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CHLORIDE/MAGNESIUM RATIO OF SHALLOW GROUNDWATERS AS A REGIONAL GEOTHERMAL INDICATOR IN HAWAII

MALCOLM E. COX
and
DONALD M. THOMAS

Assessment of Geothermal Resources in Hawaii:
Number 3

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WESTERN STATES COOPERATIVE
DIRECT HEAT RESOURCES ASSESSMENT
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HAWAII INSTITUTE OF GEOPHYSICS
UNIVERSITY OF HAWAII

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ABSTRACT

Because of the complex geological and hydrological conditions and the virtual lack of thermal springs, regional geothermal investigations in Hawaii require the use of techniques substantially different from those conventionally applied in other geothermal environments. The large number of hydrological wells in the state provides an appreciable source of groundwater chemical data. However, largely because of the island environment, interpretation of much of these data as geothermal indicators becomes ambiguous. Initially, SiO_2 and temperature of groundwaters were used to identify thermally anomalous zones, but on a regional basis it has been found that these criteria are not always successful. As a further criterion for assessment, the Cl/Mg ratio of the groundwater has been used. On a state-wide basis, this ratio has been successful in further "screening" the SiO_2-temperature selected sites, and in defining more specific areas which warrant further investigation. Temperature, SiO_2 and Cl/Mg values for nearly 400 groundwater samples are included.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
LIST OF TABLES	vii
LIST OF FIGURES	ix
INTRODUCTION	1
OCCURRENCE OF GROUNDWATER IN HAWAII	2
Dike-impounded	2
Sedimentary and alluvial	2
Basal	3
SILICA - TEMPERATURE CRITERIA	4
Silica	4
Temperature	5
CHLORIDE/MAGNESIUM RATIOS	8
General	8
Theory	9
Chloride	9
Magnesium	11
COMPARISONS OF Cl/Mg RATIOS IN OTHER THERMAL WATERS	12
APPLICATION OF Cl/Mg IN HAWAII	16
Kauai	18
Molokai	18
Oahu	23
Maui	23
Hawaii	23
CONCLUSIONS	30
ACKNOWLEDGMENTS	30
REFERENCES	31
APPENDIX	35

LIST OF TABLES

Table		Page
1.	Comparison of different analyses	6
2.	Averaged values of known thermal and other waters	10
3.	Chemical data of various geothermal waters	13

Appendix

Table

Kauai 37

Molokai 39

Oahu 40

Maui 44

Hawaii 48

LIST OF FIGURES

Figure		Page
1.	Log-log plot of Cl versus Mg for a variety of geothermal waters from different environments . .	15
2.	Characteristics of Cl/Mg ratios for different water types in Hawaii	17
3.	Triangle diagram of Cl and Mg concentratons from Kauai	19
4.	Location of groundwater wells on Kauai	20
5.	Triangle diagram of Cl and Mg concentrations from Molokai	21
6.	Location of groundwater wells on Molokai	22
7.	Triangle diagram of Cl and Mg concentrations from Oahu	24
8.	Location of groundwater wells on Oahu	25
9.	Triangle diagram of Cl and Mg concentrations from Maui	26
10.	Location of groundwater wells on Maui	27
11.	Triangle diagram of Cl and Mg concentrations from Hawaii	28
12.	Location of groundwater wells on Hawaii	29

INTRODUCTION

Geothermal investigations conducted during the 1973-1977 Hawaii Geothermal Project, which led to the successful drilling site of geothermal well HGP-A, were largely restricted to several specific areas. To gain a more complete understanding of the geothermal potential in Hawaii, the current geothermal investigation (Hawaii Geothermal Resource Assessment Program) is conducting a systematic study of the Hawaiian Islands on a state-wide basis.

The initial phase of the regional survey has been the compilation and assessment of all available groundwater chemistry within the state. This approach to geothermal exploration in Hawaii has largely been of necessity. Thermal springs occur only in a small number of coastal locations because of the basaltic terrain and the complex hydrological conditions in this island environment. Consequently many of the reconnaissance investigation techniques employed in continental, or older environments, are unsuitable in Hawaii. The use of existing groundwater chemistry data has provided an excellent first stage reconnaissance tool because of the large number of groundwater wells drilled in Hawaii. Most chemical analyses used in this report are from the files of the Honolulu office of the U. S. Geological Survey.

Two basic criteria were initially established to assess the water chemistry data: temperature and SiO_2 concentrations. Temperatures of greater than 26°C or SiO_2 concentrations greater than 55 ppm for Oahu and 30 ppm for the other islands (H.G.R.A.P., 1978; Thomas et al., 1979) were considered to be anomalous. Studies in the Puna area on the island of Hawaii (McMurtry et al., 1977) showed that the SiO_2 content of groundwater in this active area was indicative of zones of high subsurface temperature. Further application of these criteria for use on a regional basis has shown that many variables exist which lead to ambiguities in interpretation, therefore another geochemical parameter was sought in an attempt to clarify or reinforce the SiO_2-temperature criteria.

Examination of the chemical analyses available showed that under Hawaiian conditions, difficulties arise in using the majority of elements, or ratios of elements, as geothermal indicators. The Cl/Mg ratio appeared to be the most successful indicator for the type of water being studied (shallow groundwater). It distinguishes between those SiO_2-temperature anomalies most likely to be caused by anomalous geothermal heat from those due to other conditions.

This report discusses some of the problems in using the SiO_2-temperature criteria for shallow groundwater assessment

and the applications of the Cl/Mg ratio. Also presented are those areas within the state that are considered to possess potential on the basis of their Cl/Mg ratio.

OCCURRENCE OF GROUNDWATER IN HAWAII

Any regional assessment of the chemical properties of groundwater from a large number of environments is difficult due to the variation in such parameters as depth of well (and casing), topographic and geographic location and the type/s of aquifer which each well penetrates. These variations are major problems in utilizing the SiO_2 concentrations and temperature values of groundwater and make relative comparisons difficult.

One of the most important factors defining the character of the groundwater in a given locale is the type of aquifer from which the water is drawn. Generally, three basic groundwater types can be considered in Hawaii:

(i) dike-impounded - occurs within basalts from near sea-level to high elevations, but is most often associated with rift zones; usually of local recharge. Where this aquifer type occurs near sea-level, and the dikes are parallel to the coast, encroachment of saline water is restricted, and the fresh groundwater will not necessarily be continuous to the deeper underlying saline water (Stearns et al., 1940). Numerous dike formations can form successive reservoirs of this type to higher elevations resulting in a "stepped" groundwater gradient.

(ii) sedimentary and alluvial - occur at lower elevations, usually within the larger valleys and in coastal areas. The sedimentary material is usually of limited thickness and low permeability; however, in large valleys the sediments can be several hundreds of meters thick and of both marine and terrestrial origin. These sedimentary areas are often highly populated and contain many groundwater wells, and consequently infiltration of saline water into alluvial aquifers has in many places been enhanced by continuous pumping. Most of the groundwater is of local recharge, but is often altered chemically because of irrigation and the consequent recycling.

(iii) basal - non-artesian groundwater; underlies all of the major islands in the Hawaiian chain, and can extend to great depth. It is usually transitionary through a zone of mixing to deep saline water in permeable areas with deep lavas (Stearns et al., 1940). This water probably extends to 5 to 6 km below the largest islands and is the major source of groundwater in Hawaii. Cumulative pumping of wells within this aquifer type has also produced some local upwelling of the underlying saline water (Swain, 1973). In much of the state, and especially southern Oahu, the Ghyben-Herzberg freshwater-saline water interface is replaced by a transition zone of mixing due to the artificial and natural dynamic stresses arising from heavy withdrawal and the seasonal nature of the recharge imposed on this deep groundwater (Mink, 1961). On the oldest islands (e.g. Maui, Oahu), the basal aquifer in the coastal regions is capped by marine sedimentary deposits which largely retard inward or outward groundwater migration in the shallow parts of these reservoirs (Mink, 1964).

Divisions among the different aquifers are not always well defined, and aquifers with intermediate characteristics also exist. In some areas of higher elevation, groundwater can be perched on impermeable ash beds. Areas with a low density of dikes and structural permeability will allow more extensive subsurface movement of water. In areas where significant subsurface heat exists, the equilibrium of the Ghyben-Herzberg zone may be destroyed by a lowering of the density of the saline water thus inducing localized upwelling of saline water into the freshwater lens. The chemistry and volume of surface waters and groundwaters in Hawaii is also affected by the prevailing trade wind patterns. The island topography produces distinct windward and leeward climatic conditions which affect recharge rates and create large variations in erosion, weathering, and soil types, in some cases within relatively localized areas; thus any regional survey of groundwaters in Hawaii must be able to distinguish between chemical anomalies due to mixing of geothermally altered groundwater and those caused by other phenomena arising from the localized nature of the hydrogeology.

SILICA-TEMPERATURE CRITERIA

Silica

The silica concentration in thermal waters is widely used as both a qualitative and quantitative indicator of subsurface heat (Mahon, 1966; Fournier and Rowe, 1966; Ellis, 1970; Fournier and Truesdell, 1970). On the island of Hawaii the concentration of SiO_2 was also successfully applied to shallow thermal groundwater (McMurtry et al., 1977). While SiO_2 concentration is reasonably successful as a broad qualitative indicator of anomalous subsurface temperature conditions when applied to all groundwaters in Hawaii, it is affected by many factors which render the interpretation of the data ambiguous.

Two areas of uncertainty exist with the use of the reported SiO_2 concentrations. One is that a variation of from 20 to 85 ppm SiO_2 can occur among different aquifers in the same region; secondly, variations of up to 45% have been noted in different analyses from the same well waters (Table 1). The latter appears to be due to both analytical procedure used and conditions of collection and storage.

The ranges of SiO_2 within waters from different aquifers has been summarized by Davis (1969). He notes that 1 to 3 ppm SiO_2 will almost immediately (minutes) go into solution as rain comes in contact with the ground surface. During surface and subsurface movement of this water, it will reach a SiO_2 content of 5 to 20 ppm before entering high level aquifers. During residence there, the SiO_2 increases to approximately 15 to 45 ppm and is typified by high level (water supply) tunnel water. Water leaking from these aquifers and from soil to the basal aquifers dissolves more silica, resulting in SiO_2 concentrations of 30 to 60 ppm. Higher level water which discharges as streamflow has a SiO_2 content of 15 to 30 ppm. One feature noted by Davis (1969) is that the SiO_2 content of flood or ephemeral streamflow from heavy rainfall is not appreciably lower than that in more continuously flowing streams.

Water entering sedimentary aquifers commonly has a SiO_2 content of 25 to 45 ppm, which increases to 60 ppm while in the aquifer. This water is especially susceptible to further increases in SiO_2 due to recirculation by irrigation and reinjection of industrial water. These latter occurrences can increase the range of SiO_2 values up to 50 to 85 ppm. Visher and Mink (1964) consider that the SiO_2 concentration of 40 to 75 ppm in return irrigation water is derived from accelerated leaching of soil and rock because of the cumulative effect of a greater volume of water, plus the slower movement of groundwater within these low permeability materials.

A further variable in SiO_2 concentration is the residence time of water in aquifers; groundwater appears to continuously dissolve available SiO_2 from the rocks through which it percolates. The high rainfall on the windward side of the islands removes silica more rapidly from soil and rock, resulting in a relatively greater availability of silica for dissolution than in the less weathered rocks of the leeward sides. Other factors causing increases in dissolved SiO_2 are agricultural phosphates (Fox et al., 1967), burning of agricultural wastes and reduction of soil pH (Davis, 1969). A further cause of SiO_2 variations is the natural difference in the chemical composition of the rock types between different areas.

Table 1 compares analytical results from eleven wells in various localities until the present. Six of these wells have average temperatures of 30°C or greater and their complete analyses are included in Table 2. Without engaging in a detailed discussion, the variations in reported silica concentrations can be attributed to both differences in analytical technique as well as in the methods of collection and storage. The earliest analyses by State and Federal agencies are more consistent over time, but the more recent analyses (individuals or departments of the University of Hawaii) show greater variation due to the different storage and analytical techniques applied. Probably the major cause of these variations is the form of storage. Ideally, analyses for silica should be conducted within several days, but it is likely that for most of the older analyses the samples were not analyzed for many weeks. This increases the likelihood of polymerization and many of the earlier reported analyses are lower than more recent ones. Current work by HIG, however, suggests that temporal variations in the SiO_2 concentration do occur.

Temperature

The temperature measurement of groundwater is probably a more reliable identification criterion for a thermal anomaly than is SiO_2; however, its use is currently limited because of the relatively small number of measurements and some questions concerning the accuracy of the reported data. On the extinct volcanic islands groundwater temperatures 27°C and over are considered significant; those greater than 29°C, highly anomalous.

The temperature of groundwater within the aquifers above sea-level is related to both temperature of precipitation and temperature of surface water as it enters the aquifer. Mink (1964) considers that the original water entering an aquifer can gain heat from (i) volcanic activity; (ii) frictional flow;

Table 1. Comparison of different analyses

Well Number	Location	Date	Temp. (°C)	Cl (ppm)	Mg (ppm)	SiO_2 (ppm)	Cl/Mg
HAWAII							
2982-01	Geoth. Test 3	7/75	--	3410	59	--	57.80
		1/75	93.0	3274	52	96.6	62.96
		12/74	86.0	4200	--	184	--
		12/74	88.0	3850	--	187	--
	Average		89.0	3684	55.5	156	60.38
2783-01	Malama-Ki	1/75	52.2	3811	210	100.7	18.15
		1/74	54.0	11000	--	90	--
		9/62	--	5850	324	59	18.06
	Average		53.1	6887	267	83.2	18.11
3081-01	Kaphoho Test	7/75	33.5	316	27.2	--	11.62
		1/75	36.8	303.5	28	71.3	10.84
		12/74	34.0	750	--	53	--
		1/74	38.0	560	--	56	--
		1961	--	320	17.1	70.5	18.71
	Average		35.6	450	24.1	62.7	13.72
2881-01	Allison Well	1/75	37.8	281	15	24.1	18.73
		1/74	38	1400	--	53	--
	Average		37.9	840.5	15	38.6	18.73
6147-01	Kawaihae 3	2/74	31.0	300	--	8	--
		1974	31.0	253	32	84	7.91
		6/63	--	255	31	78	8.23
		6/63	35.8	250	33	89	7.58
	Average		32.60	264.5	32	64.8	7.91
3758-01	Kailua/Kona	1974	25.0	459	27	43	17.0
		6/74	25.0	800	--	40	--
		12/58	--	440	37	26	11.89
		3/55	--	485	35	33	13.86
		11/49	--	450	9.7	46	46.39
		9/49	--	460	28	68	16.43
	Average		25.0	515.7	27.3	42.7	21.11

Table. 1. Comparison of different analyses (cont.)

Well Number	Location	Date	Temp. (°C)	Cl (ppm)	Mg (ppm)	SiO_2 (ppm)	Cl/Mg
MAUI							
4835-01	Ukumehame	10/78	33.1	459	26	115	17.65
		9/74	32	660	--	66	--
		2/70	--	400	29	60	13.79
		10/69	33.0	354	15	59	23.60
		8/69	--	373	17	58	21.94
		4/69	34.0	432	21	71	20.57
		1/69	33.0	400	24	71	16.67
		7/68	--	420	23	68	18.26
	Average		33.0	437.3	22.1	71.0	18.93
OAHU							
2508-02	Waianae	8/78	27.0	260	80	32	3.25
		8/75	28.0	520	--	101	--
		10/71	29.0	292	102	92	2.86
		10/71	29.0	382	108	89	3.54
		2/54	--	520	127	84	4.09
		2/39	--	250	111	87	2.25
		8/39	--	360	130	88	2.77
	Average		28.3	369.1	109.7	81.9	3.13
2808-01	Lualualei	8/78	26.5	138	2.7	38	5.11
		7/75	27.0	430	--	74	--
		2/72	26.7	160	28	63	5.71
		9/57	26.6	165	--	--	--
		12/56	--	164	--	34	--
	Average		26.7	211.4	27.5	52.3	5.41
2812-01	Makaha	8/78	26.0	92	34	40	2.71
		3/71	--	88	--	82	--
		6/70	--	95	--	73	--
		1969	26.5	93	4.9	66	18.98
		2/62	--	100	33	71	3.03
	Average		26.3	93.6	24.0	66.4	8.24
2808-02	Lualualei	8/78	19.0	23	6.5	27	3.54
		2/72	18.5	26	7.4	49	3.51
		2/72	--	26	7.3	49	3.56
		6/67	--	32	6.0	56	5.33
		1966	--	30	8.2	62	3.66
	Average		18.8	27.4	7.1	48.6	3.92

(iii) return irrigation water and relatively limited recharge from rain in irrigated areas; (iv) terrestrial heat flow. The temperature of saline water in deep basal aquifers is increased by approximately 14°C by terrestrial heat flow to temperatures of approximately 23.3°C, as the water migrates from the ocean bottom to the aquifer (Mink, 1964). In regard to the supply of heat to groundwaters for geothermal consideration, the residual heat within intrusive material is considered to be the most significant.

Groundwater temperatures in areas where surface manifestations of volcanic or geothermal activity occur (such as on the lower east rift of Kilauea) have been measured from 30°C to approximately 90°C in shallow hydrological drillholes. In other areas, and especially on the islands where there are no surface expressions of current activity, temperatures are lower, ranging from 18.5°C to as high as 33°C (Appendix I). Observed groundwater temperatures can be related to different aquifer types. High level (usually dike-impounded) groundwater ranges from 18° to 21°C; basal groundwater from 20° to 24°C and sedimentary groundwater from 22° to 26°C. Anomalous temperatures of 27°C and above do not, however, necessarily denote the existence of a significant thermal anomaly. It appears that in some areas, localized and relatively shallow low magnitude thermal anomalies may exist which increase groundwater temperatures by 2 or 3°C.

CHLORIDE/MAGNESIUM RATIOS

General

Because of the numerous factors in Hawaii which affect the chemistry of groundwater, it is difficult to apply a chemical "geothermal indicator" without making a complex and individual assessment of the data from each well. Further, the chemical geothermometers (SiO_2, Na/K/Ca, Na/K) commonly utilized for thermal waters are not applicable to low temperature shallow groundwaters of Hawaii.

Limited application of the Cl/Mg ratio to low temperature groundwaters in New Zealand (Schofield, 1956) was to some degree successful in distinguishing between saline groundwater of marine origin and high chloride groundwater of geothermal origin. Application of this ratio to those groundwaters in Hawaii that have been selected as anomalous (by SiO_2-temperature) provides a further, more controlled criterion for selecting anomalous localities. Of the 397 sets of SiO_2-temperature analyses studied, 53 sets have a significantly anomalous Cl/Mg ratio ($\geq$15) and 30 sets have a marginally anomalous ratio (12.0 to 14.9). The Cl/Mg ratios of an

additional 50 analyses, which were originally rejected by the SiO_2-temperature criteria, were also calculated (not included in this report); except for 6 slightly anomalous cases, all were found to be consistently very low.

Theory

The assumption in using the Cl/Mg ratio as a "geothermal indicator" is that the chloride content of seawater and groundwater remains largely unaffected by thermal processes or ion exchange when seawater infiltrates the island aquifers, or during subsurface groundwater migration. The magnesium ion, however, is strongly depleted in concentration where groundwaters have been affected by thermal processes, thus producing a higher Cl/Mg ratio. Assessing the chemical data available suggests that ratios of greater than that of seawater ($\simeq$15) indicate that anomalous thermal conditions have affected aquifer rock chemistry by hydrothermal alteration or have caused an increased degree of reaction between groundwater and rock (including sedimentary material and clays). Heating of saline water in the deep basal aquifers also enhances Mg depletion.

Chloride

Chloride is the major ion in all forms of water within an island environment such as Hawaii. This includes rain, streams and high level groundwater as well as waters of lower elevation aquifers (Table 2). The chloride is almost entirely of marine origin from airborne salts or saline water infiltration. The higher concentrations of chloride in groundwaters can be related to the amount of "seawater" infiltration by the approximation

$$\% \text{ Seawater} = \frac{100 \text{ (Cl groundwater - Cl streamwater)}}{\text{Cl seawater}}$$

The suitability of chloride as a standard in assessing the amount of seawater mixing is that the chloride ion is highly stable in the groundwater in both basaltic and sedimentary rocks (marine and terrestrial). It does not enter into chemical reaction with other ions or anionic exchange within sediments (Schofield, 1956; Mink, 1961; Swain, 1973). Further, the Cl content of seawater is unaffected even at temperatures of up to 350°C (Bischoff and Seyfried, 1978).

Sources of chloride other than sea salts to groundwaters in Hawaii are considered to be minimal. The chloride content of Hawaiian lavas is low, in the range of 0.01 to 0.2% (Macdonald et al., 1973). Some contribution of chloride from rocks to deep, high temperature groundwaters in areas of

Table 2. Averaged values of known thermal and other waters

Well Number	Name	Temp. (°C)	pH	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Cl (ppm)	SiO_2 (ppm)	HCO_3 (ppm)	SO_4 (ppm)	F (ppm)	NO_3 (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)	As (ppm)	Fe (ppm)	Mn (ppm)
HAWAII																			
--	HGP-A	300	4.4	800	149	96	1.0	1150	501	≈45	≈176	--	--	0.13	<2	0.37	<0.5	--	<0.1
2317-01	Kilauea	79	7.1	610	130	124	63.5	1660	170	--	--	--	--	--	--	--	--	--	--
2982-01	Geothm. Test 3	89	6.4	2025	193	78.9	55.5	3684	156	30	325	--	--	--	--	--	--	--	--
2686-02	Geoth. Test 2 (condens.)	84.5	6.7	--	--	--	--	--	0.55	--	--	--	--	--	--	--	--	--	--
2783-01	Malama-Ki	53.1	7.1	2695	129	122	267	6887	83.2	178	583	1.5	0.5	0.2	0.01	0.2	0.01	3.16	0.05
3081-01	Kapoho Test	35.6	7.1	231	15.2	16.5	24.1	450	62.7	46	160	0.1	0.1	0.1	0.03	0.03	0.01	0.2	0.1
2881-01	Allison Well	37.9	7.18	216	10.8	13.4	15	840	38.6	132	69.2	--	--	--	--	--	--	--	--
--	Allison Spring	31	6.7	--	--	--	--	6500	100	--	--	--	--	--	--	--	--	--	--
--	Isaac Hale Beach Spring	35.5	7.28	2080	86.8	32.4	219.5	4062	88.8	58.5	530	--	--	--	--	--	--	--	--
6147-01	Kawaihae 3	32.6	7.05	132	14	32	32	265	64.8	105	52	0.2	3.6	0.1	0.01	0.1	0.01	1.41	0.05
MAUI																			
4835-01	Ukumehame Shaft	33	7.4	206	18.8	62	22.1	437	71.0	116	44	0.92	9.1	--	--	--	--	--	--
MOLOKAI																			
1011-01	Kahalelani	33.9	7.3	820	--	393	395	2890	38.8	44	244	--	--	--	--	--	--	--	--
OAHU																			
2043-01	Waimanalo	30	7.3	28	1.1	14	2.8	24	22	84	5.4	0.1	0.1	--	--	--	--	--	--
2053-05	Kalihi	30	7.4	52	4.7	23.7	21.9	136	33.5	62	22.9	0.11	0.93	0.11	0.01	0.13	--	0.02	0.05
2054-03	Puuloa Road	32	7.7	58	16	3.4	1.5	620	28.4	--	25.5	0.1	1.86	0.1	0.01	0.1	0.01	0.2	0.05
2300-07	Waipahu PGA	30	7.6	100	0.2	35.7	13.1	131	37.8	51.7	30.5	0.08	0.38	0.05	0.05	0.08	--	0.06	0.01
OTHER WATERS																			
--	Dike-impounded groundwater	20.6	7.49	22.9	2.4	9.3	8.8	19.9	30.1	86.5	13.7	0.17	1.75	0.02	0.01	0.06	--	0.01	0.03
--	Sedimentary acquifer	23.6	7.53	348	14.8	110	74.6	544	62.2	156	122	0.54	9.4	--	--	--	--	--	--
--	Streams	24.5	7.24	12.7	1.1	9.8	8.4	24	15	64	5.9	--	--	--	--	--	--	--	--
--	Rain	--	5.25	4.5	0.4	0.9	1.1	7.9	0.2	--	1.8	--	--	--	--	--	--	--	--
--	Seawater	25	8.2	9600	398	450	1290	19500	4	130	2200	1.0	--	--	--	--	--	0.3	0.07

active volcanism may occur, however. Ellis (1966) experimentally obtained aqueous solutions with 60 and 250 ppm Cl from reactions with distilled water and basalt at 200°C and 300°C respectively. Experiments by Ellis and Mahon (1964) showed that basalt easily lost about 75% of its total chloride to water at temperatures of 300° to 350°C. The conclusion of Ellis and Mahon (1964) was that chloride is easily lost from basalt because much of the leached chloride is held on surfaces within the rocks rather than in solid solution. This may mean that minor amounts of chloride could be gained by groundwaters through low temperature water-rock interaction and a long residence time which would enhance the use of Cl/Mg ratio as a geothermal indicator.

Magnesium

Magnesium ion concentrations can be substantially altered by high temperature reactions. Laboratory studies of water-rock equilibria have shown that magnesium can be effectively removed from solution by the formation of high temperature rock alterations products (Ellis and Mahon, 1964; Mahon, 1967). The two primary removal mechanisms are through formation of chlorite [$Mg_3(Si_4O_{10})(OH)_2Mg_3(OH)_6$] under extreme conditions and illite [$(AlMgFe)_4(SiAl)_8O_{20}(OH)_4$] at lower temperatures. Another high temperature reaction is that of seawater with basalts, which produces precipitates of magnesium oxysulfates (Bischoff and Seyfried, 1978) and hydroxylated magnesium silicates (Mackenzie et al., 1967).

Field studies in Hawaii have identified the higher temperature magnesium silicates (chlorite and illite) in both extinct hydrothermal systems (Fujishima and Fan, 1977) and in drill core from HGP-A geothermal well (Stone, 1977; Stone and Fan, 1978) Intermediate temperature (70° to 150°C) reactions can also deplete magnesium through the formation of smectite clays (Seyfried and Bischoff, 1979).

The sequence of low temperature reactions undergone by magnesium in a basaltic environment can be quite complex. Rainfall, especially on windward sides of the islands, generally carries small concentrations of sea salt and has a Cl/Mg ion ratio of approximately 7. This water percolates down through the island aquifers and very rapidly dissolves enough magnesium from the ferromagnesian minerals in the basalt to lower the Cl/Mg ratio to approximately 2 to 3. Infiltration of saline water into the basal aquifers involves a somewhat different series of reactions. The most important of these is the cation-anion exchange between the intruding seawater and the calcareous marine sediments through which it must pass. Observations on Oahu (Mink, 1961) suggest that the intruding water gains Mg and Ca and loses Na and K to the sediments.

Mink (1961) expresses this reaction by the following generalized equation:

$$Ca, Mg\ clay + 2Na^{+}, K^{+} \Rightarrow 2Na, K\ clay + Ca^{++}, Mg^{++}$$

The saline water, after entering the basaltic aquifer, undergoes little further exchange and, as a consequence, basal waters that have been mixed with small amounts of intruding seawater commonly have Cl/Mg ratios ranging from 2 to as high as 6. Ratios of 5 to 8 are common in sedimentary aquifers in areas of low topography (large valleys; coastal strips) where some Mg loss to clays produced by weathering occurs. Some saline water infiltration is also common within these aquifers, often having been enhanced by continuous pumping of a large number of wells.

Thus the overall indication and assumption applied is that lower temperature reactions undergone by magnesium maintain a Cl/Mg ratio in the range of 1 to 8 for most Hawaii groundwaters; however, as groundwater temperatures increase, magnesium concentrations are severely depleted, resulting in a substantial increase in the observed Cl/Mg ratios. The depletion of magnesium and consequent higher Cl/Mg ratios appear to continue to be reflected even after the heated waters have been cooled to near-ambient temperatures through conduction or mixing with cooler non-saline waters.

COMPARISONS OF Cl/Mg RATIOS IN OTHER THERMAL WATERS

In order to further assess the applicability of the Cl/Mg ratio as a tracer for thermal groundwaters, the ratios have been calculated for a number of geothermal systems (Table 3) in a variety of terrains. Included in this tabulation are thermal waters from other island environments, many of which also have appreciable seawater mixing, as well as those typical continental geothermal systems. The Cl and Mg values for these waters have been plotted logarithmically (Fig. 1) relative to the average parameters of these ions in Hawaiian waters.

Three general groupings emerge: waters from vapor-dominated systems, low chloride thermal waters, and high chloride waters associated with area of active volcanism. True vapor-dominated systems are generally characterized by low chloride, high SO_4, and low pH. Water discharged from steam-dominated systems plot in the upper left-hand quadrant of Figure 1 because of the relatively low Cl/Mg ratio due to higher magnesium concentrations. This is not unexpected, in that Cl/Mg ratios reflect temperature dependent water-rock equilibria; water discharged from these systems is generally

Table 3. Chemical data of various geothermal waters

Loc. No. on Fig. 1	Ref*	Locality	Water Type	Quartz Estim. Temp. (°C)	pH	SO_4 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
VAPOR SYSTEM OR STEAM HEATED									
1	A	White Island, N.Z.	surface in crater	163	acid	10500	61840	7310	8.5
2	I	Rabaul, New Britain, P.N.G.	shoreline thermal spring	158	7.9	1420	9264	550	16.8
3	F	Tatun, Taiwan (Hole E102)	deep thermal	180	3.5	825	149	6.1	24.4
4	D	Carboli A, Italy	deep thermal	--	--	137	42.6	5.0	8.5
5	D	Matsukawa, Japan (Well MR-1)	deep thermal	244	4.9	1780	12	8.7	1.4
6	D	Yellowstone (Mud Volc), Wyo.	thermal spring	173	7.0	65.3	13.5	16.4	0.8
7	D	The Geysers, Calif.	thermal spring	115	neutral	766	1.5	108	0.01
HIGH CHLORIDE WATER SYSTEMS									
8	A	Wairakei, N.Z. (Hole 20)	deep thermal	239	8.4	35	2215	0.04	55375
9	B	Waiotapu, N.Z. (Hole 6)	deep thermal	222	8.9	52	1450	0.06	26167
10	D	Yellowstone (Norris Bas.), Wyo.	thermal spring	230	7.5	38	744	0.2	3720
11	A	Rotorua, N.Z. (Hole 137)	deep thermal	196	9.4	30	632	0.2	3160
12	D	Steamboat Springs, Nev.	thermal spring	191	7.9	100	865	0.8	1081
13	K	HGP-A, Hawaii	deep thermal	218	4.4	≈176	1150	1.0	1150
14	A	Ngawha, N.Z. (Jubilee Bath)	thermal spring	163	6.4	347	1250	2.5	500
15	A	Wairakei, N.Z.	thermal spring	178	6.8	72	1110	4.2	264
16	J	Pt. Resolution, Tanna, New Heb.	thermal spring	156	8.5	365	1775	4	444
17	L	Nakama, Savusavu, Fiji	thermal spring	156	7.8	236	4762	3	1587
18	C	Akrane, Iceland	deep thermal	111	7.1	60	3017	12	251
19	C	Reykjanes, Iceland	deep thermal	219	6.6	94	23250	25	930
20	E	Wilbur Spring, California	thermal spring	169	6.9	390	9700	38	255
21	J	W. Takara, Efate, New Heb.	thermal spring	125	7.5	140	8670	47	185
22	E	Oilfield brine, Wilbur, Calif.	deep brine	cold	8.6	72	11400	92	124

Table 3. Chemical data of various geothermal waters (cont.)

Loc. No. on Fig. 1	Ref*	Locality	Water Type	Quartz Estim. Temp. (°C)	pH	SO_4 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
WATER SYSTEMS WITH GROUNDWATER MIXING									
23	L	Wainggele, Fiji	thermal spring	110	6.0	514	138	0.02	6900
24	G	Granite Mt., Alaska	thermal spring	121	10.1	62	9.3	0.04	233
25	C	Hengill, Iceland (Well G-3)	deep thermal	212	6.8	89	153	0.24	638
26	A	Hanmer Spring, S. N.Z.	thermal spring	100	8.0	43	451	0.2	2255
27	H	Paraso, Vella Lavella, Solomon	thermal spring	126	7.0	224	149	6.1	24
28	L	Emperor Gold Mine, Fiji	deep thermal groundwater	100	7.25	667	404	23	18
29	A	Lyttelton, S. NZ.	thermal spring	130	7.1	110	513	163	3.2

* A. Ellis and Mahon, 1964
B. Ellis, 1966
C. Árnason and Tomasson, 1970
D. White et al., 1971
E. White et al., 1973
F. MRSO, 1974
G. Miller et al., 1975
H. Taylor, 1975
I. Green et al., 1976
J. MacFarlan, 1977
K. Kroopnick et al., 1978
L. Cox and Hulston, in press

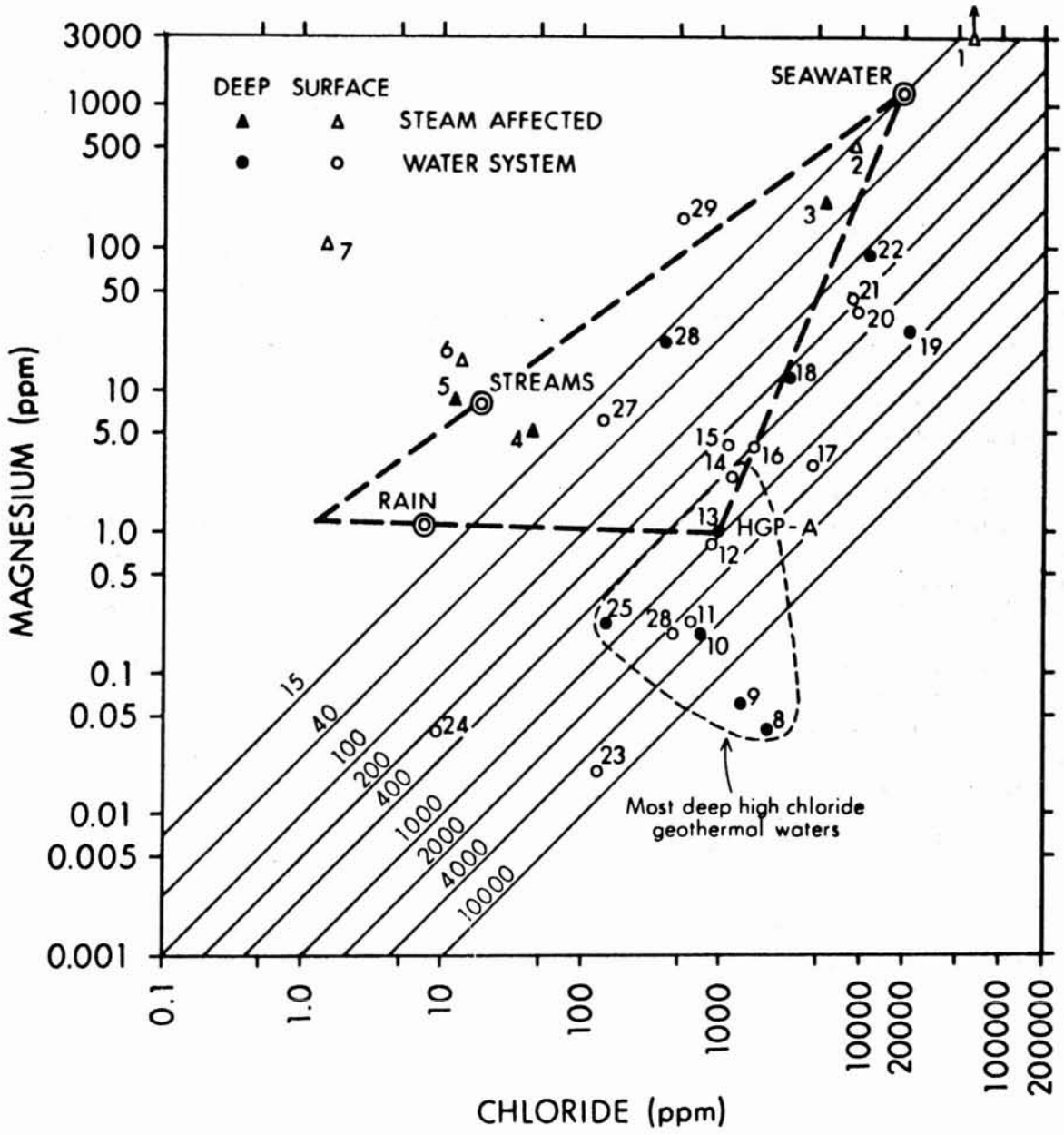

Fig. 1. Log-log plot of chloride versus magnesium concentration for geothermal waters (Table 3) from various world environments. The triangle shows the Cl and Mg parameters for different water types in Hawaii. The solid parallel diagonal lines represent Cl/Mg ratios.

steam heated, near-surface water which often has not come into contact with reservoir rocks. Another category of the steam-dominated systems or systems with a steam phase, is found in island or coastal environments where saline water of marine origin is being steam heated. These systems have high chloride (and other ocean salts) concentrations and because of generally short residence times, have not achieved equilibrium with the heated aquifer rocks. Under these circumstances the Cl/Mg ratio is even lower because of the appreciable chloride concentration.

Low chloride thermal systems usually also show elevated Cl/Mg ratios. In some instances, however, particulary in low temperature systems and in thermal waters that are appreciably diluted by fresh groundwaters, the ratios observed do not conform to the Cl/Mg ratios characteristic of high chloride water systems. These lower ratios can probably be attributed to non-equilibration between the liquid and mineral phases of the country rock.

Thermal groundwaters in Hawaii typically fall in the category of high chloride thermal systems. The Cl/Mg ratios in these systems generally increase with increasing temperature; however, quantitative estimates of temperature based on Cl/Mg ratios are generally precluded due to the variable amounts of dilution and mixing of thermally equilibrated fluids with non-thermal fluids. The deep thermal water from the Hawaii geothermal well (HGP-A) is a high chloride type and has a Cl/Mg ratio of over 1000. Cl/Mg ratios tending toward the upper right side of the diagram (Fig. 1) indicate degrees of mixing between thermal waters and saline waters (see Fig. 2). The surface discharges of these waters all have Cl/Mg ratios well over 15, and the deep waters of this type have a ratio of greater than 400.

These comparisons show that high Cl/Mg ratios occur in other high temperature thermal waters that have similar chemical characteristics to those in Hawaii. More importantly, (especially to this application in Hawaii), high Cl/Mg ratios occur in high chloride thermal spring waters which are known to have both saline water and cool groundwater mixing, circumstances under thich neither silica nor Na-K-Ca geothermometers can always be reliably applied.

APPLICATION OF Cl/Mg IN HAWAII

Figure 2 presents the Cl/Mg parameters of different types of water in Hawaii. The common grouping trends of non-thermally altered groundwaters of different types are shown to the left of the triangle boundary. High level waters close to

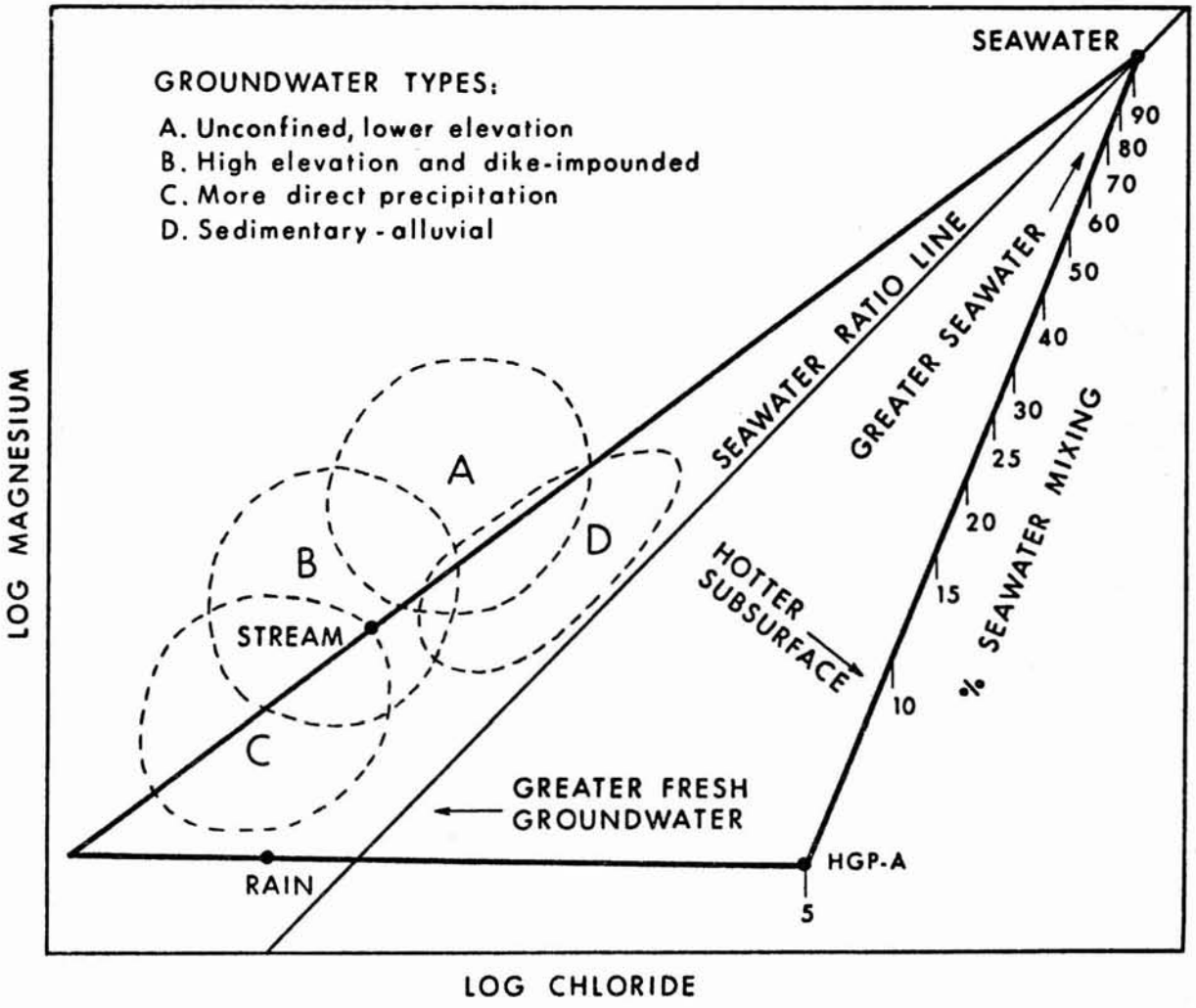

Fig. 2. Characteristics of Cl/Mg ratios of different water types and of groundwaters in Hawaii. The triangle outlines the broad parameters for Hawaii conditions. The common groupings of non-thermal water to the left of the triangle are denoted by A, B, C and D: A - lower elevation unconfined groundwater and basal groundwater; B - high elevation, largely dike-impounded groundwater; C - shallow groundwater, usually characterized by high recharge, and commonly occurring on windward sides of islands; D - groundwater in sedimentary aquifers (usually shallow) and basal groundwater with saline water mixing.

their precipitation source tend to fall along, or above, the line between the Cl/Mg ratios of seawater and stream water. Sedimentary aquifer waters have ratios that fall between this upper line and the Cl/Mg ratio line of seawater; this relative displacement to the right indicates a (non-thermal) loss of Mg to clay minerals. Waters with Cl/Mg ratios falling to the right of the seawater ratio line (i.e., Cl/Mg $\geq$ 15) are considered to be anomalous. In general, the higher the ratio, the greater is the thermal effect indicated. The degree of displacement towards seawater approximates the amount of seawater mixing (based on chloride content). The degree of displacement to the left of the triangle (i.e., decreasing chloride) indicates relative amounts of "fresh" groundwater mixing. Highly anomalous ratios in low temperature groundwaters that plot near the extreme bottom of the triangle or points that plot to the right of the triangle have been found to indicate erroneous Mg data. Erroneous Mg concentrations were found in some of the older analyses; in some of these cases the wells were resampled and reanalyzed for Mg. The recalculated Cl/Mg ratio follows the typical pattern and plots within the triangle.

In considering the distribution and the number of points in these triangle diagrams, the distribution of the location of groundwater wells (Fig. 4, 6, 8, and 10), and the availability of chemical data must be considered.

Kauai (Figures 3 and 4)

Kauai, the oldest major island in the Hawaiian chain, is a low temperature environment. The Cl/Mg ratio of groundwater largely approximates that of stream water, indicating that it is largely unconfined or dike-impounded groundwater containing an appreciable amount of water from sedimentary and basal aquifers. Both of these groundwaters have varying degrees of seawater mixing.

Many of the SiO_2-anomalous groundwaters on the island are found within sediments and probably show some recirculation-concentration of dissolved silica. The one Cl/Mg anomaly is considered due to a spuriously low Mg analysis.

Molokai (Figures 5 and 6)

Few SiO_2-temperature anomalies occur on Molokai and of these only two have Cl/Mg anomalies. Both are of low order. Most wells penetrate sedimentary or basal aquifers and some show saline water mixing. Well 1011-01 in the west, with a reported water temperature of 33.9°C, has a low Cl/Mg ratio (7.3). This well is apparently within an area associated with

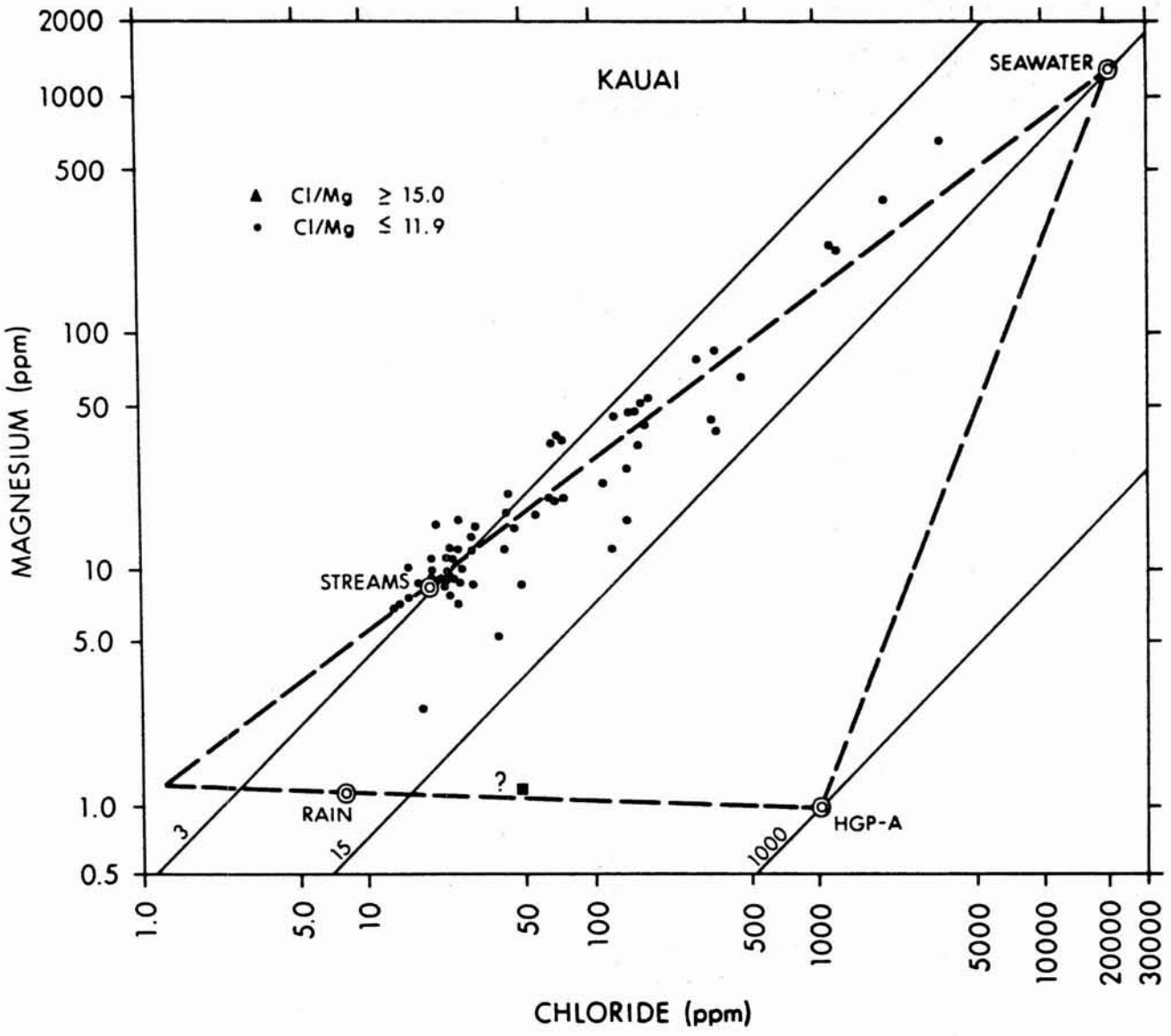

Fig. 3. Log-log triangle diagram of chloride and magnesium concentrations of groundwater for the island of Kauai. A suspect ratio is denoted by "?"; there are no Cl/Mg anomalies in these data.

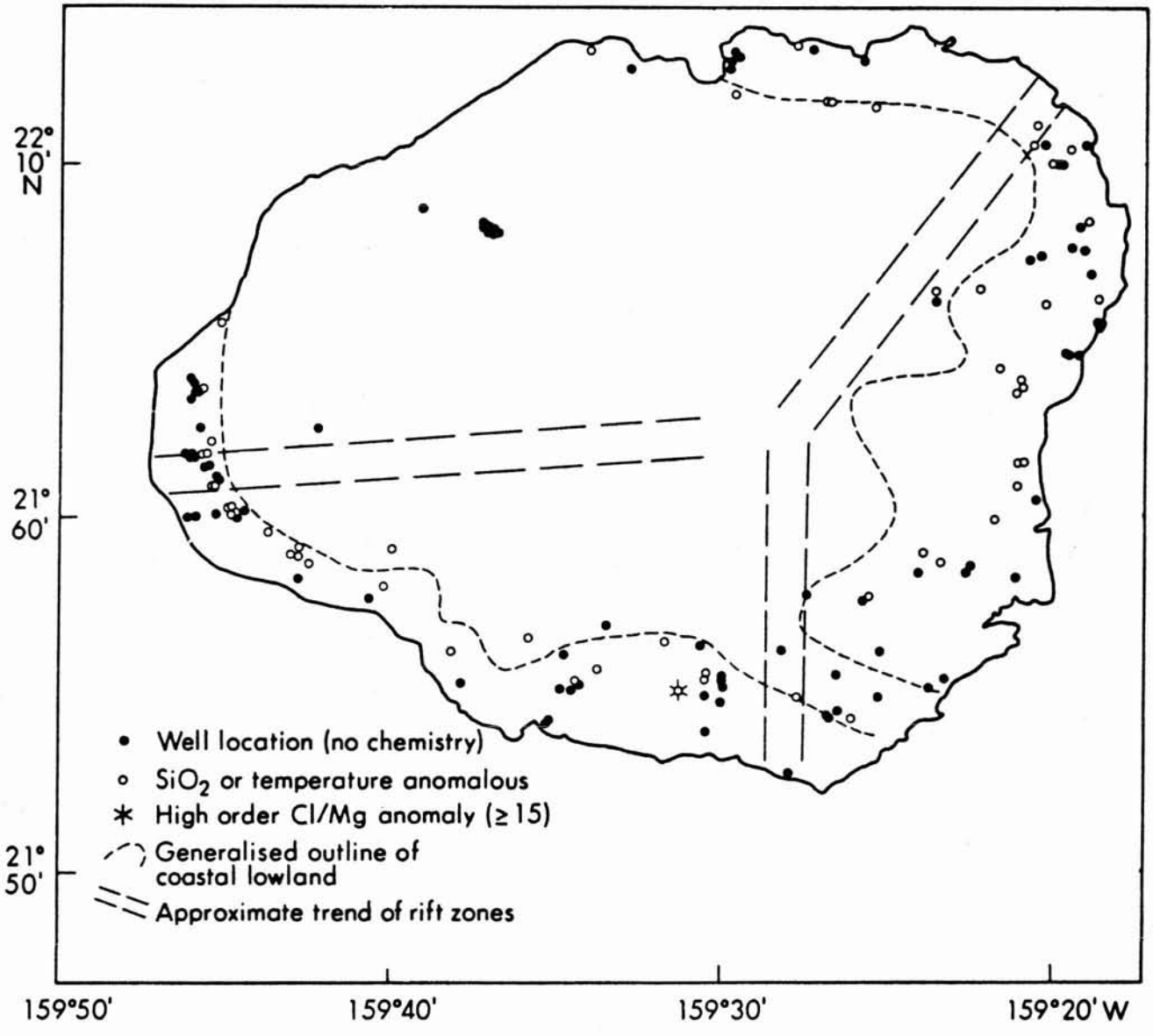

Fig. 4. Location of groundwater wells on the island of Kauai including those having anomalous chemistry.

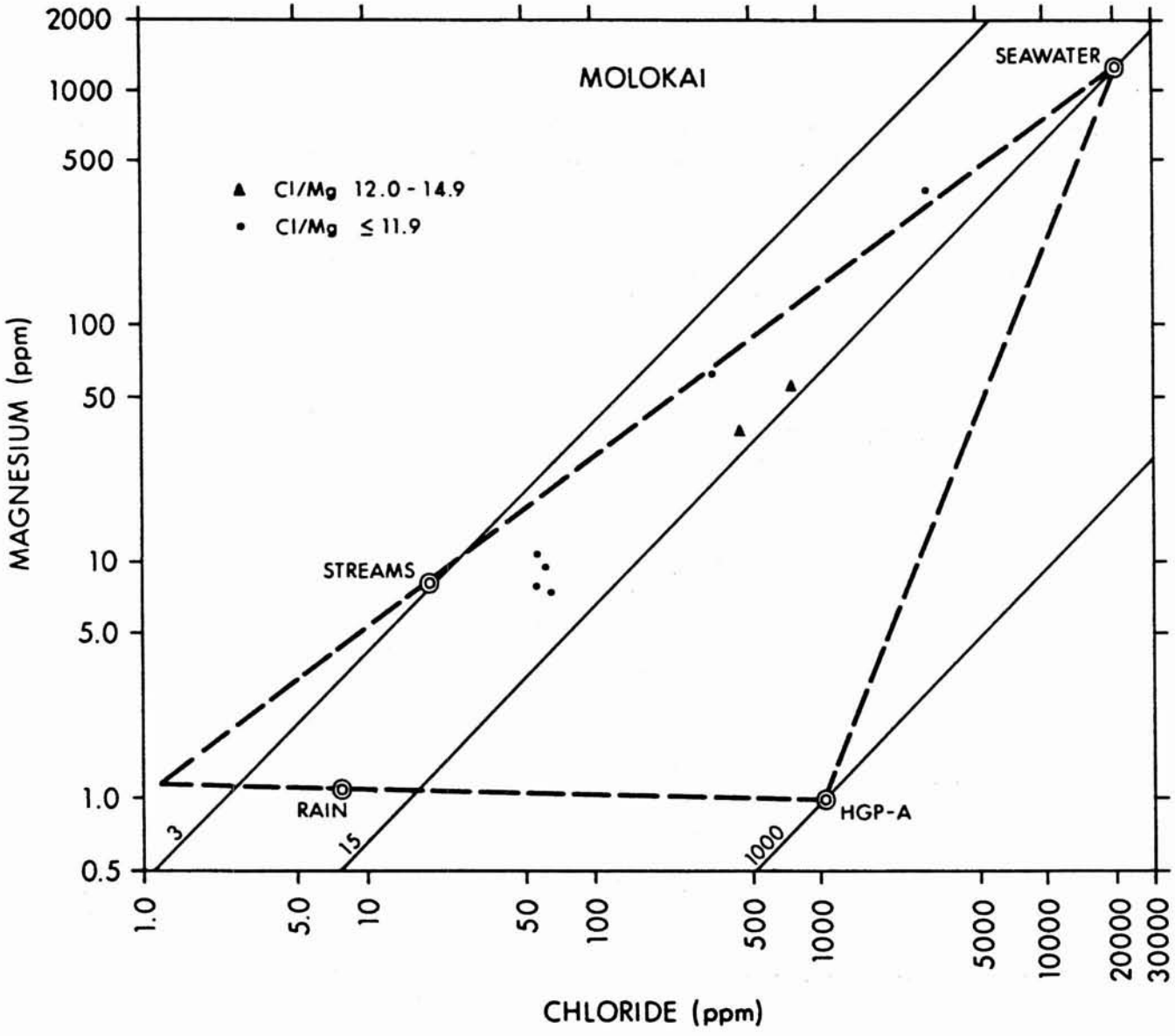

Fig. 5. Log-log triangle diagram of chloride and magnesium concentrations of groundwater for the island of Molokai. Solid triangles indicate low order Cl/Mg anomalies.

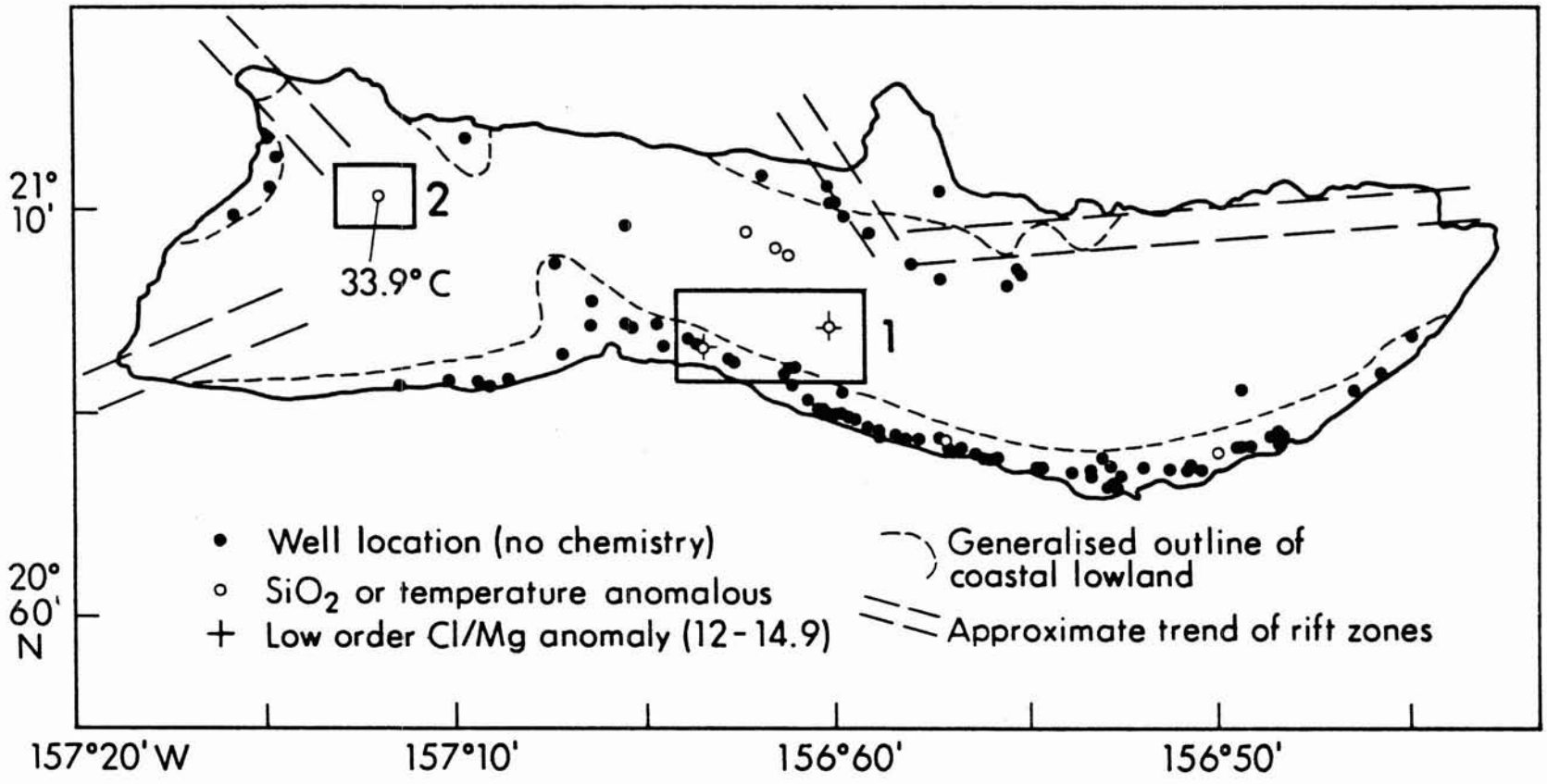

Fig. 6. Location of groundwater wells on the island of Molokai including those having anomalous chemistry and temperatures $\geq$ 30°C. Two low magnitude anomalous areas are enclosed in boxes.

an ancient rift zone. The island is indicated to be generally a low temperature environment which contains localized, possibly shallow, low magnitude thermal zones.

Oahu (Figures 7 and 8)

A large number of wells on Oahu are within, or pass through, the sedimentary aquifer. Many of these are withdrawing water from the basal aquifer underlying the island. Of the wells with anomalous Cl/Mg, 1749-18 and 2054-03 are considered to have suspect Mg values. The other anomalous ratios are considered real and worthy of further investigation. Wells 2409-07 and 2409-23 in the Lualualei Valley are indicated by water chemistry to be significantly anomalous. A detailed investigation of this area, within which is the caldera of the ancient Waianae volcano, was completed in 1978 (Cox et al., 1979). These data strongly suggest the presence of anomalous subsurface heat in the west, central north, south and possibly southeast of Oahu. Significantly elevated (30°C+) groundwater temperatures occur in several localities, but do not always correlate with Cl/Mg ratios.

Maui (Figures 9 and 10)

The distribution of Maui wells suggests that a large number are within the sedimentary aquifer. Some saline water infiltration is also indicated. There are very few wells plotted near the ratio of stream water, suggesting that only a limited amount of high elevation water is present, probably because most of the wells are located on the leeward (low rainfall) side of the island. The high number of SiO_2 anomalies in the alluvial isthmus between west and east Maui is due to recirculation and residence time effects caused by extensive agricultural irrigation in this district. Based on the data available, this island is indicated to be a medium to low temperature environment, however, several regions show definite indications of anomalous subsurface thermal conditions. These areas of interest are in the north, northwest, and southwest (Figure 10).

Hawaii (Figures 11 and 12)

The plot of the data shows a considerable spread demonstrating the range of groundwater environments. The large number of wells plotted between stream and rainwater ratios mostly located on the windward side; both dike-impounded groundwaters and those with more direct precipitation are indicated. Sedimentary aquifers are much more limited on Hawaii than on the other islands and the trend towards the seawater ratio line is commonly due to thermal disruption of the Ghyben-Henzberg lens caused by anomalously high subsurface

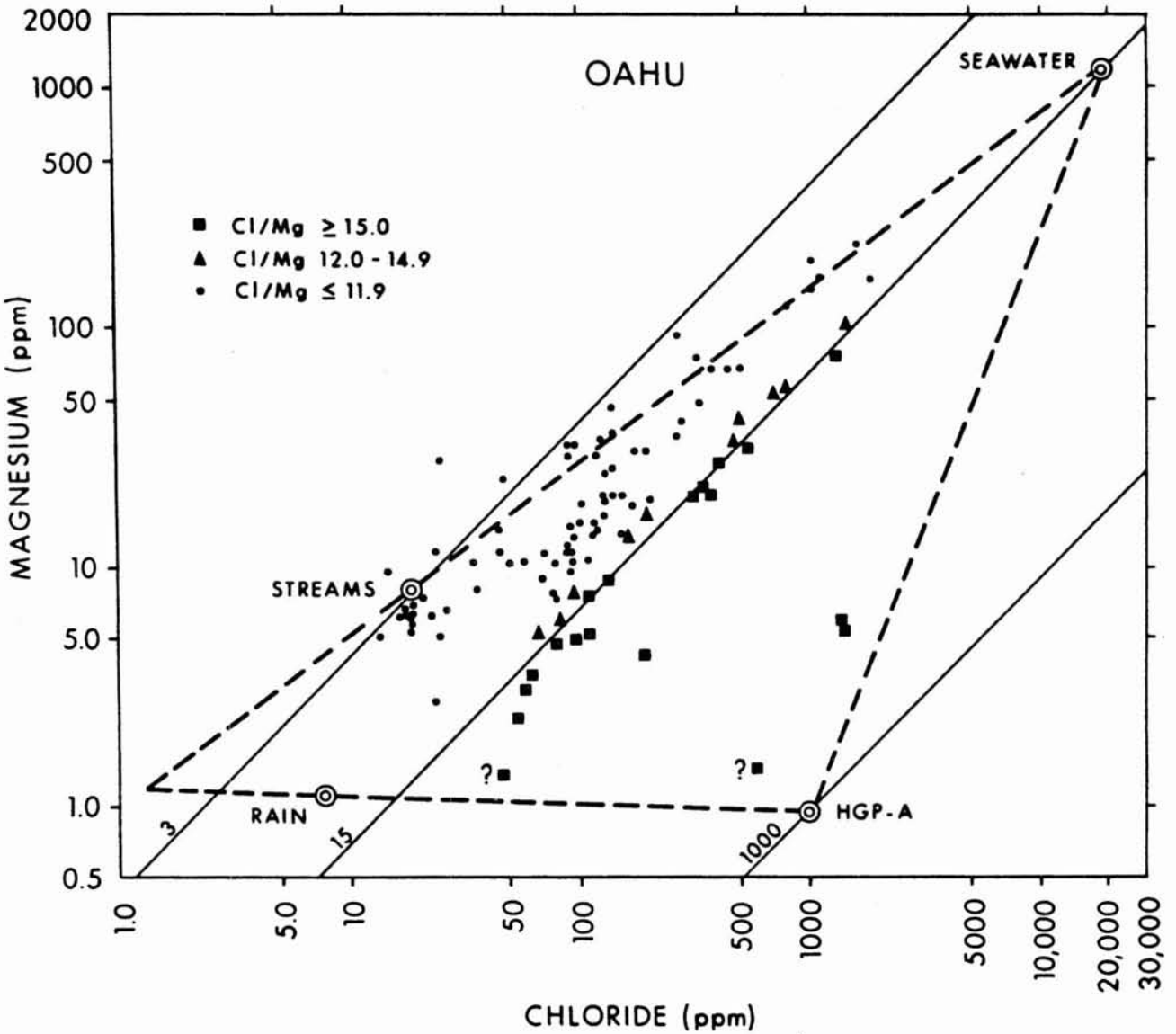

Fig. 7. Log-log triangle diagram of chloride and magnesium concentrations of groundwaters for the island of Oahu. A suspect ratio is denoted by "?"; solid triangles show low order Cl/Mg anomalies and solid squares indicate high order anomalies.

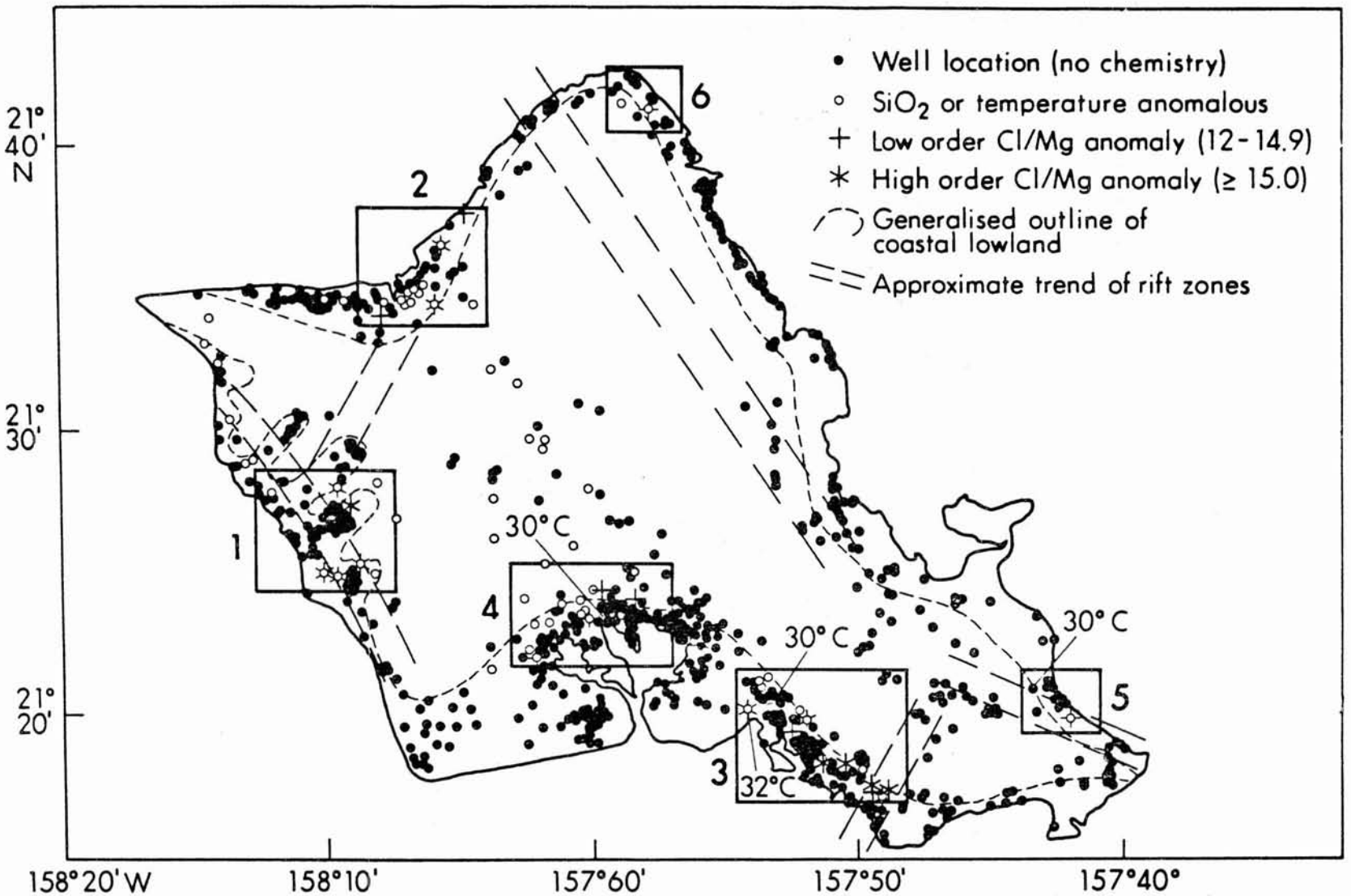

Fig. 8. Location of groundwater wells on the island of Oahu including those having anomalous chemistry and temperatures ≥ 30°C. Six Cl/Mg anomalous areas enclosed in boxes are shown in order of importance to geothermal studies. The area denoted "1" covers the caldera of the Waianae volcano.

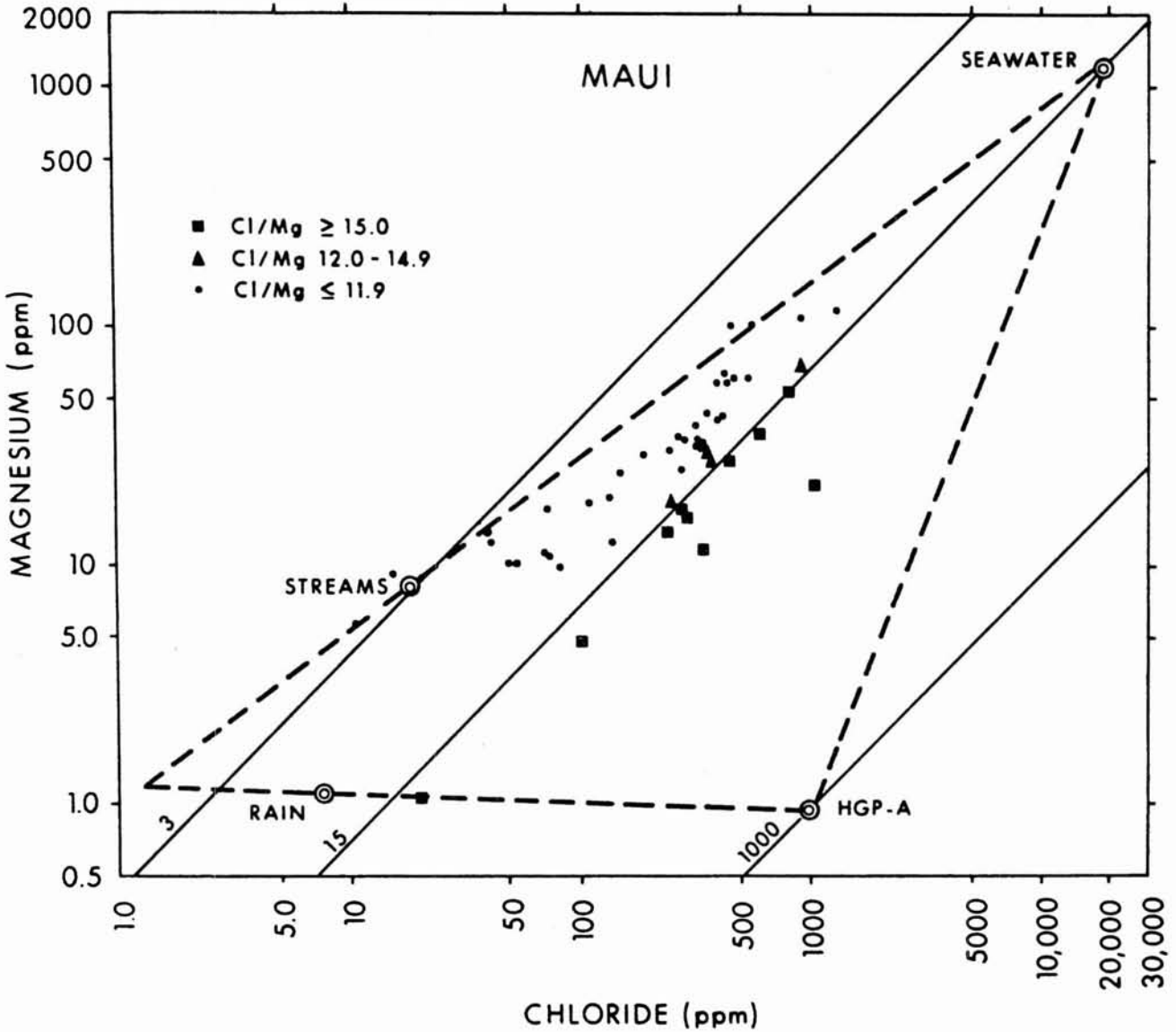

Fig. 9. Log-log triangle diagram of the chloride and magnesium concentrations for the island of Maui. Solid triangles indicate low order Cl/Mg anomalies solid squares show high order anomalies.

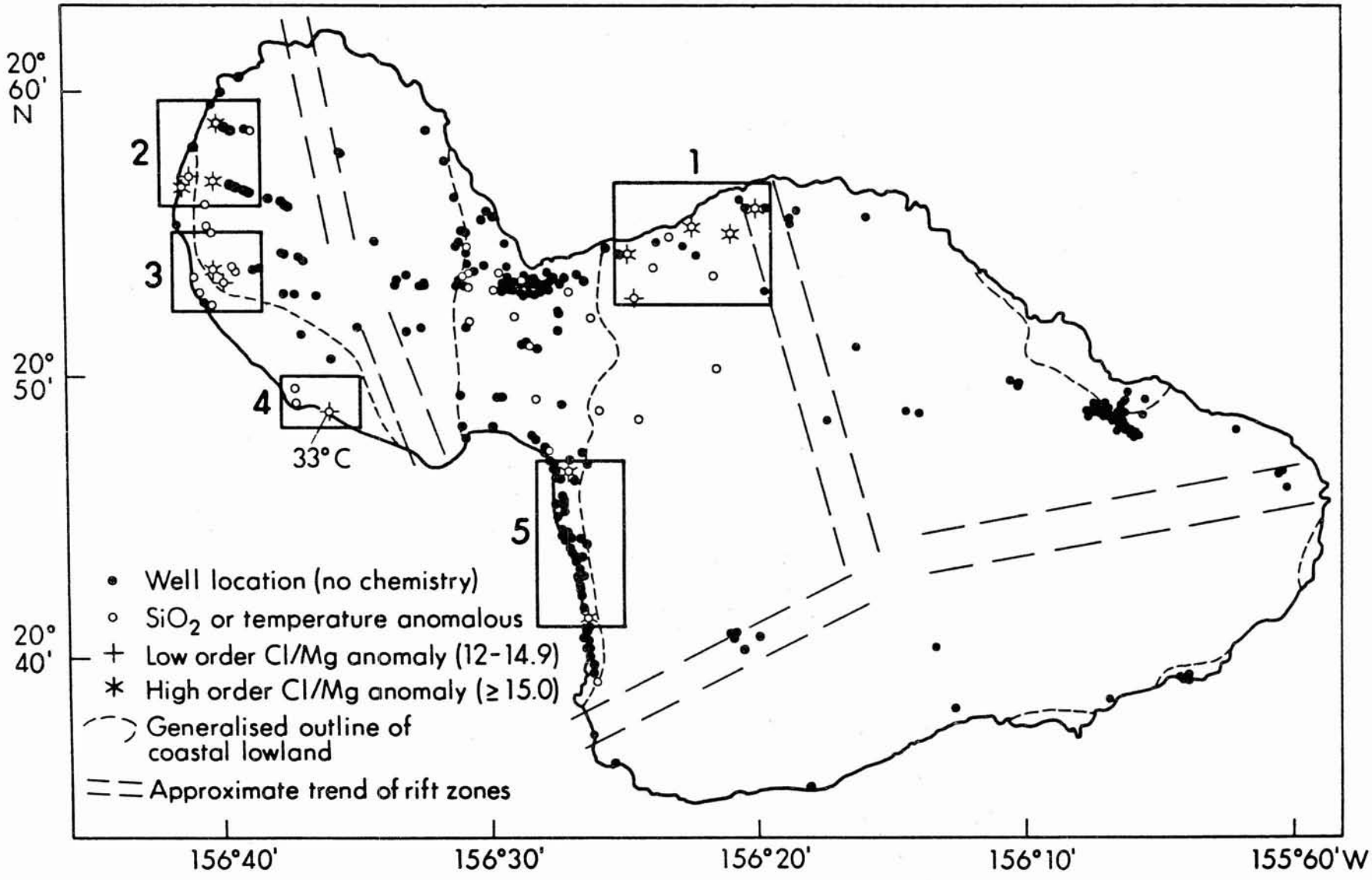

Fig. 10. Location of groundwater wells on the island of Maui including those having anomalous chemistry and temperatures $\geq$ 30°C. Five Cl/Mg anomalous areas enclosed in boxes are in order of importance to geothermal studies.

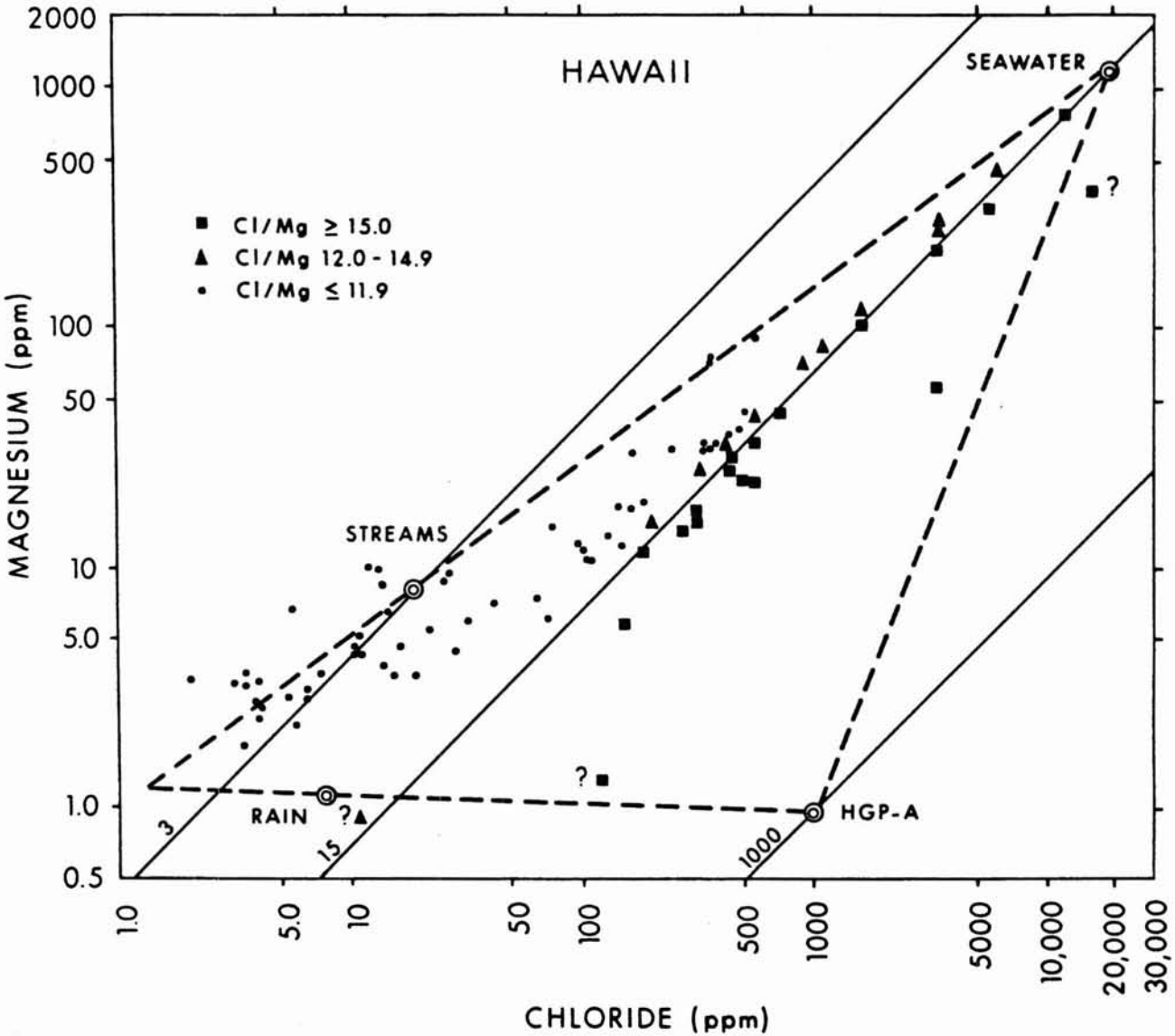

Fig. 11. Log-log triangle of the chloride and magnesium concentrations for the island of Hawaii. A suspect ratio is denoted by "?". Solid triangles show low order Cl/Mg anomalies and solid squares indicate high order anomalies.

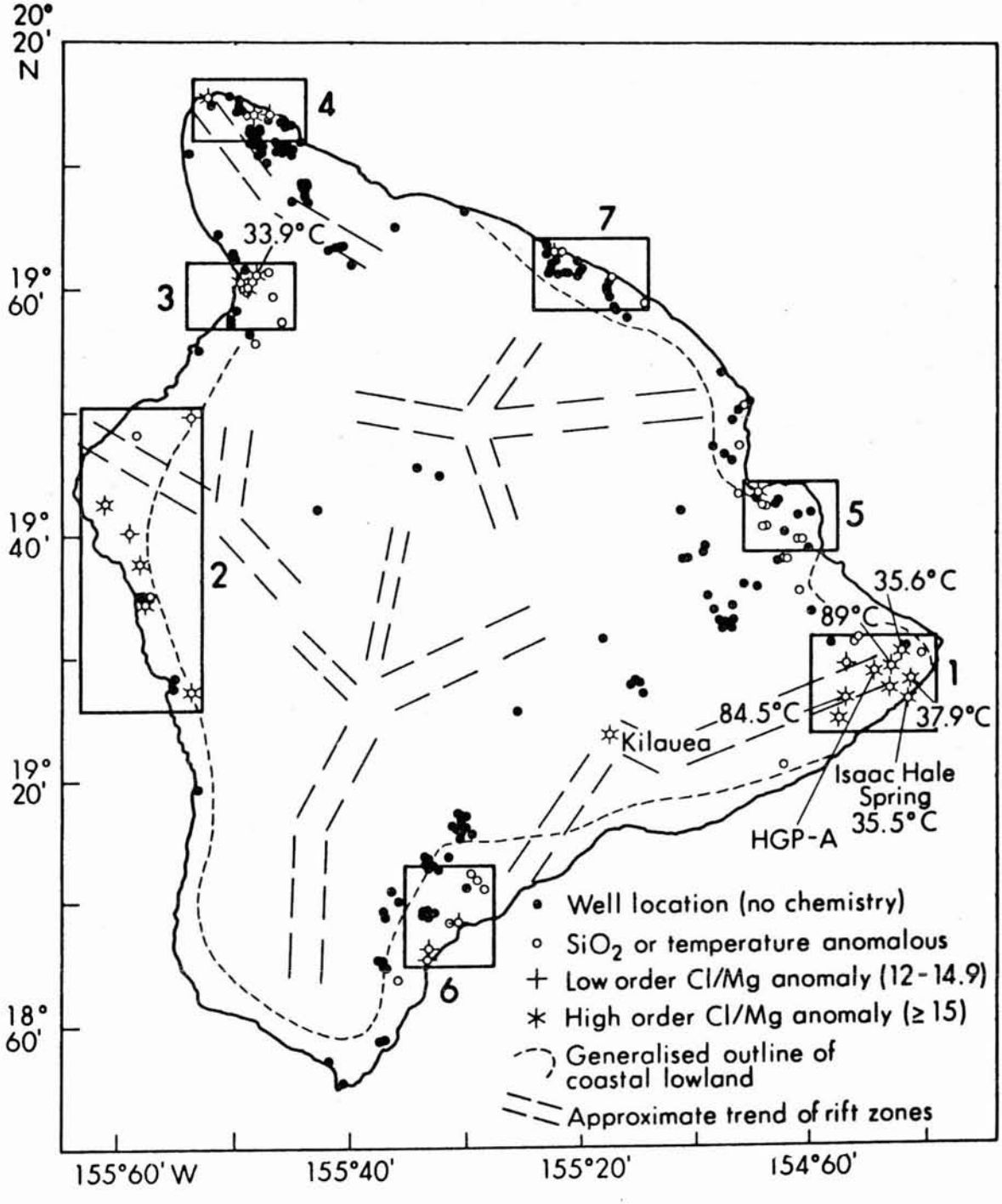

Fig. 12. Location of groundwater wells on the island of Hawaii including those having anomalous chemistry and temperatures $\geq$ 30°C. Seven Cl/Mg anomalous areas enclosed in boxes are in order of importance to geothermal studies.

heat on this volcanically active island. The majority of wells on Hawaii penetrate basal and low elevation dike-impounded aquifers. Several of these aquifers show seawater mixing, which is especially most significant in those wells within areas of known high subsurface temperatures such as the lower east rift of Kilauea. The overall distribution of points indicates the high temperature environment of the Big Island.

CONCLUSIONS

The Cl/Mg ratio of groundwaters is a suitable geochemical indicator for regional reconnaissance assessment of a large volume of data in an environment where much of the other water chemistry can be ambiguous. We believe that use of this indicator has successfully located areas in which follow-up surveys are warranted. It further appears that this ratio can also be applied in a similar way in other environments which possess characteristics similar to Hawaii and which may have geothermal potential but limited surface manifestations and a large volume of groundwater chemistry. The use of Cl/Mg on previously existing data sets, however, is obviously not infallible and should be related to other criteria such as SiO_2 concentration and temperature.

Areas of apparent anomalous thermal conditions have been determined and are indicated within boxes in Figures 4, 6, 8, 10, and 12 and numbered in order of priority for each island. A more comprehensive assessment of the potential of these and other areas on a state-wide basis is presented in Thomas et al. (1979).

An obvious feature in this type of assessment is the limitation placed upon it by the location of wells and the availability of chemical data. It is highly likely that other anomalous areas exist in the state, which were not reflected by this study because of the lack of wells in those areas.

ACKNOWLEDGMENTS

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APPENDIX I

WATER CHEMISTRY DATA

The following groundwater data are largely from U.S. Geological Survey, Honolulu, Hawaii records. Data sets marked by "*" were collected by HIG during 1978 and 1979, and are in most cases from groundwater wells for which the data did not previously exist. The groundwater data included here from the U.S. Geological Survey files are those which are anomalous for SiO_2 or temperature. The HIG-collected data are not necessarily anomalous by SiO_2 or temperature criteria.

The well numbers used follow the coordinate identification system used by the U.S. Geological Survey, Honolulu.

KAUAI

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
0021-01	Kalepa Ridge	25.3	66	29	8.4	3.5
0044-03	Kaunalewa 2	23.5	65	3500	610	5.7
0044-04	Kaunalewa 3	28.0	31	350	82	4.3
0044-10	Kaunalewa 12	23.5	50	1200	220	5.5
0044-12	Kaunalewa 11	22.5	72	2000	360	5.6
0044-13	Kaunalewa 7	22.0	70	1180	228	5.2
0045-01	Camp 2 KS19	22.5	67	290	76	3.8
0045-03	Camp 2 KS5	21.4	71	145	47	3.1
0120-01	Kalepa Ridge	25.5	77	160	33	3.4
0120-02	Kalepa Ridge	27.5	73	110	23	4.8
0145-08	Mana 4	22.5	67	122	44	2.8
0145-09	Mana 5	22.5	66	152	46	3.3
0145-10	Mana 6	22.5	65	350	38	9.2
0145-11	Mana 7	22.5	59	175	52	3.4
0145-12	Mana 8	22	64	165	50	3.3
0145-13	Mana 9	22	62	72	35	2.1
0145-16	Mana 12	22	65	65	34	1.9
0245-02	Mana Shaft	23	66	70	36	1.9
0320-01	Nonou A	23.0	63.4	45	15	3.0
0320-02	Wailua	--	59	25	12	2.1
0320-03	Nonou 9-1B	24.5	51.1	48	8.4	5.7
0321-01	Wailua 3	24.2	68	64	20	3.2
0345-04	Saki Mana Shaft	23	72	460	65	7.1
0421-01	Wailua Homestead	24.5	83	41	21	2.0
0545-01	Kaulaula W59	25	57	170	42	4.1
0618-05	Kealia 7	24.5	36	40	12	3.3
0620-01	Kapaa Cannery	26.5	30	28	12	2.3
0622-01	Akulikuli	19	33.6	15	7.4	2.0
0623-01	Makaleha 6	19.1	31.5	14	7	2.0
0818-01	Anahola A	23.5	36	25	16	1.6
0818-02	Anahola B	23.5	29.8	24	11	2.2

Kauai (cont.)

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
1020-02	Moloaa 1	21.5	35	19	11	1.7
1020-03	Moloaa 2	22	36	15	11	1.4
1020-04	Aliomanu	20.8	39	22	11	2.0
1120-01	Moloaa Tun. 3	25.5	13	25	7	3.6
1125-01	Kilauea 1	24.5	39	13	6.8	1.9
1126-01	ECDC 1	--	32.8	17.3	2.5	6.9
1126-02	ECDC 2 Hanale	23.5	47	17	8.7	2.0
1229-03	Maka Ridge	24	38	22	9.9	2.2
1327-01	Anini Tunnel	23	36	23	7.7	3.0
1333-01	Haena Deep	22.5	33	19	9	2.1
5426-04	Koloa C	--	58	55	17	3.2
5427-01	Koloa A	23	59	27	10	2.7
5427-02	Koloa B	23	36.8	30	15	2.0
5530-02	Lawai Cannery	22	52	26	8.9	2.9
5530-03	Lawai Deep	22.5	59	23	9.4	2.5
5531-01	Kalaheo 24	25	59	46	1.1	41.8
5533-01	Hanapepe	21.5	49	28	13	2.2
5534-03	Hanapepe Valley	22.5	50	37	5.1	7.3
5631-01	Kalaheo	20.7	42	22	9.0	2.4
5635-01	Manienieula	22.5	43.3	140	16	8.8
5638-01	Mahinauli	23	52	20	15	1.3
5725-01	Kokolau Tun.	21.5	36.6	19	11	1.7
5823-01	Garlinghouse	22	32	22	8.6	2.6
5840-02	Waimea 26	24.5	73	120	12	10.0
5842-02	Kekaha PLS 11	24.5	40.2	140	26	5.4
5842-03	Huluhulunui	25	--	310	--	--
5843-01	Kekaha Shaft	24	56.1	67	19	3.5
5921-01	Kalapa Ridge	23	32	23	12.8	1.8
5923-02	Kilohana	23.3	33	24	9.3	2.6
5939-01	Waimea 9	24.5	36.1	74	20	3.7
5942-01	Paua Valley	24	48	41	17	2.4
5943-01	Waiawa Shaft	24.5	77	340	43	7.9

MOLOKAI

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
0449-01	Ualapue	20	47	65	7.7	8.4
0457-01	Kawela	22.5	32	58	11	5.3
0603-01	Umipaa DW 14	24.5	53	750	55	13.6
0700-01	Kaluakoi	23	49	440	36	12.2
0801-01	Kauluwai	21	44	62	9.7	6.4
0901-01	Kalualohe	19.5	47	56	8	7.0
0902-01	Kualapuu	--	38.8	340	64.8	5.3
1011-01	Kahalelani	33.9	--	2890	395	7.3

OAHU

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
1748-05Z	-----	--	16	56	2.4	23.3
1749-01	-----	--	35	70	5.5	12.7
1749-08	Kapahulu	22	55	208	4.4	47.3
1749-16	-----	--	33	102	5.1	20.0
1749-18	-----	--	67	50	1.4	35.7
1849-10	Manoa Valley	25	29.7	18	6.5	2.8
1850-27	-----	--	26	85	4.8	17.7
1851-09	Kawaiahao Church	21	77	80	8.0	10.0
1851-30	Kawaiahao Church	--	29	63	3.2	19.7
1952-04	Kapalama	26	10	118	5.5	21.5
1952-11	Kapalama	--	28	99	8.0	12.4
2042-13	Waimanalo	25	26	1500	110	13.6
2043-01	Waimanalo	30	22	24	2.8	8.6
2043-02	Waimanalo	25	35.6	27	6.8	4.0
2052-07	Kapalama Avenue	26	20.2	130	36	3.6
2053-05	Kalihi	30	41.6	60	11	5.5
2054-03	Puuloa Road	32	28.4	620	1.5	413.3
2103-02	Puu Makakilo	25.5	--	251	--	--
2142-03	Bellows AFB	26.1	--	238	--	--
2153-02	Moanalua	21.5	63	74	12	6.2
2153-07	Moanalua	25.6	44	76	12	6.3
2153-09	Moanalua	25.0	--	1050	203	5.2
2202-03	Honouliuli	22.2	63	145	27.4	5.3
2202-09	Honouliuli	--	83	145	27.4	5.3
2202-15	Mill Pump 7A	25.5	82	840	59	14.2
2255-07	Halawa	21.7	64	96	14	6.9
2256-12	Aiea	27	--	160	21	7.6
2300-02	Waipahu	23	66	135	20	6.8
2300-07	Waipahu P6A	30	44.5	89.3	6.4	14.0
2300-11	Waipahu	22.5	60	180	19	9.5
2300-18	Waipahu	22	60	96	13	7.4

OAHU (cont.)

Well Number	Name	TEMP. (°C)	SiO (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
2301-01	Waikele P81A	22	67.2	51	10.7	4.8
2301-11Z	Waikele	--	74	113	11	10.3
2301-34	Hoeaea 1	22.5	71	120	15.7	7.6
2302-01	Kunia 1	22	73	103	16.2	6.4
2302-02	Kunia 1	22.4	75	135	17	7.9
2359-04	Waipahu	22.5	68	395	71	5.6
2359-05	Waipahu	22.5	59	340	80	4.3
2359-06	Waipahu	22.5	66	280	38	7.4
2359-14	Waipahu	21.6	66	840	130	6.5
2359-15	Waipahu	22	64	1050	150	7.0
2359-16	Waipahu	22	62	1650	240	6.9
2359-17	Waipahu	22	65	1110	175	6.3
2400-01	Waipahu	--	57	80	7.9	10.1
2402-01	Kunia II	--	71	105	18	5.8
*2409-07	Maili	25.5	171	1410	61	23.1
*2409-23	Maili	25	156	1480	60	24.7
2458-01	Pearl City	21.5	61.6	172	14.5	11.9
2459-01	Waipio Heights 1	--	60	82	11	7.5
2459-062	Waipio Heights	--	33	519	43	12.1
2501-01	Waipahu	--	56.6	121	31	3.9
*2508-01	Lualualei	27	68	260	80	3.3
2508-02	Lualualei	27.5	92	280	102	2.8
*2508-07	Lualualei	25.5	186	1330	81	16.4
2558-10	Waiawa	22	58	160	14	11.4
2600-02	Kipapa Gulch	25	61	35	12	2.9
2603-01	Waikele	22	74	46	15	3.8
*2607-01	Lualualei	24	96	41	12	3.4
*2609-05	Lualualei	24	41	141	50	2.8
2703-01	Kunia	23	65.4	37	8.4	4.4
*2709-08	Lualualei	26	165	147	9.6	15.3

OAHU (cont.)

Well Number	Name	TEMP. (°C)	SiO (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
*2712-01	Kamaile	24.5	94	143	39	3.7
2712-30	Kamaile 1	25.5	75	97	34	2.9
2800-01	Mililani	22	63	18	6.3	2.9
2800-03	Mililani	20.5	64	18	5.6	3.2
*2808-01	Lualualei	26.5	81	138	27	5.1
*2808-02	Lualualei Tunnel	19	58	23	6.5	3.5
2809-05	Waianae Valley	--	62	67.7	3.7	18.3
*2809-06	Waianae Tunnel (Ent.)	22	73	26	29	0.9
*2809-06	Waianae Tunnel (Ov.fl.)	20	51	15	10	1.5
*2811-02	Makaha	25	81	48.6	24	2.0
*2812-01	Makaha Shaft	26.0	86	92	34	2.7
2901-01	Schofield B	21.6	69	19	7.2	2.6
2901-02	Schofield B	23	64	18	7.4	2.4
2901-07	Schofield	23	69	19	7.2	2.6
2901-08	Wahiawa	22.7	72	19	6.4	3.0
2901-09	Wahiawa	21.5	74	21	7.8	2.7
2901-11	Wahiawa	21.5	74	19	7.0	2.7
2902-01	Wahiawa Expl.	23	81	17	6.1	2.8
2908-02	Waianae Tunnel	18.3	31	14	5.4	2.6
*2911-01	Makaha Tunnel	20	73	24	12	2.0
2912-01	Makaha	25	66	92	30	3.1
*2912-01	Makaha	--	--	89	31	2.9
3013-09	Ohikilolo	27	77	1900	170	11.2
3102-02	Helemano	21.1	72	18	7.7	2.3
3203-01	Halemanu P25	22	69	19	6.9	2.8
3213-06	Makua	26.5	61	210	20	10.5
3314-01	Keawaula	--	69	510	73	7.0
3314-02	Keawaula	25.7	78	470	70	6.7
3314-03	Keawaula	--	68	290	44	6.6
3404-02	Waialua	21.1	61.6	25	5.3	4.7

OAHU (cont.)

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
3405-01	Waialua	21.8	63.2	94	15.1	6.2
3405-02	Waialua	23	70	120	8	15.0
3406-02	Waialua	21.6	70	95	12	7.9
3406-03	Waialua	22.3	74	98	11	8.9
3406-05	Waialua	23.4	79	145	21	6.9
3406-06	Waialua	22.8	75	126	15	8.4
3406-08	Caprock 17	--	70	94	12	7.8
3407-02	Waialua	22.3	72	112	14	8.0
3407-07Z	Waialua II	22	60	135	20	6.8
3407-30	Waialua	24.7	36	745	57	13.1
3409-13	Mokuleia	22.4	56	205	32	6.4
3409-16	Mokuleia	22.5	57	180	32	5.6
3505-01	Opaeula P3	22	71	73	9.1	8.2
3506-03	Haleiwa	21.5	72	98	10	9.8
3506-06	Haleiwa	22.1	71	92	13	7.1
3605-03	Kawailoa 4	21	64	590	33	17.9
3605-15	Kawailoa 4	21.6	64	370	24	15.4
3605-16	Kawailoa 4	21.5	64	420	28	15.0
3605-21	Kawailoa 4	21.5	65	390	22	17.7
3605-23	Kawailoa P4	21.6	65	335	22	15.2
3704-01	Meadow Gold	21.8	64	490	35	14.0
4157-03	Meadow Gold	26	--	208	17	12.2
4158-12	Kahuku Air Base	25	48	350	52.6	6.7

MAUI

Well Number	Name	TEMP. (°C)	SiO (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
*3625-01	La Perouse Bay	22.5	85	1482	178	9.2
*3726-02	Glenn Fultz	23.5	--	1470	162	9.1
*3726-03	Hunter's	24.5	87	1435	172	8.3
3925-01	Makena 68	20	41	500	64.2	7.8
*3925-01	Makena	20.4	--	621	66	9.4
*4019-01	Poli Poli Tunnel	--	--	2.1	1.8	1.2
*4020-02	Cornwall	11.8	--	5.6	3.6	1.6
*4021-01	Waikaahi	14	--	3.7	3.6	1.0
*4021-02	Waihau Tunnel	13	--	9.7	5.0	1.9
*4022-04	Waikaalo Tunnel	11.8	--	2.1	3.4	0.6
4126-02	Wailea 2	19	45	460	28	16.4
*4600-01	Hana Ranch	19.5	--	67.9	16.1	4.2
*4600-02	Maui County A	20.2	--	115	3.9	29.5
*4600-03	Maui County B	18.5	--	30.1	1.5	20.1
4627-14	TMK 3-9-01-3	22.5	59	280	18	15.6
4727-01	Kihei Shaft	24.3	48	575	64	9.0
4824-01	Kihei Explor'y	24	57	73	18	4.1
*4824-01	Kihei Explor'y	23.2	≈32	81	21	3.9
4825-01	Kihei Shaft 15	23	58	340	35	9.7
4835-01	Ukumehame	33	60	400	29	13.8
*4835-01	Ukumehame	33.1	46	459	26	17.7
4837-01	Olowalu	25.5	45	460	67	6.9
*4837-01	Olowalu	25.9	≈40	676	96	7.0
4928-02	Puunene	--	44	390	45	8.7
4937-01	Olowalu Sh 10	25	52	1400	120	11.7
*4937-01	Olowalu Sh 10	25.6	--	669	78	8.6
5021-01	Pukalani	21	43	480	103	4.7
5128-02	Waikapu	24	51	410	42	9.8
5130-02	Waikapu 2	21	34	16	9.5	1.7
*5130-02	Waikapu 2	21.6	≈32	36	13	2,8

MAUI (cont.)

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
5224-01	Haiku Ditch	23	59	287	36	8.0
5224-02	Puunene 9	23.8	62	390	31	12.6
5226-01	Puunene 5	26	59	477	62	7.7
5226-02	Puunene 6	23.5	56	376	34	11.1
5228-06	Passion Acre	--	45.6	113	19.3	5.9
5229-01	Waiale	22	61	260	32	8.1
5240-01	Mill Pump C	24.5	55	980	111	8.8
*5240-01	Mill Pump C	26.8	≃39	1030	119	8.7
*5240-02	Lahaina A	--	≃40	1360	140	9.71
5240-03	Lahaina B	28	60	600	109	5.5
*5240-03	Lahaina B	24.9	≃37	1040	132	7.9
*5319-01	Silveno Spring	19.8	--	17.3	4.1	4.2
5321-01	Kaheka 18	21	5.3	76	11	6.9
*5321-01	Kaheka 18	20.5	--	431	32.5	13.3
5323-01	Paia 2A	22	56	448	46	9.7
*5323-01	Paia 2A	22.8	--	543	47.9	11.3
5328-01	Cannery Shaft	22	47	159	26	6.1
5329-04	Mem. Gym	22	42	300	37	8.1
5330-05	Wailuku Sh 33	20.5	53	51	11	4.6
5330-06	Mokuhau Th1	--	50	42	14.1	3.0
5330-09	Mokuhau 1	23	31	85	10	8.5
*5330-09	Mokuhau 1	23.5	≃38	81.5	16	5.1
5330-10	Mokuhau 2	22	53	74	13	5.7
*5330-10	Mokuhau 2	23.6	≃36	158	23	6.9
5330-11	Mokuhau 3	22	76	43	13	3.3
*5330-11	Mokuhau 3	23.5	≃38	47.5	14	3.4
5339-01	Lahaina 1	21.5	57	290	27	10.8
5339-02	Lahaina 2	20	57	200	30	6.7
5339-03	Kanaha 1	20	42	260	19	13.7
5339-04	Kanaha 2	20.5	44	11	5.7	1.9
*5339-04	Kanaha 2	20.3	≃32	403	37	10.9

MAUI (cont.)

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
5340-01	Wahikuli 1	24.5	45	410	62	6.6
*5340-01	Wahikuli 1	25.2	≃32	1180	174	6.8
5340-02	Kahona Sh 5	25	61	1100	23	47.8
*5340-02	Kahona Sh 5	23.6	≃36	1070	102	10.5
*5419-01	Haiku	22.0	--	26.3	6.6	4.0
5420-01	Maui High	22.2	53.3	100	4.7	21.3
*5420-01	Maui High	21.5	--	44.3	3.3	13.6
*5422-01	Paia Mill 13A	22.5	--	531	53	10.0
*5422-02	Paia Pump 17	21.2	--	316	33.3	9.4
*5423-01	Kailua Gulch Country Club	23.2	99	706	56.4	12.5
5423-02	Low Paia 16D	25	51	342	40	8.5
*5423-02	Low Paia 16D	23.5	102	1572	123	12.8
5424-01	Specklesville	23	66	640	37	17.3
5430-01	Waiehu Heights 1	--	54	53	11	4.8
*5430-01	Waiehu Heights 1	23.5	≃38	45	7.2	6.3
*5430-02	Waiehu Heights 2	23.9	≃46	13	5.36	2.4
*5519-01	Pauwela (Haiku School)	19.1	--	130	14.6	8.9
5519-02	Haiku (Behnke)	--	40.8	21	1.0	21.0
*5519-02	Haiku (Behnke)	23.5	--	18.1	0.8	21.6
*5520-01	Maliko II	20.5	--	887	64.5	13.8
5522-01	Kuau Pump 12	23	52	300	17	17.7
*5522-01	Kuau Pump 12	21.3	--	295	18	16.4
5540-01	Puukolii	23.3	49	362	34	10.7
*5540-01	Puukolii	21.8	≃40	582	62	9.4
5540-02	Hahakea 1	--	54	340	34	10.0
5540-03	Hahakea 2	--	46	149	20	7.5
*5615-01	Jeremy Storm	23.5	--	38.3	4.2	9.1
*5620-01	Maliko Tunnel	22.1	--	23.2	0.4	58
5640-01	Honokowai	20.5	45	250	14	17.9
5641-01	Kaanapali D	22	50	850	56	15.2

MAUI (cont.)

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
*5641-01	Kaanapali D	22.9	≃44	1530	149	10.3
5641-02	Honokowai F	23	50	975	70	13.9
*5641-02	Honokowai F	22.7	≃36	1470	128	11.5
*5731-01	Mende	22.8	--	25.2	8.9	2.8
5838-01	Napili 1	21	51	148	13	11.4
5840-01	Alaeloa	21.1	53	352	10.8	32.6
*5840-01	Alaeloa	21.4	--	291	20	14.6

HAWAII

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
0335-01	Naalehu 1	19.0	43	10	4.6	2.2
0533-01	Honuapo Mill	19.0	43	1240	86	14.5
0533-02	Honuapo 1	19.0	43	580	44	13.2
0533-03	Honuapo 3	19.0	43	500	38	11.4
0632-01	Honuapo 2	19.0	41	440	33	13.3
0830-01	Punaluu	19.0	32	205	16	12.8
0831-01	Ninole	18.0	41	130	12	10.8
0831-02	Ninole A	18.0	43	150	18	8.3
0831-03	Ninole B	21.0	48	166	18	9.2
1128-01	Pahala Shaft	19.0	42	3.5	3.6	1.0
1128-02	Palima	21.0	54	12	4.3	2.8
1229-01	Pahala	17.0	42	3.2	3.3	1.0
2102-01	Pulama	28.0	72	345	31.2	11.1
2317-01	Kilauea	83	163	1660	63.5	26.1
2487-01	Keauohana 1	24.0	41	70	3.3	21.2
2487-02	Keauohana 2	24.0	45	160	5.9	27.1
2686-02	Geoth. Test 2	83.0	--	--	--	--
2753-01	Keei A	21.0	53	180	12	15.0
2753-02	Keei B	19.5	50	180	12	15.0
2783-01	Malama-Ki	53	59	5850	324	18.1
2881-01	Allison Well	37.5	24	281	15	18.7
2982-01	Geoth. Test 3	93	97	3410	59	57.8
2986-01	Pahoa 2A	22.5	39	12	0.9	13.3
2986-02	Pahoa 2B	23	55	5.8	2.4	2.4
3080-01	Kapoho Crater	25	58	170	31	5.5
3081-01	Kapoho Test	28	70.5	320	17.1	18.8
3185-01	Haw. Shores	21.5	51.9	14	3.8	3.7
3185-02	Haw. Shores	--	49	28	4.5	6.2
3457-02	Keauhou 2	--	33	1700	110	15.5
3500-01	Pahoehoe	22	46.5	5.5	6.7	0.8

Hawaii (cont.)

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
3557-01	Kahaluu A	22	52	14	6.5	2.2
3557-02	Kahaluu B	20	41.7	32.1	7.1	4.5
3557-03	Kahaluu C	20	43.6	11	5.2	2.1
3557-04	Kahaluu D	20	45	17	4.8	3.5
3702-01	Olaa Shaft 7	23	40	4	2.7	1.5
*3702-01	Olaa Shaft 7	19.7	39	5.1	3.3	1.5
3758-01	Kailua Kona	25	43	459	27	17.0
3802-01	Keaau 1	24.5	37.7	3.4	1.8	1.9
3802-02	Keaau 2	24.5	34.6	5.4	2.8	1.9
*3802-02	Keaau 2	19.2	39	3.6	2.5	1.5
3802-03	Keaau Mill 1	18.5	36	3.5	3.1	1.1
*3802-03	Keaau Mill 1	19.4	39	2.5	2.5	1.0
3802-04	Keaau Mill 2	22.0	36	4	3.3	1.2
*3802-04	Keaau Mill 2	19.7	36	3.3	2.5	1.3
3802-05	Keaau Mill 3	22.0	36	4	3.3	1.2
*3802-05	Keaau Mill 3	19.7	39	3.9	3.2	1.2
3900-01	Keaau Orch. 1	18.5	39	64	7.7	8.3
*3900-01	Keaau Orch. 1	--	39	66.6	7.8	8.5
3900-02	Keaau Orch. 2	19.5	33	156	13.6	11.5
*3900-02	Keaau Orch. 2	--	39	88.4	9.7	9.1
4003-01	Panaewa 1	20	34	4	2.7	1.5
*4003-01	Panaewa 1	--	36	3.4	2.6	1.3
4003-02	Panaewa 2	20	36.6	4	2.3	1.7
*4003-02	Panaewa 2	--	36	2.7	2.5	1.1
4059-01	Palani	19.7	43.2	3600	250	14.0
4202-01	Palani	--	8	108	12	9.0
4203-02	Waiakea TH 2	21.1	33	11	4.4	2.5
*4203-02	Waiakea TH 2	25	39	10.4	3.3	3.2
4203-03	Waiakea TH 3	23.5	36	7.5	3.6	2.1
*4203-03	Waiakea TH 3	21	36	9.2	3.1	3.0
4203-04	Waiakea 4	26	55	6.5	2.9	2.2

Hawaii (cont.)

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
*4203-04	Waiakea 4	21	38	39.8	5.9	6.8
*4203-05	Hilo Electric 6	23	39	27	4.8	5.6
4203-06	Kanoelehua 2	21	37	18	3.5	5.1
*4203-06	Kanoelehua 2	--	39	28.3	5.0	5.7
4203-07	Kanoelehua 3	26	55	6.5	2.9	2.2
*4203-07	Kanoelehua 3	23	36	24.5	4.6	5.3
*4203-10	Hilo Electric 4	20	37	38	5.8	6.6
4304-01	Waiakea	20.5	44	16000	390	41.0
4304-02	Waiakea	19.5	33	12500	800	15.6
4304-03	Waiakea	20	46	6250	460	13.6
4306-01	Piihonua	17.8	37	2	3.3	0.6
*4306-01	Piihonua	--	41	1.4	3.4	0.4
4360-01	Kalaoa	20.8	39	740	46	16.1
4706-01	Papaikou	--	29.8	15	3.6	4.2
*4706-01	Papaikou	20	34	2.1	5.0	0.4
4858-01	Kona Vill. 1	20	78	370	73	5.1
4858-02	Kona Vill. 2	22.2	84.4	380	77	4.9
4858-03	Kona Vill. 3	20	47.9	580	92.7	6.3
4953-01	Kiholo	21	36	330	26	12.7
5005-01	Pepeekeo	21	45	12	10	1.2
*5005-01	Pepeekeo	21.5	32	9.9	9.1	1.1
5005-02	Pepeekeo	--	12	13	9.6	1.4
*5005-04	Pepeekeo	20	--	5720	--	--
5005-05	Pepeekeo	20	23	322	33	9.8
5548-01	Parker 1	28	56	520	47	11.1
*5548-01	Parker 1	--	68	545	49	11.1
5745-01	Parker 5	26	46.8	26	8.6	3.0
*5745-01	Parker 5	--	71	23	10.5	2.2
5745-02	Parker 4	26.5	57	27	9.9	2.7
*5745-02	Parker 4	--	71	28	10.4	2.7
5814-01	Laupahoehoe	19	40	100	13	7.7

Hawaii (cont.)

Well Number	Name	TEMP. (°C)	SiO_2 (ppm)	Cl (ppm)	Mg (ppm)	Cl/Mg
5946-01	Lalamilo	26.5	55	78	15	5.2
5948-01	Hapuna Bch.	25	49	440	37	11.9
*5948-01	Hapuna Bch.	--	68	436	42	10.4
6048-01	Kawaihae 2	26.1	30	504	27.8	18.1
6048-02	Kea Bch.	26	51	390	34	11.5
*6048-02	Kea Bch.	--	71	394	40	9.9
6049-01	Kea Bch.	25	51	590	34	17.4
*6049-01	Kea Bch.	--	66	406	40	10.2
6049-02	Kea Resort 3	26	50	1740	119	14.6
6049-03	Kea Resort 4	25	53	3600	270	13.3
6117-01	Ookala Shaft	17.8	43	135	14	9.6
6147-01	Kawaihae 3	31	84	253	32	7.9
*6147-01	Kawaihae 3	--	51	171	8.5	20.1
6148-01	Kawaihae 1	27	66	360	32	11.3
*6148-01	Kawaihae 1	--	75	352	36	9.8
6148-02	Kawaihae 4	26.4	52	460	29.9	15.4
*6148-02	Kawaihae 4	--	77	370	38	9.7
6321-01	Paauilo Mill	18	37	195	19	10.3
6321-02	Paauilo Shaft	20	26.9	320	14	22.9
7446-01	Kohala Shaft	22.5	43	920	73	12.6
7448-04	Union Mill 1	21.5	38	42	7	6.0
7448-05	Union Mill 2	22	31.2	129	?1.3	99.2
7650-01	Hoea Shaft	21	38	71	6.2	11.5
7652-01	Waikane Shaft	22	54	560	27	20.7
	Thermal Spring Isaac Hale Bch.	36	81.5	3534	200	17.7
*	HGP-A	≃250	942	1040	1.0	1040
	Puuwaawaa	≃35	60	28	5.3	5.3
	Waikaloa		64	821	61	13.5