

Defining Structural Lineation Associated with Geothermal Manifestations Using Remotely-Sensed and Seismicity Datasets

Nathan Mosusu¹, Maxine Lahan¹, Dorothy Pion¹ and Felix Tararu²

¹Mineral Resources Authority, ²Port Moresby Geophysical Observatory, P.O. Box 1906, Port Moresby, Papua New Guinea

nmosusu@mra.gov.pg

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ABSTRACT

Geothermal manifestations on West New Britain Province (WNBP), Papua New Guinea, are structurally controlled by N-S and trending structures. While these structures may be visually mapped on the ground, others occur within thick sedimentary and volcanic sequence cover, and are not easily detectable. Here we explore the application of radar imagery and seismicity to trace geothermal manifestations to structural trends and faults.

The Mineral Resources Authority conducted a geothermal sampling program in West New Britain, whereby at least 30 geothermal features were sampled for their water, gas and rock samples. Analytical results obtained from these samples identified several neutral-chloride mature geothermal fields that have the potential to be developed for geothermal energy. However, given the areal extent of some of the geothermal fields and difficulty in accessing them, it appears that a large number of features remain unidentified, may never be sampled, and their geothermal characteristics may never be known. This has the potential to underestimate the real potential of the geothermal system.

Using remote sensing techniques we are able to identify geothermal features. And with the availability of near-shallow seismicity data, we are able to link these geothermal manifestations to existing faults and other geological structures.

1. INTRODUCTION

The geothermal fields of West New Britain lie on the northern coast of the New Britain Island and span over 200 km between Talasea station in the west and Bialla station in the east (Figure 1). The fields are divided into two main areas, Hoskins to the east and Talasea to the west.

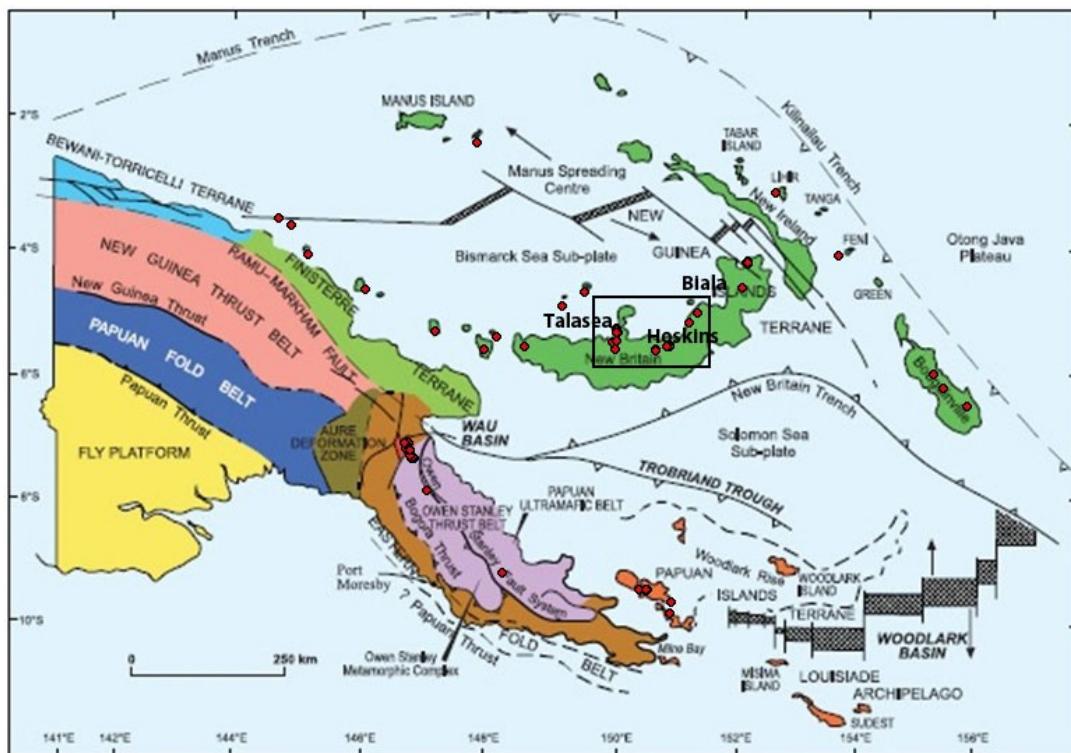


Figure 1: Geothermal hotspots on tectonic setting (Hotspot location updated from Mosusu (2008) and tectonic framework from Williamson and Hancock (2005))

Interest in the geothermal activity of the West New Britain area probably started when Fisher (1939, 1940, 1942, and 1957) investigated the volcanoes in the area and examined the sulfur deposits from Mt Gabuna and Mt Pago. The thermal fields were later

investigated in more details by Reynolds (1954) and Heming and Smith (1969) when they carried out geological mapping and geochemical sampling of the Talasea and Kasiloli geothermal fields respectively.

A large number of these investigations concentrated on the geology and hazards associated with volcanoes (Branch, 1967, Bake and Bleeker, 1970, and Lowder and Carmichael, 1970). Other authors used deep geophysical methods, such as crustal seismic refraction datasets (Finlayson et al., 1972 and Wiebenga, 1973), and regional heat flow studies (Finlayson and Cull, 1973). Few authors have attempted to investigate the geothermal manifestations and the associated geological structures that play a role in ensuring their existence.

In this paper we present results of a geothermal sampling program conducted by the Geological Survey Division in West New Britain Province (Figure 1), and attempt to link the existence of the geothermal features with pre-existing faults and other geological structures. These structures are mapped using radar imagery and also from seismicity datasets.

2. GEOLOGICAL SETTING AND REGIONAL SEISMICITY

2.1 Geology and geothermal characteristics

New Britain Island mostly comprises of Tertiary to Quaternary volcanic materials. Several dormant and active volcanoes exist along the northern coastline from west to east (Lowder and Carmichael, 1970). Baining Volcanics (Teb) which accumulated in an Eocene island arc is the oldest rock type on the island. It comprises of massive to well-bedded indurated and strongly-jointed volcanic breccia, conglomerate, sandstone and siltstone, basic to intermediate lavas and hypabyssal rocks, tuff and minor limestone. There is widespread occurrence of andesitic to basaltic intrusives on the island. In the West New Britain area, deposition of Kapuluk Volcanics (Tok) occurred when volcanism resumed in the late Oligocene. The Kapuluk Volcanics is of similar lithology to the Baining Volcanics but markedly less indurated, jointed and fractured and widely zeolitized. Slow regional subsidence during a period of volcanic quietness in the early Miocene to early Pliocene, allowed large thicknesses of the Yalam Limestone (Tmy) to accumulate in reefs and inter-reef basins with little or no contaminations from terrestrial sources. It consists of compact or porous, massive to well-bedded bioclastic limestone, chalk, calcareous siltstone and mudstone with minor calcirudite (Ryburn, 1975).

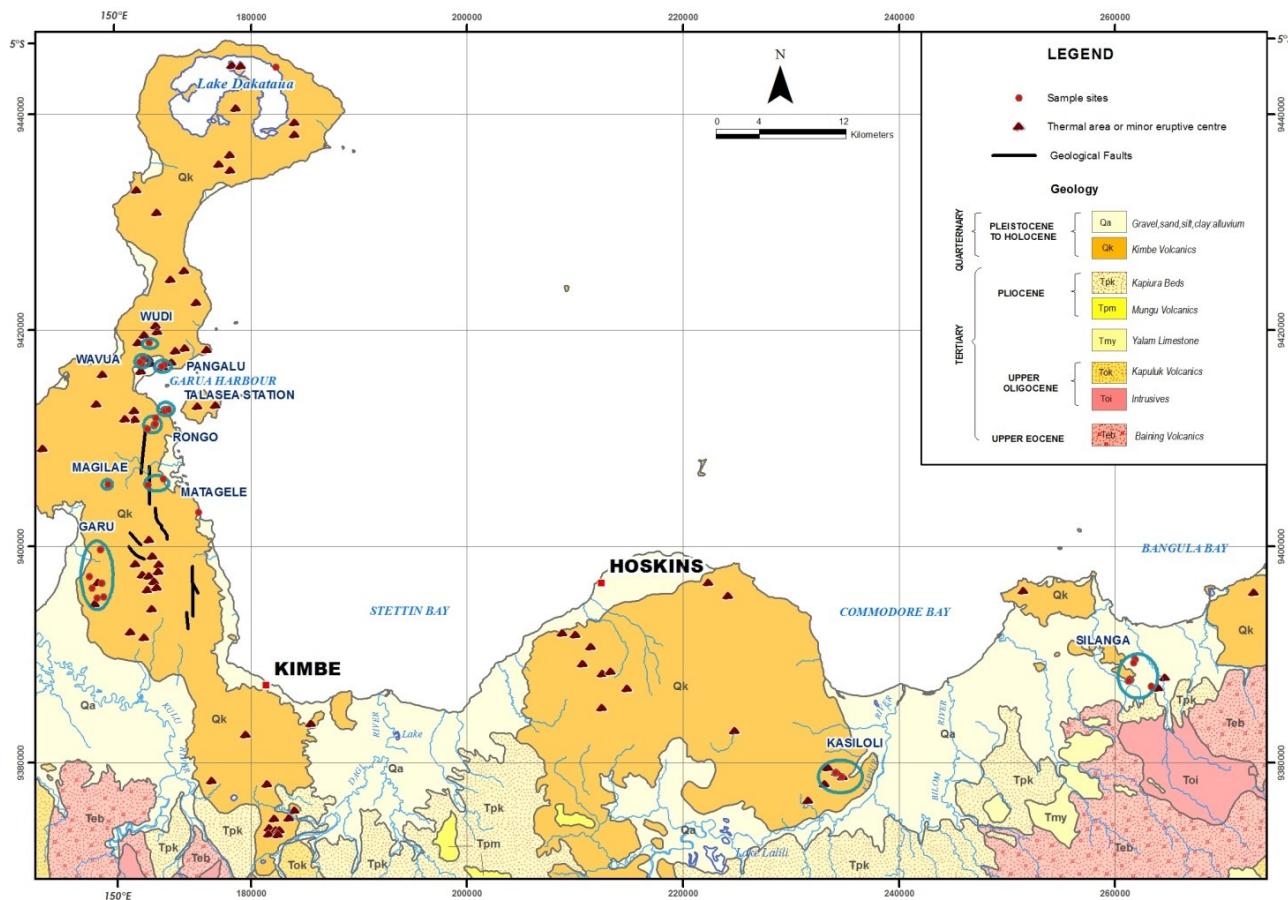


Figure 2: Geology of the Talasea-Hoskins area, showing locations of geothermal sites visited (After Ryburn, 1975)

Renewed volcanism in Pliocene formed the Mungu Volcanics (Tpm) found southeast of Stettin Bay which comprises dacite, rhyodactie, andesite and pumiceous tuff. They possibly represent the volcanoes that supplied the tuffaceous material in the Kapiura Beds (Tpk) found east of Kasiloli thermal area. The Kapiura Beds consists of semi-consolidated, massive to well-bedded acid tuffaceous sandstone, siltstone and conglomerate, tuff, calcareous sediments and limestone. All the geothermal manifestations visited including those not visited such as Gabuna, Galloseulo and Ulawun fields occur in Quaternary Kimbe Volcanics (Qk) and alluvium in the lowland areas. The Kimbe Volcanics are basaltic to rhyolitic pyroclastics, principally ash, lapilli, scoria and rubble, andesite, basalt, dacite, rhyolitic extrusives and hypabyssal intrusives. Field observations during this survey noted that the Kimbe

Volcanics at geothermal sites are strongly altered to clay due to thermal activity. Structures are difficult to identify however, observations of the geothermal occurrences (Figure 2) show existence of northerly trending faults in the Talasea Peninsula which is a similar trend to faults mapped by Ryburn (1975).

Water samples from 13 hot springs in the survey area were collected including a meteoric water sample from Lake Dakataua located at the northern tip of Talasea Peninsula (also known as Williaumez Peninsula). The hot springs are Rabili (Ra) from Pangalu thermal field, Galu (Ga) and Tabero (Tb) near the Garbuna thermal field, Wavua 1 (Wv), Wudi, Talasea Station (TS), Rongo 1 (Ro), Matagele (M) and Magilae (MG) from the Talasea Peninsula. The hot springs located in Hoskins are Bakama 1 (B), Taliau (TL) and Sakalu (S) in the Silanga thermal field south of Bangula Bay and Magouru (Ma) in Kasiloli thermal field south of Commodore Bay. The hot spring locations and thermal fields are shown in Figure 2.

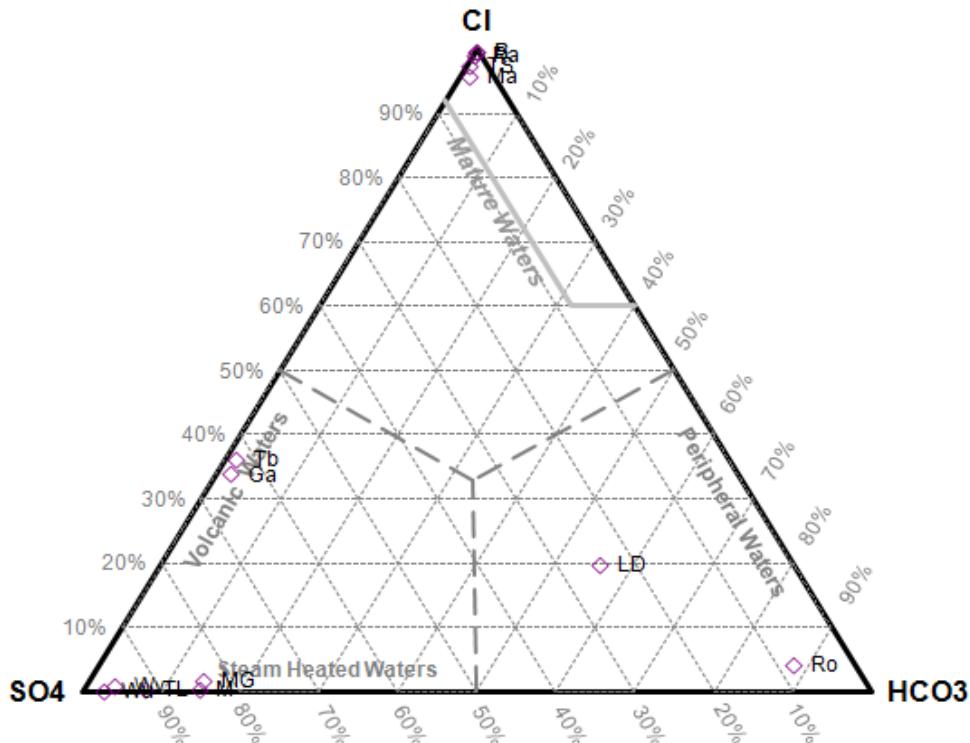


Figure 3: Ternary plot showing relative concentrations of the anions chloride (Cl), sulfate (SO₄) and bicarbonate (HCO₃).
Plot generated using Powell and Cumming (2010)

Using the Cl-SO₄-HCO₃ plot in Figure 3, different types of thermal waters are distinguished such as steam-heated and volcanic waters based on major anion concentrations (Cl, SO₄ and HCO₃). As shown in Figure 3, the Rabili, Talasea Station, Bakama 1 and Magouru springs are classified as matured waters, Galu and Tabero as volcanic waters, Lake Dakataua and Rongo 1 as peripheral waters and the rest of the springs as steam heated waters. The Na-K-Mg plot in Figure 4 further classifies the waters into fully equilibrated, partially equilibrated and immature waters based on the temperature dependence of the full equilibrium assemblage of potassium and sodium minerals that are expected to form after isochemical recrystallization of average crustal rock under conditions of geothermal interest (Giggenbach, 1988). It can be used to predict the equilibrium temperature and also the suitability of thermal waters for ionic geothermometers.

As shown in Figure 3, Sakalu is the only spring that has fully equilibrated with a calculated reservoir temperature of 295 °C while Magouru, Rabili, Talasea Station and Bakama 1 have partially equilibrated with calculated reservoir temperatures of 300°C, 295°C, 310°C and 245°C respectively.

The application of chemical geothermometry to fully and partially equilibrated waters directly estimates the reservoir fluid temperatures. This is based on the principle that specific temperature-dependent mineral-solution equilibria are attained in the geothermal reservoir. As some fluid in this equilibrated reservoir escape and rise to a hot spring through buoyancy, it will usually cool by conduction and mix faster than it will chemically re-equilibrate. Some chemical species like silica equilibrate faster than others like sodium and potassium, therefore, the chemical composition of hot springs can be used to interpret the temperature and mixing history of a fluid in its path from the reservoir to the surface (Giggenbach, 1998). The most widely used liquid geothermometers involve silica concentration and relative concentrations of the cations Na, K, Mg and Ca. Geothermometry calculations were applied to Sakalu, Magouru, Rabili, Talasea Station and Bakama 1 chemical analyses which generated the geothermometry temperatures in Table 1.

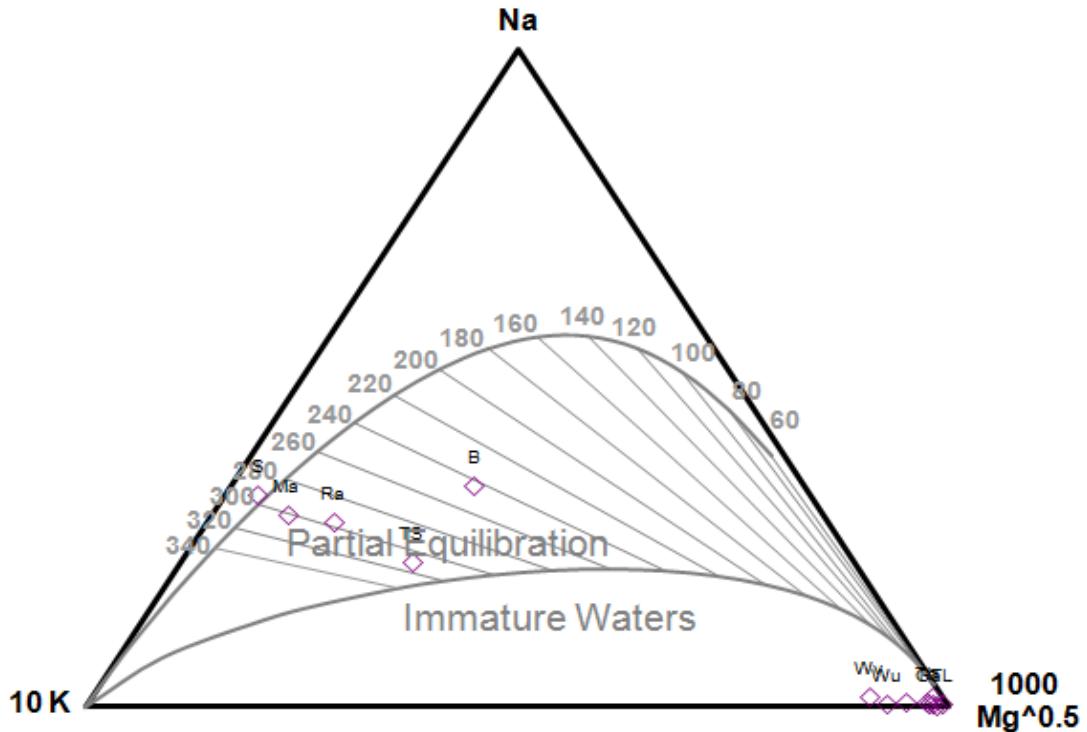


Figure 4: Ternary plot showing relative concentrations of Na, K and Mg and the Na-K and K-Mg geothermometers (Giggenbach, 1988). Plot generated using Powell and Cumming (2010)

Table 1: Water (solute) geothermometers (temperatures in C) generated using Powell and Cumming (2010), based on Giggenbach (1991). Immature waters are omitted.

Sample Name	Meas. T °C	T_{AmS} cond.	T_{Ch} cond.	T_{Qz} cond.	$T_{\text{Na-K-Ca}}$	$T_{\text{Na-K-Ca}}$ Mg corr	$T_{\text{Na/K}}$ Fournier 1979	$T_{\text{Na/K}}$ Giggenbach 1988	$T_{\text{K/Mg}}$ Giggenbach 1986
Rabili	100	118	233	246	273	265	286	296	230
Talasea Stn	100	59	162	184	271	239	301	310	197
Bakama 1	70	31	128	153	210	210	228	242	182
Sakalu	100	58	161	182	267	267	283	293	318
Magouru	100	112	226	240	275	275	291	300	262

Amorphous silica temperatures for Talasea Station, Bakama 1 and Sakalu are lower than the measured values (Table 1) while higher for Rabili and Magouru. The low silica geothermometry for Talasea Station, Bakama 1 and Sakalu is possible indication of dilution with cold water before reaching the surface or precipitation of silica before sample collection.

Reservoir temperatures obtained by Na-K-Ca and Na/K geothermometers compare well with the values obtained from the quartz and chalcedony geothermometer temperatures in waters from Rabili and Magouru but not so for waters from Talasea Station, Bakama 1 and Sakalu. The calculated quartz geothermometer temperatures for the Rabili, Talasea Station, Bakama 1, Sakalu and Magouru hot springs indicate reservoir temperatures of 246°C, 184°C, 153°C, 182°C and 240°C respectively. The Na/K and Na-K-Ca geothermometers indicate reservoir temperatures of 270-295°C, 270-310°C, 210-240°C, 265-290°C and 275-300°C for Rabili, Talasea Station, Bakama 1, Sakalu and Magouru hot springs respectively.

2.2 Regional seismicity

The regional seismicity of New Britain Island is determined by the tectonic activities which go on within the region. Seismicity is generated by the subduction of the Solomon sea plate beneath the Bismark plate along the New Britain Trench (Figure 5). The figure shows a deepening seismicity towards north-west dipping over the recording period, seismicity data show a general deepening of located activity in the northerly direction. This is in agreement with the north-ward subduction of the Solomon Sea plate under the Bismark Sea micro-plates (Johnson and Molnar, 1972). The occurrence of volcanoes and geothermal features along the northern coast of the island are closely associated with the subducting Solomon Sea plate beneath the Bismark Sea Plates.

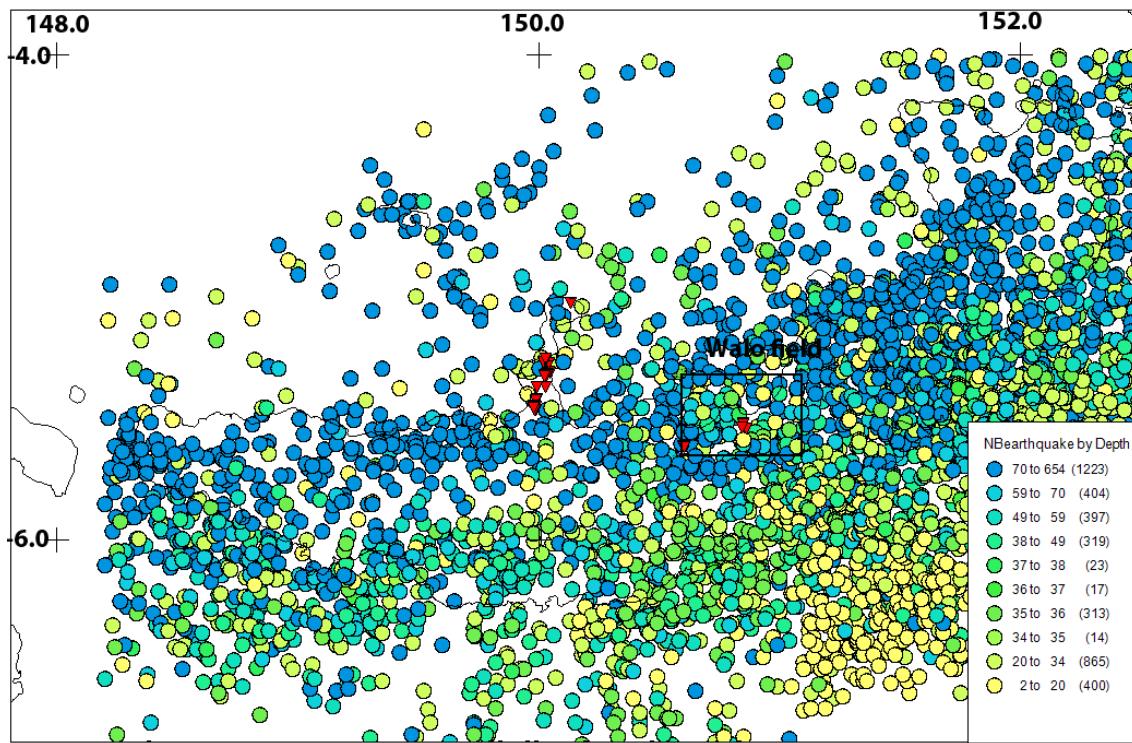


Figure 5: A plot of the regional seismicity of New Britain over a 48 year period recorded by 20 or more stations. The location of the Walo geothermal area is also shown

3. REMOTE SENSING IMAGERY

A computerized approached of using Remote Sensing and GIS data, where an integrated interpretation of a 3D terrain model and digital geo-scientific data, was successfully applied to identifying structures that were related to the geothermal systems in parts of West New Britain Province.

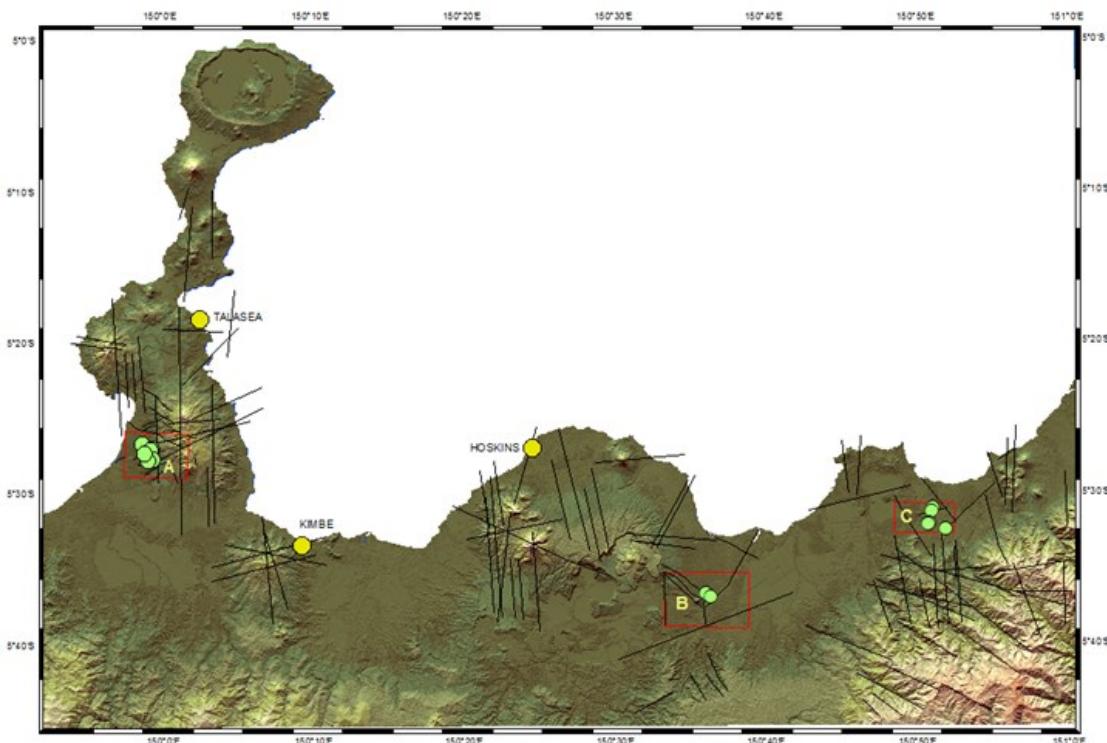


Figure 6: The painted relief image of Garu (A), Kasiloli (B) and Walo-Silanga (C) with interpreted structures from remote sensing

In this study we use a 30-m Landsat ETM image of 2009 acquired from Centre for Advanced Satellite and Mineral Exploration. Additionally, a 5-m resolution Digital Elevation Model (DEM), generated from RADAR data ASCII files, was used to define the landforms. All images were radiometrically and geometrically-corrected, where regional structural lineaments were subsequently drawn by heads-up digitizing. The results were first delineated from the enhanced true color of Landsat bands 4, 5 and 7 overlaid with the DEM to get the 3D view (Fig. 6) which provided the best visualization of the faults and lineaments. The combination of bands 4, 5 and 7 was most useful in distinguishing lineaments as they appear as natural simple or composite-pattern linear or curvilinear features that can be easily discerned on the Earth's surface. In geologic sense, these features may show crustal structure or may depict a zone of structural weakness (Yazdi, et al., 2011). Simultaneous visual interpretation of lineaments with the Landsat and Radar on ArcGIS ArcView complemented the process of deriving lineaments and faults from the 3D view.

ER Mapper (Intergraph, 2012) was used to create a 3-D view of the areas where structures were not visible in the normal view, to clearly demarcate structures. ArcGIS (ESRI, 2004) software was then used to perform GIS analysis and assist in the selection of other prospective sites. Each data layer is overlain with the images to show the location of the geothermal sites and the numerous structures that have been visually identified (Fig. 6)

4. CASE STUDY- SILANGA (WALO) THERMAL FIELD

The existence of deep-seated fracture systems that contribute to surface geothermal manifestations may be mapped by seismicity datasets. In this example we showcase the Silanga-Walo geothermal area. Earthquake events were acquired near the Walo geothermal field (Fig. 7). The earthquakes, most of which were aftershocks of the magnitude 7 Sulu Range earthquake of 2006 (Taranu et. al., 2007), were located from the data obtained from a local seismic network for the period 21 July to 7 August 2006.

Detailed analysis of the network-recorded earthquakes revealed arrival time delays for some earthquakes located within the area that experienced the maximum shaking intensity from the earthquakes.

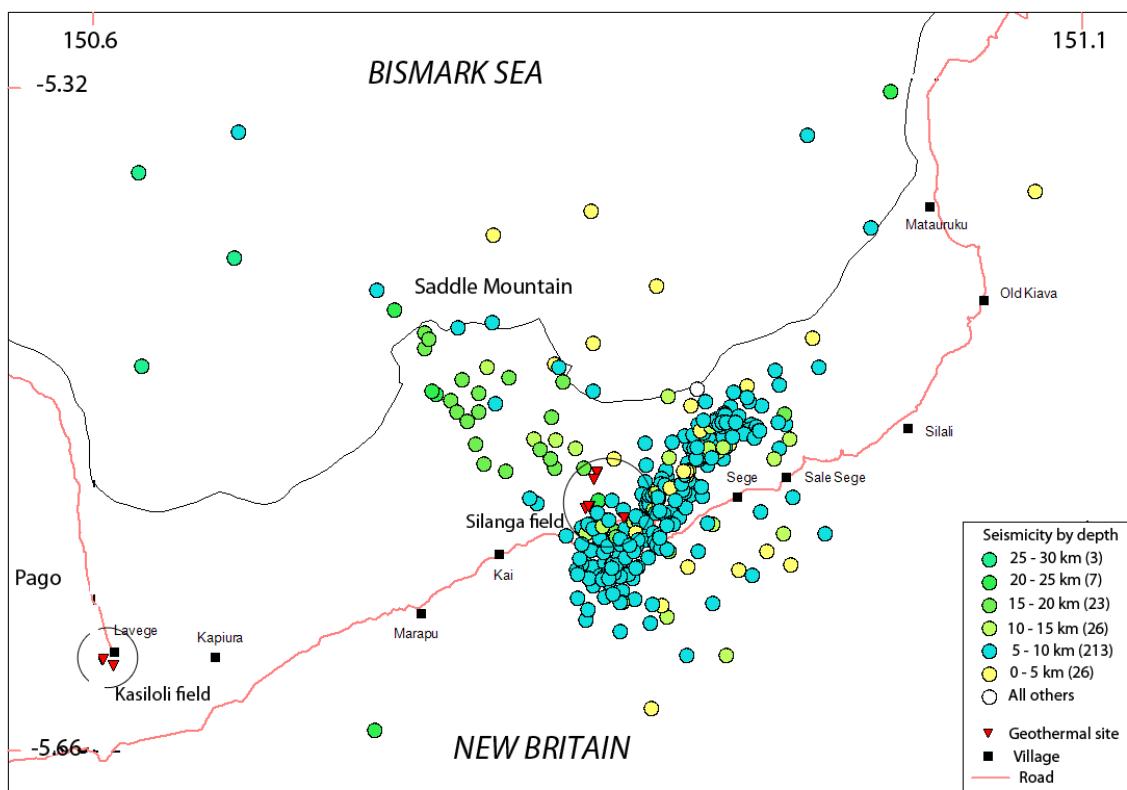


Figure 7: The figure above shows the Silanga (Walo) thermal field seismicity. Shallow seismicity trend in a north-easterly direction perpendicular to the north-westerly trending seismicity.

Focal mechanism solutions were sourced from Global CMT solutions and cover the period 9 to 23 July 2006. Plotting the solutions as depth reveals the physical details of seismic source zones as two zones but interconnected. The first zone suggests A NE-trending zone rising from a depth of about 10 km under Walo thermal field to within a few km beneath the Sulu Range complex. The next zone is a northwest-trending zone extending about 30 km to the northwest from beneath the Walo thermal field, and passing beneath the Saddle Mountain volcanic centre.

Earthquakes at depth range 0-4 km in the Bangula Bay area between the NW-trending and the NE-trending zones of seismicity are scarce. This near-aseismic region coincides with the NE-trending area of maximum subsidence identified by InSAR. The reason for the low level of seismicity in this region may be influenced by the fact that this region is rich with sediments from the Ala River delta, which may have low mechanical strength.

The larger earthquakes of the swarm ($M_w \geq 4.8$) occurred in the period 09 – 23 July and were recorded by stations of the Global Seismograph Network (GSN). A total of 19 such events were recorded. Most of these earthquakes were located in a broad zone extending from beneath the southwestern part of Sulu Range to beneath the eastern tip of Saddle Mountain. The large-magnitude earthquakes, the $M_w 6.4$ and $M_w 5.9$ events of 19 July, occurred west-northwest of the main grouping.

A striking similarity in structural patterns may be observed between seismicity data and the NE and NW structural observations identified using remotely-sensed and GIS datasets from the Walo-Silanga area (Figure 6 (c) and Fig.8). These observations suggest that the geothermal manifestations of the Walo-Silanga area, manifested at the surface by NE-trending fracture zones, are actually connected to the deeper ($>5\text{km}$) fault systems that are discernible by seismicity datasets.

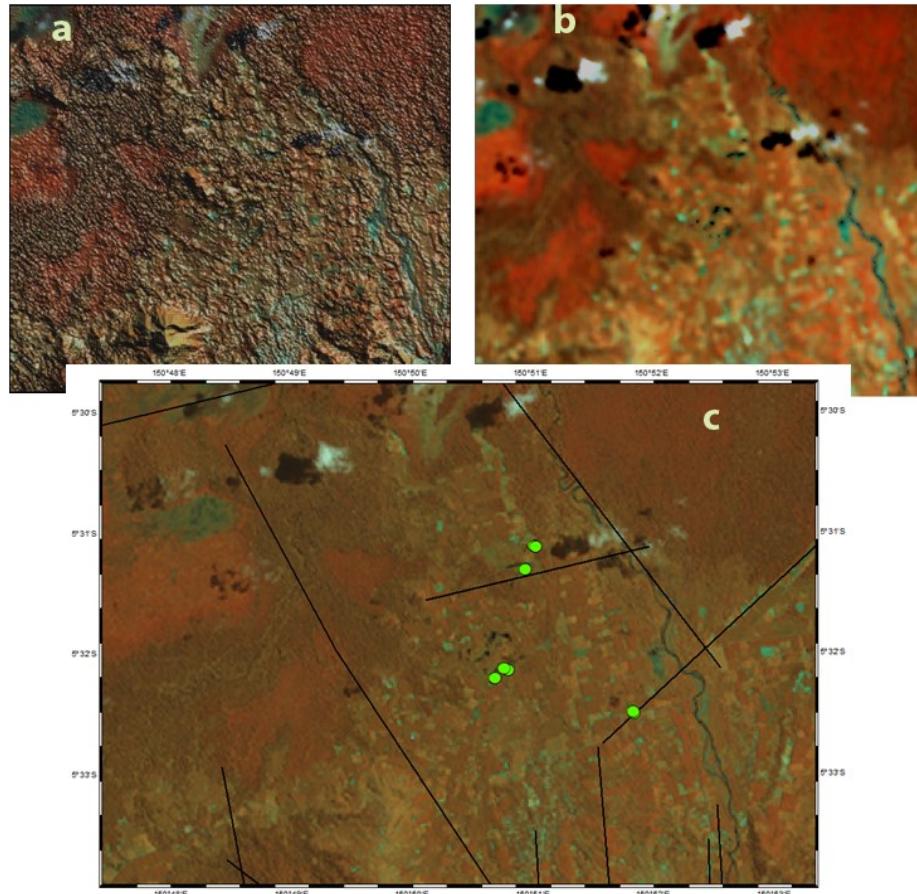


Figure 8: Walo-Silanga geothermal site showing the 3-D view (a), the normal view of the Landsat ETM 4, 5, 7 (b) and the sampling sites and structures overlain on the normal view of the same area (c).

Given the complementing evidence between seismicity and remotely-sensed datasets in defining fracture systems that relate to geothermal systems, applying that to other geothermal manifestations is strongly encouraged. This is to determine how these geothermal systems may be fed by deep fracture systems.

The significance of deep fracture systems on geothermal resources is critical as they may be the determining factor in how long geothermal systems may last, when developed.

5. CONCLUSION

This paper provides strong evidence of the combined application of remotely-sensed datasets and seismicity, to define fracture systems that link surface geothermal manifestations to shallow and deep fracture zones.

Given that quite a few fracture systems and deep-seated faults are often buried by thick sedimentary cover, the application of a combined remotely-sensed data with seismicity and other GIS packages, will determine whether the geothermal manifestations are fed by deeper structural systems.

The linking of surface geothermal manifestations to deep fracture systems is critical in ensuring sustainability of geothermal resources.

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