Proceedings, 7th African Rift Geothermal Conference
Kigali, Rwanda 31st October – 2nd November 2018

Zambia: Exploration of the Non-volcanic, Fault Hosted Bwengwa River Geothermal Resource Area

Peter Vivian-Neal[1], Maxwell Wilmart[2], Jill Haizlip[2], Nicholas Hinz[2], Peter Harrison[3] and Sendoi Sikokwa[1]
[1] Kalahari GeoEnergy Ltd, 40 Jesmondine, Lusaka, Zambia,
[2] Geologica Geothermal Group Inc, 5 Third Street, Suite 420, San Francisco, CA 94103, USA
[3] Pretoria, South Africa

peter.vivian-neal@kalaharigeoenergy.com

Keywords

Zambia, Bwengwa River, fault hosted, resource assessment

ABSTRACT

The Bwengwa River Geothermal Resource Area is associated with a Karoo basin bounding regional extensional normal fault, with prolific near-boiling hot springs and terrace deposits that is constrained by embayments. Temperature gradient holes have encountered a >100°C reservoir at the contact between the base of the Karoo sediments and the Proterozoic basement. Fluid geochemistry and cation geothermometry are consistent between the well fluids and the hot springs and indicate a deeper reservoir of ~150°C. Geophysics surveys indicate a buried zone of sub-parallel subsidiary basement splay faults basinward of the main basin bounding fault zone.

The conceptual model of the reservoir has a ~150°C up-flow ascending along the buried splays beneath the Karoo sediments that act as a cap rock, and outflow both basinward and up-dip within the fault zone coming to surface at hot springs that extend over 9 km. Recharge is along subsidiary faults and the elevated topography. This model has been refined with the benefit of ongoing exploration and has been used for an initial resource capacity estimate and for slim well targeting.

A probabilistic power density estimate of a discovered 150°C resource yields an expected power capacity of 2-93 MWe (P90-P10) with a most likely value of 15 MWe (P50). Ongoing exploration in 2018 2019 may increase this capacity estimate and confidence level prior to a planned feasibility study that will include the concept of cascaded energy being supplied to a community agro-processing hub.

1. Introduction

Kalahari GeoEnergy Ltd ("KGE") is exploring the Bwengwa River Geothermal Resource Area ("BWGRA") within the Kafue Trough in southwestern Zambia (Figure 1). This area includes the Bwanda, Gwisho, Mulundu and Namulula hot springs, all located along the Southern Bounding Fault ("SBF") zone of the Kafue Trough. To date, the exploration of BWGRA has included geological, geochemical, and geophysical surveys including resistivity, gravity, ground magnetics and LiDAR, among others. Six temperature gradient holes ("TGH"s) have been drilled up to depths of 577 m. Several of these have flowed spontaneously which yielded water samples for analysis and provided data for an assessed 15 MWe (P50) probabilistic power density. KGE's goal is to initially develop a ~15MWe power generation project with cascading direct energy applications to be utilised in a local agro-processing enterprise hub that is being designed to have a strong community input and may lead to increased food security and climate mitigation and adaption. Successful development of the BWGRA would be a stimulus for further geothermal exploration in southern Africa's Karoo (Permian) era basins and thus could lead to the adoption of geothermal as a source of low cost sustainable baseload power in the southern Africa region.

A version of this paper was previously presented at the 43rd Stanford Geothermal Workshop in February 2018 and follows up on the findings presented in the papers "Exploration for Sedimentary Basin Hosted Low-Enthalpy Geothermal Systems in Zambia" at ARGeo5 and "Country Update Report for Zambia", ARGeo6.

Figure 1: Location map. Red oval represents BWGRA

2. Geology

2.1 Regional geologic setting

The Kafue Trough lies at the intersection of the Zambezi Mobile Belt and the Mwembeshi Dislocation or Shear Zone (Figure 2). The latter is a regional transfer fault transferring movement from a series of thrust belts (Daly et al, 1984 and Daly, 1986). It is evident that the Kafue Trough is associated with the Mwembeshi dislocation zone, a pre-existing line of major structural weakness associated with the late Pan-African tectono-thermal event (Kasolo and Forster, 1991 and Unrug, 1987). The Permian-era Karoo basins developed as a result of sinistral shear along the reactivated Mwembeshi Shear Zone (Figure 2). Pull-apart basins developed from strike-slip when the basin was located in the shear (Kafue Trough and Luano Rift in Zambia, Ruhuhu in Tanzania, and Manaimba in Mozambique) and grabens developed where the basins were an angle to the shear zone (South-, Mid- and North-Luangwa Rifts, Lower and Mid-Zambezi Rifts, and the Lukuakasi Rift). The pull-apart basins were probably initiated by a strike-slip fault couplet along the Mwembeshi and sub-parallel lateral thrust ramps. Continued subsidence then took place through tensional block faulting and sag – these look like normal interior fracture tensional grabens.

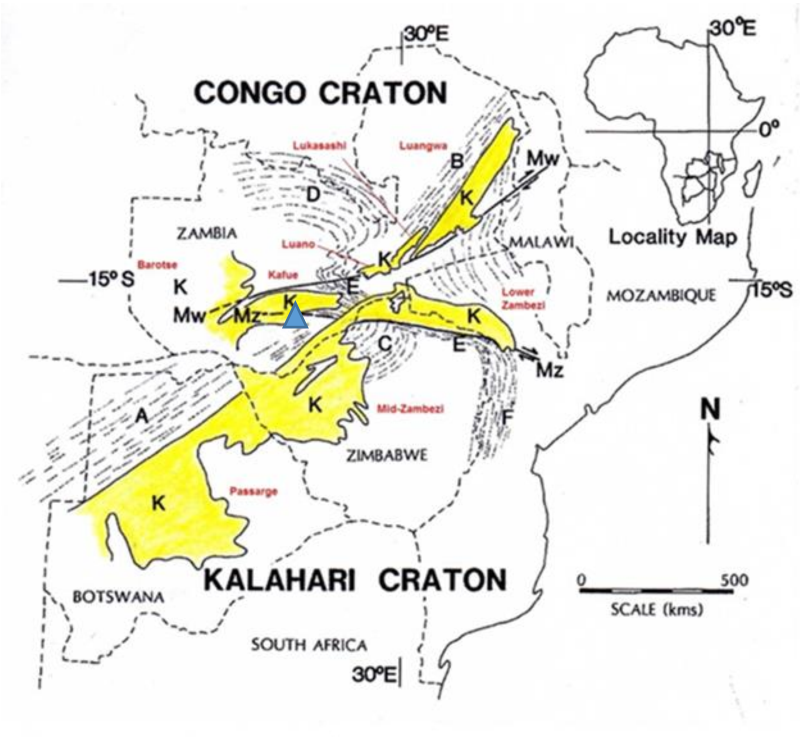

Figure 2: Sketch map showing the mobile belts of Central Africa and the distribution of Karoo Basins (yellow); K=Karoo basins, Mw=Mwembeshi shear zone, Mz=Mzarabanzi shear zone, , A=Damaran belt, I=Irumide belt, C=Magondi belt, D=Lufilian Arc, E=Zambezi belt, F=Mozambique belt, Blue triangle = BWGRA. From Orpen, 1989 modified after Coward and Daly, 1984).

2.2 Structural Setting of the Bwengwa River Prospect

The surface manifestations of the BWGRA include four clusters of geothermal springs that extend over 9 km and lie on the southern bounding fault (the "SBF") of the Kafue Trough, which marks the boundary between the Karoo and the Basement (Katangan and Paleoproterozoic) on the southern margin of the Kafue Trough. The Basement/Katangan rocks form a thrust stack which strikes northwest-southeast and intersects the bounding fault almost at right angles; the stratigraphic layers dip to northeast at moderate to shallow angles and are displaced by the SBF. The mapped SBF is well defined on the ground magnetic and gravity surveys and is characterized by a noticeable gradient in the conductivity data from the AMT survey.

Mapping and interpretation indicates that the SBF is a steeply dipping (70°-80°N), ENE-WSW trending, oblique dip slip fault, which also has a prominent right lateral (dextral) strike-slip component (Figure 3). The fault trace shows a noticeable change, or bend, in strike, which is convex basinwards at Sebanzi Hill, between the southern and northern groups of springs. In this area where the strike changes the fault bifurcates and duplexes are developed (strike-slip component). The dip of the stratigraphic units within the Karoo steepens to 30°N in the vicinity of the SBF as a result of downward drag down along the fault plane (normal slip component).

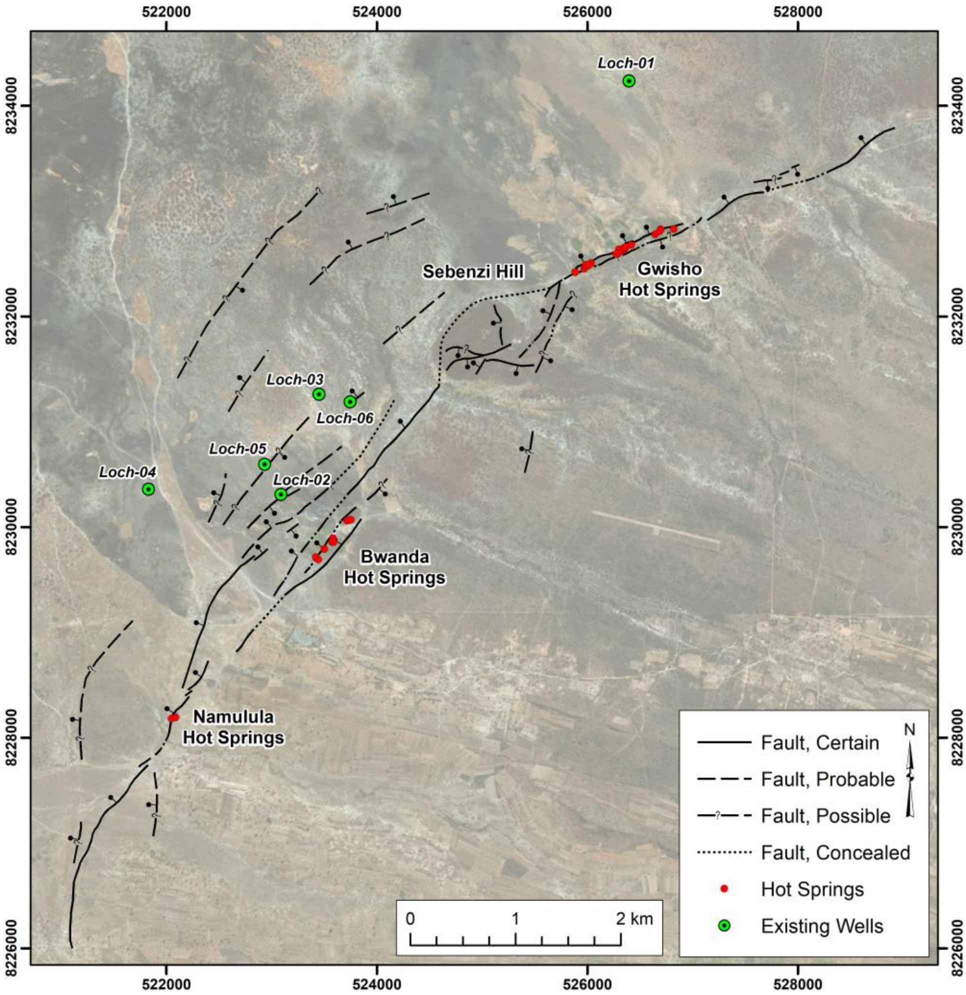

Figure 3: Map of the BWGRA area with faults interpreted from the LiDAR, hot springs, and existing wells. Mulundu spring to SW of this map

A prominent basement fault which parallels the SBF has been defined at a depth of some 500m basinward of the SBF. In addition, ground magnetics identified some cross faults paralleling the trend of the bend in strike of the SBF down dip of the springs. These add further credence to the existence of a major fault zone which would be essential for hosting a significant thermal reservoir. The hot springs exhibit a strong structural control with respect to the SBF in that they are located close to the major intersections at either end of the anastomosing fault zone.

The main rocks exposed at the surface (SE of fault) are quartzites and gneisses, which are well foliated, have a constant ESE strike, and generally dip toward the NNE. Rock exposures near the fault zone are fractured and traversed by narrow veins containing quartz (Legg, 1974). The quartzite near the Namulula hot spring is composed of quartz, amphiboles, epidote, and chlorite, all consistent with >350°C metamorphism rather than the current hydrothermal activity. The quartzite is highly jointed in parts with smooth joint surfaces, trending 290°/70° SW and occasionally in-filled with quartz.

Outcropping Karoo rocks are represented by the whitish, feldspathic sandstone around Sebanzi Hill (SW of Gwisho Springs), which is bound by faulting. The sandstone is cut by crisscrossing quartz veins similar to those in the main fault breccia. Southeast of the SBF, the Katanga rocks consist of marble and pink quartzite in the central and southwestern areas while the northeastern area comprises of Proterozoic granitic gneiss. The foliation in both the quartzite and granitic gneiss trends about 105°/45° NE.

3. Hydrogeochemistry

The Bwengwa geochemical database includes >60 geothermal water samples collected between 2010-2017 from the BWGRA including both from hot springs and TGH's and four groundwater samples taken between 2013-2014 from nearby ground water sources (Figure 3).

3.1 Water Type

Thermal waters from Bwengwa are all sodium (Na)-sulfate (SO_4)-chloride (Cl) type waters. This composition is within the range of non-magmatic geothermal systems which are typically lower in chloride and anions are dominated by SO_4 or bicarbonate (HCO_3). Elevated SO_4 may be related to the dissolution of gypsum known to be present in nearby late Tertiary shallow formations and the alluvial cover in the Bwengwa River area. The concentrations of major chemical constituents of near-boiling waters of Bwanda Hot Spring (~92-95°C) and wells Well 02 (102-105°C) and Well 05 (~100°C) are almost identical (within 10% relative percent difference). While Gwisho Hot Spring has a similar composition, the concentrations are different and the fluid is slightly cooler (~75°C); furthermore, the concentrations of all major solutes are higher in concentration (~30%). Based on the increase in concentration of all of the major chemical constituents (although to varying degrees) this difference between Gwisho and Bwanda is likely the result of evaporation rather than chemical or water/rock reaction, but could also be the result of mixing with cold groundwater high in dissolved solids ("TDS").

Comparison of the relative major cation and anion chemistry of Bwanda, Gwisho, and the TGH holes shows that each location hosts water of a similar composition with a few minor exceptions in cation chemistry (Figure 4). All samples have very similar relative concentrations of major anions (Figure 5). While there is some variation in the minor chemical constituents (concentrations <1 mg/kg), the variation is not considered significant. This suggests that waters from Bwanda, Gwisho, Well 02, Well 03, Well 04, and Well 05 have a common source; and the thermal waters from Bwanda, Well 02 and Well 05 have followed a similar pathway along the SBF such that the fluids have not been affected by different process. In contrast, the other thermal waters have been affected by other processes such as conductive cooling, evaporation, etc. (Figure 6).

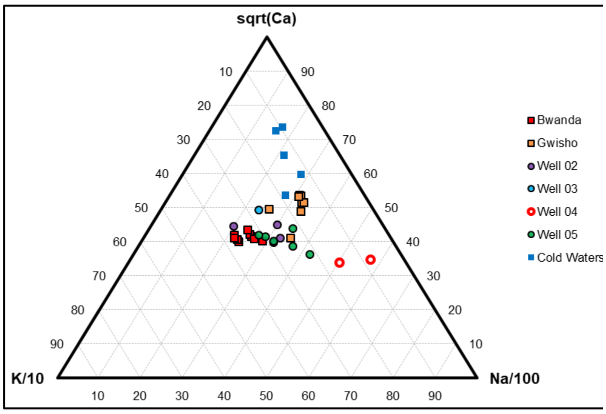

Figure 4: A trilinear diagram relating the relative concentration of major cations for samples from Bwengwa.

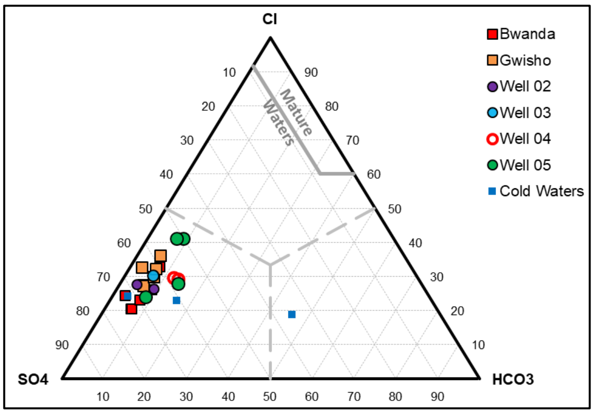

Figure 5: A trilinear diagram relating the relative concentrations of Cl, SO_4, and HCO_3 for water samples for Bwengwa.

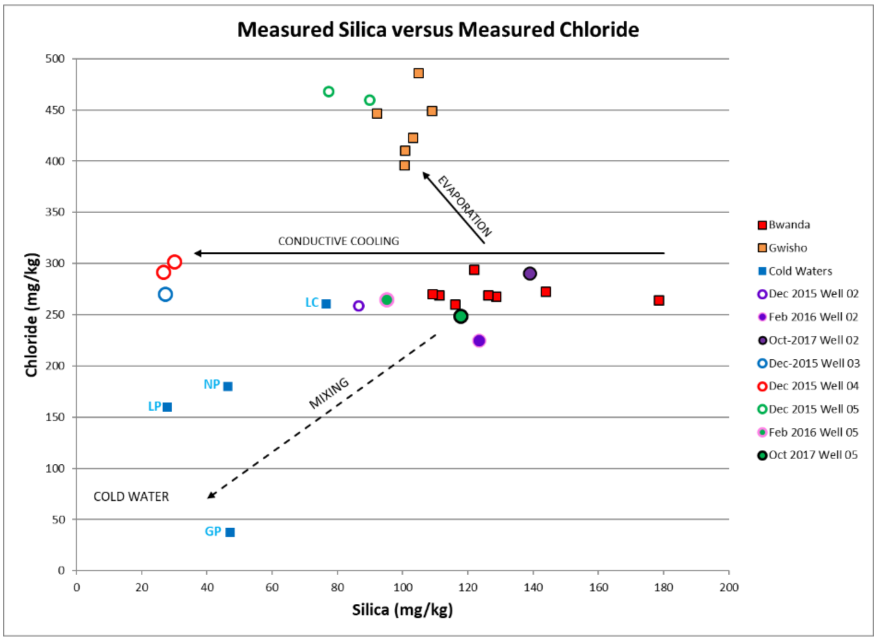

Figure 6: Concentration of chloride and silica from the Bwengwa river area. Possible mechanisms are indicated which may explain the distribution of samples.

Site/Well	Quartz (adiabatic)	Na/K	K/Mg	Na/Li
	Fournier (1973)	Fournier (1981)	Giggenbach (1988)	Fouillac and Michard (1983)
Bwanda	143	184	140	164
Bwanda 2017	142	211	152	146
Cold Waters	102	188	79	110
Gwisho	134	164	124	160
Gwisho 2017	140	185	134	133
Well 02	137	193	158	142
Well 02 2017	149	208	178	147
Well 03	80	231	96	145
Well 04	82	113	87	100
Well 05	128	200	133	146
Well 05 2017	141	208	144	149

Table 1: Typical liquid Geo-thermometers applied to thermal waters from Bwengwa. Averages for samples collected before 2017. Note that all temperatures are in degrees Celsius.

Geothermometer temperatures calculated from the 2017 samples confirm indications of reservoir temperatures of greater than 140°C from previous samples based on quartz and K-Mg geothermometers (Table 1). While the commonly used Na/K geothermometers indicate higher (>200°C) temperatures, this often occurs in non-volcanic systems and is seldom representative of reservoir temperatures (Figure 7). Relatively high temperature estimates from the Na/K geothermometers suggests these waters are not in equilibrium with the appropriate minerals or that the equilibrium has occurred at some distance from sampling points.

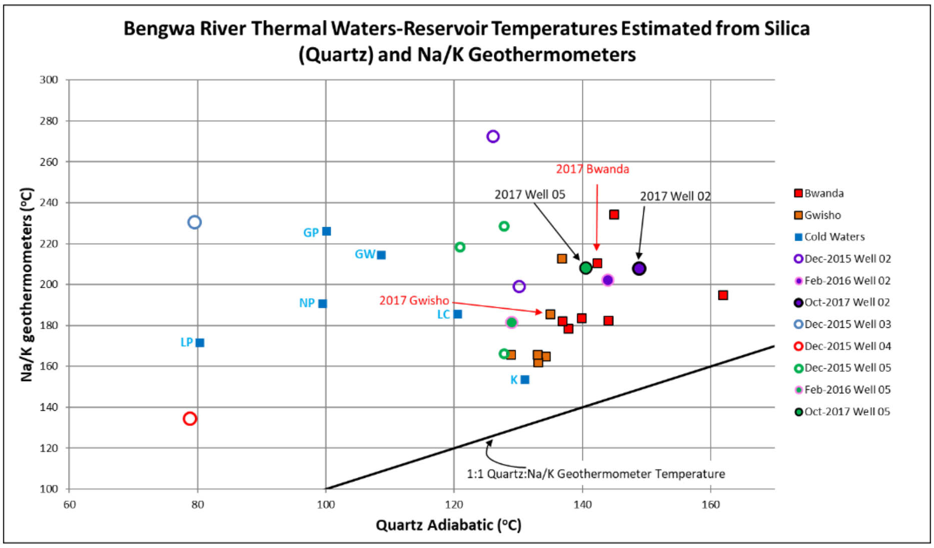

Figure 7: Reservoir temperatures estimated with the quartz adiabatic geothermometer (Fournier 1973) and the Na/K geothermometer (Fournier 1981) are shown.

4. Geophysics

Resistivity, gravity, ground magnetic with 3D modelling and LiDAR surveys have amongst others been performed within the BWGRA.

4.1 Resistivity and gravity

The resistivity survey was an audio-magnetotelluric (AMT) survey with coverage across all three areas of hot springs (Figure 8). AMT surveying is not typically as deeply penetrative as MT surveying, meaning the interpretation of the data was truncated at ~1000m depth (~0 meters above sea level, masl). Even with the relatively shallow depth of penetration, the AMT was able to resolve the unconformity where the impermeable Lower Karoo sediments overlie the Proterozoic ("Ptz") metamorphic rocks, as well as the shallow, low-resistivity smectite-rich Upper Karoo sediments (Figure 8). The AMT appears to show the Upper Karoo cap truncating at or near the Kafue Trough SBF Zone. The geometry of the conglomerates and fault breccias in the Lower Karoo, immediately overlying the Ptz unconformity, are a likely host to lateral outflow of thermal aquifers, and the discontinuities imaged by the AMT could host thermal upflow. The base of the smectite cap shallows to the southeast, before truncating near the wells. Beyond the wells to the southeast the Ptz metamorphic basement is likely to be uplifted.

A gravity survey was conducted in an effort to characterize the structure of the base of the Karoo formations (the likely cap rock to the geothermal reservoir) with respect to the underlying dense Katanga carbonates and Proterozoic metamorphic rocks (the more likely reservoir rock) in the basin northwest of the SBF. A total of 637 stations were collected along 25 survey lines with 1000 m line spacing and 500-1000 m station spacing.

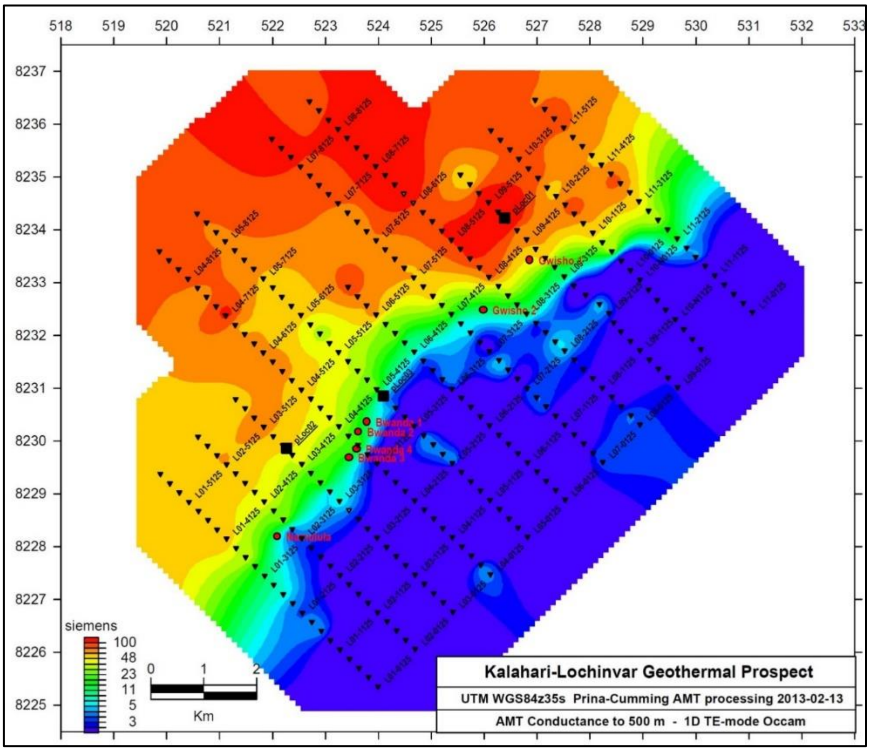

Figure 8: MT conductance to 500 m depth. The yellow-red areas are where clay content is most significant and hydrothermal smectite alteration is particularly intense. Solid triangles show the location of the AMT stations.; solid squares are locations of wells and the hot springs shown as red circles

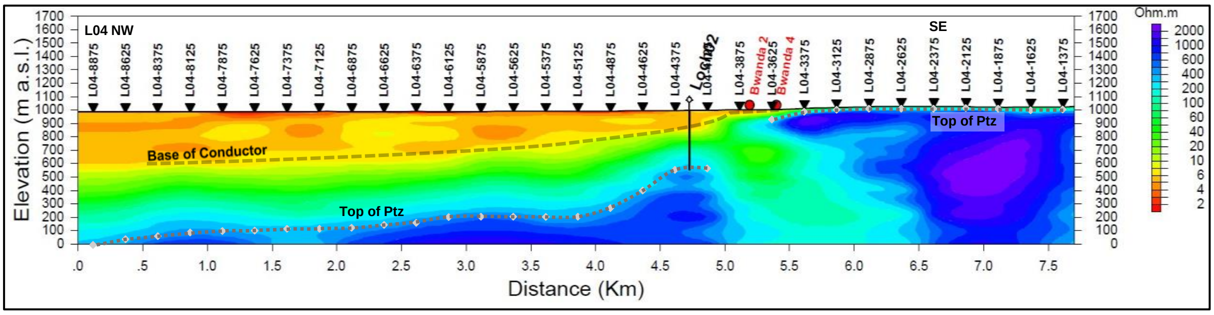

Figure 9: Profile L04 MT resistivity cross-section. Color shading is resistivity from 1D TE-mode smooth inversions.

4.2 Magnetic Survey and 3D Modeling

Additional ground magnetic data was collected at Bwengwa to increase the reliability of subsurface imaging of the basement and to allow three-dimensional modeling of the data. The objective of the survey was to evaluate the dip on the primary structure. This fault zone is considered to have multiple sub-parallel splays. The magnetics identified a range of dips from 34° - 78°. The trend of the fault bends at Sebanzi Hill from ENE northeast of the hill to NE, southwest of the hill. The dips also appear to change, from 60-78° northeast of the hill to 34-56° southwest of the hill, but this could be the apparent dip across multiple higher angle step faults. This suggests that the hill is located at the apex of a structural complexity, which may focus the up-flow of hot fluids. Furthermore, the magnetics appears to have identified a possible section of Katangan carbonate rocks in the basement west of the Gwisho Hot Springs.

Carbonates are typically brittle and break in complex structural settings providing the potential for fracture-hosted permeability. Brittle carbonates are typical reservoir rocks in fault-hosted non-volcanic geothermal systems in the western US and in Turkey.

5. Flow Tests

Well 02 and Well 05 were produced during 2017 testing. Prior to flowing each well, a static pressure-temperature (PT) survey was conducted (Figures 10 and 11). During the brief periods of flow, a dynamic PT survey was performed in the flowing well while monitoring pressure in the other well. Geothermal fluid produced from each well was sampled during the flow period.

Both Well 02 and Well 05 have artesian flow from relatively limited perforated sections of small diameter core hole casing near the bottom of the holes. Well 02 produced 600-650 kg/hr (through pipe ID=62 mm); and Well 05 produced 625-725 kg/hr increasing throughout the test (through 46 mm ID tubing). PT surveys confirmed that fluids produced from Well 02 and Well 05 are ≥100°C at the top of the basement formation.

Results of this preliminary testing indicate that the geothermal fluids discharge along the SBF/Karoo interface over a subsurface extent of at least 1.2 km, extending from Well 05 to the Bwanda Hot Springs, roughly perpendicular to strike from the SBF.

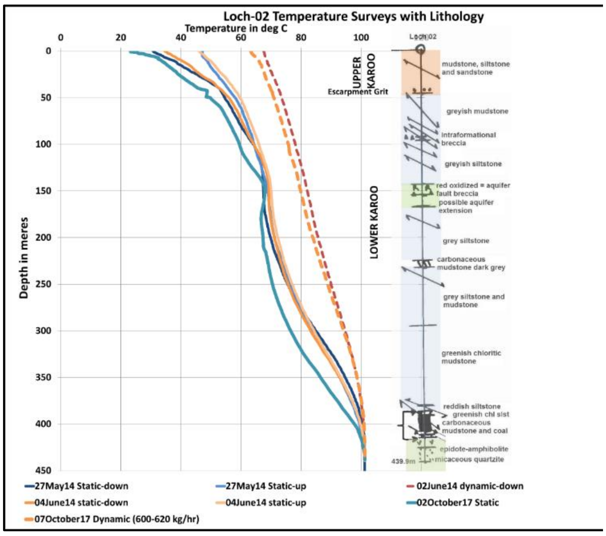

Figure 10: Well Summary plot of Well 02.

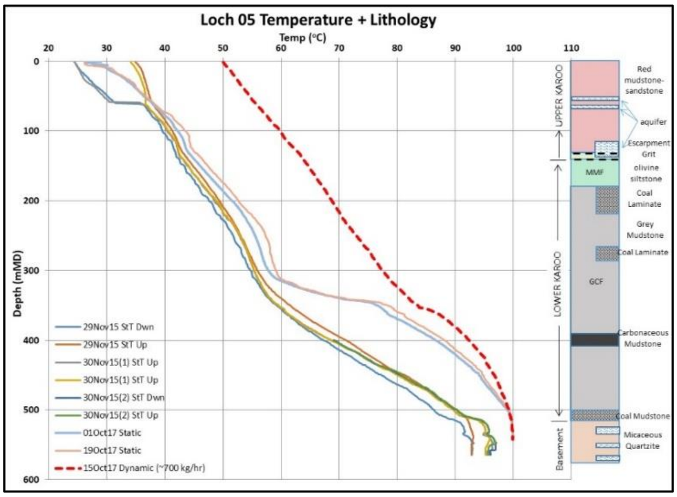

Figure 11: Well Summary plot of Well 05.

6. Updated Conceptual Model

The conceptual model of the Bwengwa River Geothermal System is that of a fault-based non-volcanic geothermal system composed of deeply circulating water heated by natural conductive heat flow. In well-known fault-based geothermal systems, locally-derived meteoric water circulates along permeable faults and fractures related to extensional tectonic settings to depths where temperatures are elevated and water is heated by the rock; the bouancy of hot water causes it to rise along other permeable faults. The extensional stress supports permeability at fault and fracture intersections and complexities (Faulds et al, 2012; Faulds et al, 2016).

At Bwengwa River cold local meteoric water circulates to depths of 3-5 km along permeable faults and fractures created by structural complexities developed by the intersection of NW-SE extensional stresses and the SBF. These extensional stresses have transformed and reactivated the ENE to NE trending transform SBF, an ancient plane of weakness, into a complex fault zone with oblique movement. Complexities are indicated by a well-mapped bend at Sebanzi Hill between Gwisho and Bwanda Hot Springs, and SE-NW cross faults. High flow-rate near-boiling springs reflect upflow of hot water along this structure. The hot springs and the fluid in the wells originate from the same source as evidenced by very similar temperature, chemistry and geothermometry.

The WSW-ENE trending SBF is developed at the NW end of a NW-SE trending Basement uplift (possibly a horst) which is flanked by prominent embayments to the ENE (e.g. the Mazabuka synclinorium) and to the WSW (e.g. the Monze embayment). Displacement along the SBF is NW-SE to WNW-ESE normal dip-slip with a limited component of right lateral (dextral) oblique slip. This geometry is supported by the complete lack of shear fabrics within the SBF (Harrison, 2018).

The cross section through the SBF (Figure 12) illustrates the updated conceptual model. An upflow of ~140°C to ~150°C ascends bouyantly along splays and transtensionally-propped open fractures in the SBF Zone ("SBFZ") beneath the Karoo basin sediments, and outflows both basinward and up-dip within the the damage zone in the basement rocks along the SBF to expressions at Bwanda and the Gwisho Hot Springs. Where the basement rocks include carbonates, brittle fracturing and/or karstification along paleo-faults enhances permeability. Recharge of meteoric water occurs along subsidiary faults conjugate to the SBF, as well as at the structural complication and elevated topography of Sebanzi Hill.

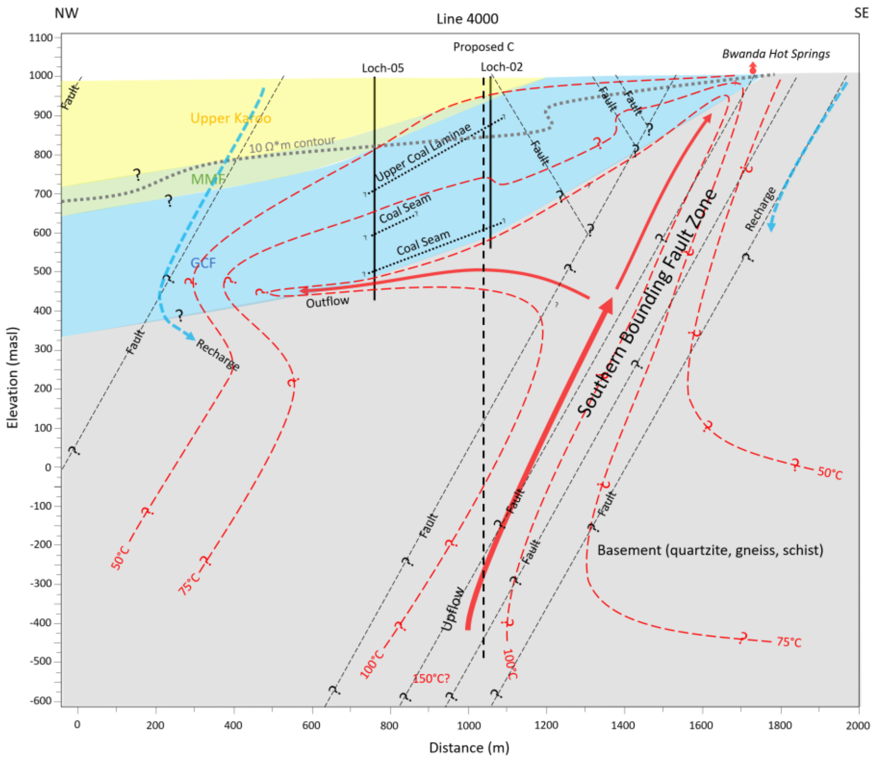

Figure 12: Conceptual cross section NW-SE through the Southern Bounding Fault Zone.

7. Updated Power Density Reservoir Capacity Estimate

Heat-in-place estimates for geothermal systems are common but often overestimate resource capacity by large factors, even orders of magnitude, due to unreasonably optimistic recovery factors (Grant, 2015). Power density estimates can often be as accurate as more complex heat-in-place estimates at the exploration stage as they rely on fewer assumptions and are calibrated against a large number of known operating fields (Wilmarth and Stimac, 2015).

A power density estimate was made for the Bwengwa reservoir using log-normal distributions; areas were based on the drilled wells and hot springs. The P90 area is a 500 m buffer around wells Well 02 and Well 05. This area does not include wells Well 03 and Well 06, which were completed in an intermediate aquifer. This area is ~1.1 km^2. The P10 (optimistic) area is a 750 m buffer of a line basin-ward and parallel to the SBF between the three areas of hot springs; this area is ~13.3 km^2.

A range of power densities was chosen based on the plot of Power Density vs Average Reservoir Temperature for 80 operating fields (see Figure 13). The Bwanda and Gwisho Hot Springs have average cation geothermometers of up to ~150°C. Therefore, an estimated temperature range of 125-150°C was used. The high hot spring flow and apparent high permeability encountered in the temperature gradient wells justifies using a larger power density range than indicated by the main trend line in the plot ("The Main Sequence") and would be analogous to other shallow high-permeability reservoirs in the U.S. Basin and Range. This corresponds to an expected power density range of 1-15 MW/km^2 (Figure 13).

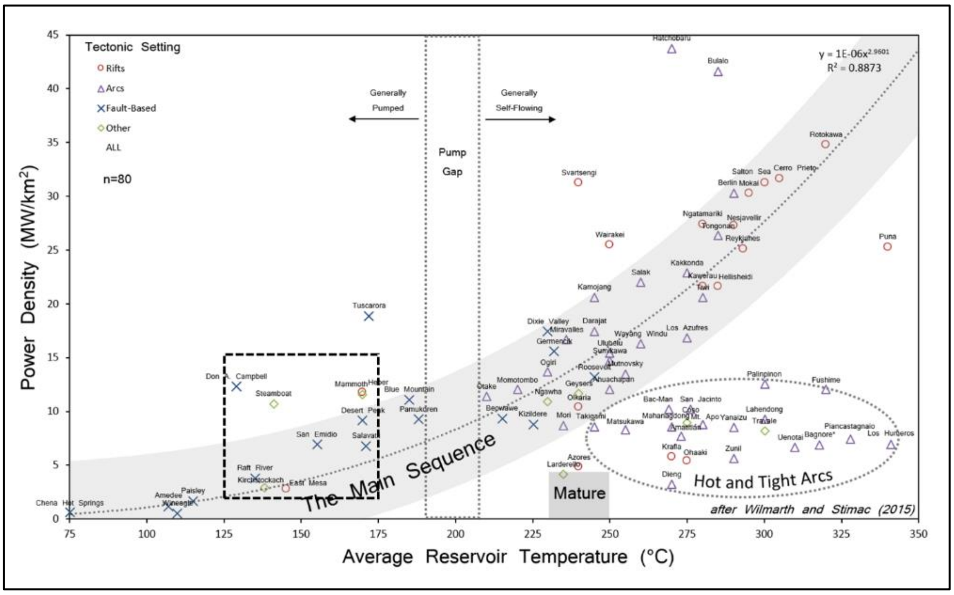

Figure 13: Power Density vs Average Reservoir Temperature for 80 operating fields, after Wilmarth and Stimac (2015). Estimated range of reservoir temperature and power density for Bwengwa indicated with black dashed rectangle

This worksheet handicaps undiscovered resources with exploration confidence factors for the probability of discovering commercial temperature, permeability and benevolent reservoir chemistry. Given the measured temperatures of >100°C, a $P_{Temperature}$ was chosen of 90%. A lower $P_{Permeability}$ of 70% was chosen, typical of other undiscovered resources at this stage of exploration in similar favorable structural settings. Reservoir chemistry is rarely a determinant of project success in the Basin and Range and consequently a $P_{Chemistry}$ of 99% was chosen. The combination of these factors results in a Probability of Exploration Success (POS_{expl}, the chance that at least one commercial well will exist) of 62%. The expected mean capacity is 25 MWe and the P50 (most likely) capacity is 15 MWe (Figure 14). The optimistic high end of the range of power capacities is over 90 MWe

Geothermal Power Capacity Reserve Estimation: based on Lognormal Distributions of Area and Power Density

This spreadsheet is used to constrain geothermal resource capacity assessments based on analogies to the area and power density of developed fields.
In this spreadsheet, 90% of all cases are larger than P90 and 10% are larger than P10. That is, P90 is the smaller number and P10 is larger.

EXLORATION: Is it there?

Assuming a likely exploration geoscience program and drilling program, what is the percent confidence that at least one well is commercial

	Confidence in temperature.		Confidence in permeability. Commercial mDarcy		Confidence in chemistry. Not corrosive or scaling		Probability of exploration success
	$P_{Temperature}$		$P_{Permeability}$		Pchemistry		POSexpl
Exploration Confidence	0.90	*	0.70	*	0.99	=	0.62

APPRAISAL AND DEVELOPMENT: Assuming it's there, how big is it?

Cumulative confidence of representative optimistic case = **10%** That is, the larger, more optimistic case is assumed to be P10

Temperature range of permeable reservoir area from resource conceptual model. This should be consistent with assumed power density distribution.
Startup average production temperature for P90 reserves = **150** °C **125** °C = minimum temperature for P10 reservoir

Nu and Sigma are the mean and variance in log units required for specifying lognormal distributions in tools like @RISK

Representative Cases				Pessimistic	Middle	Optimistic					
		P99	P90	P90	P50	P10	P10	P01	Mean	nu	sigma
Area > 125°C	(km^2)	0.4	1.1	**1.1**	3.8	**13.3**	13.3	36.7	6.1	1.34154	0.97244
Power Density 125 to 150 °C	(MWe/km^2)	0	12	**1**	4	**15**	15	45	7	1.35403	1.05655
MWe Capacity		1	2	2	15	93	93	418	42	2.69556	1.43594

EXPECTED POWER CAPACITY RESERVES (based on analogous reservoirs used to assess confidence in power density and area)

Expected Mean Capacity = 25 MWe = [Probability of Exploration Success] * [Mean Capacity of Development Assuming Exploration Success]
Expected P50 Capacity= 9 MWe = [Probability of Exploration Success] * [P50 Capacity of Development Assuming Exploration Success]

Adapted from Cumming, W., 2000. Spreadsheet for geothermal resource capacity scoping using lognormal area and power density distributions. Proprietary course material.

Figure 14: Bwengwa Reservoir Potential Power Capacity reserve calculation based on lognormal distributions of Area and Power Density. After Cumming (2016). The expected mean capacity is 25 MWe and the P50 (most likely) capacity is 15 MWe.

8. Next Steps: Drilling

During the next drilling campaign planned for late 2018 – early 2019, KGE intends to drill through the upper basement rocks and penetrate the top of the geothermal reservoir at a depth of 1000-1500 m. Work performed in 2017 confirmed that the deeper and hotter (>140°F) geothermal system believed to underlie the area and provide the source of thermal water discharged in the springs and Well 02 and Well 05 wells is within the basement rocks where permeability is fracture controlled; targeting of specific well locations is in progress. The final targets will be based on a detailed examination of faulting and fracturing and the most likely structural settings for permeable fractures such as extensional/trans-tensional fault intersections (i.e. the NE trending SBFZ and subparallel splays).

The Kafue Trough and environs are also highly prospective for additional geothermal resources similar to Bwengwa River; it is therefore considered realistic that ongoing exploration may well significantly increase the current estimated resource capacity. The most prospective of these are the Longola springs, which are evident along a strike length of 3.25km in a similar position along the northern margin of the Kafue Trough and are essentially a mirror image of the Bwengwa River springs.

9. Socio-Economic Impact

The BWGRA straddles the southern boundary of the Lochinvar National Park, which was established 1972 having been a cattle ranch. Too small at 410km^2 to contain the ranges of most large mammals, it is noted for its wetlands around Chunga Lagoon which are part of a RAMSAR site with significant diversity of wetland birds. It also hosts the much diminished endemic Kafue Letchwe (>250,000 in 1932 – <28,500 in 2015) (DNPW figures). Human encroachment, wide scale poaching, and domestic/wild animal conflict has seen the degradation of the southern part of the park, which is now dominated by cattle herds seeking water and grazing under pre-existing access rights.

Any commercial development of geothermal power within the BWGRA could create the catalyst for addressing local land management issues and for subsequently securing the boundaries of the National Park; this in turn could allow the recovery/restocking of the wildlife, and so attract increased tourism. Direct use cascade applications, clustered around the anchor power production investment in an agro-processing hub, could provide the vehicle to stimulate sustainable and equitable local economic development if approached with this objective in mind. While the viability of such an integrated management plan would depend on the successful development of a commercial power plant as the 'anchor' investment, the concept has caught the attention of the development community in Zambia and the initiative is to be examined in detail in parallel to a planned feasibility study for a power plant. The geothermal aspect should become the lynch pin for a wider initiative that includes economic activity, climate mitigation, land management and environmental rehabilitation of the park.

The Community within BWGRA is pastoral with considerable traditional focus on cattle. Direct cascaded energy applications could be used for dairy processing as happens in New Zealand where the Maori Tuaropaki Trust run the successful Miraka milk plant and is being piloted in Kenya by Geothermal Development Corporation ("Powering African Agriculture" 2015). Onyango and Varet (S. Onyango, and J. Varet 2016 'Future Geothermal Energy Development in the East African Rift Valley through Local Community Involvement: Learning from the Maori's Experience') support this inclusive approach strongly: *'However, it is still imperative to engage a process of change for a new approach to geothermal development that would be inclusive, rather than exclusive of ..... Indigenous people'* and: *'Such a situation would enable them to participate in decision-making processes related to geothermal energy development as equal partners to developers and other stakeholders; regardless of whether it is large or small size projects'.*

Cascade applications, in a locally owned and managed agro-processing hub, would create rural development opportunities with sustainable employment. It would also create the demand for local agricultural input supply, providing wider opportunities for economic growth in areas beyond the geothermal plant and clustered processing hub investments. This is particularly pertinent in the context of developing resilience to implications of climate change evident in the Kafue basin. At the end of the cascade utilisation of thermal energy the geothermal fluid would be re-injected into the reservoir.

10. Conclusions

Zambia's Karoo basins, while not previously recognized as a likely host to geothermal systems suitable for commercial power production, can now be re-evaluated in light of Kalahari GeoEnergy's work and results. The BWGRA contains compelling evidence of the three key elements required for hosting a hydrothermal system: temperature, permeability and water. Evidence for minimum reservoir temperature from 130°C to more than 150°C is provided by both the fluid chemistry and temperature gradient holes. Permeability is confirmed by the discharge of the hot springs along the regional bounding fault and the associated geologic structures. The reservoir is determined to be in fractured basement rocks at a shallow to medium depth adjacent to the bounding fault fed by local meteoric water that is plentiful.

Results obtained during 2017 provide further confidence that Bwengwa River has a geological setting conducive for geothermal hydrothermal systems. A power density estimate indicates a usable resource capacity in the range of 9-15MW; this is to be quantified with a further drill programme. Ultimately, geothermal power may provide a valuable component in Zambia's drive to increase generation capacity and distribution.

Concurrently, the opportunity to develop community agro-processing hubs could create economic growth and resilience to evident climate change.

REFERENCES

BC Consulting, (2017) "Notes on 3D modelling of magnetic data acquired over the Bwengwa River Project Zambia." Internal report dated July 21, 2017.

Coward, M.P. and Daly, M.C., (1984) "Crustal Lineaments and Shear Zones in Africa: their Relationships to Plate Movements." *Precambrian Research,* Vol. 24; pp.27-45.

Cumming, W., (2016) "Resource Capacity Estimation Using Lognormal Power Density from Producing Fields and Area from Resource Conceptual Models; Advantages, Pitfalls and Remedies." *Proceedings, 41st Workshop on Geothermal Reservoir Engineering,* Stanford University, California, 22-24th February 2016.

Daly, M.C., Lawerence, S.R., Kimuna, D. and Binga, M., (1991) "Late Paleozoic Deformation in Central Africa: a Result of Distant Collision?" *Nature,* Vol. 350; pp.605-607.

Daly, M.C., Chorowicz, J. and Fairhead, J.D., (1987) "The Reactivation of Steep Basement Shear Zones and their Influence on Rift Basins in Africa." In: Williams, G. and Cooper, M.A., (eds*). Inversion Tectonics. Geol. Society Spec. Publ*., No.29. Blackwell, Oxford.

Daly, M.C., (1988) "Crustal Shear Zones in Africa: a Kinematic Approach to Proterozoic Tectonics." *Episodes,* Vol. 11, No. 1; pp. 5-11.

Daly, M.C. (1986). "Crustal Shear Zones and Thrust Belts: their Geometry and Continuity in Central Africa." *Phil Trans. R. Soc.* London, A317; pp.111-128.

Daly, M.C., Chakraborty, S.K., Kasolo, P., Musiwa, M., Mumba, P., Naidu, B., Namateba, C., Ngambi, O. & Coward, M.P., (1984) "The Lufilian Arc and the Irumide Belt of Zambia: Results of a Geo-traverse across their Intersection." *Journal of African Earth Sciences,* Vol. 2, No. 4; pp.311-318.

Department of National Parks and Wildlife, Zambia – Figures 2016

Faulds, J.E., Hinz, N. & Kreemer, C., (2012) "Structural and Tectonic Controls of Geothermal Activity in the Great Basin Region, Western USA." *Proceedings of the New Zealand Geothermal Workshop,* Vol. 34.

Faulds, J., Hinz, N., Coolbaugh, M., Depolo, C., Siler, D., Shevenell, L., Hammond, W., Kreemer, C. & Queen, J., (2016) "Discovering Geothermal Systems in the Great Basin Region: an Integrated Geologic, Geochemical, and Geophysical Approach for Establishing Geothermal Play Fairways." *Proceedings: Workshop on Geothermal Reservoir Engineering,* Vol. 41.

Faulds, J.E. & Hinz, N.H., (2015) "Favourable Tectonic and Structural Settings of Geothermal Systems in the Great Basin Region, Western USA: Proxies for Discovering Bling Geothermal Systems." *Proceedings, World Geothermal Congress*, Melbourne, Australia, 6pp.

Faulds, J.E., (2013) "Keeping Nevada in Hot Water." Presentation in Tectonic and structural controls of Great basin Geothermal Systems: developing successful exploration strategies. Nevada Bureau of Mines and Geology.

GEOLOGICA, (2013) "Preliminary Geothermal Resource Assessment: Bwengwa River Geothermal Area, Zambia." Internal report dated February 2013.

GEOLOGICA, (2016) "Update: Preliminary Resource Assessment, Bwengwa River Geothermal Project." Internal report dated April 2016.

Grant, M.A. & Bixley, P.F., (2011) "Geothermal Reservoir Engineering." *Academic Press.*

Haizlip, J., (2016) "Update to Preliminary Resource Assessment, Bwengwa River Geothermal Project." Geologica inc. (Unpublished)

Harrison, P., (2012) "The Stratigraphy and Regional Tectonic Setting of the Karoo Sediments on the southeastern Margin of the Kafue Trough, Zambia." (Unpublished)

Harrison, P., (2012) "Some Comments on the Sense of Movement and Direction of Maximum Extension along the SBF". Internal memo: date January 22, 2018.

Harrison, P, (2016) "The Geology of the Kafue Trough – An overview" (unpublished)

Hinz, N.H., Faulds, J.E. & Coolbaugh, M.F., (2014) "Association of Fault Terminations With Fluid Flow in the Salt Wells Geothermal Field, Nevada, USA." *GRC Transactions*, Vol. 38.

Kasolo, P.C. & Foster, R.P., (1991) "Fluid Channelling and Gold Mineralization Within the Late Proterozoic Mwembeshi Shear Zone, Zambia." In Ladeira, E.A., *Brazil Gold '91: the Economics, Geology, Geochemistry, and Genesis of Gold Deposits*. Balkema, Rotterdam; pp.673-679.

Land o'Lakes International (2015) 'Powering African Agriculture' final report October 2015

Legg, C.A., (1974) "A Reconnaissance Survey of the Hot and Mineralized Springs of Zambia." *Republic of Zambia Ministry of Mines and Industry, Economic Report of the Geological Survey,* No. 50. 60pp

Milani, L., Lehmann, J., Naydenov, K.V., Kinnaird, J.A., Daly, S.A., Frei, D. & Lobo-Guerrero Sanz, A., (2015). "A-type Magmatism in a Syn-collisional Setting: the Case of the Pan-African Hook Batholith in Central Zambia." *Lithos,* Vol. 216-217; pp.48-72.

Miraka milk plant www.miraka.co.nz and www.tuaropaki.com

Onyango, S., Varet, J (2016) 'Future Geothermal Energy Development in the East African Rift Valley through Local Community Involvement: Learning From the Maori's Experience', *Proceedings, 6th African Rift Geothermal Conference (ARGeo),* Addis Ababa, Ethiopia, 2nd –4th November 2016

Unrug, R., (1987) "The Tectonic Position of the Karoo Basalts, Western Zambia." *American Geophysical Union.*

Vivian-Neal, P.F.R., (2014) "Exploration for Sedimentary Basin Hosted Low-Enthalpy Geothermal Systems in Zambia." *Proceedings of ARGeo5* 29-31 October 2014

Vivian-Neal, P.F.R. et al., (2016) "Country Update Report for Zambia." *Proceedings of ARGeo6*

Wilmarth, M. & Stimac, J., (2015) "Power Density in Geothermal Fields." *Proceedings, World Geothermal Congress*, Melbourne, Australia.

Wilmarth, M., Haizlip, J., Prina, N. & Vivian-Neal, P.F.R., (2018) "Bwengwa River, Zambia – Exploration of a Non-Volcanic African Geothermal System." *Proceedings, Stanford Geothermal Workshop*.

Wisian, K.W., Blackwell, D.D., & Richards, M., (2001) "Correlation of Heat Loss and Total Energy Production for Geothermal Systems." *Geothermal Resource Council Transactions*, Vol. 25; pp.331-336.