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Geothermal Resource Assessment of the Commonwealth of the Northern Mariana Islands

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ABSTRACT

Facing increasingly higher cost of diesel-generated electrical power, the Commonwealth of the Northern Mariana Islands (CNMI) government initiated an assessment of geothermal energy potential on the islands. As part of this effort, the Southern Methodist University Geothermal Team visited the CNMI Islands of Pagan and Saipan. The team was on Pagan from March 5 to 11, 2008, to conduct a preliminary assessment of the geothermal resource potential of the Island, which was selected for assessment because of its size, proximity to Saipan, relative accessibility, and characteristics of volcanic activity. These suggest the potential for a significant geothermal resource.

The team then conducted an assessment of Saipan from March 12 to 18 which involved geologic assessment and logging of selected water wells. The assessment is based on helicopter and ground surveys and analysis of samples of rock, water, and gas. New and previously existing data indicate the presence of a geothermal reservoir on the southwest side of South Pagan which has a minimum temperature of 194 °C (385 °F). The size of the field(s) is estimated to be a minimum of five to eight square kilometers with an electric generating capacity in the range of 50 - 125 MW based on the surface area and fluid chemistry.

Reconnaissance geologic and geo-chemical studies were conducted on Saipan following the work on Pagan. These studies included spring sampling for geothermal indicators and temperature logging of selected wells to determine geothermal gradients on the island. Saipan does not have the young volcanic rocks to form a high temperature geothermal system but deep faulting may allow thermal waters from greater depths to migrate upward for a low to medium temperature resource. A deeper thermal gradient well is scheduled to be drilled on Saipan in quest of additional information.

1. INTRODUCTION

The Commonwealth of the Northern Mariana Islands (CNMI) government under the direction of Governor Fitial is investigating a range of renewable energy options. Recent spikes in the cost of diesel-generated electrical power have induced the CNMI government to initiate this review of local renewable energy sources for the islands. As part of this effort, the Southern Methodist University Geothermal Team visited the CNMI islands of Saipan and Pagan from March 5 to 18, 2008 to conduct an assessment of the geothermal resource potential. Pagan was selected as the first island to be evaluated within the CNMI because of its 1)size, 2)proximity to Saipan, 3)relative accessibility, 4)characteristics of volcanic activity, 5)reports in the literature of geothermal springs (Corwin et al., 1957; Trusdell et al., 2006), and 6)recent observations that included off-shore thermal and conductivity anomalies. Thus in addition to the active volcanism on the northern part of the Island, there was preliminary evidence of a geothermal system on both the northern and southern portion of the Island.

Saipan is the largest of the 14 islands of CNMI and is located in the Western Pacific Ocean. Saipan is 14 miles long and averages about 4 miles wide with a surface area of approximately 48 square miles.

The island of Saipan is divided into six physiographic provinces with the Central Highlands being the largest composed of a central volcanic ridge and mountainous area. Limestones border the Central Highlands and consist of a series of terraces and platforms forming the Kagman Peninsula, Southern Plateau and Bonaderse areas. The Western Coastal Plain forms the western side of the island and is composed of emerged calcium carbonate sands.

The on-site scientific team consisted of Roy Mink, Al Waibel, and Maria Richards from the Energy Center at Southern Methodist University and was supported by personnel from the CNMI Emergency Management Office.

2. BACKGROUND

2.1 Pagan geology

Pagan, one of the largest of the volcanic islands of the Mariana Volcanic Arc, is located about 320 kilometers (200 miles) north of Saipan (Fig 1). The Island covers approximately 48 square kilometer and is part of a much larger volcanic complex, the remainder of which is submarine. The northern and southern portions of Pagan are dominated by two calderas named respectively North Caldera and South Caldera (Corwin et al., 1957). The most prominent Island feature currently is Mt. Pagan, a resurgent basaltic volcano that erupted in 1981, located within North Caldera. South Caldera has four smaller volcanic cones within it.

The volcanic structures on the island of Pagan are predominantly composites of lava flows, scoria, ash, surge deposits and lahars, mostly of basaltic composition. Post caldera eruptions have occurred at Mt. Pagan in the North Caldera and from the four-vent cluster within the South Caldera (Fig 2).

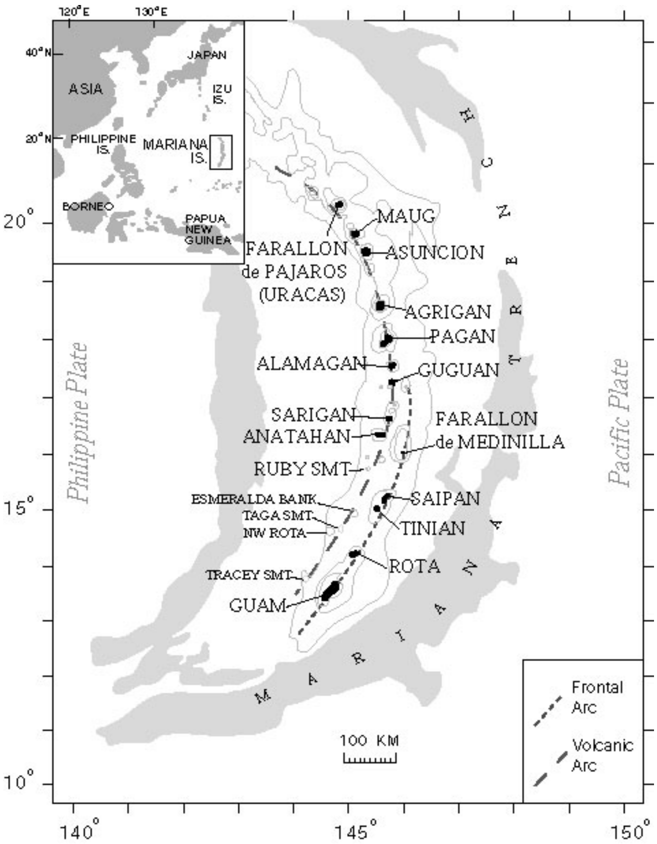

Figure 1. Regional map of the Mariana Islands and the adjacent Mariana Trench (Trusdell et al., 2006). The Commonwealth of the Northern Mariana Islands consists of two concentric lines of islands and extends from Rota at about 14 degrees N latitude to Uracas at about 20 degrees N latitude. Pagan Island is located along the inner arc and near the center of the arc at about 18 degrees N latitude.

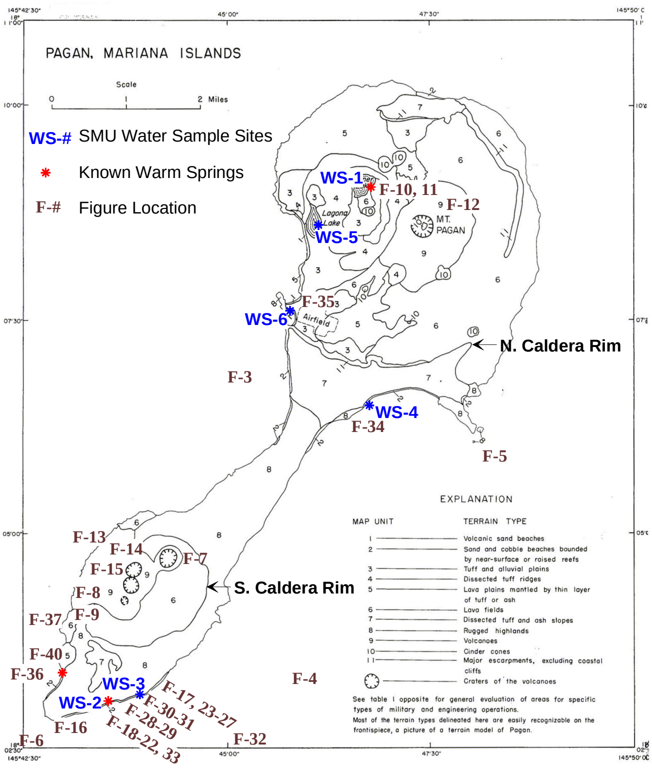

Figure 2. Simplified geologic index map of Pagan Island (Corwin et al., 1957). Shown are known warm springs (*), SMU water sampling sites (WS 1-6), and photo locations (F-#) identified by the Figure number.

Erosional remnants of volcanic vents on the flanks of the calderas, consist of feeder necks and remnant flank deposits. Larson et al. (1974) observed that pre-caldera lavas cropping out on Pagan are of normal magnetization, and are therefore younger than 700,000 years old.

South Volcano is a single name for the four resurgent composite cones within South Caldera. They are made up of pyroclastic deposits, with minor lava. Three of the cones are closely spaced, slightly overlapping, in a North-to-South alignment. The fourth cone is to the northeast of the 3-cone cluster and is an intact round cone. All of the cones show white kaolinite patches indicative of fumarole-related alteration. The north-south aligned, three-cone-cluster shows similar alteration well outside of the central vent areas (Fig 3). One area southwest of the resurgent South volcano, shows evidence of advanced kaolinite alteration and slope instability suggestive of pervasive alteration.

Figure 3. Northern portion of Pagan Island with a view of Mt. Pagan. Picture is taken looking towards the northeast. The rim of the North Caldera corresponds to the ridge line identified by the black arrows.

2.2 Saipan geology

The volcanics form the core of Saipan and area of Eocene Age (approximately 41 million years) (Carruth, 2003). The oldest rocks are rhyolite and dacite flows of the Sankaknyuma Formation and are exposed on the Flank of Mount Achugao. Other volcanic rocks include Pensinyama and the Hagman Formation, a sequence of andesitic pyroclastic rocks, lava flows and volcanic sediments which are exposed on the Flank of Mount Achugao and Mount Loulane. (Reagon et al, 2008; Carruth, 2003) (Fig 4).

Figure 4. Southern portion of South Pagan Island. The outer walls of South Caldera correspond to the ridge lines identified by black arrows. The yellow dashed line is area of data collection along the south eastern shoreline.

Younger limestone and calcareous rocks overlie and lap onto the volcanic sequence. These include the Miocene Tagpochase Limestone, the Mariana Limestone and the Tonapag Limestone. The Miocene Togpachou Limestone makes up a large portion of Central Highlands in the Mt. Tagpochu area and the northern part of the island between Mt. Achugao and Pidos Kalahe. The Tagpochau formation is composed of Calcaseous clastic generally pure pink to white intergranular limestone facies of re-worked volcanic material (Carruth, 2003). The thickest part of the Tagpochau limestone is in the northern part of Saipan where depths are estimated to be greater than 900 feet. The Mariana Limestone of Pleistocine Age is mainly located in the southern and eastern sides of Saipan. The formation is a porous fragmented limestone with abundant coral. This formation is a dominant source of fresh water for Saipan.

The Tanapog limestone is a coral-algal reef and bioclaster limestone. The formation is found at lower elevations and was formed from fringing reefs which have emerged. It is of Pleiostocene and Holocene Age and occurs as shoreline deposits on the south and eastern edges of Saipan. Deposits of Pleistocene and Halocene material also form lowlands and beaches along the western side of Saipan.

Much of the past geology and subsurface investigations in Saipan have been oriented toward groundwater investigations for domestic and municipal water supply. As a result the investigations have focused on the limestone and permeable pathways for ground water movement. Extensive drilling has occurred on Saipan for ground water with wells rarely exceeding the depth of the fresh water lens overlying the brackish and saline waters found at depth.

Faulting on Saipan is normal with a north-east trend. Some faults in the limestones show higher zones of permeability while others indicate a zone of compression with lower permeability (Carruth, 2003).

Preliminary structural mapping of Saipan indicates major faults in a NE/SW trend along both the western and eastern highlands paralleling the axis of the island. The faults splay out creating a complex set of fault intersections both in the southern and northern parts of the island. A dominant zone of fault intersections occurs in the area west of the town of San Vinhie and south of Mt Tagpochau. To the north of Saipan, a number of fault intersections occur in the Mt Achuyao and Pidos Kalale areas. These zones of fault intersection generally indicate possible zones of high permeability and the possibility of deep circulation. This coupled with areas of volcanic rock in the subsurface could result in upwelling of geothermal water.

3.0 METHODOLOGY

The preliminary assessment of the geothermal potential for the island of Pagan included emphasized identification of changes superimposed on the geology as a result of discharging geothermal fluids, and changes in geothermal dynamica over time.

Saipan assessment included a geologic reconnaissance spring sampling and temperature logging of selected ground water wells on the Island. Phase II of the Saipan study is to drill deeper gradient wells in areas showing higher thermal gradients.

3.1 Pagan geothermal areas

3.1.1North Caldera

The most volcanically active area on Pagan Island is Mt. Pagan in the North Caldera. There is one warm spring, along the shore of the upper lake, which was sampled for water chemistry (Fig 5). Numerous gas vents are present on the upper reaches of Mt. Pagan. A gas sample was collected from one of these vents. Although the vent temperature was over 100 degrees C (212degrees F) the gas sample composition was primarily meteoric. Based on the observations, there is no evident of a large, deep geothermal reservoir in this area. Mt. Pagan continues to have seismic tremors and shows signs of volcanic activity. Thus northern Pagan Island is considered not suitable for geothermal power development.

Figure 5. North Pagan, east shoreline view is across Togari Rock. This feature is a relict of subvolcanics (intrusive dikes and sills) in the area.

3.1.2 South Caldera

The majority of current geothermal activity is located around the less volcanically active South Caldera which comprises most of the southern part of the Island. This volcanic center has had little volcanic activity since the 1864 eruption.

The South Caldera is about 2.5 kilometers in diameter and extensively breached on the east and west sides. The southern remnant wall is irregular and may be faulted or may represent a composite feature. The geothermal manifestations on this part of the Island are all south of this crater wall, although there are extensive areas of alteration associated with the young vent areas within the caldera.

Locations with white kaolinitic clay alteration, an indication of low-pH fumarole alteration, were recognizable in and on the flanks of the South Caldera from the aerial survey. Within the South caldera kaolinite alteration was associated with all four of the southern volcanic cones, specifically within the northern most volcanic vent cone and on the upper west flank of the three-cone-cluster (Fig 3). The geothermal significance of these areas is equivocal as fumaroles alterations within the four cones could be due to processes associated directly with volcanic activity, or due to later steam condensation from boiling geothermal brine. One location on the southwest side of the South Caldera shows extensive fumarole alteration. Slope instability and slump features are observed, associated with this alteration, suggesting sustained fumarole activity. This location may be overlying a zone of subsurface boiling of geothermal brine. Alteration areas within the South Caldera need to be ground checked in the future.

The southern shoreline shows the steep cliffs of the unaltered volcanic and volcaniclastic rocks in the foreground, and the lower-angle slopes of the strongly clay-altered zone dominated by slumps and landslides in the background (Fig 6 foreground). The southern sharp cliffs are composed of intercalated mafic lava flows, scoria and tephra, that form steep cliffs. However when the same material is impacted by an area of high-temperature geothermal fluid discharge it has a completely different topographic expression. There is more than one and a half kilometers of the coastline, showing pervasive, extreme alteration of the bedrock and soils that has altered and lowered the strength of rocks, resulting in slumping. Subsurface boiling of the geothermal fluid formed this zone of warm steam condensate, combined with geothermal gasses, to produce a highly reactive sulfuric acid solution. Within many of the outcrops little of the original rock structure and texture are identifiable the physical rock properties change from brittle layers of lava to soft clay. This change in rock mechanic properties results in decreased slope stability, ensuing in landslides and slumping (Fig 7).

Figure 6. South Pagan, South Volcano, upper west side vents looking north from south end of the Island, showing in the foreground the three overlapping cones and in background the fourth cone. In the distance the topographic feature is the remnant of the caldera wall.

Figure 7. South Pagan, South Volcano, northern side with focus on fourth crater (looking south southeast).

The evolution of the geothermal system can be observed in the outcrops along the southeastern shoreline. Current water chemistry, geology, and topography indicate a geothermal reservoir below sea level with its boiling, deep brine creating the low-pH condensate, which alters the water and rock visible at the surface. Thus the entire outcrop in the alteration zone is dominated by sulfuric acid-rich condensate, produced by degassed sulphur gasses from underlying geothermal brine, mixing with condensate. The past reservoir dynamica is represented by rock with cryptocrystalline silica and pyrite, which precipitated directly from earlier shallower geothermal brine. The precipitated pyrite now exposed in outcrops is weathering to hydrous Fe oxides, leaving some relict micro-box-work structure.

For this assessment, six sites on Pagan Island were sampled for water chemistry. Two of the three previously identified geothermal springs were revisited and sampled to confirm flows with high temperatures. The other previously known location on the southwest side of the southern island was not accessible. Table 1 presents the comparison of water sample analyses from the springs on Pagan in 1954 by the US Army (first two columns), 2001 by the USGS (middle three columns) and by the SMU team in March 2008 (last three columns).

3.2 Pagan water chemistry

The water chemistry for the three samples from the upper lake hot spring, WS-1, (Table 1) shows significant variation with time. The sample collected in 2008 is markedly diluted in sodium, potassium, calcium, and chloride compared to that collected in 2001, but similar to the 1954 analysis. The dilution, however, is neither systematic nor proportional and could be a.) due to collecting of samples at slightly different locations, b.) due to a change in the hydrothermal pathways over the years, or c.)due to some near-surface dilution of the discharging brine. Based on the data from the 2008 sample, the water chemistry results in a silica geothermometer temperature of about 130+or- 10 degree C (260 degrees F). The overall sample chemistry suggests that this warm spring is leakage from a geothermal brine of moderate temperature or is a diluted higher temperature brine.

The water sample at WS-2 was taken from the middle of a hillside where the water was seeping out of the ground. Near the base of the slope all the seeps formed a stream of warm water which flowed into the ocean. The WS-2 location (Table 1, 1954, 2001 and 2008) is along the southeastern margin of the massive alteration zone, with slumps and land slides, extending along the coast for slightly over one and a half kilometers (Fig 7). The WS-2 chemistry appears to be a hybrid fluid. The chloride content is one order of magnitude lower than that observed in the geothermal brines of North Pagan WS-1 and South Pagan "SW Spring". The overall dissolved cations are low, though the silica values are well above that expected for meteoric water. These observations suggest the WS-2 water may be a mixture of evolved condensate water mixed with meteoric water. The very low chloride values exclude a major geothermal bring component to this sample location.

The WS-3 was sampled from an area where low-pH (2.8), high-surface water was seeping out of intensely clay-altered rock. Water chemistry is consistent with the low pH mineral alteration of the host volcanic and volcaniclastic rocks. The sampled water is a condensate of steam emanating from a deeper boiling of high-temperature geothermal brine. Volatile sulfur dioxide degasses from the boiling brine then combines with the hot condensate to form sulfuric acid, which then aggressively alters the host volcanic rocks to clays.

Contrast between the compositions of the WS-2 and WS-3 (Table 1) reflect the location of the sample points. The WS-2 location is on the distal southern margin of the geothermal alteration zone. The water chemistry shows only minor affects of the condensate chemical reactions (i.e., relatively low cations and surface values). The WS-3 location is central to the chemically dynamic system. The water chemistry reflects the aggressive chemical reactions of the condensate fluid (i.e., pH and relatively high cations and sulfate values).

Table 1. Historical record of volcanic eruptions on Pagan Island (Banks et al., 1984).

Historic activity of Pagan Island, Mariana Islands

Year	Date	Type of Activity	Volcano	Source
1664		Eruption, no details	S	5, 7
1669		Major eruption	N	5, 7
1825+5		Eruption, no details	N	2
1864		Eruption, no details	S	5, 7
1872-73		Major ash-scoria eruption, lava flows, decrease in height of summit	N	1, 4
1890		Continuing nonviolent emission of fume	N	1
1902		Reports of fumarolic activity	N+S	2
1909		Slightly active, fire columns at night	N	3
1917		Intermittent earthquakes and fire phenomena	N	3
1923	pre-Mar	Frequent earthquakes and fire columns	N	3
	3-Mar	Major ash-scoria eruption	N	3
	7-Mar	Ash-scoria eruption	N	3
	Mar-Apr	Weak eruptions	N	3
1923-25		Continuous gas emissions	N	3
1925	Feb-Mar	Frequent ash eruptions, preceded by several months of earthquakes	N	3
	Mar 11-May 4 or 5	Lava overflowed the western crater rim into eastern lagoon basin	N	3
1929-30		Copious gas emission	S	6
1981	Mar-Apr-early May	Frequent earthquakes, increased gas emission	N	8
	15-May	Frequent earthquakes, major plinian column and lava flows to north, west, and south of crater; three vents, north flank, north summit, and south summit	N	8
	May 15-	Mild to moderate ash eruptions, minor continuing lava flows from summit vents	N	8

N = Mount Pagan Volcano, resurgent basalt cone.
S = South Pagan Volcano, resurgent basalt-andesite cones.
1 = Marche, 1890; 2 = Maso, 1902; 3 = Tanakadate, 1940; 4 = Corwin et al., 1957;
5 = Corwin, unpubl. data; 6 = Kuno, 1962; 7 = Simpkin et al., 1981; 8 = Banks, 1984.

3.3 Selected temperature well logging on Saipan

Temperature logging of wells in Saipan confirmed a higher geothermal gradient in Well GR-6 (Fig 8). This well had a bottom hole temperature of 33.84 degrees Centigrade and a thermal gradient of 0.05 degrees

Figure 8. South Pagan, upper west side vents with low-pH alteration shown as white discoloration (view east). The caldera rim is in the background.

Centigrade/meter. The temperature of this well indicated a temperature reversal from depths of 60 meters below surface with an increase of temperature from 27.03 degrees Centigrade to 33.84 degrees Centigrade at depths of 60 meters to total depth at 125 meters. Well AG-MW-1 exhibited isothermal temperatures of approximately 27 degrees Centigrade and was one of the higher elevation wells logged with well head at elevation of 2180 feet above sea level. Wells KG-MW-3, IF MW-4, 00MW-1 and 03MW-1 exhibited isothermal temperatures of approximately 28 degrees Centigrade and were at elevations of 75-50 meters above sea level. KG-MW-1 exhibited a temperature reversal at 50 meter depth to total depth at 80 meter depth (Fig 9).

Figure 9. South Pagan, South Volcano, upper part of southeast side, showing slumping and alteration in the slumped area. View looking northeast.

The higher gradient and bottom hole temperature of GR-6 is thought to be related to its location near one of the major fault systems in Saipan. Major north south faults have been mapped in the vicinity of MW-6 by several investigators (Cloud, et all, 1948; Cloud et al, 1956; USGS Unpublished Draft, 2007)

Cloud et al 1956 indicated major faulting of Saipan are high angle northeast trending faults with 60 to 70 degree dip to the west. Most faults observed by Cloud offset the Tonapog limestone of Pleistocene Age. This combined with seismic activity indicates the Mariana geosyncline is still developing and movement continues to occur along existing structures or new ones formed parallel to them.

The potential exists for deeper thermal water to be moving upward along the fault due to higher fracture permeability and intersected by MW-6. The temperature reversal in KG-MW-1 could be the result of cooler ground water entering the well at 50 meter depth and moving down a fault structure as part of a dynamic circulation system of recharge within the near surface carbonate rocks.

3.4 Selected spring and well chemistry on Saipan

Water samples were collected from Susupe Lake, GR-Well, Donni Spring, Tonapog 1 Spring and two samples Achugao springs discharge (Fig 8). The waters of Susupe Lake were brackish with EC value of 3680ms/cm and contained high chloride and sodium, sulfate and magnesium levels (Table 2).

Spring samples were indicative of fresh water with EC values between 465 and 740 ms/cm. Bicarbonate, chloride, sulfate, sodium values were low, in the range of fresh water. Tonapog Spring contained elevated silicate concentration of 46.3 mg/l which was higher than the other springs sampled. Achugao Springs had silicate values of 13.8 and 16.9 mg/l and Donni Spring had a silicate value of 7.5, similar to the GR-Well sample of 5.3 mg/l. Tonapog Spring issues near a mapped fault and in the Tagpoclau limestone composed in part of reworked volcanic material (Cloud et al, 1948-49). Achugao Springs appear to issue near fault intersections from the Sankakuyama Formation, a dacitic volcanic rock. Both formations could account for the high silica concentrations in the Tonopog and Achuguo Spring waters, however the higher silica concentrations of the Tonapog Spring could be related to a larger flow path or deeper circulation within the volcanic sequence. Donni Spring appears to also issue from the Tagpochau limestone but is not located near any mapped faults (Cloud, 1948-49). Water chemistry shows the spring to be higher in bicarbonate water and calcium than waters from other springs. This could be resulting from circulation mainly within the limestones.

4.0 CONCLUSIONS

4.1 Pagan

A review of available data and a field site visit identified potential locations for up to four geothermal locatolities on the island of Pagan. These are: 1) A lower-temperature geothermal system is active in the vicinity of upper lake on the flank of Mt. Pagan; 2) A moderately high temperature geothermal system along the shoreline southwest of Southern Calderas; 3) A large high-temperature geothermal system is active along the shoreline southeast of South Caldera/ 4) Thermal water is leaking into the sea at shallow depths off the southeast coast and in areas along the western side of Pagan Island. The southern Pagan areas may be connected at depth and the southeast tip of the Island may be underlain by one single very large geothermal system or by a number of smaller geothermal cells. All of the areas identified as geothermal features on the southern island can be explored by directional drilling, including the offshore area to determine their connection and total production capacity.

Table 2. Water Quality Data from the US Army (1954), USGS (2001), and SMU Geothermal Laboratory (2008) Field Reconnaissance on Pagan Island.

1954 - Table 37, Corwin, Military Report
2001 - Table 1, USGS Water Quality Data
2008 - SMU Geothermal Laboratory, this report

Parameter	Upper Lake Spring	SE Spring	Upper Lake Spring	SE Spring	SW Spring	Upper Lake Spring	SE Spring	SE Seep
SMU Site	WS-1	WS-2	WS-1	WS-2		WS-1	WS-2	WS-3
sample date	*9/1954*	*9/1954*	*5/2001*	*5/2001*	*5/2001*	*3/2008*	*3/2008*	*3/2008*
pH (field)	7.7	8.1	7.19	8.22	7.21	7.3	8	2.8
pH (lab)	7.3	7.1				7.6	7.5	3.5
Temp. (°C)			44.2	37	60.2	44.4	36	28.2
Sodium	1480	122	1295	71	1747	842	84	310
Potassium	82	10	82	6	208	56	5	9
Calcium	172	41	248	17	215	112	26	458
Magnesium	15	129	161	6	126	80	8	82
Sulfate	292	63	700	25	551	337	33	1650
Chloride	2750	224	2367	84	3381	1510	101	530
Silica	85	63	104	68	246	89	64	145

4.2 Saipan

Volcanic rocks on Saipan are of Eocene Age (approximately 40-50 million years old) (Cloud, 1956) and as a result have probably lost most of their near surface residual heat. Deep circulation through major structural features could bring geothermal fluids near the surface under the right circumstances of fluid circulation and heat flow. The most recent volcanism on Saipan was of Oligocene Age (Approximately 30 million years) but was not extensive or prolonged (Cloud, 1956).

There are no active volcanoes on Saipan with the nearest being Anatahan about 60 miles to the north. A sulfur boil was reported about 25 miles west of Saipan (Cloud, 1954) and may be the southern end of the young volcanic centers to the west. Cloud indicated the front of the volcanic arc would not likely to become active in the foreseeable future.

Saipan appears to not contain the young volcanic rocks which are needed to form an active high temperature geothermal resource. Recent and active faulting on the island could allow low temperature thermal waters to migrate upward beneath the island which may be within reach of intermediate to deep wells. Gradient drilling, as planned, is recommended to further evaluate the geothermal potential of the deeper geologic formations beneath Saipan.

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