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Thermal Water Classification of Morobe, Ferguson Is., West New Britain and Feni Is of Papua New Guinea using Water Chemistry and Isotope Analysis

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ABSTRACT

The Morobe field is structurally controlled and shows no characteristics of volcanic influence. The elevated temperature of hot springs is observed to be due to downward percolating meteoric waters that heat up due to higher geothermal gradient and ascends to surface. The two distinct inferred temperature of Buluwat and Wandumi at ~80 °C and ~160°C respectively is directly associated with the geological structure. Thus, the Morobe field is considered a low to intermediate temperature field (<150 °C). The travertine deposits also indicate up-flow and could also represent an ancient geothermal system worthy of further work.

The Deidei samples in Milne Bay, Rabili, Talasea St., Gariki, Magouru and Sakulu in West New Britain and Balamuson and Waramong in Feni Island all demonstrated reasonably high reservoir temperatures of > 250 °C and are therefore considered high enthalpy systems. The natural surface manifestation also shows signature features such as clear-bluish alkali chloride pools, active geysers, boiling pools and silica terraces. Rabili, Talase St., Balamuson and Waramong are observed to have sea water signatures and are likely hybrid heated waters. Further work including geophysical surveys and exploration drilling will be helpful to ascertain reservoir extent and further understanding of the reservoir.

1. INTRODUCTION

A total of 55 geothermal sites (Figure 1) have been identified and mapped in PNG by different studies since 1970's (Reynolds, (1956), Studt, (1961), Wiebenga, (1962), Heming (1969), and Berhane, (1997)). However, in recent years, the Mineral Resources Authority (MRA) of Papua New Guinea (PNG) through its Geological Survey Division (GSD) has carried out a number of reconnaissance in some of the known sites. Thermal waters were sampled for chemistry and isotope analysis and a number of geophysical surveys have been carried out in selected sites. This paper covers the water chemistry and further classifies the thermal waters of the four sites highlighted in green boxes in Figure 1 into high, medium or low temperature waters.

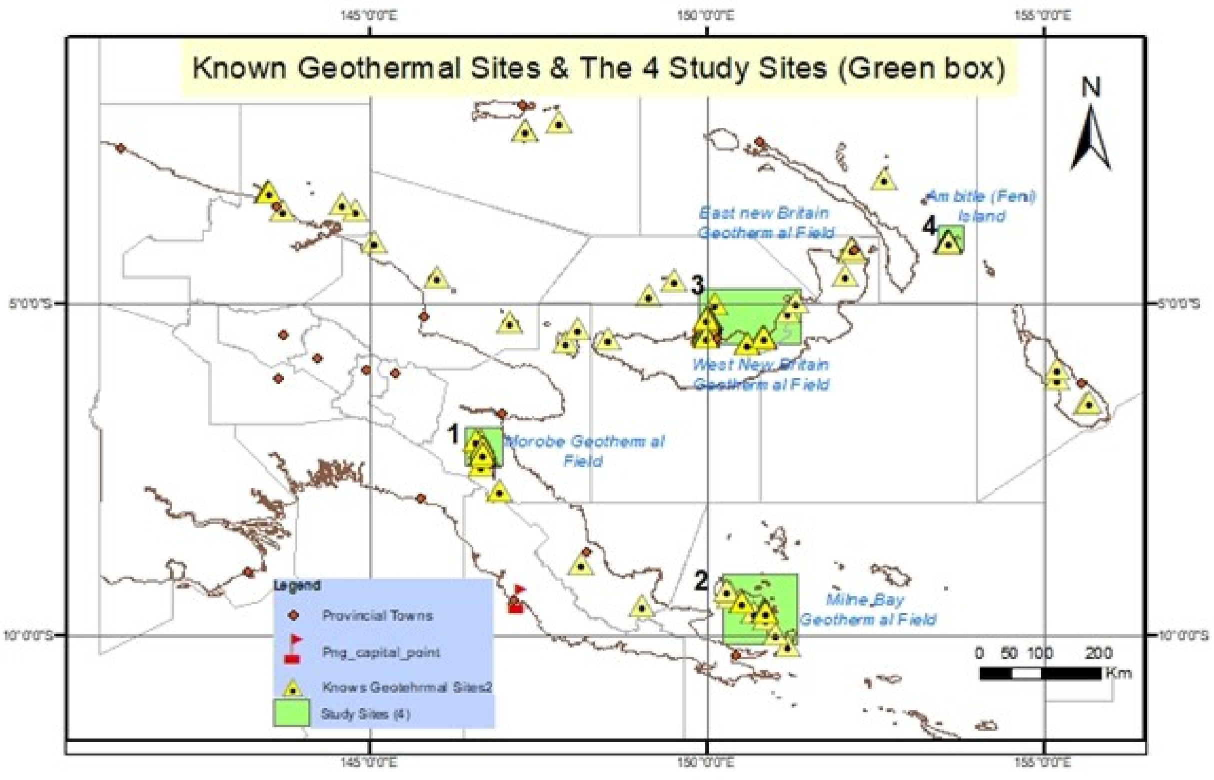

Figure 1: Map of Papua New Guinea showing the four study sites

2. GEOTHERMAL SITES

Geothermal resources in PNG occur mostly in isolated locations, far from large population centers. The logistics and economical challenges in reaching these sites contributes to the limited scientific studies, hence the sparse scientific information available (Kumul, 2015). However, since the 1950's, there are three distinct period of geothermal work in PNG.

The first period includes earlier work carried out in the late 1950 and 1960's as a result of request from the colonial government for power generation needs by various scientists including, Reynolds, (1956), Studt, (1961) and Wiebenga, (1962). These were followed by data collection by volcanologist from the Rabaul Observatory for inventory purposes and among other reasons rarely included chemistry of water and gas emissions (Berhane, 1997).

The second period included more structured geosciences surveys where the thermal features were mapped, and water and gas samples were collected and analyzed for its various chemical component. Some of the work included Heming (1969), Grindley (1974), Crick (1975) and Williamson (1983). Williamson (1983), worked on the Thermal activity in Lihir Island, whose work formed the basis of geoscientific data that developed the Lihir geothermal power plant. However, these earlier works were not done for geoscience repository and not aimed at power development. Lihir's geothermal power was developed as a secondary product when geothermal steam was discharged as a hazard mitigation to depressurize the mine pit and also for dewatering strategies (Berhane, 1997).

The third period included the more recent work carried out post Lihir power development, led by the Geological Survey Division of the MRA in collaboration with geoscientists from New Zealand's (NZ) Geological Nuclear Science (GNS

2.1 Morobe

The Morobe geothermal field is located in the Wau Bulolo district of Morobe province in mainland PNG, about 300 km north of Port Moresby and two and half hours' drive south of Lae - the main township of Morobe Province.

The geothermal manifestations are restricted within the structural boundaries of the Wau graben, a basin about 600 km^2 (20 km wide x 30 km long) (Lahan, et al, 2015). The main structures identified are the southwest striking Sunshine fault to the north and north-west trending upper Watut and Wandumi faults on the flanks and Lakekamu faults to the south (Dow, 1974; Findley et al., 2002; Saroa, 2015) (Figure 2).

Over thirteen hot springs were sampled by the MRA in 2011. The samples were all neutral to alkaline with field temperatures ranging from 30 – 70 ^oC. The chemistry results of the water samples are shown in Table 1.

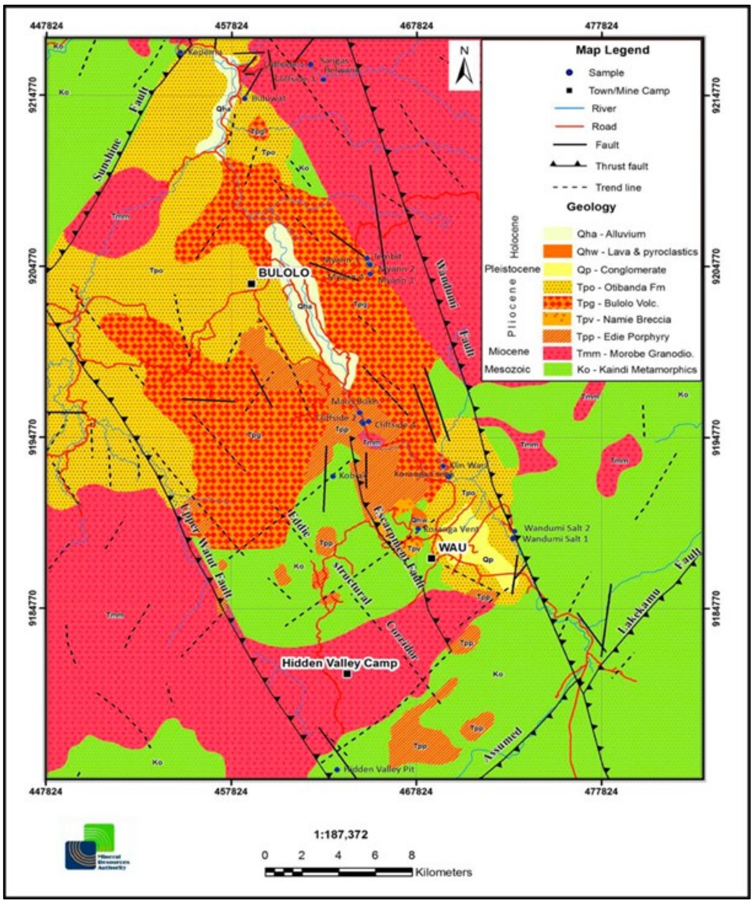

Figure 2: Local geology of the Morobe geothermal field, modified from Dow et al., 1974 (Taken from Lahan et al, 2015)

2.1.1 Spring Composition

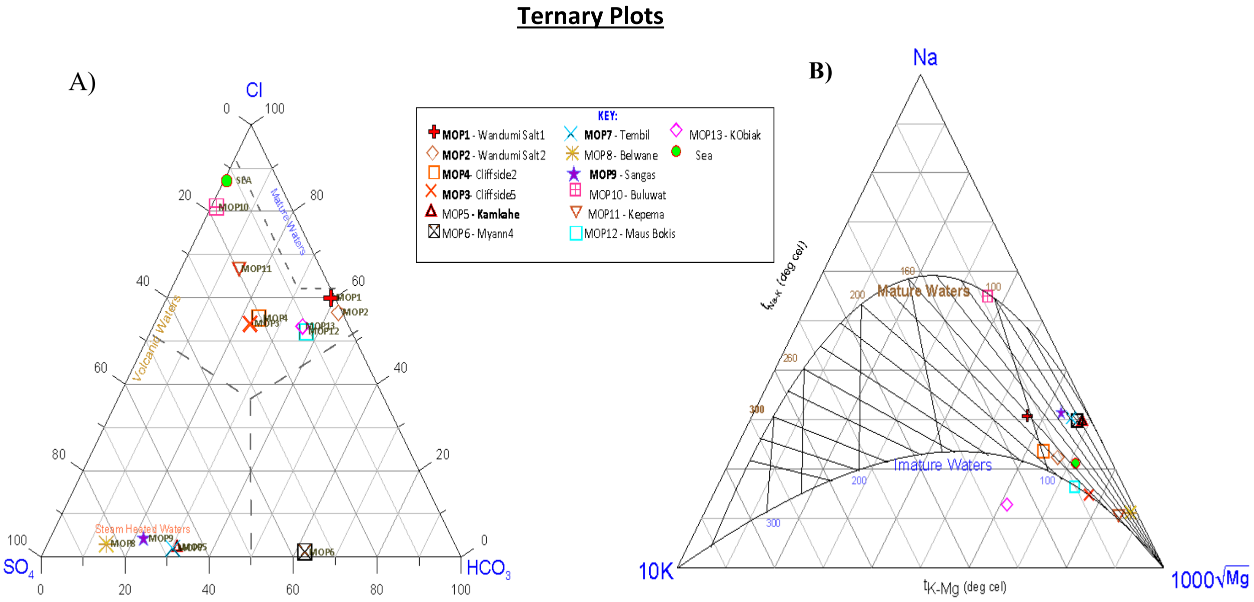

Figure 3: (A) C-S-H water classification plot and (B) Mg-Na-K Geothermometry plot (Source: MRA)

The hot spring show neutral to alkaline pH and are exhibit two distinct water type (Figure 3);

(i) Neutral alkali chloride water with some carbonate mixed water: (Wandumi Salt 1, Wandumi Salt 2, Buluwat, Kepema, Maus Bokis, Cliffside 2 and Cliffside 5).

(ii) Neutral to alkaline waters with relatively high sulphate: (Kamkahe, Myann 4, Tembil and Sangas)

The cation, Mg-Na-K ternary plot (Figure 3b) shows Buluwat (MOP10) on the mature water line with the fast reacting $T_{K\text{-}Mg}$ geothermometer at 100 °C. All the other hot spring appear as peripheral waters and plot within the mixed water category while Kobiak (MOP13) plots in the immature water category therefore are not suitable for geothermometry applications.

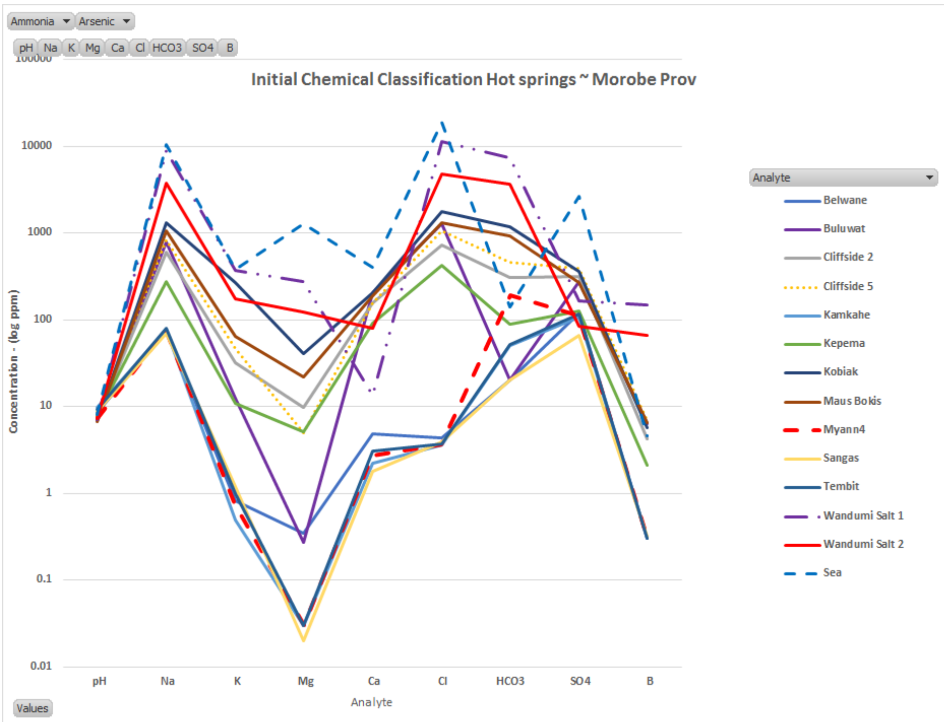

Figure 4: Schoeller plot for initial water classification (Source: MRA)

The schoeller plot (Figure 4), also demarcates two water types; the Solid red line (Wandumi 2) is a typical representation of the cluster of hot springs, which are identified by higher Na, K, Cl, SO_4 and B and the dashed red lines represents water type that typically contain lower Cl, B, and at some instances contain high Mg and Ca (Marini, 2004).

2.2 Fergusson Island

Sometimes referred to as the Milne Bay geothermal field; it is located within the D'Entrecasteaux Islands, in the southern part of PNG. It takes approximately five hours to reach the island by banana boats from Alotau - the main township of Milne Bay province.

The surface manifestations are located on two main locations; Deidei towards the east-south-east and Iamalele at the western end of the island. The former has active neutral chloride boiling water whilst the later predominantly shows widespread solfatara and altered grounds.

Four water samples were collected; two samples from each site and the results are shown in Table 3

2.2.1 Spring Composition

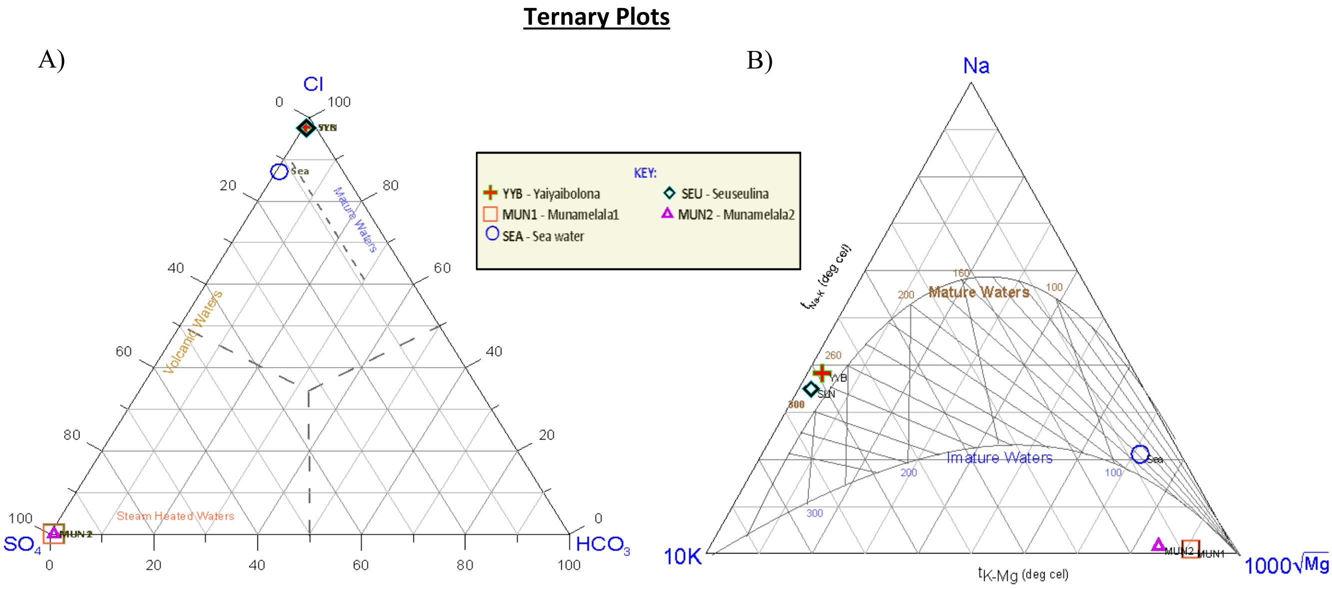

Figure 5: (A) C-S-H Ternary plot and (B) Mg-Na-K Geothermometry plot (Source; MRA)

Figure 5 illustrates two water types; Chloride rich mature waters and steam heated waters. Figure 5b further shows that the two Iamalele samples are immature and not suitable for geothermometer applications to determine reservoir temperatures.

2.3 West New Britain

West New Britain Island (WNB) is located approximately 500 km north-east of Port Moresby. The geology of the island is dominated by basic to tertiary volcanic rocks, overlain by late tertiary sedimentary sequences.

The geothermal surface manifestations in WNB are associated with volcanism and are dominant throughout the northern shores of the island. The main active area is clustered in the Talasea area, along the Willaumez peninsula. Sporadic thermal manifestation is observed along the north shores of Hoskins stretching from Mt. Pago to Mt. Ulawun, two active volcanoes that are more than 120 km's apart.

2.3.1 Spring Composition

Based on the dominant anion (Cl, SO_4, HCO_3) and the pH, the water samples exhibit four main water groups (Figure 6a);

(i) Chloride rich waters - Rabili, Talasea Station, Bakama1, Sakalu and Magouru.

(ii) Bicarbonate rich waters – Rongo 1, Lake Dakataua and Wavua Narera.

(iii) Steam heated acid sulphate waters (low Cl < 400 mg/L) – Wavua1, Matagele, Magilae, Wudi, Taliau, Gariki, Narera Kapma, and Wudi Koma

(iv) Volcanic acid sulfate waters (high Cl > 400 mg/L) - Tabero, Galu, Haella Kele.

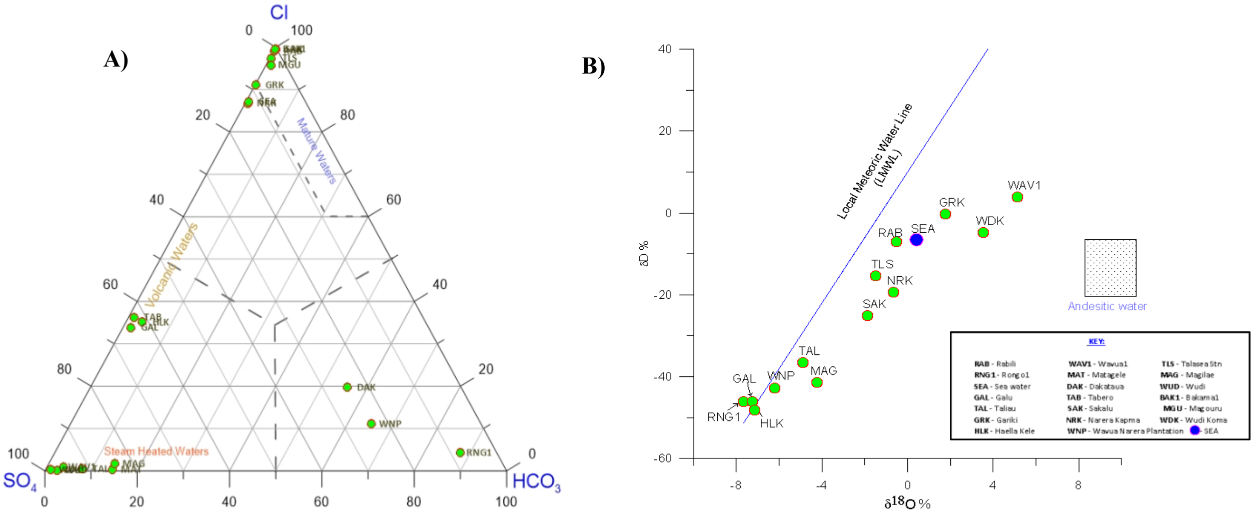

Figure 6: (A) C-S-H Ternary plot & (B) Stable isotope composition (Source: MRA)

Figure 6b, shows the stable water isotope with the calculated local meteoric water line (LMWL). Sea water and andesitic water isotopic composition are also plotted on the graph (Giggenbach, 1992). Four samples are observed to fall on the meteoric water line; Wavua Narera (3,553 mg/L Cl) and Rongo 1 (2.3 mg/L Cl) exhibit near neutral pH whilst Haelle Kele (378 mg/L Cl) and Galu (415 mg/L Cl) shows lower pH. Wavua 1 (5.5 mg/L Cl) an acidic spring plots closest to the 'andesitic water' followed closely by Wudi Koma also an acidic spring with low Cl (4.4 mg/L Cl). Rabili and Talasea St. are two boiling spring located close to the shoreline with high Cl of 18,993 mg/L and 8,122 mg/L respectively. They plot close to the sea values but exhibit a slightly negative $\delta^{18}O$ and δD values.

2.4 Feni Island

Feni Island is a strato volcanic island located within the Bismark Archipelago about 60 km east of mainland New Ireland. It is the south-eastern end of the Tabar-Lihir-Tanga-Feni (TLTF) chain, a group of islands parallel to New Ireland, trending north-northwest. The island is over 8,500 hectares with its highest elevation about ~300 meters above sea level.

The volcanic island consists of a thick succession of interbedded lavas, lahar deposits, tuffs and scoriae (Wallace et al, 1983). The Crater resulted from Late Quaternary resurgence of volcanism following sector collapse of the SW flanks of the summit of the Volcano (Lindley, 2015). The thermal activity is divided into six main areas; Waramong Creek, Kapkapi creek, Crater saddle, Nanum River, Matangkapok and Tutum bay.

2.4.1 Spring composition

All samples are neutral to alkaline however are classified into two water types based on the C-S-H ternary plot and further by Mg-Na-K plot as shown in Figure 7. Waramong and Balamuson show relatively higher Cl and SO_4 (9,670 mg/L, 4,457 mg/L Cl and 4,896 mg/L, 2,111 mg/L SO_4 respectively). Nanum and Matangkapok on the other hand show relatively higher levels of HCO_3 (355 mg/L and 596 mg/L HCO_3) about 2.5 times more than Balamuson and Waramong. The Cl-B ratio plot (Figure 7c) shows high ratio for Waramong (WM) which corresponds to boilng waters whilst Balmuson (BM) exhibits mixed water characteristics. Nanum (NM) and Matangkapok (MK) show relatively low Cl-B ratio common in immature peripheral meteoric waters (Nicholson, 1993; Marini, 2004).

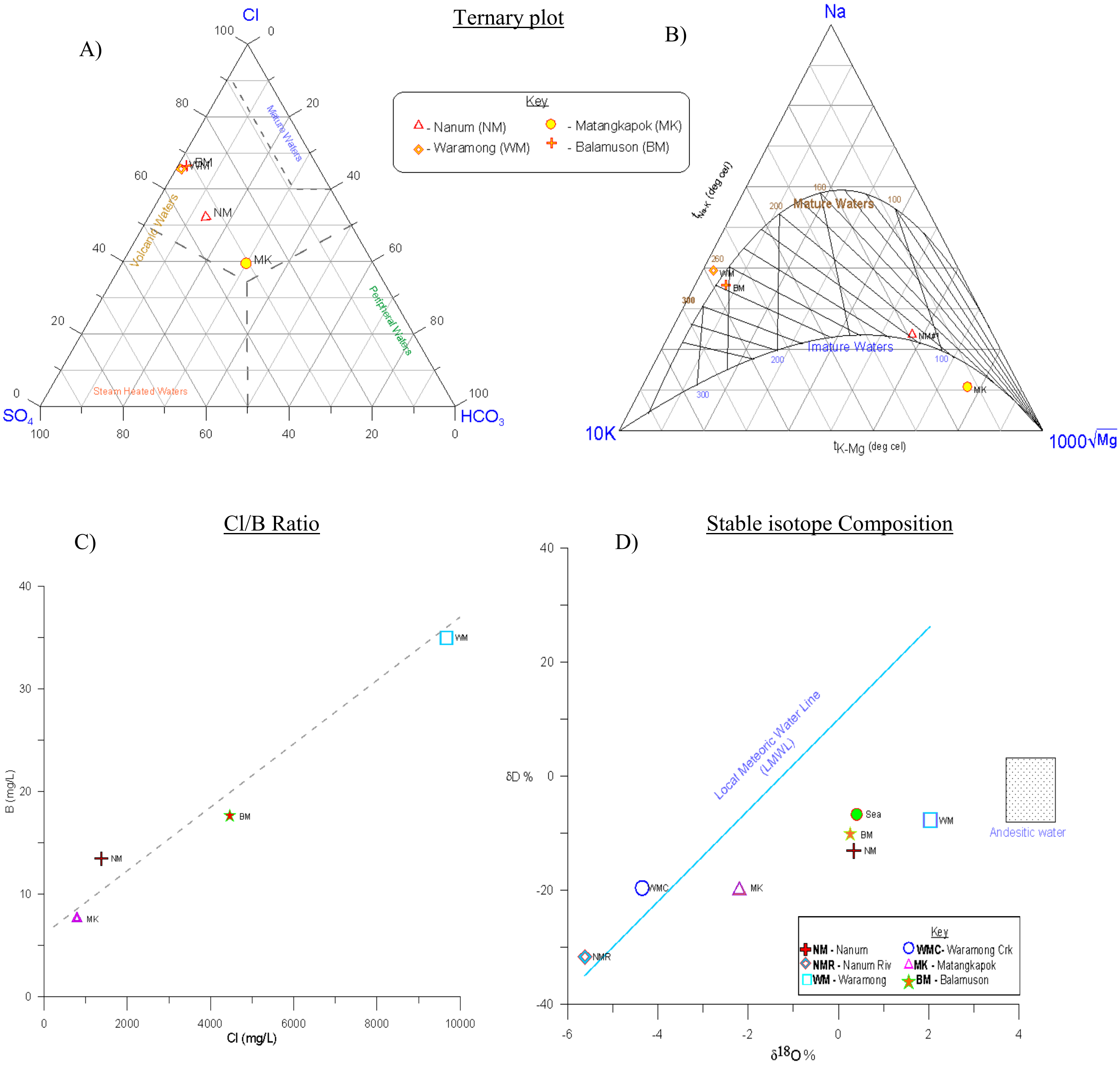

Figure 7: (A) C-S-H Ternary plot, (B) Mg-Na-K geothermometery plot; (C) Cl/B ratio and (D) Stable Isotope composition (Source; MRA)

3. RESULTS

All the results are compiled from the MRA database and tabulated per site for this paper.

Table 1: Morobe water chemistry (2011)

Sample Name	Label	Field T. °C	pH	Na	K	Ca	Mg	SiO_2	B	Cl	SO_4	HCO_3	NH_4	As	Fe	Ion Bal
Wanduni Salt1	MOP1	23.8	7.07	8996	373	13.4	274	68	150	11325	166	7357	26	<0.015	0.42	-2%
Wanduni Salt2	MOP2	25.0	7.22	3721	174	80	123	101	66	4849	85	3632	13.1	<0.015	0.23	-4%
Cliffside5	MOP4	69.7	7.76	832	46	156	5	110	6.8	1058	392	461	0.69	<0.015	0.1	0%
Cliffside2	MOP3	46.5	7.29	600	32	157	9.7	88	4.2	723	312	304	0.34	<0.015	0.05	5%
Kamkahe	MOP5	41.0	9.69	75	0.49	2.2	<0.03	48	<0.3	3.6	106	50	<0.01	<0.015	<0.02	4%
Myann4	MOP6	53.0	7.39	77	0.75	2.7	<0.03	49	<0.3	3.7	112	190	<0.01	<0.015	<0.02	-23%
Tembit	MOP7	48.8	9.36	80	0.99	3.1	<0.03	51	<0.3	3.7	116	52	<0.01	<0.015	<0.02	4%
Belwane	MOP8	44.0	8.46	76	0.83	4.9	0.35	36	<0.3	4.4	119	<20	<0.01	<0.015	<0.02	10%
Sangas	MOP9	40.6	8.8	70	1.2	1.8	0.02	38	0.32	3.9	66	<20	<0.01	<0.015	<0.08	27%
Buluwat	MOP10	46.7	7.37	790	12.5	205	0.27	31	6.3	1277	279	<20	0.01	<0.015	<0.08	3%
Kepema	MOP11	54.6	7.78	277	10.8	91	5.1	51	2.1	426	125	88	0.13	<0.015	<0.08	4%
Maus Bokis	MOP12	47.4	6.77	1050	64	189	22	89	6.5	1309	271	927	0.31	<0.015	2.2	1%
Kobiak	MOP13	57.8	6.94	1323	269	203	41	95	5.7	1754	360	1169	0.3	<0.015	0.18	1%
†Sea Water	SEA		8	10561	380	400	1272	7	4.6	18980	2649	142	0.05	0.02	0.02	

Table 2: Geothermometer temperatures of eight highest Cl samples (> 400 mg/L Cl) in Morober

Sample Name	T_{AmS}	T_{Ch}	T_{QCh}	T_{Q} Ad.Cond	$T_{Na\text{-}K\text{-}Ca}$	$T_{Na/K}$ Fourn1979	$T_{Na/K}$ Truesd 1976	$T_{Na/K}$ Giggen 1988	$T_{Na/K}$ Tonani 1980	$T_{Na/K}$ Arnors 1983	$T_{K/Mg}$ Giggen1986
Wandum salt 1	-1	88	117	115	210	152	109	171	135	120	119
Wandumi Salt 2	17	111	138	133	183	159	118	178	145	128	108
Cliffside 5	22	116	143	137	134	171	131	189	160	141	116
Cliffside 2	11	103	130	127	114	168	128	187	157	139	97
Buluwat	-32	49	81	84	78	97	49	118	69	61	121
Kepema	-13	73	103	103	79	148	104	167	130	115	77
Maus bokis	11	103	131	127	147	178	140	196	169	149	104
Kobiak	14	107	135	130	228	286	279	296	327	281	139

Table 3: Milne Bay water chemistry (2012)

Sample Name	Sample Label	pH	Na	K	Ca	Mg	SiO_2	B	Cl	SO_4	HCO_3	NH_4	As	Fe	Mn	Cond µS/cm	$\delta^{18}O$%	δD %
YAIYAIBOALANA	YYB	8.63	3273	502	54.0	0.05	394	7	4825	96	20	0.3	1.7	0.08	0.02	14385	-1.51	**-16.3**
SEUSEULINA	SLN	8.21	3107	556	46	0.04	421	6.8	4668	87	29	0.34	1.5	0.08	0.02	14025	-1.2	**-14.4**
MUNAMELALA 1	MUN1	1.69	22	16.2	6.5	3.3	326	2.7	0.81	2499	20	4.9	0.04	14.6	0.4	9361	4.49	**-1.1**
MUNAMELALA 2	MUN2	1.65	36	29	7	3.1	331	0.3	1.3	2488	20	3	0.015	11.1	0.17	11305	-1.15	**-18**
†Sea Water	SEA	8	10561	380	400	1272	7	4.6	18980	2649	142	0.05	0.02	0.02	0.01	18980		

Table 4: Milne Bay: Solute geothermometer

Sample Name	T_{AmS}	$T_{\alpha\text{-Ch}}$	$T_{\beta\text{-Cr}}$	T_{Ch} Cond	T_{Qz} cond.	T_{Qz} Adiab.	T_{NaKCa}	$T_{NaKCaMg}$ corr.	$T_{Na/K}$ Fourn 1979	$T_{Na/K}$ Trues 1976	$T_{Na/K}$ Giggen. 1988	$T_{K/Mg}$ Giggen. 1986
YAIYAIBOALANA	107	185	135	220	234	209	260	260	257	239	269	**335**
SEUSEULINA	112	191	141	226	240	214	273	273	273	260	283	**351**

Table 5: West New Britain water chemistry (2012 and 2014)

Sample Name	Date	pH	Li	Na	K	Ca	Mg	SiO_2	B	Cl	F	SO_4	HCO_3	NH_4	As	Br	Fe	Mn	Cond µS/cm	del ^{18}O	del D	Ion Bal
Rabili	8/11/12	5.32	7	9697	1965	961	25	447	24	18993	<0.03	153	<20	7.1	1.9	76	0.55	2.7	46830	-0.52	-7.1	-1%
Wavua 1	4/11/12	2.58	0.04	61	35	52	13.4	457	0.58	5.5		543	<20	9.6	0.029	<0.03	11.5	1.4	1956	5.15	3.9	-4%
Talasea Stn	5/11/12	5.91	3	4216	976	460	26	209	12.4	8122	<0.03	194	<20	3.8	0.56	32	0.09	0.66	22715	-1.49	-15.3	0%
Rongo 1	5/11/12	6.99	0.01	9.7	5.3	4	1.2	169	<0.3	2.3	0.14	4.2	47	0.009	<0.015	0.14	-0.08	<0.005	139	-7.66	-46	-4%
Matagele	6/11/12	3.51	<0.01	6.2	4.1	23	7.1	110	<0.3	0.4	<0.03	117	<20	0.32	<0.015	<0.03	0.48	0.79	395			-6%
Magilae	6/11/12	3.64	<0.01	9.1	2.5	5.8	2.3	77	<0.3	2.4	<0.03	117	<20	0.03	<0.015	<0.03	5.2	0.19	242	-4.22	-41.4	-35%
Dakataua	7/11/12	7.33	0.01	4.1	3.1	11.7	6.8	31	<0.3	24	0.18	30	68	0.03	<0.015	0.06	0.02	<0.005	284			-27%
Wudi	8/11/12	2.01	<0.01	6.1	8.3	4.1	1.2	344	0.47	1.9	<0.03	1075	29	5.2	0.015	<0.03	20	0.22	4783			-33%
Galu	10/11/12	1.93	0.02	29	10.5	58	25	256	2	415	7.6	790	21	0.39	0.07	1.3	8.8	1.2	6109	-7.24	-46	-22%
Tabero	10/11/12	1.82	0.02	39	13	75	33	334	3.2	595	10.4	1025	<20	0.51	0.09	2	15	1.7	8035			-24%
Bakama 1	11/11/12	6.19	4	1710	193	200	2	131	24	12888		28	27	0.46	0.84	10.1	-0.08	0.1	33725			-60%
Taliau	11/11/12	3.2	<0.01	11.4	1.8	25	7.8	128	1.6	1.1	<0.03	235	<20	11.1	<0.015	<0.03	11.8	0.31	856	-4.91	-36.5	-12%
Sakalu	11/11/12	7.43	15.5	5968	1177	462	0.45	205	105	11357		32	<20	0.46	7.2	37	<0.08	0.19	30260	-1.87	-25.1	-1%
Magouru	12/11/12	7.2	14.2	6626	1401	496	3.9	420	92	3097	0.71	101	34	16.7	9.5	58	<0.08	4	9335			59%
Gariki	12/7/14	1.97	2.5	5039	1007	435	37	467	10.8	8437	0.64	808	<20	22	0.9	31	9.6	1.6	26035	1.76	-0.3	5%

Wavua Narera	16/7/14	6.45	0.01	26	16.5	15.5	5.1	148	<0.3	13.1	0.04	28	77	<0.003	<0.015	0.03	<0.08	<0.005	394	-6.22	-42.7	11%
Narera Kapma	17/7/14	3.22	0.32	2331	139	180	153	255	2.3	3553	<0.03	517	24	2.6	<0.015	12.4	0.09	1.2	11310	-0.67	-19.4	7%
Wudi Koma	17/7/14	1.88	<0.01	11.6	8.5	24	13.5	381	0.31	4.4	<0.03	1698	<20	5.3	<0.015	<0.03	50	0.76	6304	3.54	-4.8	-33%
Haella Kele	22/7/14	2.26	0.02	73	33	175	40	209	4.9	378	1.97	661	38	2.2	0.11	0.68	7.5	1.5	3860	-7.16	-48.2	-7%
Sea Water		8		10450	354	405	1235	0.428	4.1	19520		2748	154		3.7	15		1.6		0.4	-6.6	

Table 6: Chemical geothermometer and inferred temperatures for 6 highest CL samples of WNB

Sample Name	T_{Field}	T_{AmS}	T_{Ch} Cond.	T_{Qz} Cond.	T_{Qz} Adiab.	T_{NaKCa}	T_{NaKCa} Mg Corr.	$T_{Na/K}$ Fourn. 1979	$T_{Na/K}$ Trues. 1976	$T_{Na/K}$ Giggen 1988	$T_{K/Mg}$ Gigge. 1986
Rabili	100	118	233	246	242	273	265	286	279	296	230
Talasea Stn	100	59	162	184	183	271	239	301	300	310	197
Bakama 1	70	31	128	153	153	210	210	228	201	242	182
Sakalu	100	58	161	182	182	267	267	283	274	293	318
Magouru	100	112	226	240	237	275	275	291	285	300	262
Gariki	100	122	238	250	246	265	216	285	277	294	190

Table 7: Feni Island water chemistry (2016)

Sample Name	Date	pH	Li	Na	K	Ca	Mg	SiO_2	B	Cl	F	SO_4	HCO_3	NH_4	As	Rb	Cs	Br	Fe	Mn	Cond µS/cm	del ^{18}O	del D	Ion Bal
Nanum #1	27/6/16	8.05	1.5	1379	109	55	10.8	155	13.5	1380	2.4	883	355	0.004	3.2	0.36	0.08	4.3	0.13	0.21	6625	0.34	-13	2.59
Waramong #1	28/6/16	8.52	4.1	7953	1170	7	0.25	144	35	9670	4.3	4896	177	0.005	3.5	2	0.3	24	-0.2	-0.05	33997	2.03	-7.7	-0.14
Matangkapok	28/6/16	7.01	0.83	708	81	104	25	159	7.6	789	0.75	611	596	0.003	0.57	0.26	0.05	2.4	0.17	0.24	4572	-2.19	-19.6	-5.35
Balamuson	28/6/16	7.92	2.4	3414	543	5.8	0.5	120	17.6	4457	2.1	2111	141	1.6	1.9	1	0.17	10.2	0.34	0.03	17145	0.26	-10.2	-2.67

Table 8: Solute geothermometer results for Feni Island waters

Sample Name	T_{AmS}	T_{Ch} cond.	T_{Qz} cond.	T_{Qz} adiab	$T_{Na\text{-}K\text{-}Ca}$	$T_{Na\text{-}K\text{-}Ca}$ Mg corr	$T_{Na/K}$ Fourn. 1979	$T_{Na/K}$ Trues. 1976	$T_{Na/K}$ Giggen. 1988	$T_{K/Mg}$ Gigge. 1986
Nanum	41	140	164	154	197	122	198	164	214	131
Waramong	36	134	159	151	309	309	252	233	265	338
Matangkapok	42	142	165	156	200	84	229	202	243	109
Balamuson	26	122	148	141	294	294	260	244	272	266

4. INTERPRETATION AND DISCUSSION

4.1 Morobe

The schoeller plot (Figure 4) delineates the neutral alkaline waters (pH ~7-9) into two groups (i) Cl enriched waters and (ii) CO_3 enriched waters. Figure 3a further groups the water into three main clusters; (i) Cl enriched waters, where Baluwat (1,277 mg/L Cl) almost plots near to the Sea water (18,980 mg/L); (ii) SO_4 enriched waters which include Tembil, Kamkahe, Sangas and Belwane and (iii) a mixed waters cluster, which include Wandumi Salt 1 and 2, Cliffside 2 and 5, Maus Bokis and Kobiak. The Wandumi Salts 1 and 2 waters have relatively much higher Cl (11,325 mg/L and 4,849 mg/L Cl) as well as high CO_3 respectively (7,357 mg/L and 3,632 mg/L CO_3) and discharging at ambient temperature (24 ° and 25 °C). However, their thermal water characteristics could suggest older hydrothermal activity which could explain the large cascading travertine deposit indicating episode of carbonate rich thermal water discharge

The odorless near neutral to alkaline pH and the relatively lower sampling temperature (< 70 °C), implies very little or no interaction of acidic fluids and magmatic volatiles, however, suggests downward percolation of meteoric water that gets heated by high thermal gradient and ascends to the surface. This can be observed in Figure 3b where the waters exhibit mixed, peripheral water characteristics on the Mg-Na-K graph at lower $T_{K\text{-}Mg}$ temperatures (< 100 °C), despite higher chloride levels thus suggesting that the waters are not deep reservoir waters. The relatively high Na, K and Mg further indicate dilution and mixing of heated meteoric waters with cold meteoric waters.

Work carried out in similar settings in Indonesia by Sundhoro et al., (2010) suggests that the formation of travertine is due to reservoir fluid that mixes with surface or meteoric waters. It is not possible to conclusively determine the fluid end member without the isotopic analysis, however, based on given results and the surface manifestations, the hot springs in Morobe are observed to be structurally controlled with deep fluid circulation in tectonically active setting and could be described as a 'heat sweep system' as described by Hochstein and Brown, (1999), referring to a system developed in fracture zones of the crust where there is anomalously large heat flow but are not associated with volcanism (Channel, et al, 2012).

The Silica geothermometer temperatures show variable results due to the obvious mixing and or dilution of heated meteoric water with colder endmembers. Silica geothermometers are usually affected by dilution and boiling of the fluid and equilibrate faster than cation geothermometers (Nicholson 1993; Mroczek and Rae, 2013). Due to the high Na (> 600 mg/L), K (> 10 mg/L) and Ca (> 90 mg/L) the $T_{NaKCa,}$ geothermometer is used to infer the reservoir temperatures.

Based on the results; two likely reservoir temperatures are noted, hugely influenced by the structural orientation and geology of the area:

i) Buluwat (MOP10), located in the Bulolo area, north of the map sheet shows an indicated reservoir temperature of ~ 80 °C. The hot spring occurs at the lithological boundary of the Morobe granodiorite and the Otibanda formation, a mid-Miocene intrusive and poorly consolidated Pliocene sediments respectively. (Figure 2).

ii) Wandumi Salt 1 and 2 (MOP 1&2), located in the Wau area, further south of map sheet indicate a temperature of ~150° - 160°C using the $T_{Na/K}$, geothermometer, Fournier (1979). The T_{NaKCa} geothermometer developed by Fournier and Truesdell (1973) was developed to specifically deal with Ca rich waters (Nicholson, 1993; Mroczek and Rae, 2013). The hot spring and the formation of travertine in this site is associated with the north-south trending Wandumi fault, therefore is deemed as the main conduit for up-flow where the hot fluid ascends to surface. Wandumi Salt 1 and 2 have higher B content (150 mg/L and 66 mg/L B) relative to the other hot springs therefore is considered to be from deep seated thermal waters therefore appropriate for geothermometry.

4.2 Milne Bay

The two local fields in Milne Bay show distinct characteristics. The Deidei field shows neutral chloride with high reservoir temperatures whilst the Iamalele fields are acid-sulfate fluid.

Yaiyaiboalana and Seuseulina, the two Deidei samples are near neutral pH boiling springs. Their physical features show distinct mature water characteristics, of clear – bluish pools, silica sinters and active geyser, hence are ideal for inferring reservoir temperatures. The two Iamalele samples on the other hand exhibit steam heated acid-sulphate characteristics with pH ~1.7, near zero Cl (~1 mg/L Cl) and relatively high SO_4 (2,500 – 2,600 mg/L) hence are not considered for deep aquifer temperatures.

Despite the very close proximity of the Deidei thermal features to the sea (~ 1km) and the observed geyser activity fluctuating with ocean tides (stories from locals), it is unlikely to associate seawater as an end member due to low HCO_3 which indicates deep reservoir fluids. The high Ca (54 & 46 mg/L) is relative to the low HCO_3 composition therefore a low calcite saturation ($CaCO_3$), hence less removal of Ca in the fluid. Mroczek and Rae (2013) also suggest that elevated SO_4 content (~ 100 mg/L SO_4) could also be due to equilibrium with respect to anhydrite ($CaSO_4$) in the reservoir or mixing with near surface acidic aquifers (Mroczek and Rae, 2013).

Silica geothermometers are usually affected by dilution and boiling of the fluid and equilibrate faster than cation geothermometers (Nicholson 1993; Mroczek and Rae, 2013). Rae and Mroczek, (2013) suggests that the calculated geothermometers of the two Deidei water samples (Table 4) shows the fast acting silica geothermometers, T_{Qz} and T_{Ch} inferring reservoir temperatures > 200 °C, whilst the cation geothermometers show much higher temperatures with $T_{NaKCa,}$ 260 °C and 273 °C and $T_{Na/K}$ (Giggenbach) 269 °C and 283 °C respectively. Assuming saturation with respect to amorphous silica (T_{AmS}), the inferred temperatures are 107 °C and 112°C, which corresponds to the actual temperature of the hot springs (103 °C and 101°C).

The original reservoir composition can be estimated by using the T_{NaKCa} when assuming maximum steam loss; hence the reservoir temperature of the two Deidei samples is inferred to be 260 °C and 273 °C respectively.

4.3 West New Britain

Nicholson (1993) suggests that ionic balance of chemistry analysis of thermal waters reflect the quality of the results. Ionic balances that are within ±5 % indicate acceptable results (Nicholson, 1993). The WNBP samples collected in 2012 and 2014 show Rabili, Wavua 1, Talasea Station, Rongo 1, Sakalu and Gariki with ionic balance that fall within ±5%, therefore their results are considered reliable and further discussed with greater confidence.

Mroczek and Rae, (2013) in their report done for these field discussed that the high SO_4 and Cl noted for acid springs are most likely caused by oxidation of H_2S to SO_4, however rule out the possibility of magmatic acidic fluid discharge at surface.

Some of the high chloride (> 400 mg/L Cl) acidic spring (pH < 3) could be due to mixing of sea with steam heated surface waters. This is particularly compelling for Narera Kapma and Gariki which plots almost identical to sea water on the C-S-H ternary plot (Figure 6a) and also contains high Na, K, and SO_4 concentrations, properties identical to sea water.

The near neutral chloride springs contain appreciable SO_4 and Ca which are inferred to be due to solubility of anhydrite in the fluid (Mroczek and Rae, 2013) which means the fluid has reached some stages of equilibrium with respect to anhydrite, thus prevents further reactions between Ca and SO_4.

The stable isotope composition plot (Figure 6b) shows the boiling springs Rabili, Talasea St. and Gariki having identical signatures to the sea water. Rabili and Talasea St. show negative enrichment which is attributed to dilution and mixing of sea and ground water, thus support the views of likely sea water intrusion. This is plausible considering the proximity of the sea to the samples. Gariki is a Cl rich acidic water (8,437 mg/L Cl; ~ pH 2) that demonstrates a more positive enrichment of $\delta^{18}O$ and δD and plots closer to Wudi Koma and Wavua 1; two springs that contain negligible Cl and low pH (~5 mg/L Cl and pH ~2). The positive $\delta^{18}O$ and δD shift is likely due to evaporation (Mroczek and Rae, 2013).

Table 6 illustrates the different solute geothermometers with respective temperatures. The T_{NaKCa} geothermometer developed by Fournier and Truesdell (1973) was to specifically deal with Ca rich waters, which is the most appropriate for the WNBP samples. The cation geothermometers are generally negligibly affected by dilution and boiling, hence the inferred reservoir temperatures of the six reliable samples (Table 6) shows T_{NaKCa} geothermometer temperatures between 260 ° - 280 °C, except Bakama 1 which shows lesser temperature of 210°C.

4.4 Feni Island

Based on the ionic balance of the hot springs measured; only Matangkapok (-5.35%) falls slightly out of the quality control (QC) limit of ±5 %, which suggests confidence in the quality of the results of the other hot springs. The reason for poor quality for Matangkapok is most likely due to cross contamination by rain water as the sample was collected on a rainy day.

Figure 7 shows Waramong (WM) and Balamuson (BM) plotting almost identical to the sea water. They have relatively high Cl content, 9,670 mg/L and 4,457 mg/L and corresponding high SO_4, 4,896 mg/L and 2,111 mg/L respectively. Given the close proximity of the hot spring from the sea (< 1km) and the influence of ocean tide on geyser activity and fluctuating hot pool volume, sea water influence is highly likely. The depleted levels of Mg (~0.5 mg/L) and Ca (~7 mg/L) also suggest water rock interaction at elevated temperatures. The Stable isotope plot in Figure 7d also shows Balamuson and Nanum as waters almost identical to sea water properties, except showing slightly negative δD enrichment most likely due to a hybrid nature as a result of mixing from heated sea and meteoric end members.

The Cl/B ratio (Figure 7c) and Mg-Na-K plot (Figure 7b) illustrates Waramong (WM) as suitable for geothermometry closely followed by Balamuson (BM), whilst Matangkapok (MK) plots in the immature water and Nanum (NM) is shown to be in the mixed water zone however with greater affinity towards immature waters. The near linear correlation of the Cl/B ratio is good indication of mixing (Marini, 2004).

Silica solubility is controlled by quartz, hence silica geothermometers are affected by both dilution and boiling and equilibrate faster than any of the cation geothermometers. At temperatures below 200 °C, the equilibrium rate is slow, thus one of the other less stable but more soluble polymorphs control the solubility (Mroczek and Rae 2013). In such conditions the boiling springs are often in equilibrium with chalcedony or amorphous silica at the temperature of the discharging spring water.

Considering maximum steam loss the quartz adiabatic geothermometer presents a more realistic temperature, however the suspected mixing as seen in Figure 7, most likely by heated sea, meteoric and acid-sulfate waters could compromises the origin and quality of SiO_2. Given the low Mg and Ca component in the fluid; $T_{Na/K}$ is considered the most appropriate geothermometer to infer the reservoir temperatures (240 ° - 270 °C), hence the, Fournier (1979) $T_{Na/K}$ presents 252 ° and 260 °C for Waramong and Balamuson respectively.

5. CONCLUSION

Reconnaissance carried out in PNG generally shows unique chemistry in each site. The Morobe geothermal field is the only field located in mainland PNG while the other three; Milne Bay, West New Britain and Feni Island all located on islands and isolated from electricity grid infrastructures.

The Morobe field is structurally controlled and shows no characteristics of volcanic influence. The elevated temperature of hot springs is observed to be due to downward percolating meteoric waters that heat up due to higher geothermal gradient and ascends to surface. The two distinct inferred temperature of Buluwat and Wandumi at ~80 °C and ~160°C respectively is directly associated with the geological structure. Thus, the Morobe field is considered a low to intermediate temperature field (<150 °C). (Sundhor, 2010). The travertine deposits also indicate up-flow and could also represent an ancient geothermal system worthy of further work.

The Deidei samples in Milne Bay, Rabili, Talasea St., Gariki, Sakalu Magouru and Sakulu in West New Britain and Balamuson and Waramong in Feni island all demonstrated reasonably high reservoir temperatures of > 250 °C and are therefore considered high enthalpy systems. The natural surface manifestation also shows signature features such as clear-bluish alkali chloride pools, active geysers, boiling pools and silica terraces. Rabili, Talase St., Balamuson and Waramong are observed to have sea water signatures and are likely hybrid heated waters. Further work including geophysical surveys and exploration drilling will be helpful to ascertain reservoir extent and further understanding of the reservoir.

Based on the water chemistry and the inferred temperatures; the four sites can be classified into different temperature ranges following Hochstein (1990) classification.

Studied sites	**Low Enthalpy** **<125 (°C)**	**Intermediate Enthalpy** **125 – 225 (°C)**	***High Enthalpy*** ***>225 (°C)***
1. Morobe	•Buluwat	•Wandumi 1 •Wandumi 2	
2. Milne Bay			•Yaiyaiboalana •Seuseulina
3. West New Britain		•Bakama1	•Rabili •Talasea St •Gariki •Sakalu •Magouru
4. Feni Island			•Waramong •Balamuson

PNG still remains a green field and more work is required to fully appreciate and understand its geothermal resources.

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