

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

CONTROLS ON GROUND-WATER CHEMISTRY IN THE
HORSE HEAVEN HILLS, SOUTH-CENTRAL WASHINGTON

By W. C. Steinkampf, G. C. Bortleson, and F. A. Packard

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COVER PHOTO: Shows contact of the Frenchman Springs Member of the Wanapum Basalt Formation (above and right of hammer) and the Vantage Member of the Ellensburg Formation, in the Horse Heaven Hills area.

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CONVERSION FACTORS, INCH-POUND TO METRIC

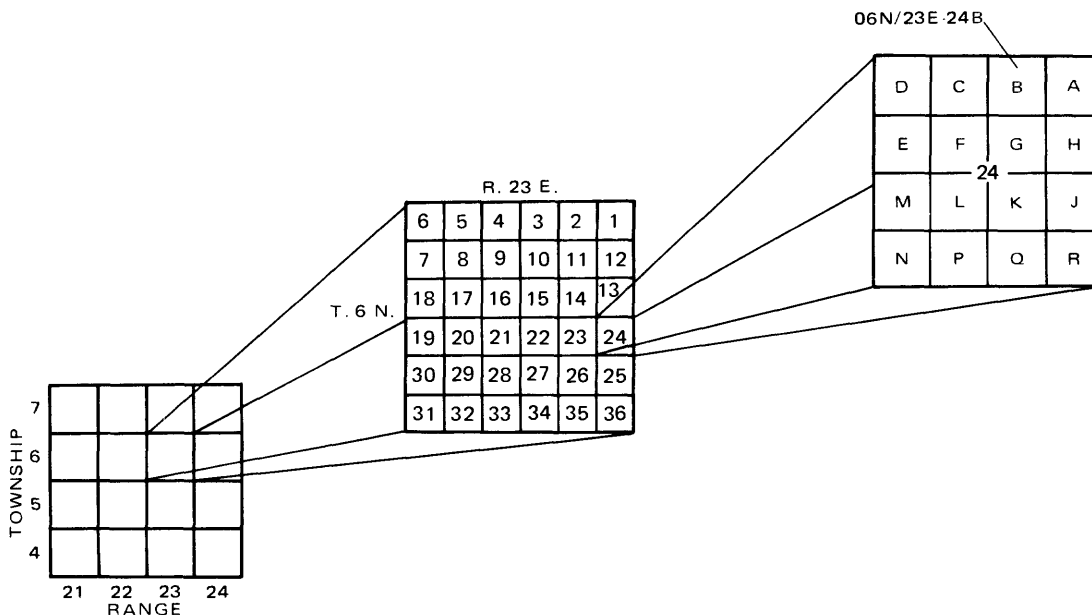
<u>Multiply inch-pound units</u>	<u>By</u>	<u>To obtain SI units</u>
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi ²)	2.590	square kilometer (km ²)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

WELL-NUMBERING SYSTEM

Wells are identified in two ways in this report. They are identified according to their location in the rectangular system used for the subdivision of public lands to facilitate locating them on maps or figures not used in this text. This identification consists of the township number, the range number, and the section number. Townships and ranges in the Horse Heaven area are north of the Willamette base line and east of the Willamette meridian, respectively. A section is further divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with A in the northeast corner of the section and progressing in a sinusoidal manner to R in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried.

Sites are additionally identified by one- or two-digit numbers for brevity. These numbers are used in the text for references to specific wells.



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ABSTRACT

Miocene flood basalt aquifers are the primary sources of domestic and municipal water, and are sources of irrigation water in the Horse Heaven Hills, an agricultural area in the southwestern part of the Columbia Plateau in Washington State. Washington farmers have, in recent years, expressed concern regarding the irrigation use of waters with relatively high sodium concentrations.

Areal variations in ground-water quality in the Horse Heaven area derive from the hydraulic characteristics of the geohydrologic system, from reactions involving ground water and the basalts, and from irrigation. The major trend noted is one of increasing dissolved species concentrations with increasing residence time. Ground waters nearest the recharge areas are calcium magnesium sodium bicarbonate waters with sodium-adsorption ratios (SAR's) less than 1.0. They evolve with time to sodium potassium bicarbonate waters with SAR's as high as 17.

Volcanic glass and cryptocrystalline phases are the main sources of dissolved sodium. They dissolve by means of silicate hydrolysis in carbon dioxide charged waters that recharge the aquifer system. Dissolved aluminum, iron, and silicon concentrations are controlled by the solubilities of subsequent amorphous secondary alteration products, which, in time, become structurally more ordered silica phases, oxyhydroxides, and smectite. Carbonate mineral precipitation is induced by the increasing pH attendant to the hydrolysis reaction. Sodium and potassium concentrations increase until the waters become saturated with respect to clinoptilolite and the mineral begins to precipitate.

Deviations from the general variation patterns are due to inferred localized geologic structures which complicate the flow regime and locally preclude downward and simple intraformational ground-water flow, and to the infiltration of Columbia River water used for irrigation in the southern and southeastern parts of the area.

INTRODUCTION

The Horse Heaven Hills is a gently south-sloping anticlinal ridge that comprises about 1,500 square miles in the southwestern part of the Columbia Plateau in south-central Washington State (fig. 1). Within this area, basaltic aquifers are the primary sources of water for domestic, municipal, and some agricultural uses. There was little irrigated agriculture until the late 1960's, when large-scale diversion of water from the Columbia River and development of high-yield wells tapping basalt aquifers began (Molenaar, 1982).

The continued success of irrigated agriculture depends in part on the quality of the applied water. Some ground waters in the Columbia Plateau, including the Horse Heaven Hills, have high sodium concentrations relative to calcium and magnesium. Continued irrigation with such waters can, without adequate management practices, reduce soil permeability and prevent water from effectively reaching plant roots.

In 1982, the U.S. Geological Survey, in cooperation with the State of Washington Department of Ecology, began a 2 1/2-year investigation of waters in the basaltic aquifers in Washington State. The objectives of the study were to map the spatial and temporal variability of dissolved sodium in the aquifers and to relate this variation to the geohydrologic system and geochemical factors responsible for the evolution of high-sodium ground waters.

The initial results of this work are being released as (1) a series of map reports covering the Columbia Plateau in Washington State, showing the spatial variation of dissolved sodium concentrations and describing the geology and hydrology of the major basaltic aquifers (Bortleson and Cox, 1985; Drost and Whiteman, 1985; and Bauer and others, 1985) and (2) a report discussing the geochemical factors affecting the occurrence of sodium (Hearn and others, 1985).

This report discusses the ground-water chemistry in the Horse Heaven Hills. The objective of this work is to investigate, within individual aquifers, the spatial variations of the sodium-adsorption ratio (SAR) and concentrations of sodium and selected other dissolved constituents, in order to characterize the evolution of ground-water chemistry and its areal variations. To this end, water-chemistry data from 34 wells (table 1) completed in single formations were used; most of the data were collected during 1982-1984.

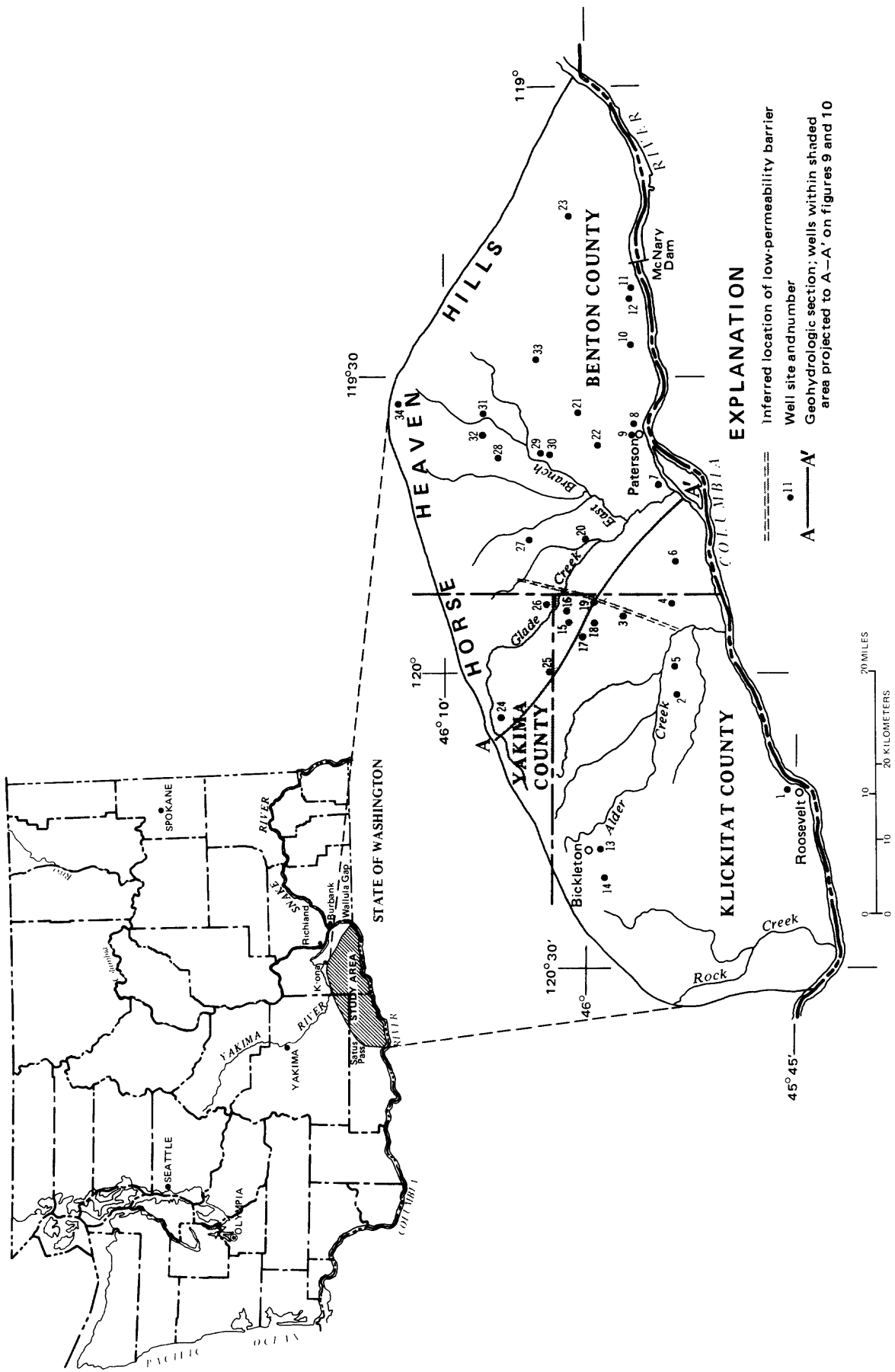


Figure 1. — Locations of study area, well sites, and geohydrologic section.

TABLE 1 --Water-chemistry data for 34 sites in the Horse Heaven Hills

[Geologic units are SDLM (Saddle Mountains Basalt) and WNPM (Wanapum Basalt); umhos, micromhos; °C, degrees Celsius; mg/L, milligrams per liter; ug/L, micrograms per liter]

Site No. (see fig. 1)	Local identifier	Geologic unit	County	Date of sample	Depth of well, total (feet)	Specific conductance (umhos)	pH (standard units)	Temperature (°C)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as mg)	Sodium, dissolved (mg/L as Na)	Sodium adsorption ratio
1	03N/21E-09N01	WNPM	Klickitat	84-04-19	201	340	7.6	15.0	24	12	39	2
2	05N/22E-27P02D1	WNPM	--do--	82-08-25	812	370	8.1	24.5	13	3.9	56	4
				83-07-19	812	369	8.2	24.0	13	4.2	56	4
3	05N/23E-03A01	SDLM	--do--	61-05-05	81	464	7.9	16.0	46	12	29	1
4	05N/23E-13R02	WNPM	--do--	82-03-31	1,440	335	8.7	25.0	2.3	.31	74	13
5	05N/23E-30D01	WNPM	--do--	82-08-25	843	351	8.0	24.0	15	7.3	44	2
				83-03-02	843	345	8.0	22.5	15	7.7	45	2
				83-07-19	843	353	8.0	24.0	16	7.9	45	2
6	05N/24E-28G01	SDLM	Benton	82-03-29	264	565	7.8	17.0	38	22	50	2
7	05N/25E-22M01	SDLM	--do--	82-08-25	336	448	7.8	18.5	16	5.8	83	5
				83-03-02	336	488	8.2	18.5	16	5.9	82	5
				83-07-21	336	490	8.3	19.0	16	5.9	82	5
8	05N/26E-05D01 ^a	WNPM	--do--	81-07-23	1,002	520	8.1	--	2.3	.23	101	17
9	05N/26E-05N02	SDLM	--do--	82-03-30	525	465	8.8	19.0	3.6	.50	100	14
10	05N/27E-04C01	SDLM	--do--	82-03-30	298	570	7.7	18.0	41	23	45	1
11	05N/28E-05C01	SDLM	--do--	71-10-18	455	522	7.9	--	14	4.1	80	5
12	05N/28E-06R02	WNPM	--do--	82-03-30	450	475	8.6	16.0	4.2	.89	97	12
13	06N/20E-22G01	SDLM	Klickitat	82-09-04	172	196	7.5	12.5	18	7.6	12	.6
				83-03-02	172	208	7.6	11.0	20	8.2	12	.6
14	06N/20E-30P01	WNPM	--do--	82-04-01	120	170	7.1	11.5	16	7.2	7.6	.4
				84-04-20	120	163	7.2	11.5	15	6.9	7.7	.4
15	06N/23E-11Q2D1	WNPM	--do--	70-10-21	892	348	8.1	22.0	6.2	2.4	64	6
				70-12-11	892	348	8.1	20.0	6.3	2.7	64	6
16	06N/23E-11Q01	SDLM	--do--	62-04-30	208	344	8.1	21.0	12	4.1	55	4
17	06N/23E-15H01	WNPM	--do--	70-10-22	683	345	7.9	21.0	6.8	2.7	64	5
18	06N/23E-22J01 ^a	WNPM	--do--	81-07-23	1,069	360	7.5	--	4.8	1.1	70	8
19	06N/23E-24B01	WNPM	--do--	82-03-29	965	333	8.3	20.5	6.2	2.2	64	6
				82-08-25	965	358	8.3	21.0	6.1	2.2	63	6
				83-03-07	965	358	8.2	19.5	6.3	2.3	65	6
				83-07-19	965	343	8.4	24.5	6.4	2.3	64	6
20	06N/24-23N01	SDLM	Benton	82-08-25	220	448	7.5	19.0	41	15	20	.7
				83-03-07	220	422	7.5	17.5	43	16	20	.7
				83-07-19	220	430	7.8	18.0	42	15	20	.7
21	06N/26E-15M01 ^a	WNPM	--do--	82-05-05	960	380	8.5	--	4.0	1.9	100	11
22	06N/26E-19K01	SDLM	--do--	82-08-26	345	1,020	7.6	19.0	85	44	85	2
				83-03-02	345	1,330	7.5	17.5	94	52	91	2
				83-07-20	345	1,460	7.6	18.5	98	58	96	2
23	06N/29E-08M01	SDLM	--do--	71-10-19	146	1,090	7.6	15.0	69	60	95	2
24	07N/22E-09E01	WNPM	Yakima	82-03-29	297	385	7.4	14.5	40	16	20	.7
				84-04-19	297	356	7.4	14.0	39	16	18	.6
25	07N/22E-36H01	SDLM	--do--	82-03-29	304	275	7.7	15.5	14	7.8	27	1
26	07N/23E-36R01	WNPM	--do--	82-03-31	805	330	8.3	19.0	9.0	2.5	58	5
27	07N/24E-26801	SDLM	Benton	82-03-31	532	290	7.8	19.5	25	10	20	.9
28	07N/25E-12R01	SDLM	--do--	82-03-30	446	450	8.1	18.5	27	9.5	49	2
29	07N/25E-36N04	WNPM	--do--	72-08-03	860	454	8.2	22.0	8.0	1.4	88	8
				72-08-04	860	454	8.2	22.0	4.5	1.4	92	10
				72-10-05	860	430	8.2	21.5	5.6	1.7	81	8
30	07N/25E-36P01	WNPM	--do--	82-03-31	860	410	8.3	21.5	6.8	1.9	80	7
				84-04-18	860	403	8.3	21.5	5.1	1.7	80	8
31	07N/26E-04E01	SDLM	--do--	82-08-26	300	470	7.8	18.5	32	13	37	1
				83-03-02	300	425	8.2	11.5	32	13	38	1
32	07N/26E-05B03	WNPM	--do--	82-03-31	1,070	490	7.6	20.5	31	11	49	2
33	07N/27E-29Q01	SDLM	--do--	82-03-30	325	1,140	7.4	15.0	120	53	42	.81
34	09N/26E-27K01	WNPM	--do--	70-10-12	670	405	7.8	21.5	30	12	32	1

^aWater analyses from Washington State University, Soil Testing Laboratory, Pullman, Washington.

TABLE 1 --Water-chemistry data for 34 sites in the Horse Heaven Hills--Continued

Site No. (see fig. 1)	Local identifier	Date of sample	Potassium, dissolved (mg/L as K)	Bicarbonate (mg/L as HCO ₃)	Carbonate (mg/L as CO ₃)	Sulfate, dissolved (mg/L as SO ₄)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Nitrogen, NO ₂ +NO ₃ dissolved (mg/L as N)	Silica, dissolved (mg/L as SiO ₂)	Iron, dissolved (ug/L as Fe)
1	03N/21E-09N01	84-04-19	6.5	207	--	15	12	0.70	--	48	69
2	05N/22E-27P02D1	82-08-25	15	211	0.00	17	6.4	.70	<0.10	59	24
		83-07-19	17	214	.00	18	6.0	.70	<.10	58	27
3	05N/23E-03A01	61-05-05	4.3	--	--	46	27	.50	--	55	--
4	05N/23E-13R02	82-03-31	13	206	5.0	<5.0	8.4	1.1	<.10	62	9
5	05N/23E-30D01	82-08-25	13	211	.00	8.0	6.9	.60	.52	58	36
		83-03-02	13	212	.00	7.5	6.9	.70	<.10	58	86
		83-07-19	14	216	.00	7.0	6.7	.60	<.10	58	43
6	05N/24E-28G01	82-03-29	5.0	183	.00	78	41	.30	4.5	50	9
7	05N/25E-22M01	82-08-25	8.6	200	.00	68	15	1.1	<.10	56	30
		83-03-02	8.3	198	.00	66	18	1.1	<.10	55	30
		83-07-21	8.6	200	.00	61	18	1.1	<.10	55	36
8	05N/26E-5D01 ^a	81-07-23	15	234	.00	5.5	--	--	<.10	--	--
9	05N/26E-05N02	82-03-30	8.7	241	7.0	5.0	25	1.9	<.10	60	9
10	05N/27E-04C01	82-03-30	6.8	214	.00	69	22	.60	10	50	11
11	05N/28E-05C01	71-10-18	26	192	.00	65	27	1.1	<.10	68	20
12	05N/28E-06R02	82-03-30	10	206	5.0	28	30	2.0	.29	61	11
13	06N/20E-22G01	82-09-04	2.3	123	.00	<5.0	2.5	.40	.80	63	<3
		83-03-02	2.4	125	.00	3.7	3.3	.40	1.3	57	<3
14	06N/20E-30P01	82-04-01	2.2	97	.00	5.0	1.1	.20	2.9	61	9
		84-04-20	2.2	87	.00	3.4	1.1	.40	--	61	<3
15	06N/23E-11Q2D1	70-10-21	15	--	--	.2	9.1	1.0	--	56	--
		70-12-11	15	--	--	0	9.2	1.0	--	52	--
16	06N/23E-11Q01	62-04-30	11	--	--	2.2	9.8	1.0	--	57	--
17	06N/23E-15H01	70-10-22	13	--	--	.2	8.6	1.0	--	57	--
18	06N/23E-22J01 ^a	81-07-23	14	202	.00	.5	--	--	<.10	--	--
19	06N/23E-24B01	82-03-29	15	210	.00	<5.0	8.7	.80	<.10	57	72
		82-08-25	14	214	.00	<5.0	8.8	1.0	<.10	54	100
		83-03-07	14	237	.00	.4	8.9	1.0	.28	57	100
		83-07-19	14	208	.00	.3	8.6	1.0	<.10	55	29
20	06N/24E-23N01	82-08-25	4.6	152	.00	48	26	.30	1.8	58	<3
		83-03-07	4.6	173	.00	49	29	.30	1.8	59	24
		83-07-19	4.7	153	.00	47	27	.30	1.9	56	25
21	06N/26E-15H01 ^a	82-05-05	16	--	--	6.0	--	--	--	--	--
22	06N/26E-19K01	82-08-26	8.9	163	.00	160	110	.40	45	55	4
		83-03-02	8.8	168	.00	200	120	.40	47	57	8
		83-07-20	9.9	157	.00	210	130	.40	54	55	26
23	06N/29E-08M01	71-10-19	13	--	--	170	43	.60	--	47	10
24	07N/22E-09E01	82-03-29	1.9	202	.00	20	13	.30	1.0	56	9
		84-04-19	2.1	200	.00	20	14	.50	--	54	4
25	07N/22E-36H01	82-03-29	12	140	.00	21	7.0	.30	<.10	53	84
26	07N/23E-36R01	82-03-31	15	210	.00	6.0	8.4	.30	<.10	57	130
27	07N/24E-26B01	82-03-31	6.5	142	.00	27	7.6	.10	.89	52	16
28	07N/25E-12R01	82-03-30	17	208	.00	45	20	.50	<.10	62	96
29	07N/25E-36N04	72-08-03	14	--	--	18	17	1.1	--	61	--
		72-08-04	14	--	--	18	18	1.1	--	61	--
		72-10-05	14	--	--	24	16	1.1	--	52	--
30	07N/25E-36P01	82-03-31	17	210	.00	27	26	.60	<.10	55	25
		84-04-18	13	211	.00	26	15	1.0	--	54	6
31	07N/26E-04E01	82-08-26	5.8	168	.00	41	19	.50	5.0	54	<3
		83-03-02	5.6	165	.00	42	20	.50	5.1	53	<3
32	07N/26E-05B03	82-03-31	18	214	.00	56	20	.20	<.10	69	290
33	07N/27E-29Q01	82-03-30	7.5	191	.00	250	120	.20	22	54	<9
34	09N/26E-27K01	70-10-12	9.0	--	--	54	12	.40	--	59	--

^aWater analyses from Washington State University, Soil Testing Laboratory, Pullman, Washington.

Water Quality for Irrigation

All water used for irrigation contains some dissolved solutes. The suitability of water for irrigation generally depends on the types and amounts of materials in solution. Irrigators must deal with the effects of water quality and irrigation practices on soil salinity and sodium content, as these characteristics can significantly influence crop production.

Continued irrigation with water having a high sodium concentration relative to calcium and magnesium can result in the formation of sodic soils. When such soils are wetted they become sticky and nearly impervious to water. They harden on drying, and when cultivated, tend to form clods that make tillage difficult. In irrigation water having a high proportion of sodium relative to total cations, sodium ions tend to adsorb on clays. Calcium and magnesium can displace this sodium (ion exchange) if calcic water is applied to the soil. This exchange is a reversible process, and the direction in which the reaction proceeds depends on the concentration of sodium and its relation to the concentration of the other cations in the soil water. Since the cation exchange process is reversible, a sodic soil can be improved by applying gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which on dissolving yields a more calcic soil water that facilitates the beneficial exchange.

The SAR of an irrigation water is a means of assessing its capacity to affect soil properties adversely. The U.S. Department of Agriculture Salinity Laboratory (1954) defined the SAR as follows:

$$\text{SAR} = \frac{\text{Na}}{\sqrt{(\text{Ca} + \text{Mg})/2}}$$

in which the concentrations of sodium (Na), calcium (Ca), and magnesium (Mg) are expressed in milliequivalents per liter. Their experiments show that the SAR predicts reasonably well the degree to which irrigation water will enter into cation-exchange reactions with clays. A high SAR indicates a greater potential for sodium replacing adsorbed calcium and magnesium on the clay fraction of the soil. This potential is evaluated by considering the SAR relative to the total amount of dissolved material present, as represented by the specific conductance. Bortleson and Cox (1985) discussed this relationship in the context of basalt ground waters in the Columbia Plateau in Washington State.

Acknowledgments

The authors extend their gratitude to farmers, ranchers, and others who made their wells available for water sampling and water-level measurements. Also acknowledged are agencies that provided personnel and special assistance to gain access to publicly owned wells.

DESCRIPTION OF THE STUDY AREA

The Horse Heaven Hills is a broad upland area in the southwestern part of the Columbia Plateau. The crest of the Horse Heaven Hills ranges in altitude from about 4,600 feet in the western part of the study area to 2,000 feet in the eastern part, near Wallula Gap. North of the crest, the hills descend steeply to the Yakima River. Except for an abrupt descent in the western part, the region slopes gently southward to the Columbia River. A narrow ridge that parallels the Columbia River interrupts the south facing slope at the river.

Geologic Structure

The Horse Heaven Hills area is one of moderately variable geologic structure. Major structural features are identified in figure 2. The asymmetric Horse Heaven anticline dominates the area, extending about 45 miles east-northeast roughly from Satus Pass, then turning abruptly southeast for about 30 miles before reaching Wallula Gap. A shallow, northeast-southwest oriented syncline is in the center of the south-facing dip slope of the Horse Heaven structure. The sharply folded Columbia Hills anticline and the accompanying Umatilla syncline bound the Horse Heaven area on the south. The Horse Heaven anticline is bounded along its north and northeast flanks, by northeast- and northwest-oriented shear faults. Isopach maps of formations within the Miocene Columbia River Basalt Group indicate that major structures were developing during extrusion of the lavas (Packard and others, U.S. Geological Survey, written commun., 1984).

Lithologic Units

The Horse Heaven Hills are composed of primarily Miocene flood basalts of the Columbia River Basalt Group (figure 3). Individual basalt flows range in thickness from a few inches to more than 100 feet, and their cumulative thickness within the study area is probably greater than 5,000 feet. The basalts probably overlie Mesozoic sediments and metasediments, but no well has been drilled to these beds in the study area.

The Ellensburg Formation comprises numerous clastic units of Miocene age. They variably overlie the Columbia River Basalt Group or are interbedded or interfingering with individual flows in the group. Some members and interbeds of the Ellensburg Formation are areally extensive and can serve as stratigraphic divisions between individual formations within the group. Members and interbeds of the Ellensburg Formation are most numerous in the Saddle Mountains Basalt, less common in the Wanapum Basalt, and rare in the Grande Ronde Basalt. They are dominantly fine-grained and consist of volcanic ash and fluvial, lacustrine, or aeolian deposits.

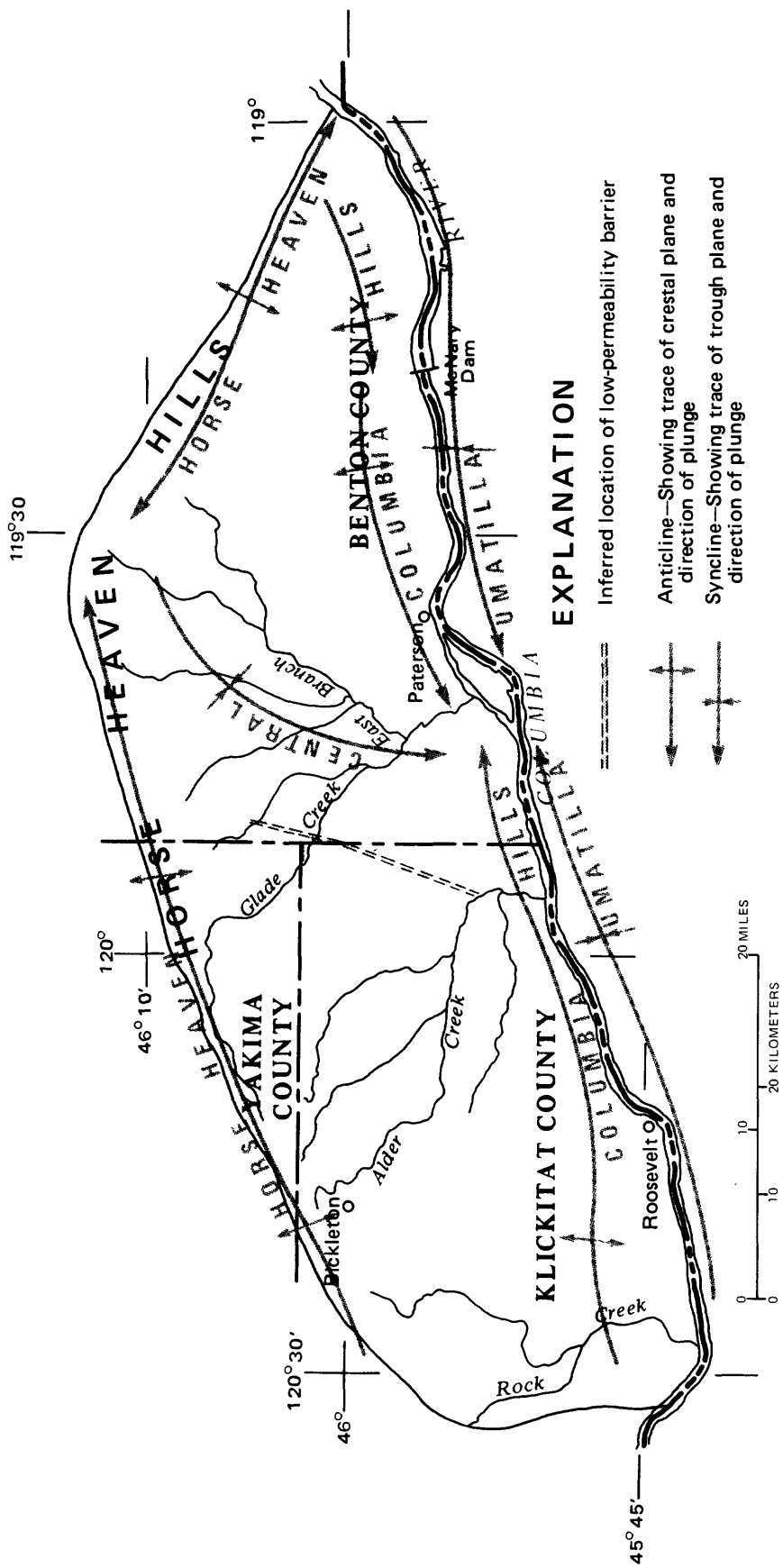


Figure 2. — Major structural geologic features in the Horse Heaven Hills area.

SERIES	FORMATION	
Holocene Pleistocene Pliocene	Surficial deposits	
Miocene	Columbia River Basalt	Ellensburg formation
		Saddle Mountains Basalt
		Wanapum Basalt
		Grande Ronde Basalt
		Imnaga Basalt
	? Pre-Tertiary ? basement rocks	
Oligocene		

Figure 3. – Generalized stratigraphic column.

The formations in the Columbia River Basalt Group of geohydrologic interest in the Horse Heaven Hills are the Saddle Mountains, Wanapum, and Grande Ronde Basalts. The youngest, the Saddle Mountains Basalt, is found at the surface over most of the area. Exceptions are where deeply entrenched streams expose the underlying Wanapum and Grande Ronde Basalts, and where faulting has brought these older rocks to the surface. The Saddle Mountains Basalt contains three major flows and is about 600 feet thick in the synclinal areas. It thins to less than 100 feet along parts of the Horse Heaven crest.

In the uneroded parts of the area, the Wanapum Basalt is made up of 8 to 10 flows. Its thickness ranges from about 600 feet at places along the Horse Heaven crest to greater than 1,000 feet in the synclinal areas to the south. The Grande Ronde Basalt underlies the entire study area, comprising up to several hundred flows, and is probably greater than 3,000 feet thick (Mitchell and Bergstrom, 1983).

Basalt Mineralogy and Physical Characteristics

The formations comprising the Columbia River Basalt Group consist primarily of plagioclase feldspar, pyroxene, and opaque metal oxides. Labradorite, a calcium-sodium aluminosilicate (plagioclase), is the most abundant crystalline component. Augite (pyroxene) is a calcium-magnesium-iron aluminosilicate, while the opaque material is commonly a titanium-iron oxide. A suite of accessory minerals, including apatite, olivine, and metallic sulfides, is present in varying amounts. The primary minerals are present as intergrown and isolated crystals in a glassy or cryptocrystalline matrix. Also present is a suite of secondary minerals that formed after the basalt was emplaced.

Igneous rocks commonly exhibit large scale structural features. These features facilitate the permeation, to some extent, of water into and through the rock, and are often the site of secondary mineral deposition. The most significant structures in the Columbia River basalts are vesicles and fractures. Vesicles are voids that formed usually in the tops and bottoms of individual basalt flows when volatile materials exsolved from the fluid lava. Together with the often rubbly flow tops and bottoms, they permit both vertical and horizontal fluid movement.

Fractures are the products of differential contraction during cooling, and of post-emplacement folding and faulting. The variations in cooling rate in thick lava flows produce fracture patterns with varying continuity and developmental symmetry. The slowest-cooled sections of thick flows commonly have fairly regular fractures manifested as roughly continuous joints, yielding vertical columns ranging from less than one inch to 16 feet in diameter. These structures comprise the colonnade zone of a flow. Typically overlying this zone is a faster-cooled section known as the entablature zone, made up of smaller columns with varying orientations, often with irregular cross joints that yield a hackly or friable structure. The entablature generally grades upward into a zone of less well-defined columns, then into the flow top. Fluid movement in these jointed zones is largely vertical.

Hydrology

Ground water in basalt aquifers occurs in joints, vesicles, fractures, and other localized features that create permeable zones (fig. 4). The highest permeabilities occur in the flow tops, while relatively high permeabilities are also found where the colonnades have vesicular bases. The entablature and much of the colonnade of most basalt flows have lower permeabilities, as they are more dense and coherent. Permeability is often increased by the presence of associated joints and fractures where basalt flows are folded or faulted. Interbeds also serve as aquifers in those areas where their lithologies facilitate the storage and transmission of water. As shown in figure 4, ground-water movement is both vertical and lateral in interbeds and flow tops, but primarily vertical in the thick central portions of most basalt flows.

Most of the water in the basalts originates as precipitation. That portion of precipitation not lost via evapotranspiration or surface runoff can percolate into the subsurface to become ground water. After entering the saturated portion of the basalts, the water tends to move both downward and laterally in the aquifer, from higher to lower water-level elevations.

The crest of the Horse Heaven anticline delineates a divide within the ground-water flow system in the Wanapum and Saddle Mountains Basalts. North of the crest ground water flows toward the Yakima River, while to the south it flows toward the Columbia River. The divide is characterized by higher ground-water recharge and lower horizontal permeabilities. The Saddle Mountains Basalt is essentially unsaturated in places along this divide.

In most of the study area, ground-water levels in the Saddle Mountains Basalt are higher than those in the Wanapum Basalt, indicating that ground-water movement is downward from the upper to the lower formation. Numerical simulation studies infer that flow is also downward from the Wanapum Basalt into the Grande Ronde Basalt (Packard and others, U.S. Geological Survey, written commun., 1984). These studies also indicate, however, upward flow from the Grande Ronde Basalt, through the Wanapum Basalt, to the Saddle Mountains Basalt in a general area beneath and several miles each side of the Columbia River (fig. 5) which is considered a line sink.

Packard and others (U.S. Geological Survey, written commun., 1984) infer from higher water levels in the Wanapum Basalt that ground-water flow is upward from the Wanapum Basalt to the Saddle Mountains Basalt in a northeast-trending zone 5 to 6 miles wide in the central part of the study area (fig. 5). This upward flow is apparently caused by a vertical, north-northeast oriented zone of low permeability. The zone is evinced by locally steep hydraulic gradients within the Wanapum Basalt, by a mapped change in structural gradient in the Mabton interbed of the Ellensburg Formation, and by thickness variations of basalts and interbeds (Packard and others, U.S. Geological Survey, written commun., 1984). Although there is no surface expression, one inference is that this barrier lies along a shear fault zone that offsets permeable flow tops and is perhaps the site of extensive secondary mineralization, which could significantly reduce permeability.

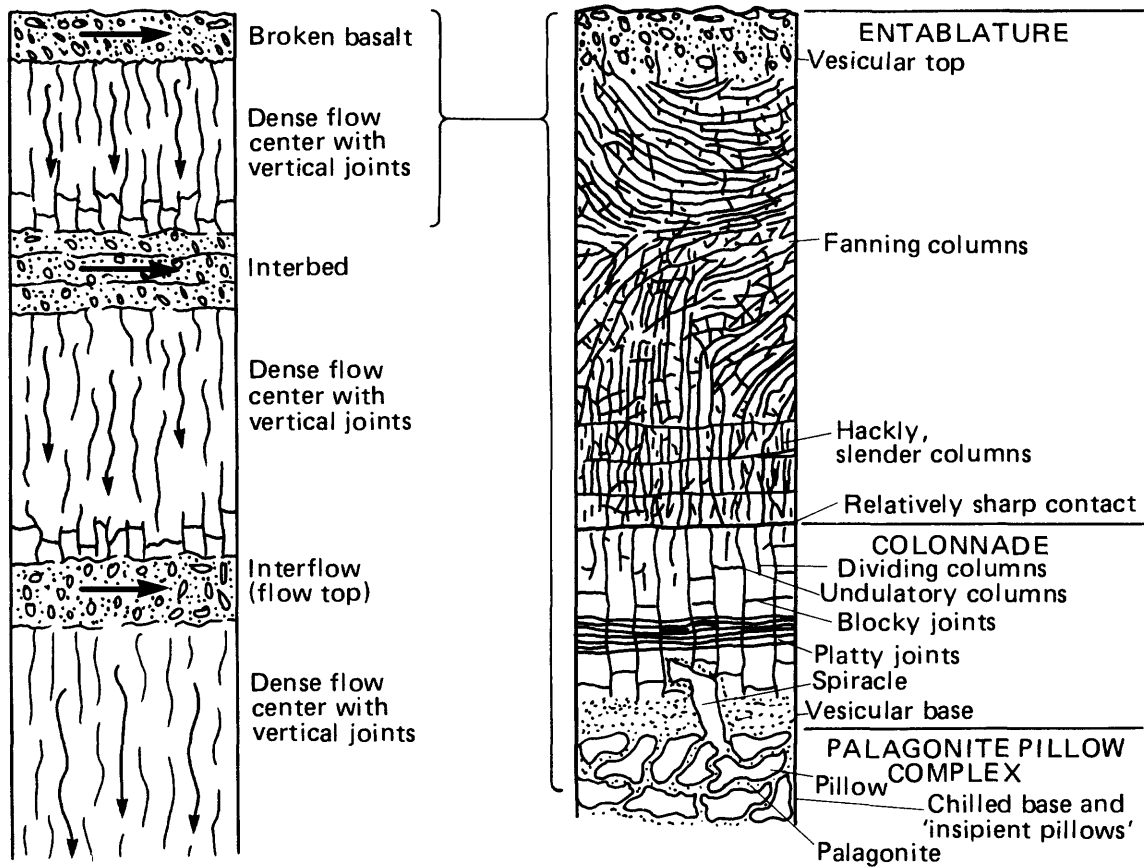


Figure 4. — Idealized basalt flow structures and ground-water flow directions. Size of arrow indicates relative ease of movement of ground water through material. Modified from Swanson, 1967.

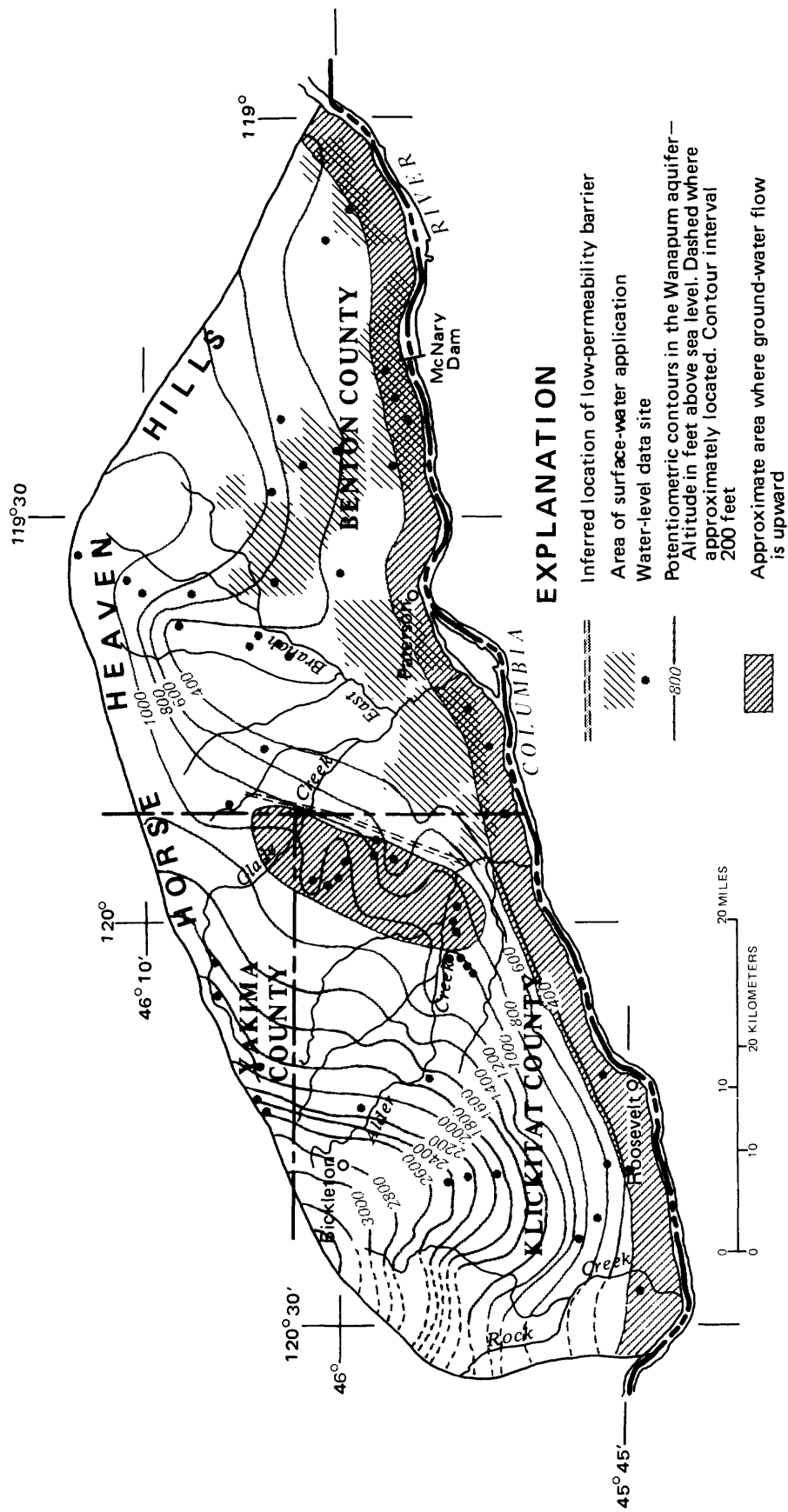


Figure 5. — Potentiometric map of the Wanapum Basalt, Spring 1980.

BASALT-GROUND WATER INTERACTION

Mineral dissolution and precipitation, ion sorption and desorption, and oxidation-reduction reactions are the likely geochemical processes that determine the dissolved materials present in ground waters in the Columbia River Basalt Group. Although the relative significance of each general process probably varies somewhat with position in the flow system (for example, very deep vs. very shallow waters), this potential variation was not investigated in this study. Crystalline and amorphous phases in the basalts participate in rock-water chemical reactions and are the sources and sinks for most of the dissolved species present.

The concentration of a specific solute in a ground water mass is determined by: 1) the composition of the water when it first entered the aquifer system; 2) the materials with which the water is or has been in contact, and their respective solubilities; and 3) the residence time of the water in the system. Waters recharging the system are of variable origin and composition. They can be precipitation; irrigation waters, both ground and surface; stream waters; or any combination of the above. The ultimate composition of these waters is a function of their origins and travel paths.

Water entering the aquifer in outcrop areas, or in areas where no significant soil has developed, is essentially unchanged during the recharge process. That entering via a soil zone dissolves carbon dioxide, lowering its pH and increasing its capacity to dissolve many of the solid phases it encounters. Subsequent water-rock interactions alter the dissolution capacity, and the direction of change is largely a function of the mineral phases participating and the degree of system isolation with respect to carbon dioxide. The suites of dissolved materials found are the integrated result of these and other related processes.

The rates at which the different aquifer materials in the basalts react with ground waters vary widely. Processes that comprise several reactions are generally limited by the slowest reaction in the sequence. This step determines the rate of production of the overall reaction products. Reaction rates and paths are often unknown, but areal compositional variations noted in ground-water systems, and the general increase in the concentrations of reaction products with increasing residence time evince their existence.

CHEMICAL EVOLUTION OF GROUND WATER

The dissolved species and their areal concentration variations in ground waters in the study area result from the combined effects of physical mixing and chemical reactions between aquifer and soil materials and the ground water. Ground water in the Saddle Mountains and Wanapum Basalts is generally characterized by increasing SAR and dissolved sodium and potassium concentrations from the crest of the Horse Heaven anticline to the Columbia River. For example, the SAR ranges from less than one in the most upgradient waters to 17 in one downgradient well. This pattern is reversed for some components, such as calcium and magnesium, which decrease in concentration downgradient. Agricultural activities probably increase the concentrations of some dissolved species, such as calcium, nitrate, chloride, and (or) sulfate, particularly in the Saddle Mountains Basalt in areas where irrigators use surface water (fig. 5).

The chemical evolution of ground water can be described with a set of hypothetical chemical reactions. One such conceptual model that is appropriate to the Horse Heaven Hills was presented by Hearn and others (1985) and is essentially as follows.

Carbon dioxide charged water enters the basalts and contacts the various solid phases. Volcanic glass, cryptocrystalline matrix, pyroxene, and labradorite begin to dissolve because of the mildly acidic character of the water and hydrolysis of the less-crystalline and silicate mineral phases. The glassy and cryptocrystalline materials are the most soluble phases present (Jones, 1966) and are likely the most significant contributors of dissolved material. Studies of weathering profiles (Goldich, 1938; Craig and Loughnan, 1964) and qualitative observations of basalt cores from the Columbia Plateau (Benson and Teague, 1982) indicate that pyroxene is more readily dissolved than the plagioclase. Dissolved oxygen reacts with dissolved ferrous iron, oxidizing it to ferric iron, which precipitates as an amorphous oxyhydroxide. Dissolved aluminum and silicon begin to precipitate as amorphous aluminosilicates and silica after their solubility limits are exceeded. These non-crystalline phases become structurally more ordered with time and form minerals such as goethite, smectite, and quartz. The smectite formation incorporates significant amounts of iron and magnesium, contributing to their removal from solution.

As dissolution progresses, the contribution of hydroxyl ions to solution by the hydrolysis reaction raises the ground-water pH. When the pH exceeds their stability limits, carbonate minerals (primarily calcite) can begin to precipitate, removing calcium, magnesium, and iron from solution, and buffering the ground-water pH. The extent to which the ground water is buffered by this precipitation is largely a function of the availability of carbon dioxide to the system. In those areas where the water is isolated from atmospheric or soil carbon dioxide, the oxidation of organic material in interbeds is probably the only source of carbon.

Sodium and potassium concentrations increase with ground-water residence time, as these species do not significantly participate in the reactions yielding the early formed solid phases. Their concentrations continue to rise until the solubility limit of clinoptilolite, a sodium-potassium zeolite, is exceeded. This is demonstrated, in part, in figure 6, which shows the changes in the relative amounts of calcium, sodium, and magnesium in ground-water samples from selected sites in the Horse Heaven Hills. The data are segregated on the basis of increasing residence time, as estimated by the percentage of modern carbon (per carbon-14 determinations) present in each sample. A trend of increasing sodium concentration and decreasing calcium and magnesium concentrations with increasing residence time (decreasing percentage of modern carbon) is evident in the plot. The sodium and potassium concentrations are the primary limiting factors of clinoptilolite formation, because the silicon concentration does not vary significantly over the study area and is likely controlled by the solubility of an amorphous silica phase. Ion exchange is possibly another mechanism for sodium enrichment. This is supported somewhat by an essentially ubiquitous secondary nontronitic smectite in vesicle and fracture fillings in the basalts.

The evolutionary sequence, in summary, rapidly transforms precipitation-quality water into an alkaline, calcium magnesium sodium bicarbonate water by means of the initial dissolution reactions. With further reaction, this upgradient water evolves to a sodium potassium bicarbonate type with a higher pH and a relatively high SAR, but without a large increase in the total amount of dissolved solutes, as indicated by specific conductance values (table 1).

Variations from the general pattern of downgradient concentration increases are evident in the data used in this study. Figures 7 through 10 show that the ground-water sodium concentrations and SAR's in the Saddle Mountains and Wanapum Basalts increase from north to south. Of particular interest are the wells in the Wanapum Basalt in the northeastern part of Klickitat County (fig. 7). Sites 15, 17 through 19, and 26 have significantly higher values than adjacent wells. The horizontal sodium concentration gradient from site 24 to these wells is about 2.5 milligrams per liter per kilometer (mg/L/km), compared to 1.2 and 1.8 mg/L/km from site 14 to sites 1 and 2, respectively. Sites 15 and 17 through 19 are within the earlier-noted area of upward flow, immediately upgradient from the inferred barrier. The natural upward flux of more-evolved water from the underlying Grand Ronde Basalt is augmented by the ground-water withdrawals in this vicinity, and is the most probable reason for the elevated concentrations found in the Wanapum Basalt.

Site 16 is completed in the Saddle Mountains Basalt, also in the area of upward flow. Its relatively high sodium concentration and SAR (figs. 7 and 10; table 1) support the thesis of contribution from below. This sample was collected in 1962, about 10 years before wells were drilled into the Wanapum Basalt (A. J. Hansen, U.S. Geological Survey, oral commun., 1984), and therefore represents essentially pre-development ground-water chemistry in the upper formation.

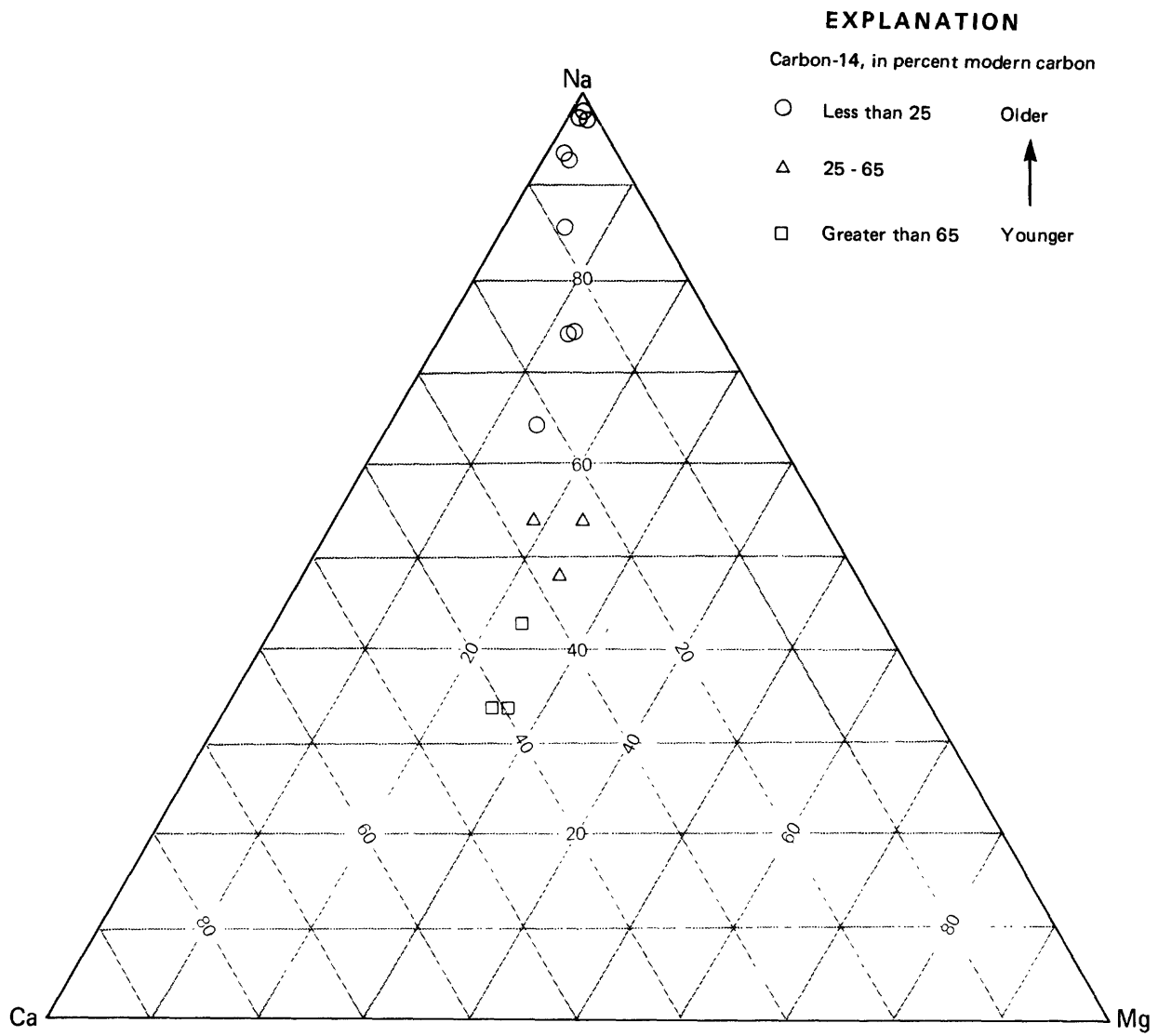


Figure 6. – Dissolved calcium (Ca), sodium (Na), and magnesium (Mg) concentrations (molar) from selected sites, grouped by carbon-14 values.

Site 3 does not appear to conform to the inferred upward flow (fig. 9), although it too was sampled well before development of the lower aquifer. This Saddle Mountains Basalt well, however, is only 81 feet deep and is located in a valley floor about 150 feet from an intermittent stream. Since the well has only 36 feet of casing (unpublished data in U.S. Geological Survey files), it is conceivable that the sample reflects, in part, the chemistry of the intermittent stream. This possibility is enhanced by the fact that the sample was collected in May, at about the mid-period of streamflow for this general vicinity, and there was perhaps sufficient time for stream water to affect the chemical character of water in the shallow basalt.

Site 7, a Saddle Mountains Basalt well nearest the Columbia River, has the highest sodium concentration in the section. This is due, in part, to the upward flux inferred by Packard and others (U.S. Geological Survey, written commun., 1984). The natural accumulation of sodium resulting from the increased residence time is the other contributing factor at this site. The two cannot be quantified at this time, but it should be noted that the sample from site 7 does resemble samples from the Wanapum Basalt in its relative solute species concentrations, and, in the same respect, does not in any way resemble a hypothetical surface water (fig. 11).

Calcium and magnesium concentrations in the Saddle Mountains Basalt are not consistent with the conceptual model described earlier (fig. 12). The anomalously high values seem to be associated largely with areas where surface water is used for irrigation. Other dissolved constituents in the Saddle Mountains Basalt that exhibit relatively high concentrations in the surface-water application areas (fig. 7) are potassium, chloride, sulfate, and (or) nitrate (table 1). The high nitrogen values, in particular, suggest that infiltrating irrigation water carrying dissolved fertilizer residues is a significant component of the ground water in these shallow, saturated basalts.

The hypothesis of the hydraulic and geochemical aspects of the evolution of current water chemistry in the basalts is based on data collected during this study and from studies previously cited. The conceptual model is applicable to the Columbia Plateau in general. It is limited, however, by the lack of thermochemical data specific to the Columbia River basalts. This information gap warrants future study. Additionally, this study did not address the potential for the degradation of ground-water quality, and attendant effects on irrigation use, which could result from current and future resource development. This subject is of significant import to the agriculture-dominated economy of the Horse Heaven Hills and most of the eastern half of Washington State.

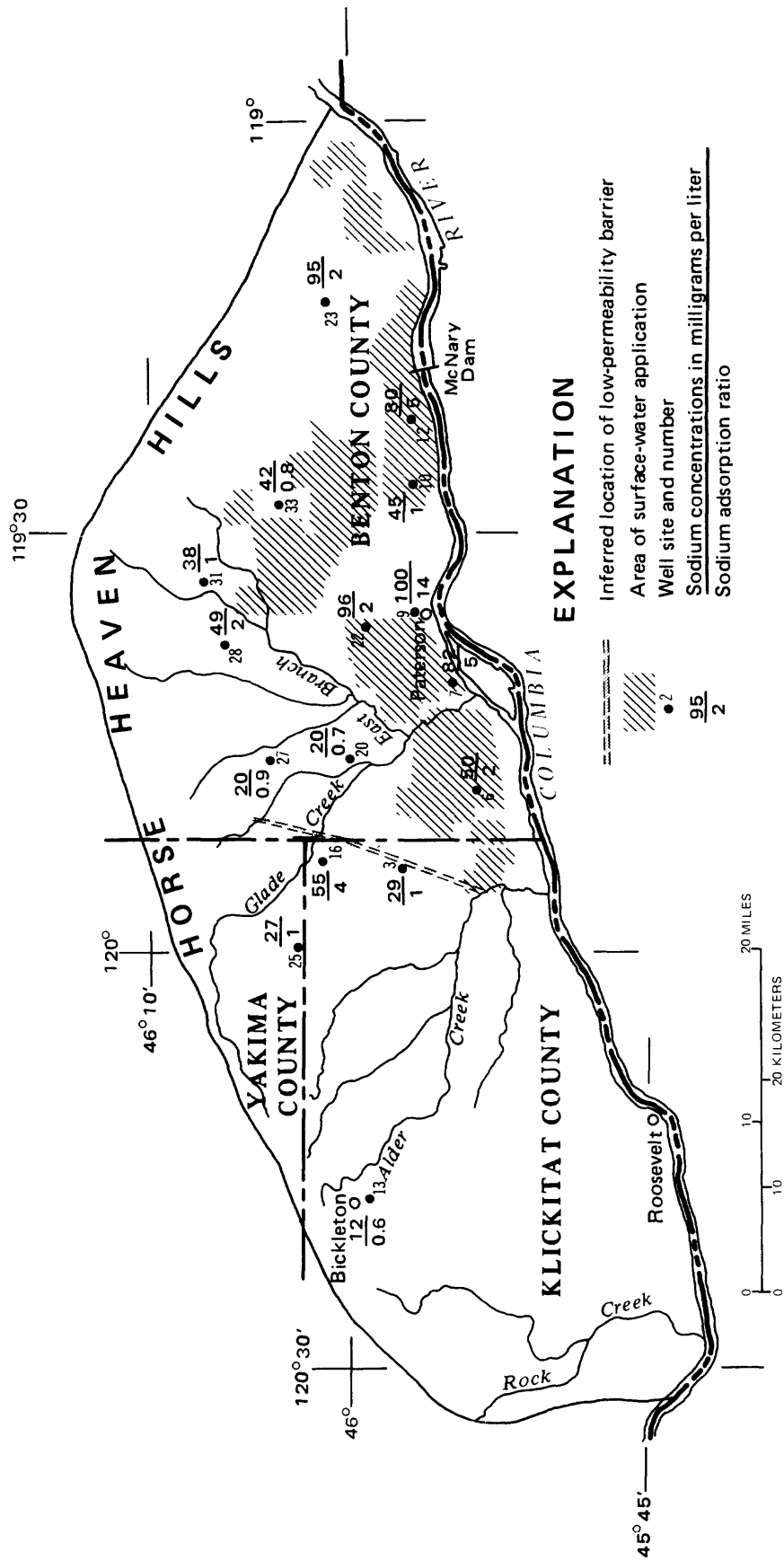


Figure 7. — Dissolved sodium concentrations and sodium adsorption ratios in ground water in the Saddle Mountains Basalt.

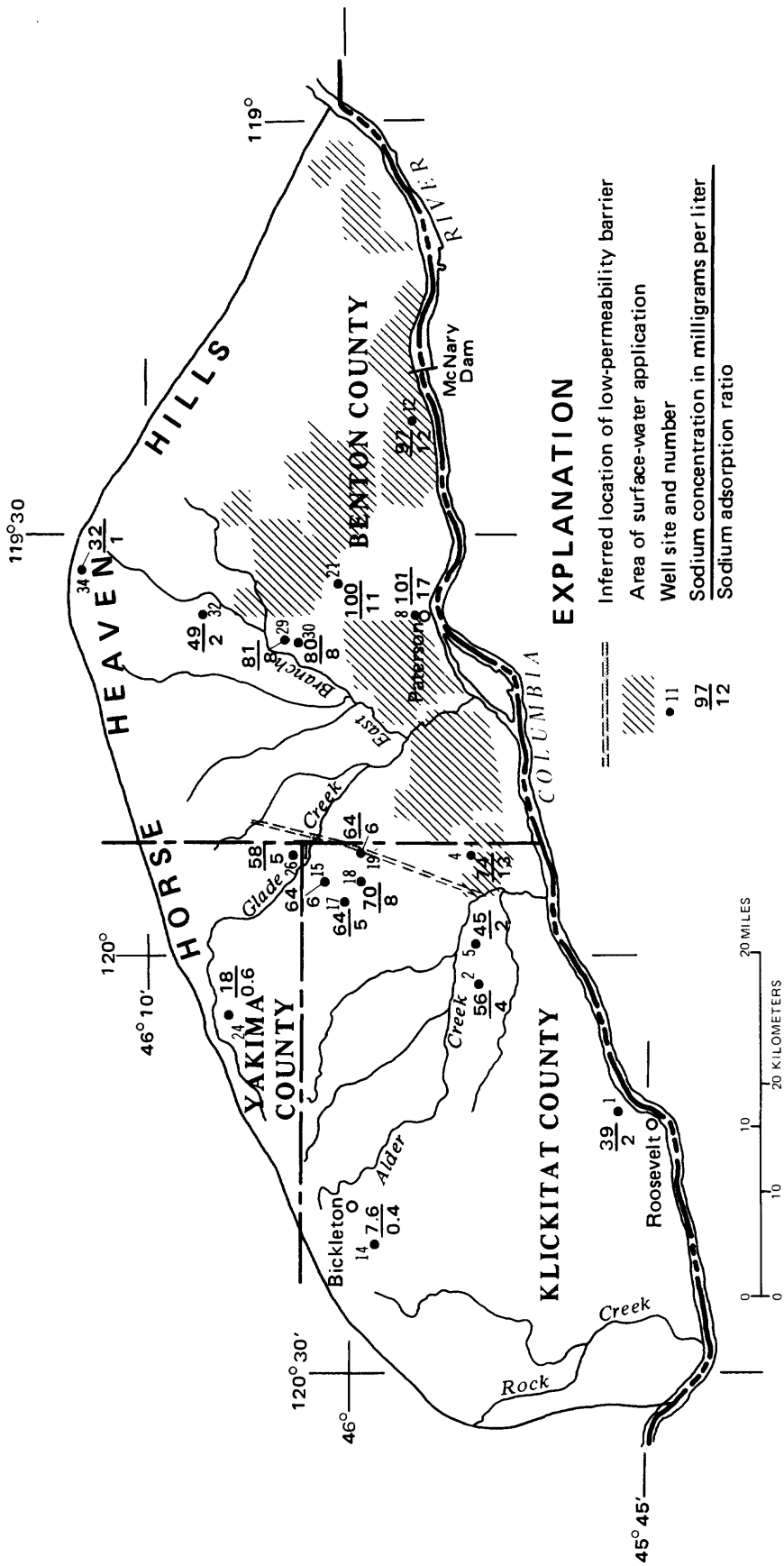


Figure 8. — Dissolved sodium concentrations and sodium adsorption ratios in the ground water in the Wanapum Basalt.

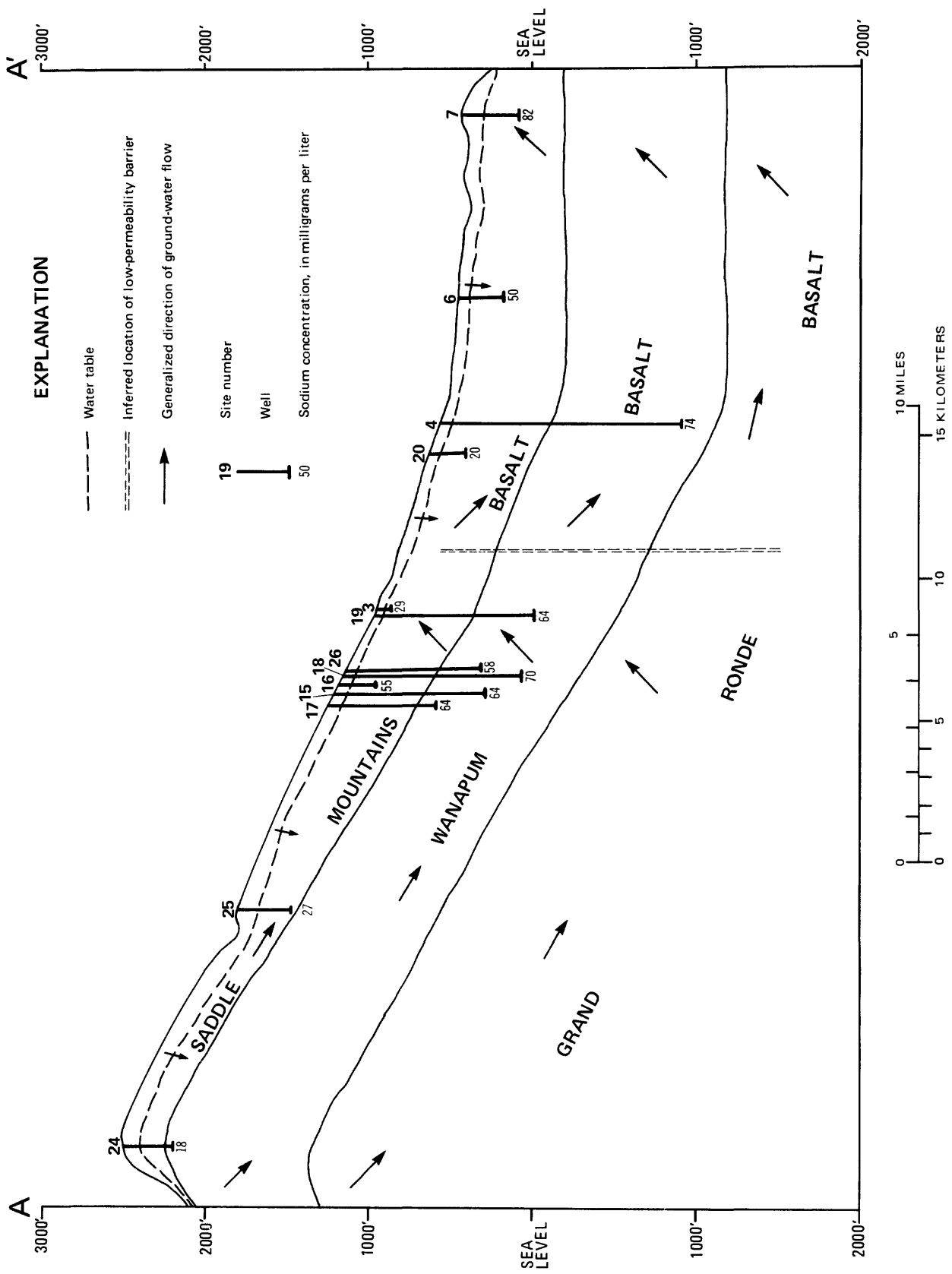


Figure 9. — Generalized geohydrologic section showing generalized direction of ground-water flow and dissolved sodium concentrations.

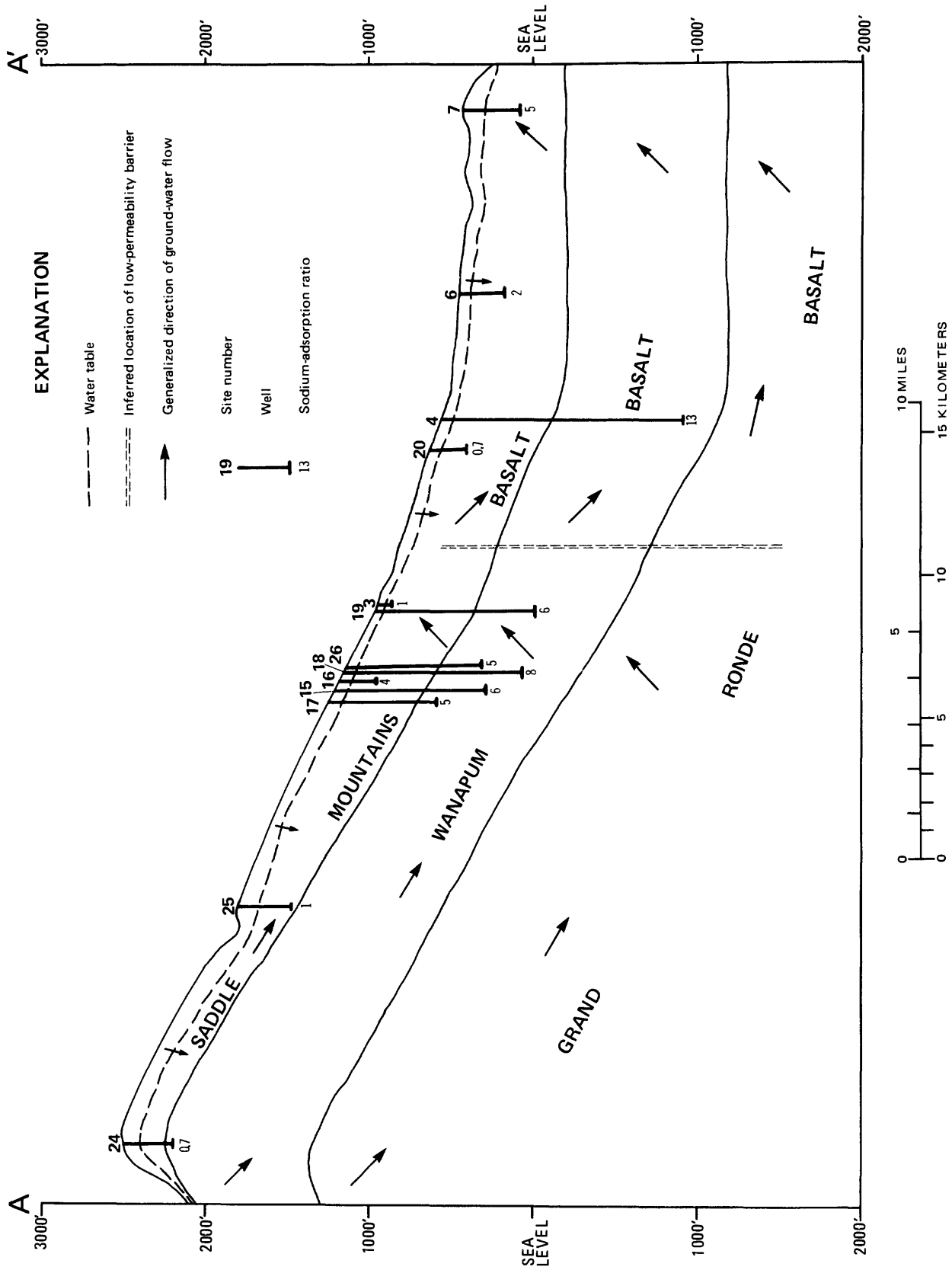


Figure 10. — Generalized geohydrologic section showing generalized direction of ground-water flow and sodium-adsorption ratio values.

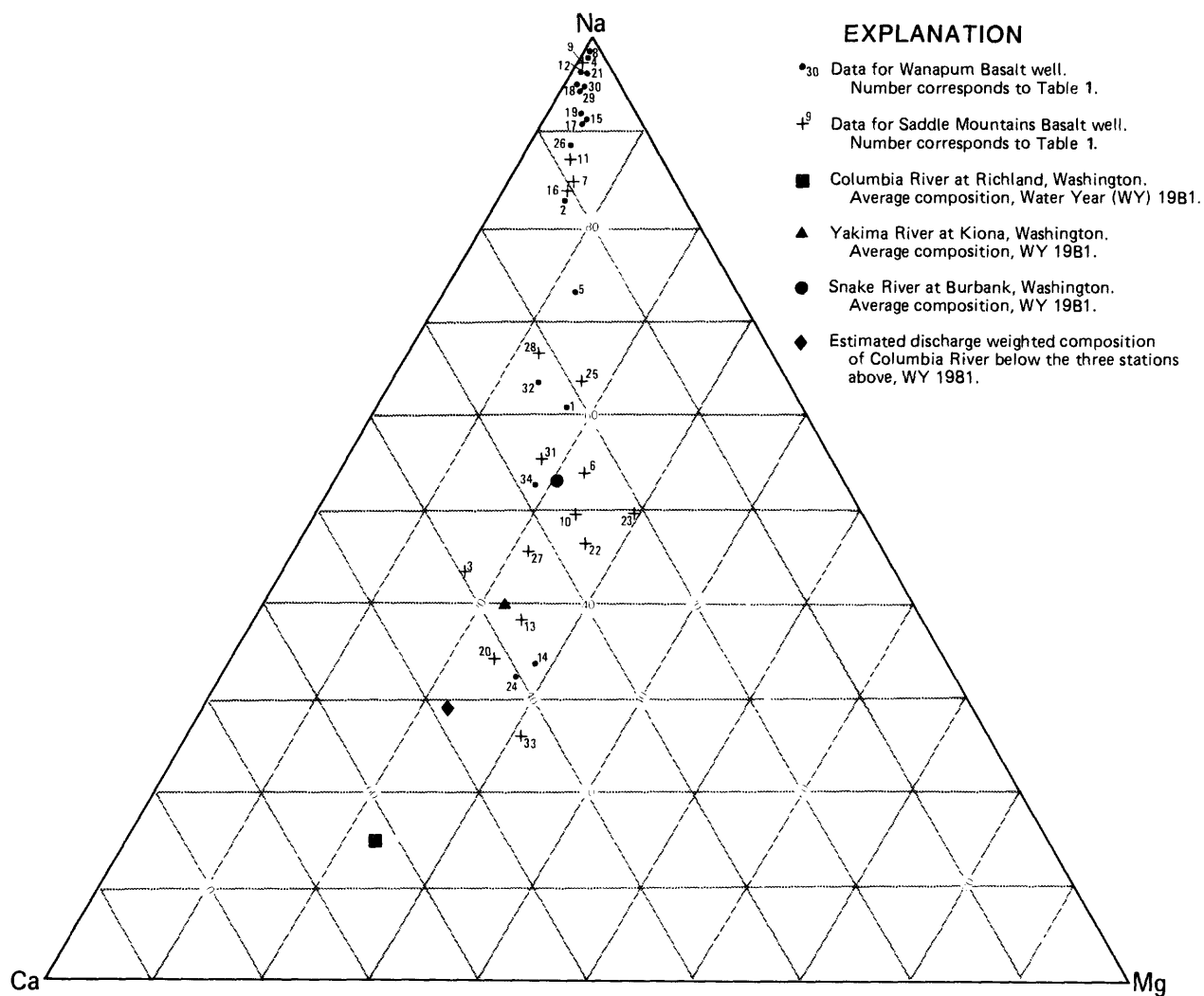


Figure 11. – Dissolved calcium (Ca), magnesium (Mg), and sodium (Na) concentrations (molar) at sites listed in table 1 and at selected surface-water stations.

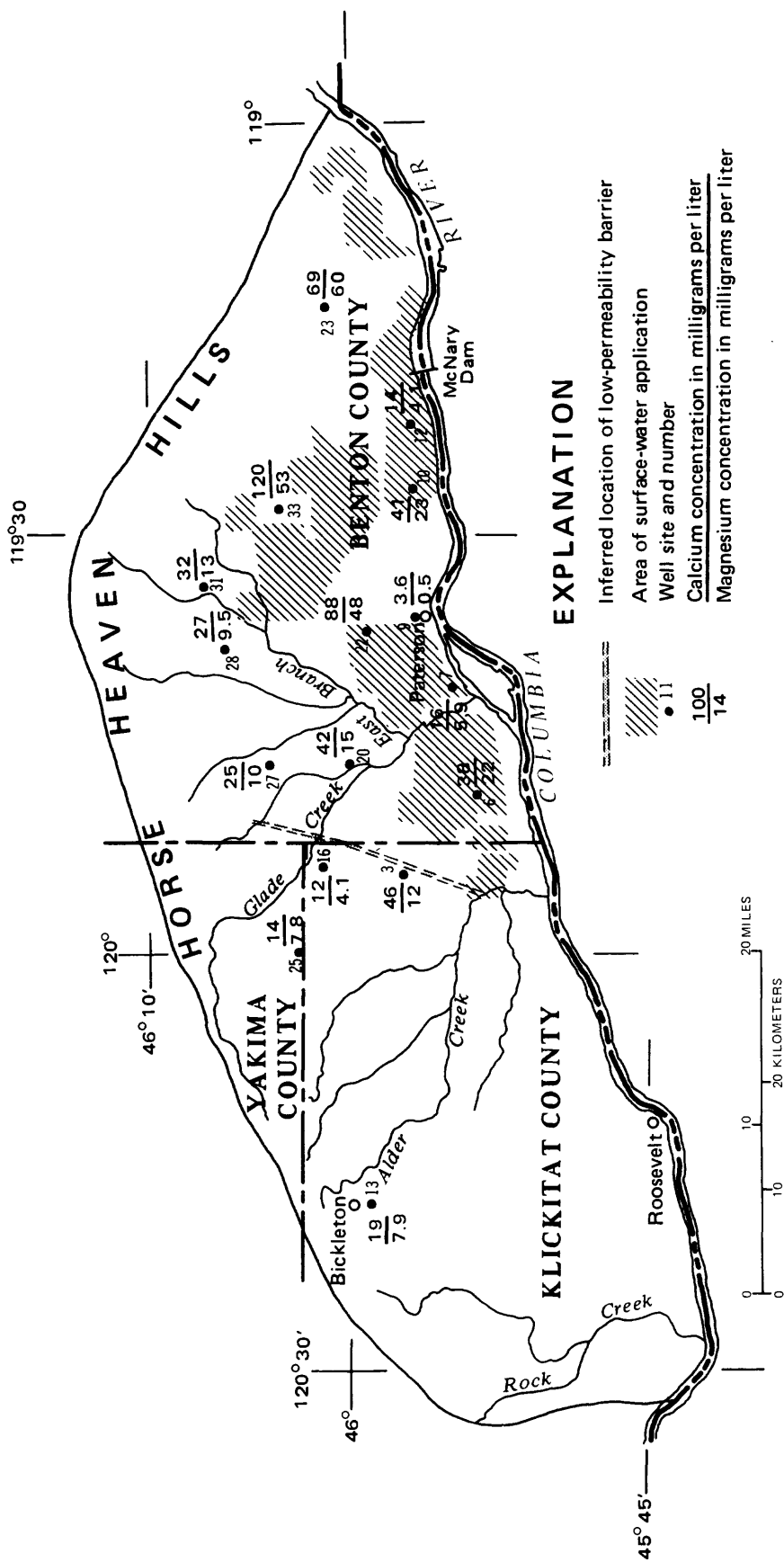


Figure 12. — Dissolved calcium and magnesium concentrations in ground water in the Saddle Mountains Basalt.

SUMMARY

Spatial variations in the concentrations of dissolved species and related water-quality characteristics in basalt aquifers in the Horse Heaven Hills result from water-rock interactions and the nature of the ground-water flow system. Structural and hydraulic data and progressive changes in water chemistry with residence time support this hypothesis.

The dissolved materials present derive largely from the dissolution of glassy and cryptocrystalline phases by carbonic acid attack and silicate hydrolysis. The pH increase resulting from the formation of hydroxyl ion by the hydrolysis reaction is somewhat buffered by the precipitation of calcite. The precipitation of calcite, iron oxyhydroxides, silica, and aluminosilicates controls calcium, magnesium, iron, silicon, and aluminum concentration levels. Ion exchange perhaps also contributes to calcium, magnesium, and sodium variations. Additional iron and magnesium are removed from solution by the formation of smectite. Sodium and potassium concentrations increase until the solubility limit of clinoptilolite is exceeded and this mineral can begin to precipitate. The net effect of this process is the evolution from an upgradient calcium magnesium sodium bicarbonate type ground water to a sodium potassium bicarbonate type downgradient.

Vertical ground-water movement in the vicinities of a geohydrologic barrier and the Columbia River alter the concentration and species distributions expected, based on the conceptual geochemical model. Additionally, irrigation use of Columbia River water appears to increase the concentrations of some solutes commonly associated with agricultural activities in the study area.

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