Senior Thesis Presentation

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"A Hydrogeochemical Assessment of Geothermal Potential in the Hawaiian Islands"

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A Hydrogeochemical Assessment Of Geothermal Potential In the Hawaiian Islands

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I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality.

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ABSTRACT

A hydrogeochemical assessment of geothermal potential across the State of Hawaii was recently conducted. Of focus here are chemical signatures - SiO_2, Cl/Mg ratios, pH – that can indicate subsurface heat, as well as the temperature, as measured in groundwater samples.

Silica increases in solubility with temperature. While chlorine is conserved, thermally altered water becomes depleted in magnesium, resulting in an elevated Cl/Mg ratio. It has been shown that in the creation of high temperature alteration products, pH will drop. Finally, temperature is the most direct way of measuring for subsurface heat. Different geologic settings, regional weathering rates, and anthropogenic inputs were also accounted for. For example silica concentration can also increase due to irrigation.

Results of data collection and analysis indicate that the islands of Lana'i as well as O'ahu may show geothermal potential. Our data show that multiple samples on certain islands have recorded anomalous and marginally anomalous values for SiO_2, temperature, and Cl/Mg ratio. The fact that there are concentrations of anomalous indicators in a given area strengthens the argument that a possible geothermal heat source may exist.

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INTRODUCTION

Each of the Hawaiian Islands is home to a unique and complex geologic environment that changes drastically depending on location. A regional assessment of groundwater in the Hawaiian Islands must account for different aquifer types, different regional weathering rates, different geologic settings, and anthropogenic variables. Due to these different factors, a regional geothermal resource assessment must be able to distinguish between chemical anomalies that are attributed to mixing of geothermally altered groundwater and those caused by other localized phenomenon. When using hydrogeochemical signatures to prospect for geothermal reservoirs in the Hawaiian Islands it has been found that multiple variables must be considered, due to the variability seen in the islands. The following is a study of geothermal indicators across the State of Hawai'i using hyrdogeochemical data, specifically silica levels, groundwater temperatures, pH, chlorine levels, magnesium levels, and Cl/Mg ratios.

A project was recently undertaken to update what was previously the most recent geothermal resource assessment across the State of Hawaii (1985, Don Thomas). This "Play Fairway" study, funded by the U.S. Department of Energy, included multiple scientific disciplines including geophysics, geology, and groundwater chemistry. It is groundwater data from Phase 2 of this Play Fairway study that I present below.

BACKGROUND

Silica

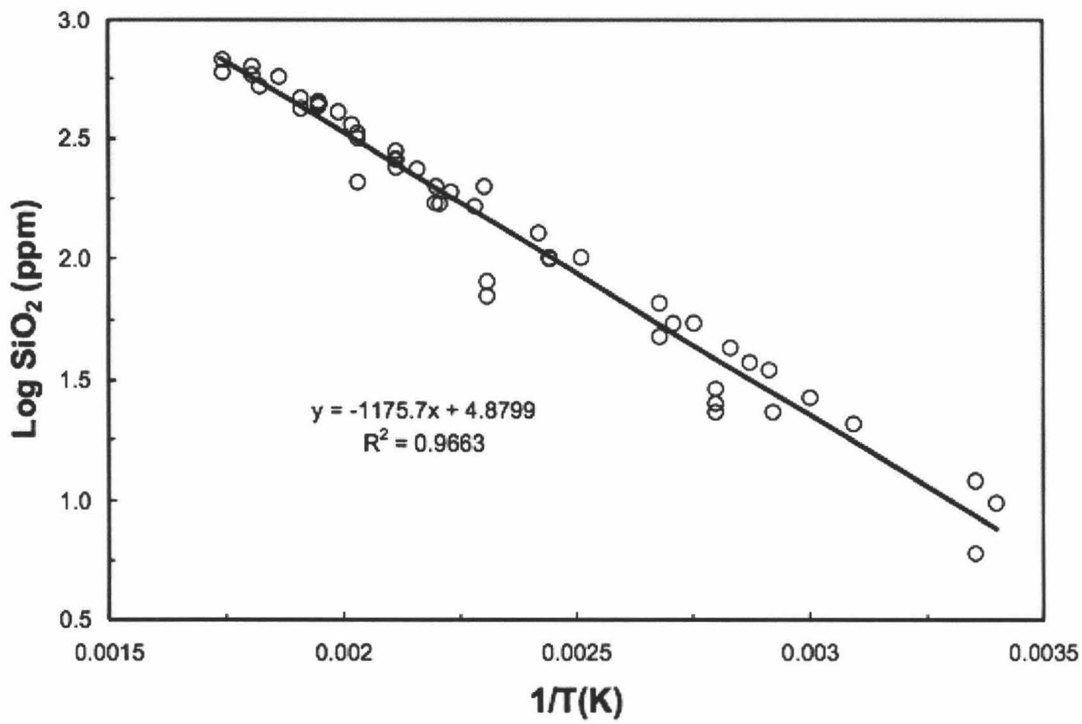


Figure 1. (Verma, 2000) Regression relation for SiO2 solubility along water vapor saturation curve.

An increase in subsurface temperature will result in an increase in the solubility of silica. This has been proven experimentally by Verma and is shown in Figure 1 above. A sample containing an anomalously high concentration of silica can be used as a indicator of subsurface heat. The following is a table (table 1) summarizing Davis's 1969 findings on dissolved SiO_2 content from different Hawaiian hydrological environments.

Type	Avg. SiO_2 Content (ppm)	Additional Comments
Freshly Percolated Rain	1-3	
Freshly percolated rain before entering high level aquifers	5-20	
Groundwater with residence time	15-45	Typified by high supply tunnel water
Basal Water	30-60	
High level water (stream discharge)	15-30	
Water entering sedimentary aquifers	25-45	Increases to 60 ppm with residence time.

(Table 1, SiO2 content of water types in the Hawaiian Islands)

It should be noted that aquifers which are introduced to irrigation or reinjection of industrial water are susceptible to dramatic increases in SiO_2 content. (Cox et al., 1979)

Temperature

Obtaining groundwater temperatures is the most direct way to measure for sub surface heat. Once water enters an island aquifer it can increase in heat due to 4 mechanisms: 1) volcanic activity, 2) frictional flows, 3) return irrigation, and 4) terrestrial heat flows (Cox, et al. 1979). It is also noted the different hydrological environments in an island aquifer have different average temperatures. Dike impounded water shows average temperatures of 18 to 21 °C. Basal ground water exhibits an average temperature of 20 to 24 °C. Sedimentary aquifers have shown an average temperature of 22 to 26 °C (Cox et al.,1979). These values are summarized in Table 3. In areas with extinct volcanism –Oahu and Kauai- temperatures of greater then or equal to 27 °C are considered significant and temperatures of greater then 29 °C are considered highly anomalous. Area with volcanic activity – Kilauea- show temperatures from anywhere between 30 to 90 °C. In areas with no surface volcanic activity, groundwater temperatures are in the range of 18.5 to 33 °C. Due to these factors, wells with a temperature greater then or equal to 27 °C are considered anomalous. (Cox et al., 1979)

pH

The formation of secondary solids like; chlorite, tremolite-actinolite, smectite, and talc, results in the rapid removal of Mg^{2+} from seawater. These reactions occur at a temperature between 70-500 °C. Basalt is able to remove large quantities of Mg^{2+} from seawater of up to 50x it's own mass when undergoing alteration. The removal of Mg^{2+} from groundwater occurs in the form of $Mg(OH)_2$ which leaves behind an H^+ ion, causing the pH to decrease. The rate of pH decrease is directly related to the rate of removal of $Mg(OH)_2$. When the removal rate is low -due to rate of formation of the previously stated secondary solids being low- the pH will still drop in response to the formation of Mg-OH-SO_4 phase precipitates. This reaction occurs by simple heating at 250-300 °C. Once Mg concentrations drop too low for formation, H^+ is rapidly consumed by silicate hydrolysis reactions and pH values will rebound to nearly neutral. Due to the above, wells with a decreased pH value can be indicative of subsurface heat, although it is important to keep in mind that even under conditions with high subsurface heat, pH can stabilize if Mg concentrations become too low (Mottle, 1983). Due to these processes, wells with a decreased pH value can be indicative of subsurface heat, although it is important to keep in mind that even under conditions with high subsurface heat, pH can stabilize if Mg concentrations become too low. (Mottle, 1983)

Chlorine

Chlorine is a major constituent of seawater and can be found in concentrations of .546 mol/kg throughout the ocean. Chlorine ions are extremely stable in groundwater environments, both basaltic and sedimentary. When basalt is introduced to elevated groundwater temperatures –approximately 300 to 350 °C- up to 75% of the Cl^2 content will be removed. Hawaiian basalts have a Cl^2 content of 0.01 to 0.12% weight, meaning exchange of Cl^2 from Hawaiian basalts is insignificant.(Cox et al., 1979).

Magnesium

Magnesium ions are much more susceptible to exchange with their surroundings then Chloride ions. Seawater that infiltrates calcareous marine sediments will increase in Ca and Mg and expel Na and K.. This happens during the following reaction:

$$(Ca, Mg)clay + 2(Na^+,K^+) \Leftrightarrow 2(Na,K)clay + (Ca^{++},Mg^{++})$$

Hawaiian basalts consist of 5 to 10% MgO. When meteoric rain percolates through the rock chemical weathering adds to Mg levels in the groundwater in the following reaction:

$$(MgFe)Si_2O_6 + 2H\text{^}+ \Leftrightarrow Mg\text{^}{++} + FeO + 2SiO_2 + H_2O$$

Both of these low temperature reactions result in an increase in Mg into groundwater (Cox et al., 1979).

In groundwater that has experienced elevated temperatures (greater than 70 °C) high temperature magnesium silicates begin to form. The formation of illite [$(AlMgFe)_4$*$(SiAl)_8$*O_{20}*$(OH)_4$] and chlorite [$Mg_3(Si_4O_{10})Mg_3(OH)_4$] result in a drop of magnesium concentrations in groundwater. When seawater comes in contact with elevated temperatures, magnesium oxysulfates and hydroxlated magnesium silicates are precipitated, which also causes magnesium concentrations in groundwater to drop (Cox et al,1979).

The lowering of magnesium concentrations in groundwater is caused by the existence of a subsurface heat source. This heat source is the mechanism for the formation of alteration minerals and weathering products that result in a direct loss of magnesium (Cox et al., 1979).

<u>Cl/Mg ratios</u>

Ratios of Cl to Mg have been used as a reliable distinguisher between saline groundwater in island environments and depleted magnesium water of geothermal origins. Sea water is known to have a consistent Cl/Mg ratio of 15. Due to the fact that Cl is relatively stable in a basaltic island aquifer during thermal processes and ion exchange via migration, Cl content can be used as a control when assessing aquifer environments. Mg becomes extremely depleted when affected by thermal processes due to the creation of alteration minerals. This results in an elevated Cl/Mg ratio in groundwater(Cox at el.,1979). Expected Cl/Mg ratios of water in low temperature Hawaiian environments are summarized Table 2 (below):

Type	Ratio	Comments
Rainwater	7	Carries small concentration of sea salt.
Percolated Rain	2-3	Dissolves Mg from ferromagnesium minerals.
Saline water entering basaltic environment	2-6	Must infiltrate calcareous marine sediments before reaching basaltic environments. Gains Mg and Ca while losing Na and K during infiltration.
Sedimentary aquifers with low topography	5-8	Areas like valleys and coastal strips. Some Mg is lost to clays produced by weathering.

(Table 2, Cl/Mg ratios of low temperature water in the Hawaiian Islands)

Overall, nongeothermal waters in the Hawaiian islands have a Cl/Mg ratio of 1-8. Due to seawater having a ratio of 15, any well containing a ratio of greater then 15 is considered anomalous. A well with a reading between 12-14.9 is considered marginally anomalous (Cox et al., 1979).

Environments

Hawaiian aquifer environments can generally be categorized into three basic types. It is important to keep in mind that the division among the three types may or may not be well defined, and intermediate characteristics do exist. The three types are dike impounded, Basal, and Sedimentary/ Alluvial environments (Cox et al.,1979).

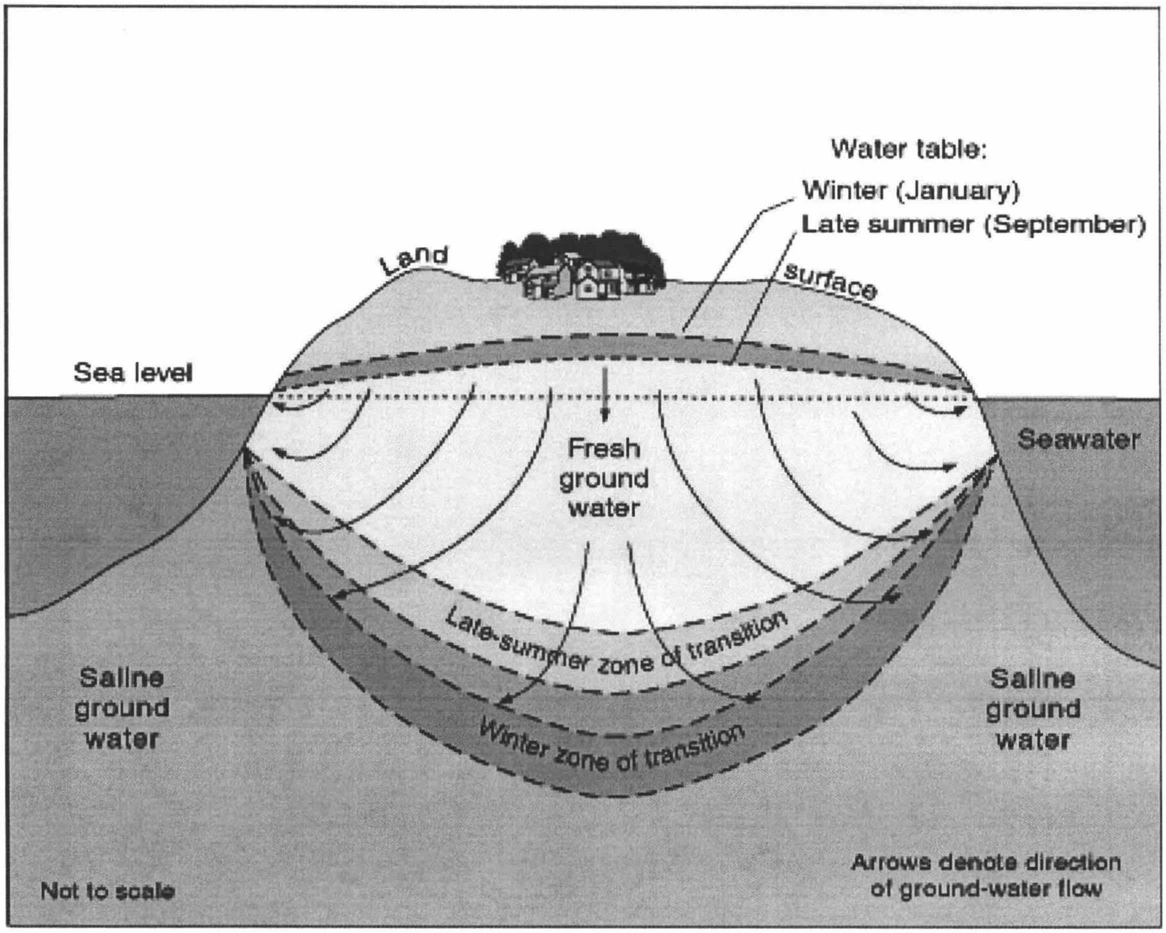
These three categories of aquifer types are summarized in Table 3 (below):

Type	Temperature (Celsius)	Comments
Dike Impounded	18-21	Most often associated with riftzones and does a good job of separating saline and groundwater. These aquifers are a product of local recharge. Source for high elevation groundwater, although can occur close to sea level.
Basal	20-24	Underlying all major island and can extend to depths of up to 6 km below sea level. Density differences are the mechanism for creating the Ghyben Herzberg lens.
Sedimentary/ Alluvial	22-26	Mostly occur at lower elevations within larger

		valleys and costal strips. Material can be either marine or terrestrial. Exhibit low permeability limited thickness.

(Table 3, Aquifer types with associated temperatures,(Cox et al.,1979))

Of these three types of aquifers, the basal aquifer is by far the largest volumetrically and supplies the majority of the island's drinking water. The basal aquifer is a lens of freshwater that sits on top of a layer of denser saline water. Between the top freshwater lens and the lower saline water is a transition zone of mixing. This density driven phenomenon is called the Ghyben Herzberg lens.



(Figure 2. USGS) Ghyben Herzberg lens.

Sedimentary and alluvial settings –especially on Oahu- are often the most developed areas in the islands. Due to this fact the aquifers are more likely to be exposed to higher amounts of irrigation and recycled water. This addition alters groundwater chemistry in a way that increases SiO_2 content, which must be kept in mind when doing a regional groundwater assessment of the islands. In addition to this, it should be kept in mind that areas with low dike density or geologic structures can more readily allow for the movement of subsurface waters, increasing recharge rates, and therefore diluting the signatures of subsurface heat.

A final note about regional Hawaiian hydrology; Due to the orographic effect, the islands have a windward side and a leeward side. The windward side is exposed to a higher concentration of rain, which affects recharge rates and increases erosion and weathering. This also results in differing soil types. This is another factor that must be accounted for when doing regional groundwater assessments of the Hawaiian Islands.

METHODS

Field

Groundwater samples were collected from existing water wells. All samples are representative of subsurface conditions, e.g do not include anthropogenic additions of chlorine or floride. In the field a YSI was used for measurements of pH, temperature, dissolved oxygen, conductivity, total dissolved solids, salinity, ORP, and time of sampling.

Laboratory

Samples were analyzed in two University of Hawai'i laboratories: The Water Resource Research Center Environmental Lab (major elements), The Oceanography Department (trace metals and silica), and The Biogeochemical Stable Isotope (Oxygen, Hydrogen, and Carbon). Given that this study focuses on silica, Cl, and Mg, the methods for the former two labs are briefly stated here. Analysis of water chemistry for **trace metals and silica** involved the use of a Varian Vista MPX inductively coupled plasma optical emission spectrometer. This method involved solubilizing with reflux of nitric and hydrochloric acids. Once treated with the acid the sample is mixed and centrifuged and then allowed to settle overnight. The instrument then uses optical spectrometry to analyze the chemical make up of the samples (Martin, 1982).

Analysis of **major ions** was done by ion chromatography. This is done introducing a small volume of sample -10 micro Liters- to the ion chromatograph. This instrument separates the anions of interest, which are then measured with a system that is comprised of an analytical column, guard column, suppressor device, and a conductivity detector. This is a two part procedure with part 1 using a sample of 10 micro Liters and part 2 using a sample of 50 micro Liters. This procedure only works for anions (Pfaff, 1999).

DATA

A total of 61 samples were collected on all islands in the State of Hawai'i, with the exception of Moloka'i

Charge Balance

To ensure the data collected are trustworthy, a charge balance calculation was conducted. All groundwater should be neutrally charged, meaning that the sum of all cations and anions in each sample should total to zero. The first step in this process was to convert the alkalinity values into the various carbonate species. To do this we take the alkalinity values of CaCO3 in mg/L and convert it into bicarbonate by multiplying by 1.22. Next the values of the major ions and trace metals were converted from mg/L (as reported by the labs) to meq/L. Finally, once all values are in meq/L a percent difference was calculated using the equation:

(Cations – Absolute value(anions)/(cations + absolute value(anions))*100

If these values did not total to + or – 10% of zero then the data were considered untrustworthy data and not included in our consideration for geothermal potential. The following data is organized by island. Cl/Mg ratios of greater than 15 are considered significantly high and values of 12- 14.9 are considered marginally significant. Temperatures of greater then 29 °C are considered significantly high and temperatures of greater then or equal to 27 °C are considered marginally significant. Charge Balances must fall within 5% to be considered extremely trustworthy data and fall within 10% to be considered trustworthy.

Kauai

Well	Cl	Mg	Cl/Mg Ratio	SiO_2 (ppm)	Temp °C	pH	charge balance
2-0124-03	15	12.32	1.22	45.82	24.9	7.34	10
2-0421-02	38	22.27	1.71	63.6	24.8	7.34	11
2-5425-15	43	16.44	2.61	68.29	23.9	7.4	8
2-5426-05	84	25.27	3.32	65.96	23.9	7.32	7
2-5427-03	28	12.20	2.29	62.09	23.5	7.5	10
2-5530-03	27	13.77	1.96	63.16	23.2	7.65	9
2-5629-01	24	11.42	2.10	54.04	23.2	7.75	8
2-5631-01	21	10.51	1.2	46.89	--	8.02	10
2-5823-01	20	9.48	2.11	35.7	23.4	7.62	8
2-5824-05	19	7.75	2.45	24.76	23.6	6.95	11
2-5824-06	21	9.42	2.23	36.22	23.2	7.3	7
2-5921-01	50	21.58	2.32	81.46	25.4	8.43	8

2-5923-07	19	9.78	1.94	36.88	23.6	7.6	10

(Table 4, Kaua'i Data)

O'ahu

Well	Cl	Mg	Cl/Mg Ratio	SiO_2 (ppm)	Temp °C	pH	charge balance
MW1	2083	247	8.433	90.20	28.4	6.96	5
MW2	412	61	6.75	46.29	27.9	6.81	7
MW3	2377	278	8.55	101.59	29.9	6.69	6
MW4	2005	245	8.18	52.17	26.8	6.17	5
RHMW04	74	18.80	3.93	57.07	22.8	6.5	8
RHMW06	416	74.17	5.61	74.34	22.6	6.93	4
RHMW07	431	82.62	5.22	76.17	22.9	7.26	4
OWDFMW1	1059	244.86	4.32	51.37	25.8	8.02	2
RHMW 2254-01	89	16.7	5.33	49.09	21.84	7.54	3
RHMW 08	169	19.6	8.62	45.59	24.01	8.2	3
RHMW 03	47	33.5	1.40	86.14	27.37	6.77	8
3-2607-001 or 3-58-006	56	14.5	3.86	97.27	24	7.18	10
3-2808-002 or 3-58-004	26	7.9	3.29	56.5	24.1	7.79	9
3-2157-005	18708	1371	13.64	35.25	21.7	7.01	2
RHMW02	37	24.2	1.53	91.25	23.54		65
RHMW05	148	13.3	11.13	86.46	23.8		20
2253-003.276	88	16.5	5.33	65.03	22.6		16
2253-003.851	1874	278.3	6.73	39.23	22.7		0

(Table 5, O'ahu Data)

Maui

Well	Cl	Mg	Cl/Mg Ratio	SiO_2 (ppm)	Temp °C	pH	charge balance
6-3826-001	676	97.19	6.95	43.87	21.4	7.36	3
6-3926-002	522	67.97	7.68	33.39	23.1	7.87	2
6-3926-003	686	70.51	9.73	32.66			2
6-3926-005	631	86	7.34		20.5	7.91	4
6-3926-011	42	9.98	4.21	48.92	26.4	7.5	8
6-4100-002	35	6.7	5.22		25.7	7.42	7
6-4122-001	6	0.3	20		21.6	8.44	43
6-4300-002	7	1.52	4.60	17.86	20.6	7.76	12
6-4559-001	63	7.6	8.29		21	7.91	7
6-4611-001	72	16.2	4.44		21.5	6.81	33
6-4600-003	58	2.27	25.55	20.47	19.4	7.49	3
6-4701-001	6	2.52	2.38	20.88	20.1	7.41	10
6-5317-001	11	7.1	1.55	52.23	21.7	7.88	15
6-5417-004	16	6.52	2.45	41.5	20.5	7.91	11
Olowalu Shaft 10-16-16	43	8.32	5.17	46.17	23	7.53	4
Olowalu Well 10-16-16	19	10.61	1.79	47.77	22.5	7.48	5

(Table 6, Maui Data)

Lana'i

Well	Cl	Mg	Cl/Mg Ratio	SiO_2 (ppm)	Temp °C	pH	charge balance
5-4753-	547	137.83	3.97	79.48	25.8	7.14	-3

001							
5-4853-002	293	77.85	3.77	86.24	28.1	7.66	5
5-4954-003	40	16.91	2.37	68.49	22.7	7.91	9
5-4854-002	836	201.84	4.14	96.02	29.8	7.23	0
5-4952-002	22	8.01	2.75	52.90	18.9	7.89	9
5-4954-002	48	18.38	2.61	67.89	22.9	8	-10
5-5054-002	32	10.87	2.94	50.59	19.8	7.9	-18
5-4854-001	425	117	3.63	99.16			1

(Table 7, Lana'I Data)

Hawai'i

Well	Cl	Mg	Cl/Mg Ratio	SiO_2	Temp °C	pH	charge balance
8-6223-001	9.6	6.52	1.47	37.97	21.8	8.24	17.00
8-6240-002	6.6	6.31	1.05	57.79	24.5	7.03	4.00

8-6528-001	95.8	23.32	4.11	45.43	22.4	6.96	2.00
8-0545-001	87	16.04	5.42	44.74			2.00
8-5239-001	17	16.88	1.01	68.44			5.00
pgv MW1	24	12.9	1.86	60	34	7.4	3.00
pgv MW2	480	13	36.92	27.1	47	6.3	0.00

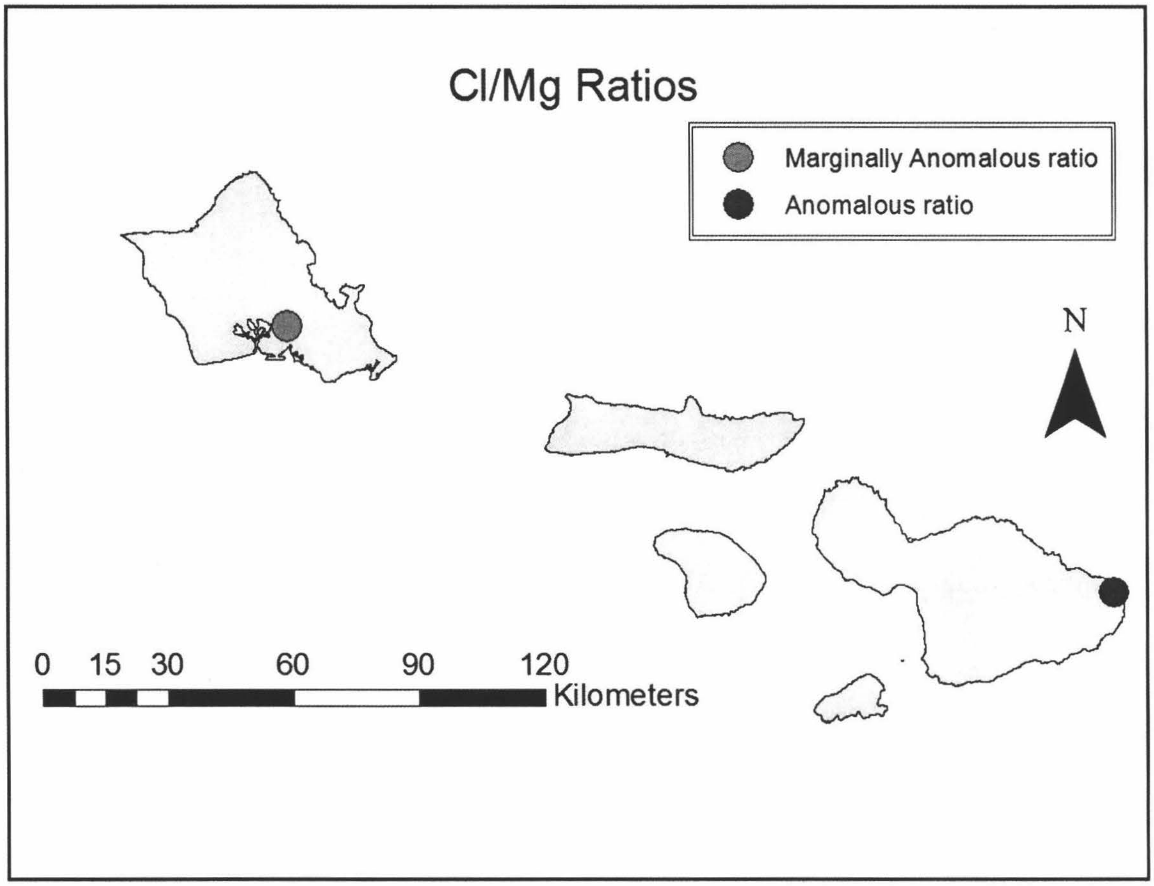
(Table 8, Hawai'I Data)

INTERPRETATION/ DISCUSSION

Cl/Mg Ratios

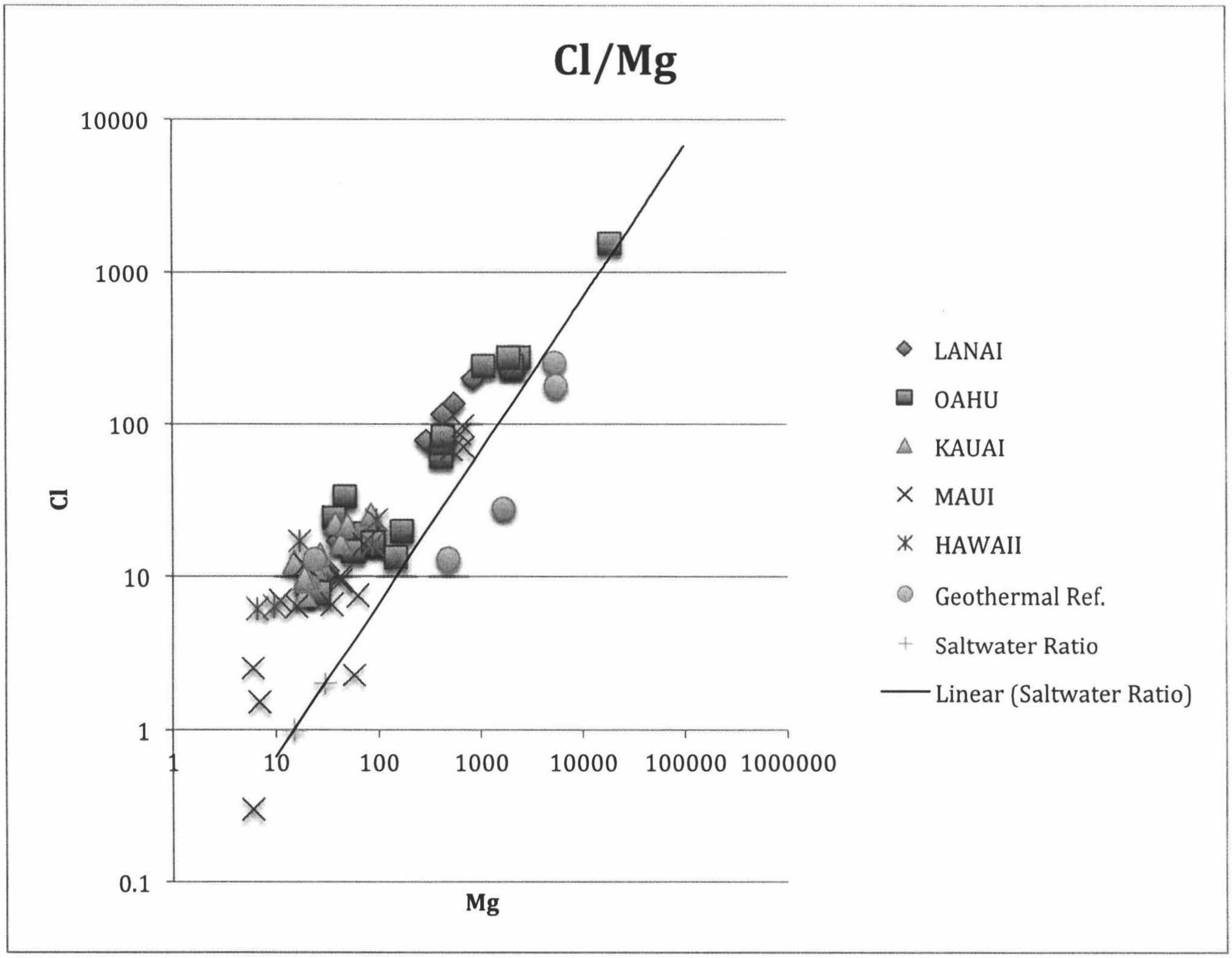
Values of greater than 15 are considered anomalous. Of the wells sampled two wells –both on Maui- have anomalous values. The two wells were 6-4600-003 and 6-4100-002. It should be noted that well 6-4100-002 had a charge balance of 43% and is considered untrustworthy data. Well 6-4600-003 on the other hand has a charge balance of 3% and a Cl/Mg ratio of 25.6. This well is located on the Hana coast of Maui on the Eastern side of the island. This area is considered to be volcanically active.

Values between 12 and 14.9 are considered marginally anomalous. There was one well that reported a marginally anomalous value. Well 3-2157-005 is located at Ford island on O'ahu and reported a Cl/Mg ratio of 13.64. The charge balance for this well is 2% and is considered trustworthy data.



(Figure 3. Cl/Mg Ratios map. Anomalous values are considered ratios greater than 15. Marginally anomalous values are those that fall between 12 and 14.9. The anomalous well on Mau'i is well 6-4600-003. The marginally anomalous well on O'ahu is 3-2157-005.)

Cl and Mg values are plotted in a logarithmic scale in Figure 2 below. The seawater ratio line of 15 is plotted as well; any value to the right of this line is anomalous. In addition to wells plotted, a few geothermal wells from Hawai'i Island are plotted as reference.

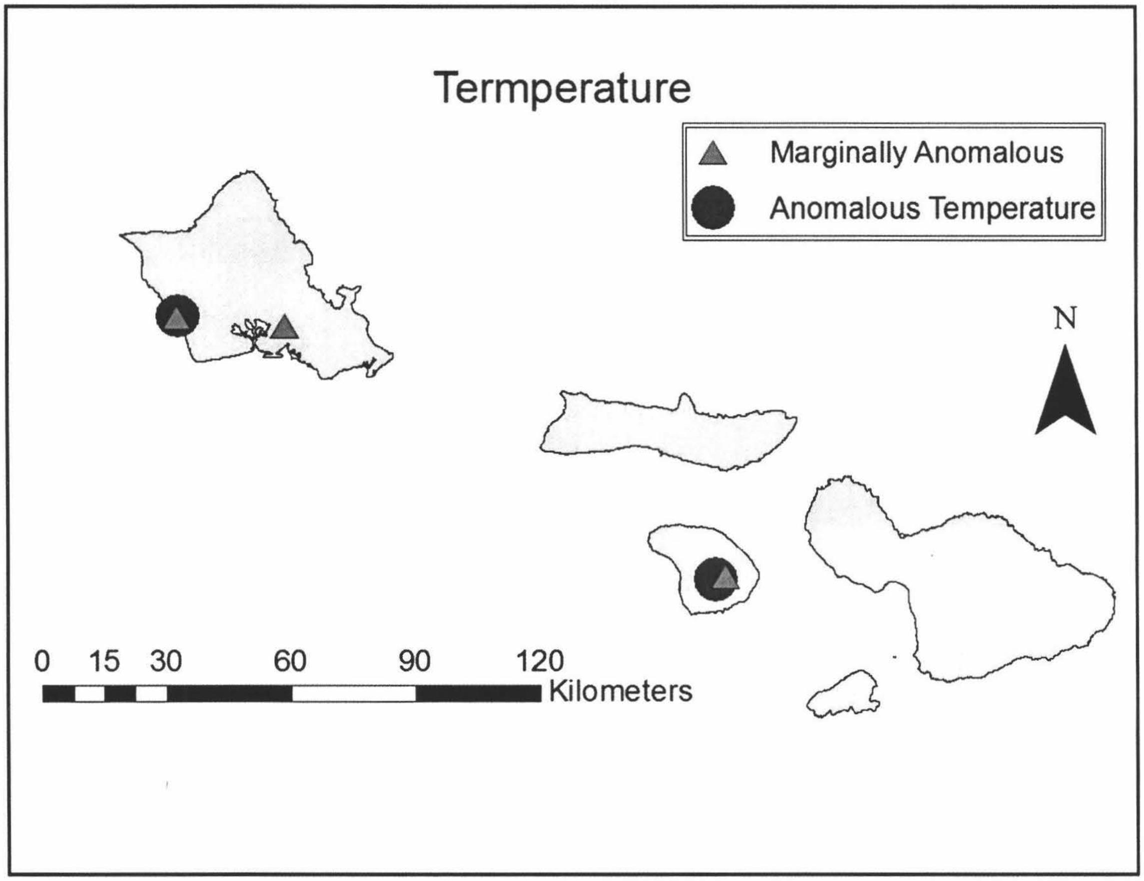


(Figure 4. Cl/Mg ratios plotted on logarithmic scale for wells sampled. The seawater ratio line of 15 is plotted as well, with anomalous Cl/Mg ratio values being anything to the left of the line. Known Hawaiian geothermal wells are plotted as well as a reference.)

Temperature

In field measurements of groundwater, temperature is the most direct way of sampling for subsurface heat. Values of greater then 29 °C are considered anomalous. Of the wells sampled, two wells came back with anomalous values. Well 5-4854-002 was located on the Island of Lanai with a value of 29.8 °C and a charge balance of 0%. Well MW3 is located on the island of Oahu with a value of 29.9 °C and a charge balance of 6%.

Values between 27 °C and 28.9 °C are considered marginally anomalous. Of the wells sampled, 4 came back with marginal temperature values and are also located on the Islands of Oahu and Lanai. On the Island of Lanai well 5-4853-002 reported a temperature of 28.1 °C and a charge balance of 5%. On the island of Oahu wells MW1, MW2 and RHMW03 had temperatures of 28.4 °C, 27.9 °C, and 27.3 °C respectively with charge balances of 5%, 7%, and 8%.

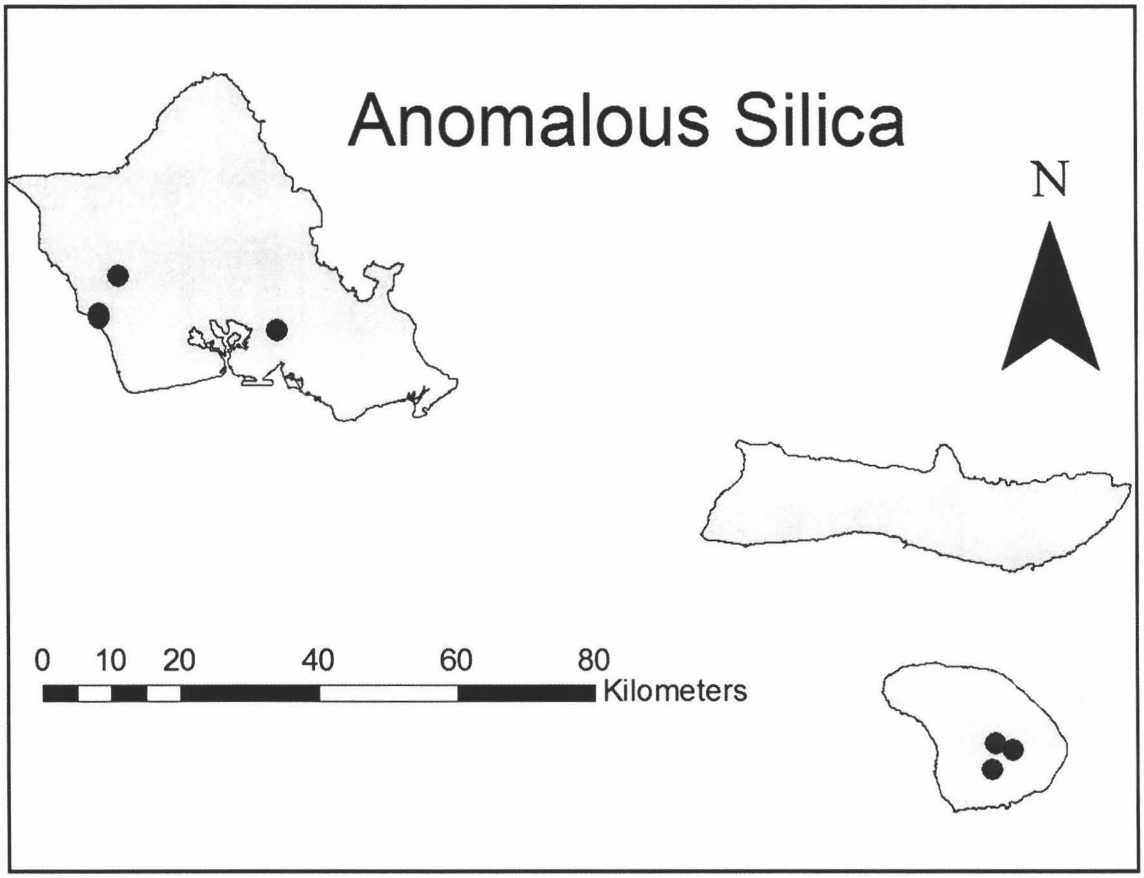


(Figure 5. Ground water temperature map. Anomalous temperatures are anything greater then 29 °C. Two wells were found to be anomalous, 5-4854-002 on Lana'i and MW3 on O'ahu. Four wells were found to have marginally anomalous values at greater then 27 °C but less then 28.9 °C. On Lana'i well 5-4855-002, and on the Island of O'ahu wells MW1, MW2, and RHMW03.)

<u>SiO_2</u>

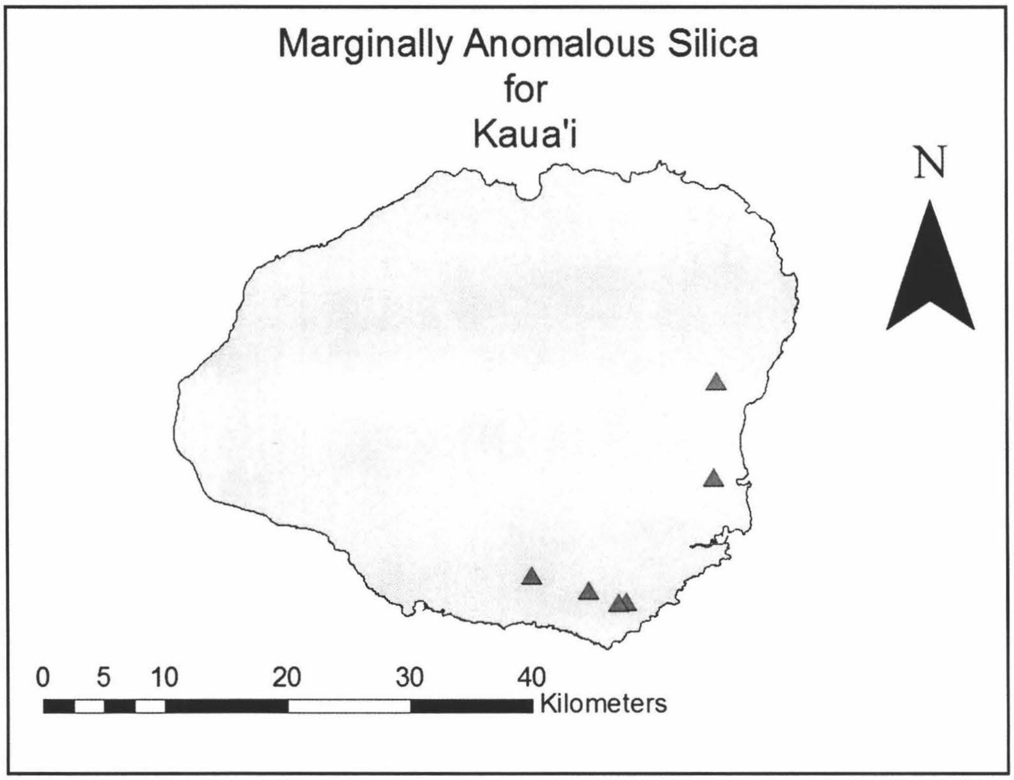
Silica values that were found with greater then 85 ppm are considered anomalous. Of the wells sampled 8 wells are considered anomalous. Two wells on the island of

Lanai, 5-4853-002 and 5-4854-002, have anomalous values of 86.2 ppm and 96.01 ppm respectively. Six wells on O'ahu have anomalous silica values. Of these 6 wells, all had charge balance percentages that are considered trustworthy with the exception of RHMW02 and RHMW05. Wells MW1, MW3, RHWM03 and 3-2607-001 had values of 90.2 ppm, 101.6 ppm, 86.1 ppm, and 97.27 ppm respectively. These wells all reported charge balance percentages within the trustworthy range.

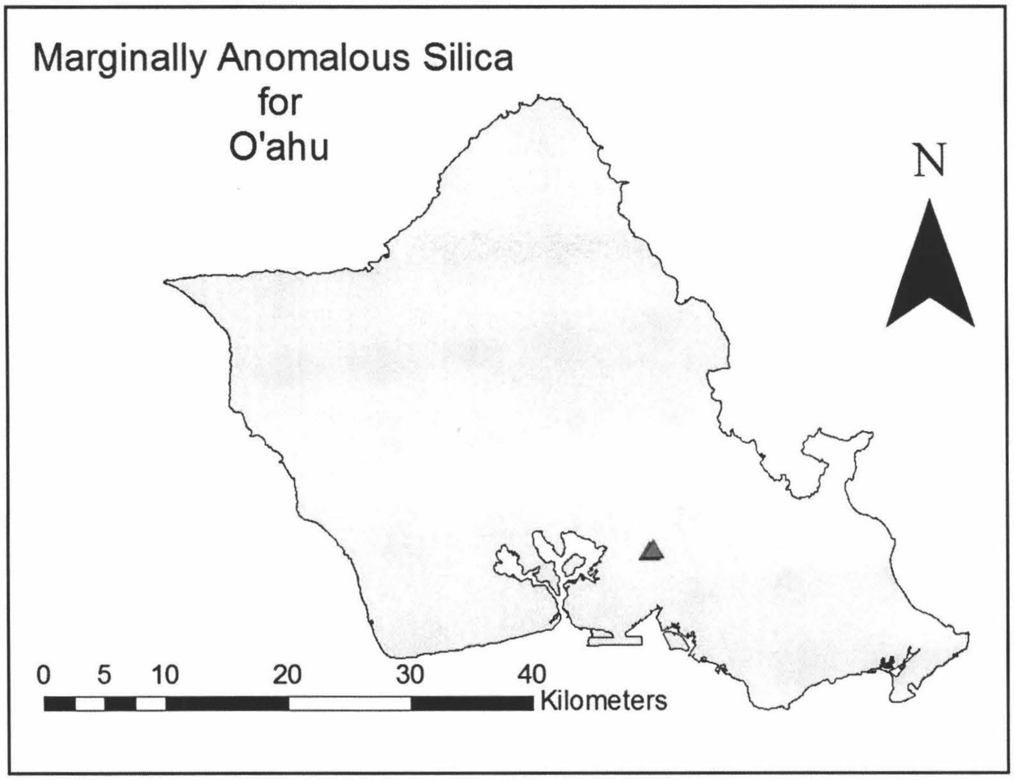


(Figure 6. Anomalous SiO2 Map. Values of greater then 85 ppm were considered anomalous values. On the island of O'ahu wells MW1, MW3, RHMW03, and 3-2607-001 were found to be anomalous. On the island of Lana'i, wells 5-4853-002, 5-4854-001 and 5-4854-002 were found to be anomalous.)

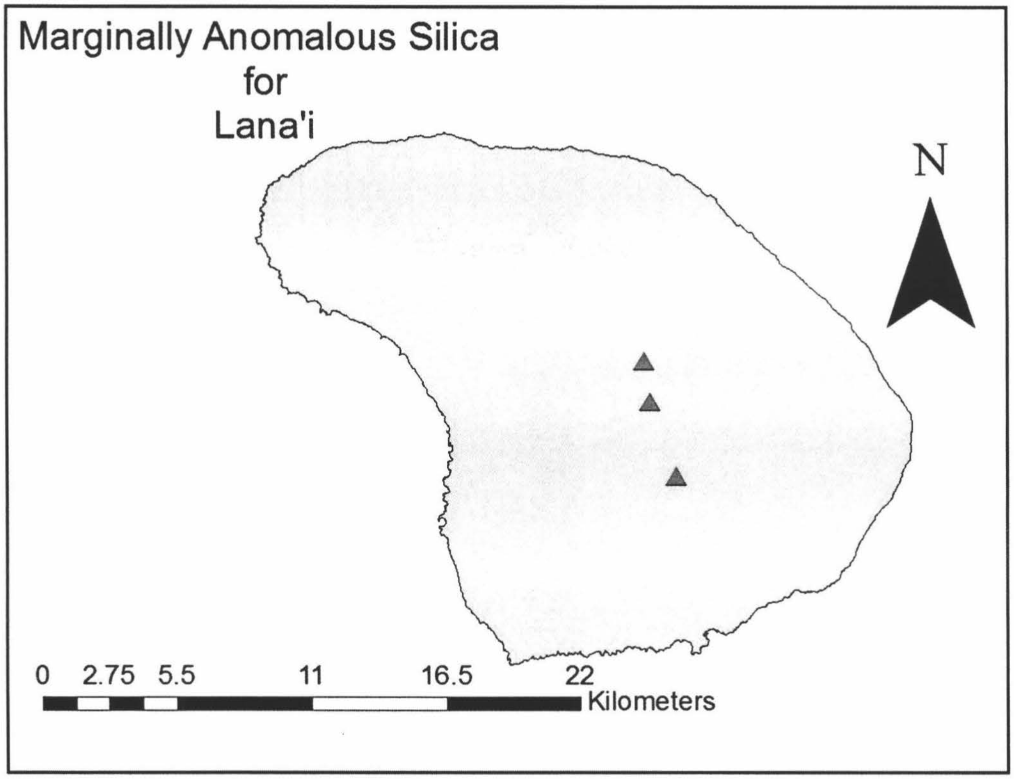
Silica values between 61 ppm and 84.9 ppm are considered marginally anomalous. Of the wells sampled, 11 fell into the marginally anomalous range while also having a charge balance percentage that was considered trustworthy. 3 of these wells are located on the Island of Lanai, wells 5-4753-001, 5-4954-003, and 5-4954-002. These wells had silica levels of 79.5 ppm, 68.5 ppm, and 67.9 ppm respectively. The island of Oahu is home to two wells, RHMW06 and RHMW07, with marginal values of 74.34 ppm and 76.17 ppm respectively. Finally the island of Kauai has 6 wells, 2-0421-02, 2-5425-15, 2-5426-05, 2-5427-03, 2-5530-03 and 2-5921-01, with marginally anomalous silica values of 63.6 ppm, 68.29 ppm, 65.9 ppm, 62.1 ppm, 63.2 ppm, and 81.5 ppm respectively.



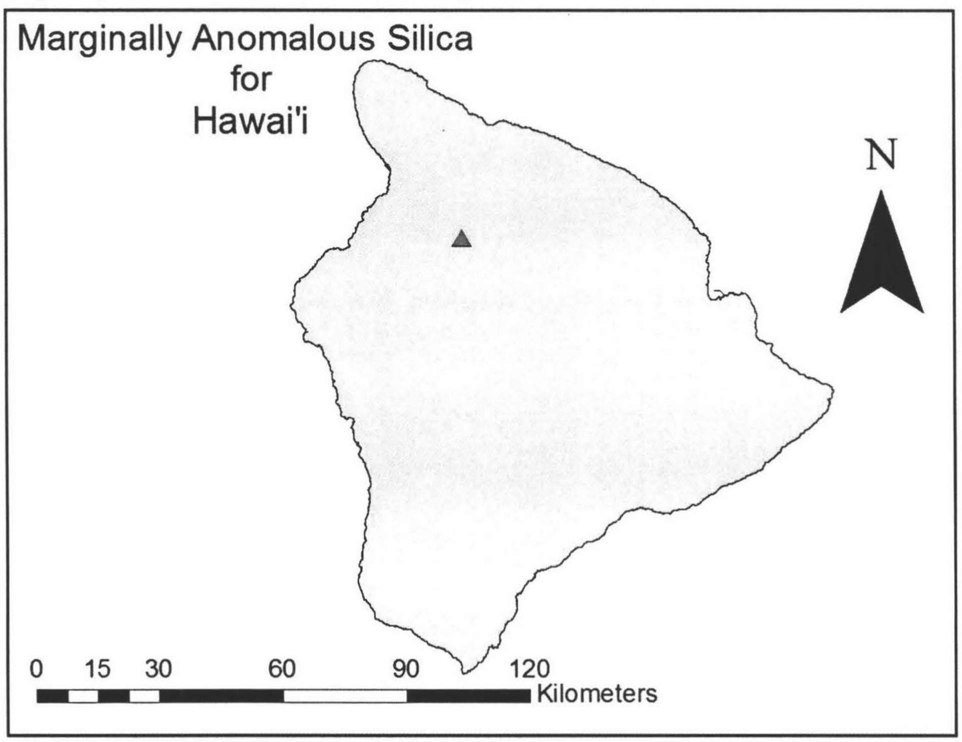
(Figure 7. Marginally Anomalous Si02 values for Kaua'i. Si02 levels between 61 and 84.9 ppm are considered marginally anomalous. Wells 2-0421-02, 2-5425-15, 2-5426-05, 2-5427-03 and 2-5921-01.)



(Figure 8. Marginally Anomalous SiO2 values for O'ahu. Values between 61 and 84.9 ppm are considered marginally anomalous. Wells RHMW06 and RHMW07 are found to be marginally anomalous.)



(Figure 9. Marginally Anomalous SiO2 values for Lana'i. Values between 61 and 84.9 ppm are considered marginally anomalous. Wells 5-4753-001, 5-4954-001 and 5-4954-002 fall into this range.)



(Figure 10. Marginally Anomalous SiO2 values for Hawai'i. Values between 61 and 84.9 ppm are considered marginally anomalous. On Hawai'i island, well 8-5239-001 has SiO2 levels that fall into this range.)

pH

Acidic water can be used as an indicator for possible subsurface heat. It is important to remember though that due to the process of H+ being created and then depleted from silicate hydrolysis, pH can stabilize even with high subsurface heat.

Possible sources for error

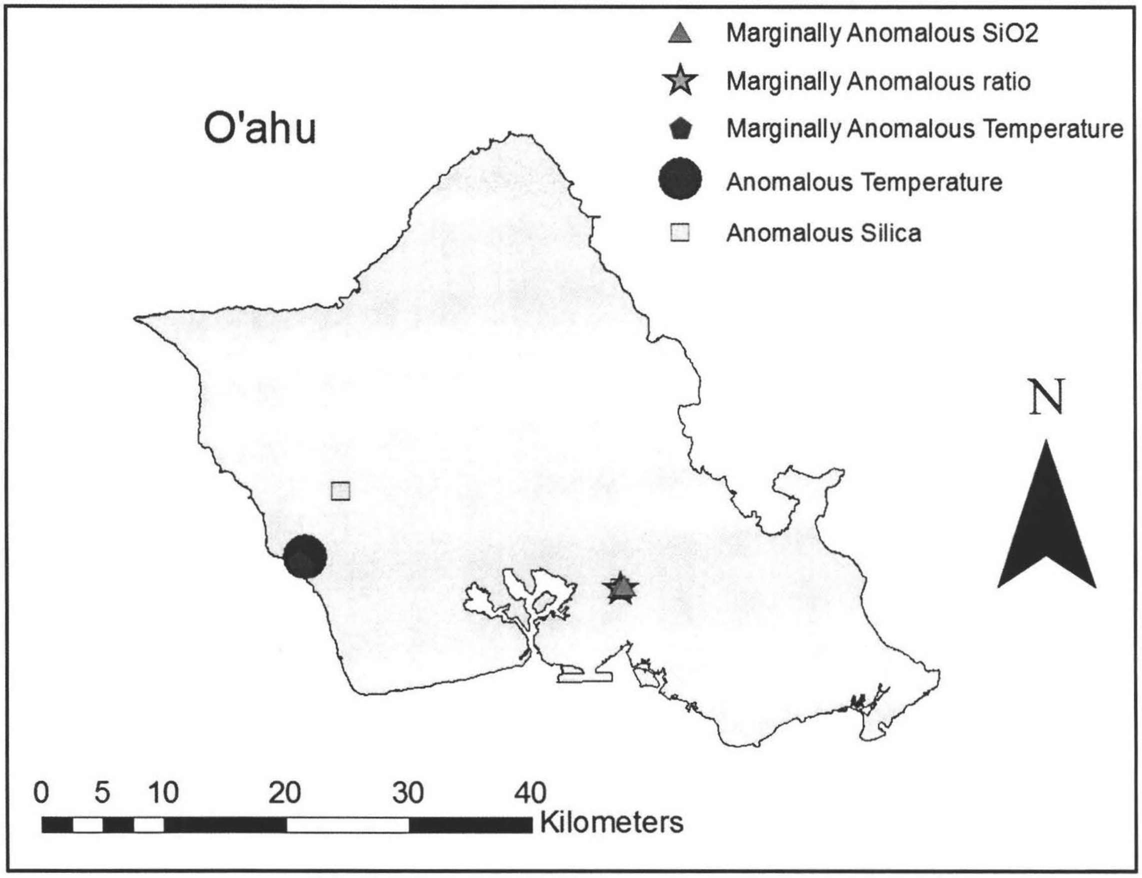
There were wells whose charge balance calculations fell outside of the trustworthy range. This is most likely due to incomplete data resulting in a unbalanced charge percentage. These wells were excluded from further investigation.

Other possible sources for error include improper sampling techniques such as; contamination with other samples, samples not being placed on ice, and improper acidification of samples.

CONCLUSION

It has been found that areas with the highest probability for subsurface heat include Lana'i, Maui, and possibly O'ahu. These islands had the highest abundance of anomalous and marginally anomalous values for the temperature and geochemical signatures that were tested for.

O'ahu

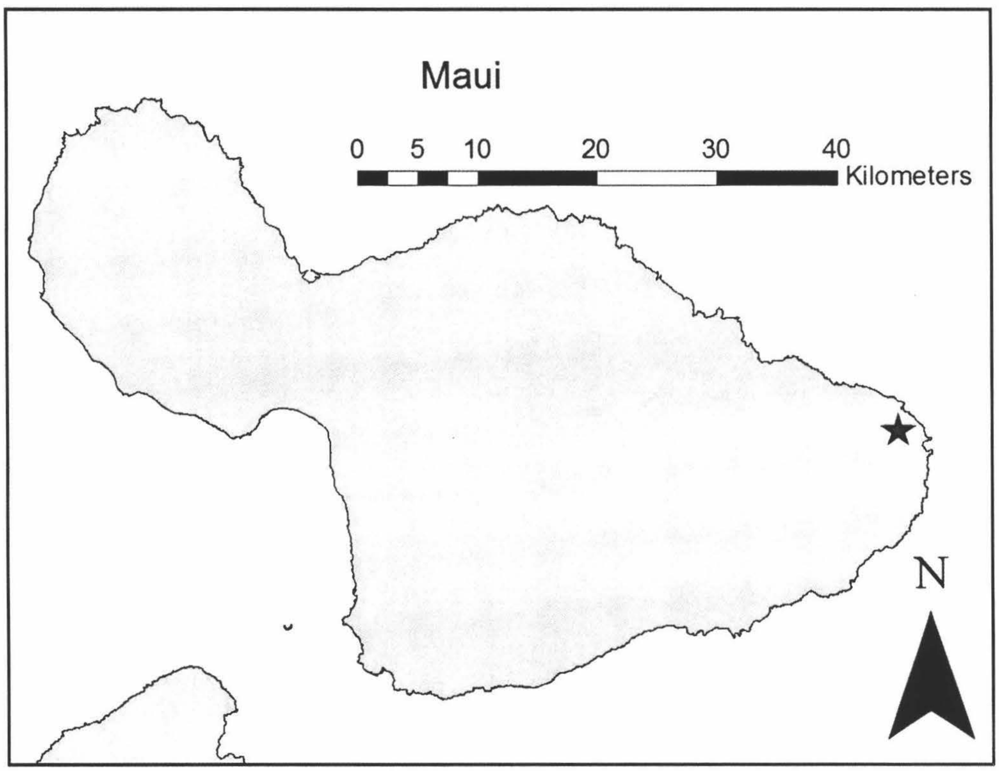


(Figure 11. Anomalous and Marginally anomalous values for the island of O'ahu.)

On the West wide of the island of O'ahu, Anomalous Silica values were found in Laulaulei Valley at wells MW1, MW3, and at Lualualei deepwell. In addition to this anomalous temperatures were also found at MW3 while marginally anomalous temperatures were found at MW1 and MW2. This area is directly above the old caldera complex of the Wai'anae volcano. This is interpreted as residual heat from the old caldera.

The Red Hill area of Oahu also yielded interesting data. Anomalous SiO_2 values were found at RHMW02 and RHMW05 as well as marginally anomalous values at RHMW06 and RHMW07. Marginally anomalous temperature values were also found at RHMW03. A marginally anomalous Cl/Mg ratio is also found in the area at 3-2157-005, the Ford Island Saltwater well. The high Cl content of this well has been attributed to the saline nature of the water sampled. Due to the area's high rate of development and contamination of ground waters by anthropogenic origins, the data from the Red Hill area should be scrutinized more closely. There is no question the groundwater in the area has been contaminated by anthropogenic means, and it may be unlikely that the chemical anomalies seen here are attributed to geothermal heat. In order to be certain, further exploration is needed.

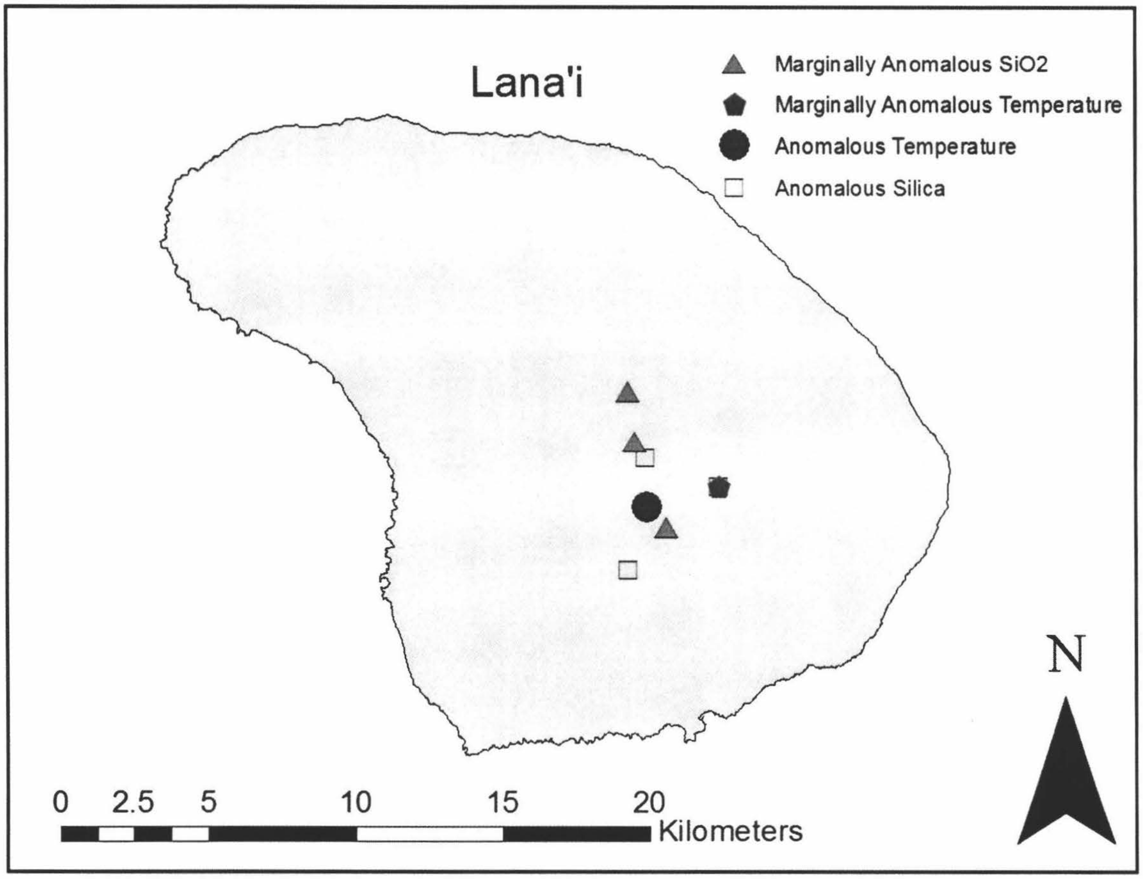
Maui



(Figure 12. Anomalous values for island of Maui. Star on map denotes location of well with Anomalous Cl/Mg ratio.)

The island of Maui yielded one interesting data point. On the East coast of Maui near Hana, well 6-4600-003 found a Cl/Mg ratio of 25.6. This was the highest ratio value found of the wells sampled with the exception of one well on Lanai that was excluded from the final report due to an extremely unbalanced charge percentage. Although this data is trustworthy, due to the lack of other anomalous data from the area it may be improbable that a geothermal reservoir exists in the area. Collection of more data in this area is warranted.

Lana'i



(Figure 13. Anomalous values for the island of Lana'i)

The island of Lana'i has one well in the anomalously high temperature range. A temperature of 29.8 °C was measured at Well 5-4854-002. In addition to this, well 5-4853-002 has a temperature of 28.1 °C. Additionally, SiO_2 values in the anomalously high range were measured at well 5-4853-002 (86.2 ppm), 5-4854-001 (99.2ppm) and 5-4854-002 (96.01 ppm). Marginally anomalous values for SiO_2 were found at wells 5-4753-001, 5-4954-003 and 5-4954-002 which had values of 79.5 ppm, 68.5 ppm and 67.9 ppm, respectively. It is notable that Lana'i had zero wells with anomalous or marginally anomalous Cl/Mg ratios. This may be attributed to the fact that the wells sampled on Lana'i were surrounded by dense host rock from the old caldera complex that formed Lana'i. This rock has a high abundance of olivine $(Mg, Fe)_2SiO_2$ and could result in waters from the area having an elevated Mg content (West 1992). This may explain why Lanai groundwater does not show the expected high Cl/Mg ratio associated with subsurface heat. The data from Lana'i leads one to believe that there is still a source for subsurface heat and further exploration is recommended.

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