentrations ranged from 56 to 1,028 mg/L. The most obvious geochemical trend is an increase in the percent sulfate and a decrease in the percent bicarbonate with increased dissolved solids. Water samples from Toquerville and Ash Creek Springs are at the median of the range of dissolved-solids concentration and have about equal fractions of sulfate and bicarbonate. The geochemical signatures of surface-water samples from upper Ash Creek and LaVerkin Creek generally show higher sulfate and lower bicarbonate percentages than Toquerville and Ash Creek Springs (fig. 14). Water samples from New Harmony LDS Well B, Sawyer Spring, the WCWCD well, and South Ash Creek, all have very low sulfate and dissolved-solids concentrations. Therefore, water lost from Ash Creek Reservoir may be mixing with other lower sulfate ground water from the Pine Valley Monzonite aquifer, the Navajo aquifer, or upper Ash Creek drainage before being discharged at Toquerville and Ash Creek Springs. Several other sources for the springs are possible, however, which also would be consistent with the scarce available geochemical data. Therefore, more water-quality data from wells, springs, and streams are needed to better determine recharge to the ground-
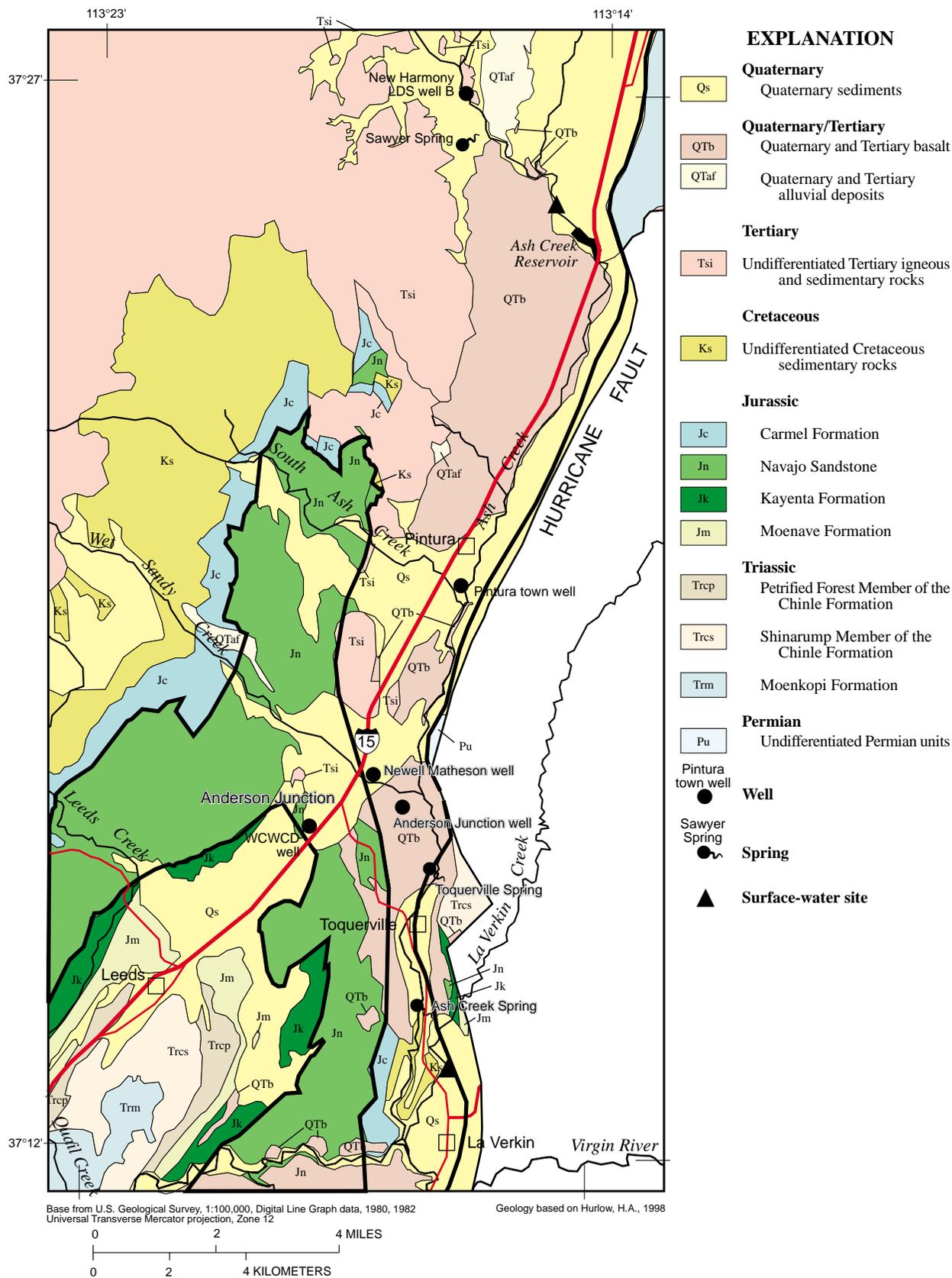
Figure 13. Location of general-chemistry sampling sites along the Ash Creek drainage, Utah.
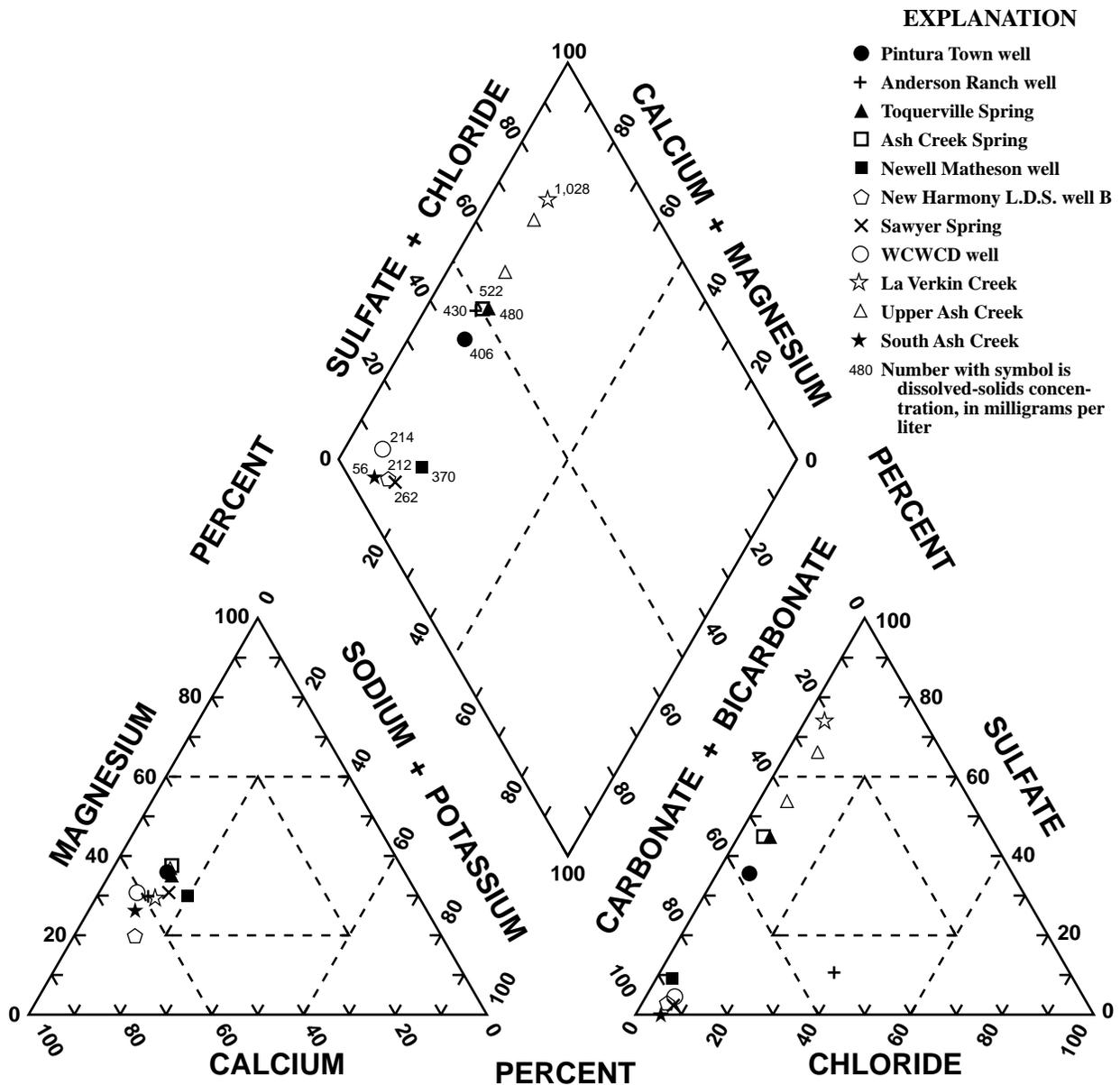
Figure 14. Chemical composition of ground water and surface water along the Ash Creek drainage, Utah.

water system. Additionally, the recharge could be better defined by measuring seepage losses (1) along creeks entering the lower Ash Creek drainage, (2) from Ash Creek Reservoir, and (3) along Ash Creek between Toquerville Springs and the confluence with the Virgin River. Such information would be helpful in more accurately identifying possible sources of water for Toquerville and Ash Creek Springs.

GROUND-WATER HYDROLOGY

Upper Ash Creek Drainage Basin Ground-Water Flow System

The 134-mi^2 drainage basin for Ash Creek Reservoir includes several geographic features that affect the ground-water system in distinctive ways. The basin floor is where most of the irrigation, evapotranspiration, ground-water discharge, and stream-aquifer interaction