GEOCHEMISTRY OF GROUND AND THERMAL WATERS IN THE NGAWHA AREA AND ELSEWHERE IN NORTHLAND, NEW ZEALAND

MALCOLM COX[1] and PATRICK R.L. BROWNE[2]

[1]School of Geology, Queensland University of Technology
[2]Geothermal institute, University of Auckland

SUMMARY - Most groundwaters in Northland are of ambient temperature (14° - 16°C), neutral to alkaline pH and of Na-HCO_3 (±Ca ±Cl) type. Their chemistry is apparently determined by the lithologies through which they move, in particular the Permian-Jurassic greywacke basement which contributes B, CO_2 and Li. There are also waters high in Ca-Mg hosted by the overlying Cretaceous-Tertiary sedimentary rocks. Several waters may contain a component of connate water and a few near the coasts probably obtain some of their Cl from seawater. The geothermal system at Ngawha itself contains ~230°C alkali chloride water which is slightly acid. The system has a high gas content, largely CO_2 which migrates at least 15 km. Both the gas and heat disseminated fiom the geothermal system influence groundwater chemistry in the peripheral areas.

1. INTRODUCTION

A notable hydrogeological feature in Northland is the Ngawha geothermal system which is the only known high temperature (220°-300°C) system located outside the Taupo Volcanic Zone (TVZ). The main thermal area lies within a shallow basin on the central plateau at about 200 m ASL. Drainage from the basin is to the NE via the Waitangi River.

There are a variety of other natural discharges of groundwater throughout Northland hosted within different geological environments. Most of these waters are at ambient temperature, although several are warm.

Apart from thermal water, groundwater as a resource is not routinely explored for in Northland, primarily because of its high rainfall and small population. The annual rainfall averages around 1500 mm at coastal locations, and 2500 mm at higher elevation.

This paper reassesses previously reported water compositions and relates many to a hydrogeological model centred on the Ngawha system.

2. GEOLOGY OF NORTHLAND

2.1 Rock types

Metamorphosed sedimentary rocks form the basement of the entire North Island. In Northland they belong to the Waipapa Group which is comprised of Permian-Jurassic quartzo-feldspathic greywacke and argillite, with zones of minor spilitic lava, chert and manganese-bearing rocks (Black, 1989; Thompson, 1961; Mayer, 1968). Exposures in quarries and roadcuts and drillcore show gradations between argillite and greywacke and that beds range in thickness from 10's to 100's of centimeters (Browne, 1980). These rocks appear typically dark grey-green, highly indurated, fine *grained* rocks, cut by numerous narrow veins.

The basement rocks outcrop in a 15-20 km wide zone along the east *coast* of Northland but deepen westward, (Spörli and Kear, 1989). At Ngawha drilling shows them to be at depths below 500-600 m. Petroleum drilling in the Waimamaku Valley, 45 km west of Ngawha, indicates the top of the basement to be more than 3300 m below the ground surface (Hornibrook et al., 1976).

Throughout much of Northland the Waipapa Group rocks are unconformably overlain by an assemblage of sedimentary rocks of Cretaceous-Tertiary age. These rocks were tectonically introduced and consist of a complex melange of variable size slabs of unbedded, poorly consolidated, calcareous and siliceous mudstones, shales, sandstones, limestones and coal measures, within a matrix of sheared, multi-coloured mudstone of Eocene-Paleocene age (Kear and Waterhouse, 1967).

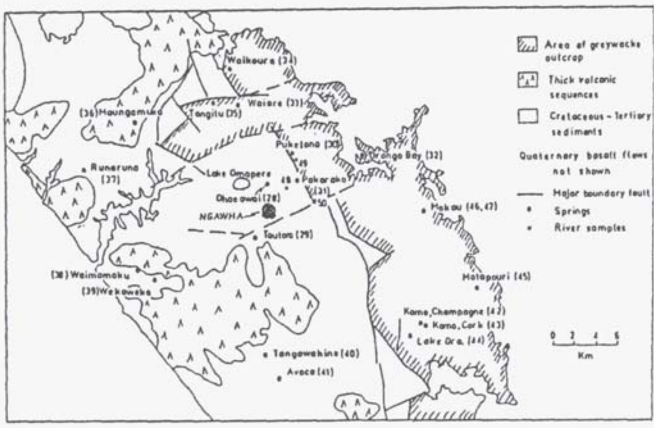

Figure 1. Location of water samples in the region surrounding Ngawha. Geology is based on Kear and Hay (1961) and Thompson (1961); spring locations are from Petty (1972)

At other locations in Northland (Figure 1), there are outcrops of various volcanic rocks. These are largely basaltic and of Cretaceous and middle Miocene age, plus some minor andesite-dacite of Miocene-Pliocene age. In central east Northland lies the basaltic Pliocene-Quatenmy Kaikohe Volcanic Field. Ngawha occurs within the Quaternary-Holocene part of this field which is largely confined to a ENE-trending fault block of about 15 km width (Heming, 1980; Cox, 1984).

The heat source for the Ngawha system is inferred to be a rhyolite intrusion produced by crystal fractionation of an alkali basalt magma. The geothermal system has developed within the Waipapa Group basement metasediments and is concluded to be of the order of 10,000-20,000 years old (Cox, 1985).

2.2 Regional structure

Large scale faults have produced many geomorphological features in Northland, notably the margins of uplifted blocks of basement along the east coast. Of importance are sets of transverse faults, notably those with ENE, NNW and NW strikes. These basement faults and associated multiple joints are important in allowing the deep circulation of groundwater over much of Northland. Some also enable groundwater to migrate over long distances.

2.3 Structural setting of Ngawha

Many of the lineaments visible on air photos showing the Cretaceous-Tertiary sediments (e.g. folds, shear fabric) do not reflect basements faults. However, some basement faults are active and penetrate into the younger sediments. A major structure is the ENE-trending Kawakawa Fault system, 2 km south of Ngawha, which has a downthrow to the south of 200 m. This fault forms the southern margin of a large fault block within which Ngawha is located.

Due to its chaotic nature and composition, the Cretaceous-Tertiary cover is permeable only locally so that groundwater circulation within it is restricted. Some of the basalt lavas transport large volumes of shallow groundwater, however, this usually discharges from permeable zones at basal lithological contacts.

2.4 Structure of the geothermal system

Faulting around Ngawha is common and the drilled reservoir is bounded on at least three sides by faults, or sets of faults. The permeability of the system (i.e. in the greywacke basement) is channel controlled by faults, associated fractures and joints (Browne, 1980; Bayrante and Spörli, 1989).

A fundamental feature of the system is the low permeability of the Cretaceous-Tertiary sediments due to their fine-grained nature and high clay contents. Locally porosities may be as high as 50% but these do not allow much fluid movement (Cox, 1985). Faults within these cover rocks appear to provide only short-lived permeability due to deposition of secondary minerals, mainly calcite and silica, and because rocks are not brittle enough to fracture when faulting occurs.

The basement metasediments have low permeability and near zero porosity. Fluids move through them via myriad joints which typically have a spacing density of around 15 per metre. Most major joints extend vertically for at least 30 m but the majority are discontinuous (Browne, 1980). Permeability can be high in fracture zones produced by faulting.

3. SPRING SITES

3.1 Northland Region

Most of the springs in Northland occur within hydrological lows and almost all have small volume discharges, usually <0.5-1 l/sec (Table 1). Most are associated with the Cretaceous-Tertiary sediments or the Permian-Jurassic greywackes. Several discharge from within or below basalt flows. Most springs are of ambient temperature (14°-16°C) except for the following:

Kamo (#42), 25°C, pH 7, Ca-Na-HCO_3 type water which discharges CO_2; within Waipapa Group rocks.

Waimamaku (#38), 21.8°C, pH 9.5, Na-Cl-HCO_3 type; within Cretaceous-Tertiary sedimentary rocks.

Mangamuka (#36), 18°C, pH 7.3, Na-HCO_3 type, discharges CO_2 and deposits calcite; within Cretaceous-Tertiary Tangihua Volcanics (basalts).

The cause of elevated temperatures in these springs is not known, but the last two may be of tectonic type (i.e. water is heated by its deep circulation). The Kamo Springs may be heated by residual heat derived from an intrusive mass, since they discharge from a fault associated with a rhyodacite dome (Parahaki Volcanics).

Two other springs of interest are the Pakaraka Soda Spring (#31) on Puketotora Stream (Figure 1) and the "Puketona" Spring (#30) on the Waitangi River, 11 km NE and 15 km NNE of Ngawha, respectively. Both springs are associated with the Same NNW-trending fault, on which the basement is uplifted. Both are at 17°C and discharge CO_2, in particular Pakaraka, where a $CaCO_3$ deposit has formed. Their waters are a Na-HCO_3 type and have high B and Cl contents (Table 1), especially "Puketona" Spring, which has even higher Cl (1370 mg/l) than fluid in the Ngawha geothermal reservoir (1170 mg/l). These springs are considered to be the most easterly expression of the Ngawha system.

3.2 Area around Ngawha

Many of the numerous discharge features in the area near Ngawha are related to the current thermal activity. These are as follows:

(a) numerous small gas seeps 3 4 km to the north and north west. These occur within low lying areas, are of ambient temperature and discharge minor amounts of CO_2. Some were recorded as being warm 30 to 75 years ago and to have discharged detectable amounts of H_2S. Vein sulphur deposits from a gas seep directly south of the Putahi Rhyolite and traces of sulphur occur at the Kopenui Springs. Some of these features discharge water after prolonged periods of rain.

Table 1 Chemistry of Northland waters (mg/kg)

No.	NAME, LOCATION	REF.	Flow (l/s)	°C	pH (20°C)	Li	Na	K	Rb	Cs	Mg	Ca	NH_3	SiO_2	B	F	Cl	SO_4	HCO_3
NGAWHA:																			
THERMAL BATHS																			
1	Jubilee Spa Area	A	<.1	46	6.0	5.1	412	36	.14	.30	1.8	16	82	85	410	1.0	514	257	271
2	Velvet Spa Area	A	-	39	6.0	5.9	461	41	.16	.37	3.5	32	94	90	445	-	619	339	328
3	Waipiro Spa Area	A	-	31	5.7	4.2	341	28	.11	.25	2.2	20	84	89	340	-	459	296	209
4	Tranquility Spa Area	A	-	39	5.7	5.2	419	37	.15	.36	4.4	15	110	140	375	1.4	528	464	120
5	Favourite Maori Area	A	.03	46	6.4	5.0	480	40	.13	.32	2.2	11	150	97	445	-	628	154	572
6	Bulldog Maori Area	A	.06	44	6.6	4.6	419	42	.15	.31	6.2	16	200	94	335	-	501	291	451
7	Velvet Domain Area	A	-	.41	6.4	2.6	331	30	.10	.21	9.2	25	210	88	255	-	372	584	318
8	Universal Domain Area	A	-	42	6.5	2.5	343	29	.11	.21	6.1	17	195	107	270	1.0	385	222	545
9	Venus Domain Area	A	-	39	6.3	1.6	248	27	.07	.14	15.0	40	180	83	173	-	277	375	395
10	Sulphurs Way Domain Area	A	-	24	6.0	1.8	240	16	.05	.12	4.3	11	250	60	152	-	220	289	554
11	Milky Way Domain Area	A	-	42	6.2	1.1	142	11	.04	.08	13.0	26	360	45	83	-	116	649	316
12	Tiger Bath Domain Area	A	<.1	36	2.7	.1	28	3	.02	.01	2.4	6	16	18	22	.3	37	344	-
SURFACE WATERS																			
13	L. Tuwhakino outlet	A	5	14	3.6	.8	66	7	.02	.03	1.5	4	15	24	72	-	111	103	-
14	Tuwhakino Stm (Spa bridge)	A	30	15	3.3	.1	20	2	.01	.01	1.9	4	9	23	11	-	28	116	-
15	Sulphur Lake	A	-	14	2.8	.01	8	1	<.01	<.01	1.2	2	1	15	< 2	-	3	155	-
16	Sulphur Pond	A	-	17	4.5	.2	24	2	<.01	<.01	3.4	9	.7	21	13	-	26	61	115
17	L. Ngamokaikai	A	-	13	3.4	.1	9	1	.01	<.01	.9	1.3	-	6	4	.3	11	33	-
18	L. Waiparaheka	A	-	14	2.6	.1	15	1	.01	<.01	1.5	2.6	-	10	15	.1	17	179	-
19	L. Omapere outflow	A	-	13	6.1	.01	6	1	<.01	<.01	2.1	2	.5	15	c 2	-	11	8	7
20	Tap(?rain) Ngawha Spg Hotel	A	-	12	6.8	<.01	5	<1	<.01	<.01	1.6	1	.4	8	2	-	10	2	1
SPRINGS, POOLS, WELLS.																			
21	Maori area well	A	.02	a7	7.2	6.1	577	45	.17	.39	2.6	12	190	98	505	-	707	97	580
22	Ngawha Spg. Hotel well (120m)	A	-	58	6.6	.6	131	10	.02	<.01	37.2	94	6	128	12	-	67	48	704
23	Neilsons Soda Spring	A	3	29	5.8	.1	46	6	.01	<.01	20.1	24	7	122	2	-	20	9	379
24	Waitotara Pond ,	A	-	17	3.1	.0S	7	2	<.01	<.01	1.3	2	5.2	8	4	-	14	106	-
25	L. Omapere Spring	A	3.5	30	5.8	.15	55	8	.02	.01	12.8	34	.3	130	4	-	26	14	283
26	Te Pua (south) Spring	E	-	14	3.4	-	9	1	-	-	2.5	2.8	.3	10	-	-	23	36	224
27	Te Pua (north) Spring	B	-	Amb	2.5	n.d	6.2	4	n.d	n.d	1.7	3.2	5.8	37	1.2	.03	17	390	-
28	Ohaeawai Spring	B	-	Amb	8.6	<.1	37.8	3.3	-	.1	27	22.8	-	97	.1	-	14	3	274
REGION AROUND NGAWHA:																			
SPRINGS																			
29	Tautoro Spring	A	30	Amb	6.5	<.01	9	2	<.01	.01	3.4	5	.1	22	3	-	18	8	33
30	Puketona, Waitangi R. Spg.	B	-	Amb	6.9	36.6	2000	80.7	-	-	57	195	13	62	366	.3	1371	22	4471
31	Pakaraka Spring	C	-	17	6.7	1.9	339	25	.08	.0S	70	162.8	24	83	74	.2	122	<10	1305
32	Oronga Bay Spring	B	-	Amb	8.0	< .1	486	14.8	-	<.01	58	152	.14	37	3.7	.14	903	98	220
33	Waiare Spring	B	-	Amb	7.5	.3	56	3.5	<.1	.14	55.5	49.8	-	80	2.1	-	35	7	S56
34	Waikoura Spring A	B	-	Amb	7.0	.9	740	18.8	.05	.0S	78	465	.1	26	10.4	.17	186	31	3200
35	Tangitu Spring	B	-	Amb	8.5	1.0	453	40.8	.23	.24	63	42.7	-	117	25.3	-	19	11	1534
36	Maungamuka Spring	B	-	18	7.3	< .1	201	.6	-	-	94	5.9	-	-	1.8	-	15	9	1039
37	Runaruna Spring	B	-	Amb	7.9	10.7	8474	238	.27	.17	181	37.9	-	22	295	.3	9961	55	5937
38	Waimamaku Spring	C	1	21.8	9.5	<.05	62	1	<.01	<.01	C.05	1.0	.3	48	<3	.2	24	11	36.5
39	Wekaweka Spring	B	-	Amb	6.7	2.9	3536	51.9	.23	.18	11.7	1120	-	35	188	-	7540	60	71
40	Tangowahine Spring	B	-	Amb	7.3	4.6	4365	305	.59	.14	162	99	-	14	244	-	5699	69	4170
41	Avoca Spring	B	-	Amb	8.8	.4	397	23.5	.12	.12	32.4	59.5	-	-	20	-	814	24	196
42	Kamo, Champagne Pool	B	.2	25	7.0	2.0	239	15.8	.2	.3	55.5	156	-	111	20.3	-	239	17	1400
43	Kamo, Cork Rd. Spg.	B	-	-	7.4	.3	82	3.6	.1	<.1	16.1	101	-	22	2.5	-	42	44	952
44	L. Oro. Spg.	B	-	Amb	6.1	.5	108	3.5	.1	.15	3.5	8.7	-	-	3.8	-	175	8	138
45	Matapouri Spg.	B	-	Amb	6.8	1.5	644	23.2	.15	<.1	101	221	-	82	42.8	-	681	26	2385
46	Mokau Spg. west	B	-	Amb	7.1	1.6	432	59.4	.25	.27	86.3	154	-	51	33.6	-	78	15	2561
47	Mokau Spg. east	B	-	Amb	8.8	1.6	434	60.9	.26	.24	80.3	.a5	-	28	34.5	-	73	9	1584
RIVERS																			
48	Waiaruhe R.	D	-	11.5	6.7	.01	10.5	1	<.01	<.05	2.6	3.3	.04	14.7	1.0	.04	15	12	-
49	Puketotara Stm.	C		13	6.9	<.05	12	2	<.01	<.01	5.5	9.9	.17	25	< 3	.12	7	<10	41
50	Otiria R.	C	-	11.1	7.6	<.05	11	1	<.01	<.01	2.8	8.4	.12	11	< 3	< .1	10	65	21.5
	Average Seawater			-	8.2	0.1	10500	380	-	-	1300	400	-	6	4.5	1.3	19000	2650	140

A: Giggenbach and Lyon (1977) and Sheppard and Lyon (1981); B: Petty et al., 1987 C: Risk (1985)
D: Coulter (1981); E: Petty (1972).

- no analysis n.d: not detected; Amb: ambient temperature.

(b) Neilson's Soda Spring, 29° C, in Te Pukoro Stream, emerges from basalt 600 m north of the northern thermal zone.

(c) Lake Omapere Soda Spring, 6 km NW of Ngawha discharges 3.5 l/sec of water at 30°C from a feature within an extensive silica terrace. The terrace was previously formed from more silica-rich waters.

(d) Ohaeawai Spring 6 km north of Lake Omapere Soda Spring has a small discharge of dilute HCO_3 water at near ambient temperature.

(e) Tautoro Spring 8 km SSW of Ngawha, discharges 30 l/sec of cool water from below a basalt flow. The water is of Ca-Na-HCO_3-Cl type with very low dissolved solids and is near pure meteoric water.

(f) a gas seep 7 km NE of Ngawha was previously described (Bell and Clarke, 1909) as depositing minor amounts of sulphur.

(g) in an area within 10 km NE of Ngawha there are at least 6 small gas seeps at ambient temperature.

3.3 Features at Ngawha itself

In the thermal area, surface activity is associated with three parallel NE-trending zones, with the central one being the most active. Comparison with early reports (e.g. Bell and Clarke, 1909) suggests that the current level of activity and temperatures may have reduced slightly.

Along the northern zone there are ambient to slightly warm (14°-21°C) acid pools, minor siliceous sinter and gas seeps with sulphur deposition. A chain of ambient to slightly warm lakes of acid pH form the southern zone, associated with which is much outgassing of CO_2 and H_2S. Sulphur also occurs in veins.

Along 500 m of the central zone is an extensive gas discharge and a variety of pools, with six main areas of activity. Baths have been constructed for balneological purposes here and are maintained at temperatures of 40°-45°C; waters have a pH around 6. There is much gas discharge over the central zone. Previously deposited mercury in fine grained sediments and siliceous sinter has been largely mined out but mercury still continues to deposit (Davey, 1979).

The area explored by drilling covers 3 x 2.5 km centred on the thermal springs. Most wells are 950-1600 m deep with the deepest being 2255 m (vertical depth). A typical reservoir fluid feed temperature to the wells is 220°-230°C (Cox, 1985).

4. CHARACTER OF THE WATERS

4.1 Geothermal system waters

The deep reervoir fluid of the Ngawha system is of similar composition to those discharged from geothermal systems of the TVZ, all being of alkali chloride type. Most TVZ system waters are of near neutral pH, however, but Ngawha water is slightly acid. The reservoir fluid pH for Ngawha is typically 5.6 at 230°C (neutral pH at this temperature is about 6.3). The salinities at Ngawha are typically 0.06-0.08 mNaCl, with a TDS of around 3850 mg/kg Table 2).

The major difference between Ngawha and TVZ system fluids is the high concentrations of B, NH_3 and HCO_3 at Ngawha. In addition, Ngawha fluids have a characteristically high gas content which is largely CO_2. For Ngawha, the reservoir fluids contain mCO_2 = 0.30, which is approximately twice that of Ohaaki (mCO_2 = 0.15) and 30 x that of Wairakei (mCO_2 = 0.01)

4.2 Source of dissolved constituents

The enrichment of some constituents at Ngawha is most likely caused by two mechanisms:
(a) from partial dissolution of Waipapa Group metasediments at depth, including some outside the reservoir, at temperatures over 300°C,
(b) minor magmatic input from the inferred rhyolitic intrusion.

As boric acid (H_3BO_3) is volatile at elevated temperatures and pressures, boron may be stripped from the metasediments, partitioned into the gas phase, then transported to mix with cooler fluids. Under these conditions, highly soluble B will thereafter remain largely in the 4uid phase (Giggenbach and Lyon, 1977).

Ammonia may also be derived fiom the metasediments. Some NH_3, however, could result from reactions involving magmatic N_2. It is also likely that the very high amounts of CO_2 present in the fluids are of both magmatic and metasedimentary derivation.

4.3 Chemistry of Ngawha surface waters

Due to the presence of the aquitard of Cretaceous-Tertiary sedimentary rocks, the total discharge of water from the central thennal zone is low, around 2 l/sec (Giggenbach and Lyon, 1977; Davey, 1979) with the central zone appearing to be the most permeable. The water in the thermal baths is indicated to be mostly of local meteoric origin which has been heated (up to 50°C) largely by rising gases. Concentrations of Cl of about 400-600 mg/kg and B of 200-400 mg/kg indicate, however, some upflow of reservoir fluid to the surface.

Table 2. Typical Composition (mg/kg) of Deep Fluid at Ngawha (based on well Ng3 discharge with separated steam and gas added back from Sheppard and Giggenbach, 1985)

pH	Li	Na	K	Rb	Cs	Mg	Ca	NH_3	SiO_2	B	F	Cl	SO_4	HCO_3
5.6	9.7	854	65	.24	.55	.04	3.4	145	370	862	1.6	1179	29	318

The water in the baths is of a Na-HCO_3-Cl-SO_4 type with relatively high TDS of around 2360 mg/kg. Of note is its high B and NH3 contents. The pH, however, is near neutral (6.2) which is unusual in that near-surface oxidation of the H_2S in rising gas has produced SO4 concentrations of 300-600 mg/kg in the waters by the reaction:

$$H_2S + 2O_2 = SO_4^{2-} + 2H^+.$$

Ammonia, although a minor gas, is highly soluble at low temperatures (Ellis and Mahon, 1977) and so rapidly dissolved in the waters (90-250 mg/kg) neutralising their acidity by:

$$NH_3 + H_2O = NH_4^+ + OH^-$$
$$H^+ + OH^- = H_2O$$

In addition, these waters have a high HCO_3 content (200-500 mg/l) partly from CO_2 dissolved from rising gases. The near neutral pH enables retention of the HCO_3, (at a pH of below about 5, the HCO_3 would be expelled as CO_2) (Giggenbach and Lyon, 1977; Sheppard and Giggenbach, 1980).

The nearby surface waters are mostly pools and lakes of near-ambient temperature but are of acid (pH 2-4) Na-SO4 type. They have low TDS, typically 220 mg/kg, low NH3 contents and very low to nil HCO_3. This indicates that there is no leakage here of reservoir water to the surface. Also, the gases reaching the surface have cooled, probably through their slow migration. Ammonia is apparently lost from gases during migration as the acid SO4 features are low in NH3. (At 100°C, the solubility of H_2S is three times and that of NH3 400 times that of CO_2).

These acid SO4 waters are superficial occurring above the water table and are derived almost entirely from local precipitation.

4.4 Aquitard waters

Groundwater with TDS around 650 mg/kg and relatively high Ca and Mg contents occur within the Cretaceous-Tertiary sediments. Their Ca/Mg ratio of about 2.5 is fairly consistent (Giggenbach and Lyon, 1977; Sheppard and Lyon, 1981). This water was encountered in the Ngawha Springs Hotel Well (#22; 120 m, 58°C) and also discharges at Neilson's Soda Spring (#23; 29°C), Lake Omapere Soda Spring (#25; 30°C) and as dilute, cool water at the Ohaeawai Spring. The water is typically of Ca-Mg-Na-HCO_3 type, with a pH of around 6 and low amounts of Cl, B and SO_4. The silica geothermometer indicates subsurface equilibration temperatures of about 140°C.

This water forms a continuous (or semi-continuous) body over an area of at least 60-70 km^2 north of the main Ngawha thermal area. Until early this century, silica sinter precipitated from this water at the Lake Omapere Soda Spring; the silica derived from the dissolution of minerals present in the Cretaceous-Tertiary rocks (Cox and Browne, 1991).

4.5 Other waters

Other groundwaters in Northland are highly variable in their chemistry. Some common features, however, are their relatively high contents of Li, B and HCO_3, all apparently derived from the basement metasediments. Another common feature is their relatively high pH (7.0-8.8) presumably due to a reaction of the type,

$$CO_2 + H_2O = CO_3^- + 2OH^-.$$

The highest pH is 9.5 at Waimamaku (38), a dilute shallow circulating water.

Some of the springs in the Cretaceous-Tertiary sediments (e.g. Runaruna (37), Wekaweka (39), Tangowahine (40)) appear to derive their water from deep basement circulation. Other springs of very low TDS, especially within the volcanic fields are of entirely superficial waters with only local circulation.

5. Chemical types of waters

5.1 Discussion

The composition of each water was classified with respect to major cations (Na, K, Ca, Mg) and anions (Cl, HCO_3, SO_4) using a trilinear Piper diagram. To clarify relationships, the waters are plotted on a log Cl versus log (Ca + Mg) diagram (Figure 2). Such a plot of reactive dissolved constituents (Ca, Mg) against unreactive ones (Cl), can assist in distinguishing between thermal processes, the origins of different waters and mixing events (e.g. Cox and Thomas, 1979). The figure shows three "end points" for the Northland waters: deep geothermal water (Na-Cl, + B), rain and lake water (Na-Cl) and non-thermal groundwater (Na-HCO_3). The relative domains on this diagram reflect degrees of mixing of different water types as well as some of the processes involved.

The aquitard (caprock) waters are indicated to be a composite from non-thermal groundwater and local river water. The acid SO4 lakes and pools are largely local near surface water and rain. The thermal baths appear to discharge a mixture of reservoir water and shallow ground water from the aquitard (mixed with some river water). There is an indication of some leakage of reservoir water into Lake Tuwhakino. A displacement appears on figure 2 between the deep geothermal water and that discharged from wells: this reflects steam loss.

Spring waters from the region surrounding Ngawha have high Ca and Mg, but highly variable Cl contents. This group is gradational from Na-HCO_3 type water to those of more saline Na-HCO_3 ± Cl type indicative of mixing of saline water of marine origin at depth. To the right of the diagram, a grouping of high B, Na-Cl water appears to be best interpreted as being of connate origin. Peripheral to the non-thermal groundwaters is a group of mildly thermal waters of Na-HCO_3 ± Ca, Mg, B, Cl type which includes the Ngawha Hotel Well (#22), Pakaraka Spring (#31) and Kamo Springs (#42, 43).

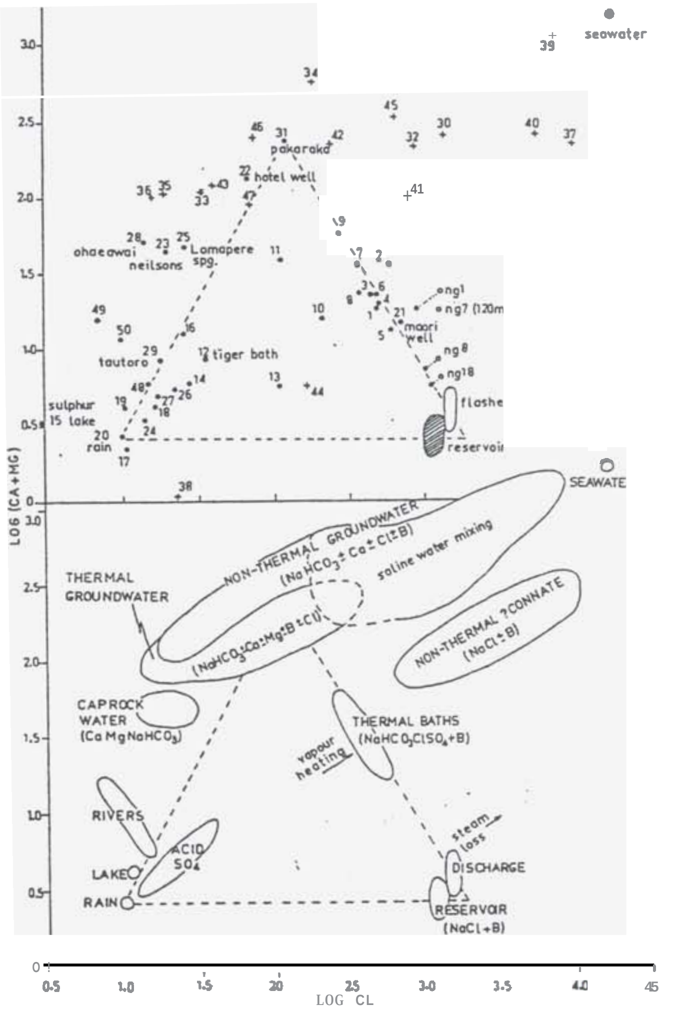

Figure 2. Plot of log Cl versus log Ca+Mg for thermal and non-thermal waters at Ngawha and its environs; numbers refer to Table 1. Figures show degrees of mixing between different water types; • = related to Ngawha; + = surrounding region.

5.2 Hydrochemical model for the Ngawha system and its environs

The main features of the fluid chemistry and hydrology of the Ngawha system are shown on a generalised NE-SW cross-section (Figure 3). The B and Cl contents of basement groundwaters are those indicated by springs discharging from metasediments. This schematic indicates that the whole geothermal system at Ngawha is extensive, notably in regard to subsurface migration of gases outward from the reservoir itself. Much of the groundwater up to 10 km to the east and north of Ngawha is influenced by the geothermal system. This includes some leakage of hot water to the north and north east below the aquitard; recharge of cooler meteoric water probably occurs below this.

Important other features are: the likelihood of recharge from the north-north-east; the amount of the HCO_3 water present in the cover rocks; the gradual increase in temperature and Cl, B contents in groundwater in the basement towards the reservoir. A zone of deep two-phase conditions in faults bounding the reservoir is depicted in Figure 3.

There appear to be two fundamental factors controlling the movement of groundwater:

(a) permeability generated by faults which have broken the basement into a series of vertically offset blocks with myriad joints;

(b) a hydraulic pressure head east of Ngawha, which allows water to flow in the Waipapa Group basement rocks which deepen westward.

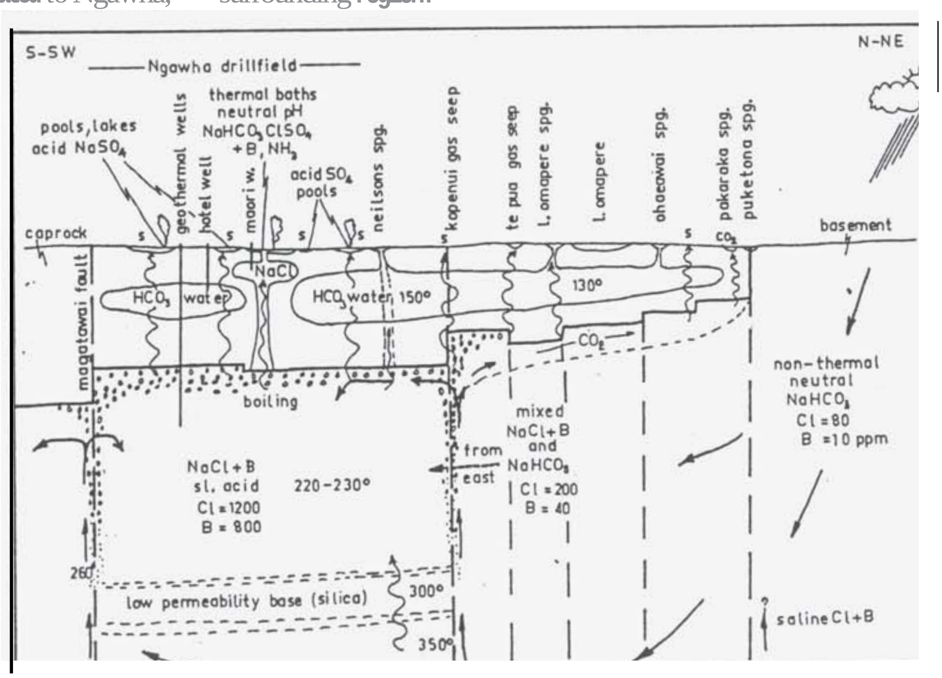

Figure 3 Schematic cross-section in general N-NE to S-SW direction, showing large scale features of hydrochemistry of the *greater* Ngawha geothermal system. Large arrows show water paths; small arrows, *gas* paths.

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