

## Reducing Risk of Geothermal Exploration Using the MMR Technique: An Early Exploration Process

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### ABSTRACT

The magmatic, mantle and radiogenic (MMR) subsurface gas geothermal exploration techniques were developed in 2010 to reduce the costs and risks of geothermal exploration at geothermal plays and to assist in locating areas at these plays for exploration geophysics and drilling. The main objective of the MMR technique is to determine if a location can be considered a geothermal resource, where further surface geophysics and exploration drilling would be beneficial. The investigation of potential geothermal sources using MMR includes: 1) desktop study 2) geologic site investigations 3) MMR subsurface gas sampling and analysis 4) quantitative and qualitative evaluation of the gases and 5) calculation of gas geothermometers. The MMR gas and geologic exploration technique has been used at 21 locations in four countries and in the United States at potential geothermal source sites. The site results discussed in this paper are from 230 sample locations where 1) no specific identification of a geothermal source has been located, or 2) siting information was needed for new drilling and production pads at a known geothermal resource. The MMR gas sampling component of this exploration procedure is a collection of gas samples from shallow gas sampling points, fumaroles, steaming ground, spring and wells. The subsurface gases are collected in Gigenbach bottles and/or copper tubes and analyzed for O<sub>2</sub>, CO<sub>2</sub>, Ar, CO, N<sub>2</sub>, He, H<sub>2</sub>S and CH<sub>4</sub> and carbon and helium gas isotopes. The integration of the data, gas ratios, analysis, geothermometers and site geologic information, is used to determine if the identified potential thermal energy resources in-place can be developed into a geothermal resource.

**1. Introduction** The magmatic, mantle and radiogenic (MMR) gas geothermal exploration technique was developed by in 2010 to reduce the costs and risk of geothermal exploration (Figure 1) and to determine if a location can be considered a geothermal resource, where further exploration, such as surface geophysics and exploration drilling would be beneficial. The investigation of potential geothermal sources using MMR includes: Phase I consists of a desktop study of the geothermal potential utilizing previous geothermal studies, tectonic history, petrology and hydrogeology of the site. Phase II consists of MMR subsurface gas sampling and analysis, CO<sub>2</sub> Flux investigation, calculation of gas geothermometers and determination of the presence and volume of thermal anomalies, such that the thermal energy in place can be estimated with a reasonable degree of confidence. After phase I and II are completed the data is used to determine if the site meets the criteria for an inferred geothermal resource based upon the Australian Geothermal Code Second Edition, 2010.

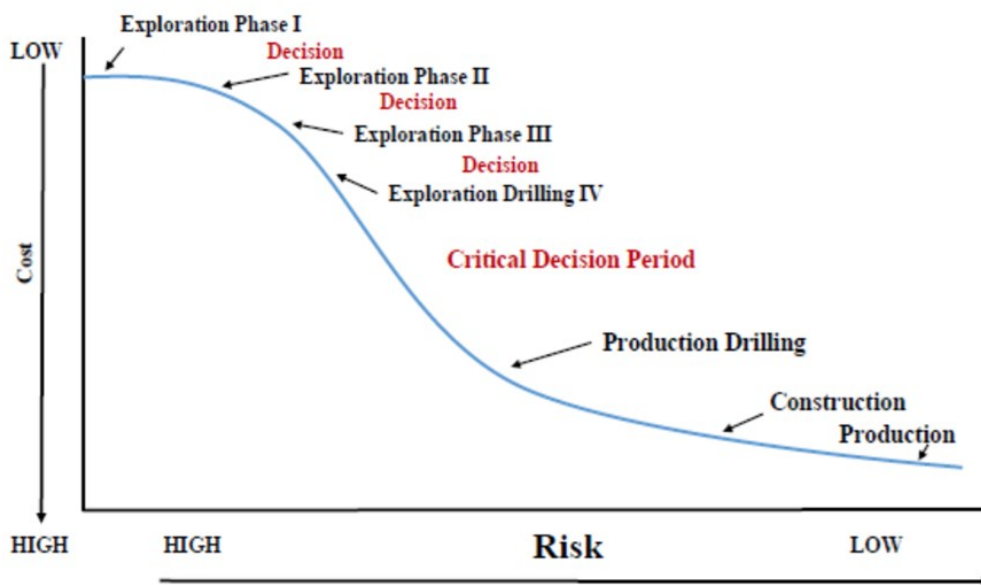
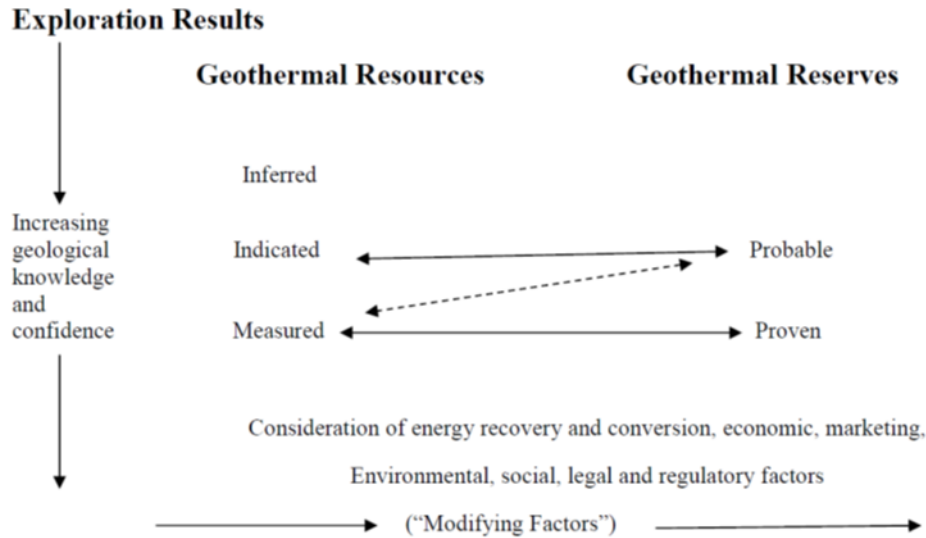


Figure 1. Graph of geothermal resource cost versus risk.



**Figure 2. The Australian Geothermal Code. Adapted from the Geothermal Reporting Code Second Edition (2010).**

Steps beyond an inferred geothermal resource are based on further measurements and investigation and are: indicated geothermal resource and measured geothermal resource, as illustrated in the Australian Geothermal Code Second Edition, 2010 (Figure 2).

**2. OBJECTIVES OF MMR GAS EXPLORATION**

The magmatic, mantel and radiogenic (MMR) gas sampling component of the exploration procedure is a collection of gas samples from shallow gas sampling points and when available from fumaroles, steaming ground, springs and wells. The objectives from the overall MMR exploration techniques are as follows:

1. Locate geothermal sources within the geothermal exploration areas
2. Collect gases of magmatic, mantel and/or radiogenic origin
3. Analyze the individual gases in terms of their relationship to each other and to a geothermal source
4. Determine gas other geothermometers
5. Identify gas geothermometer high temperature anomalies within the potential geothermal source area
6. Combined geothermometer anomalies with other field and desktop report data
7. Define the geothermal source
  - a. Estimate geometery and volume of the geothermal source
  - b. Estimate depth to geothermal source
8. Improve the siting of exploration wells and surface geophysics

**3. MMR GAS SAMPLING AND ANALYSIS**

Based on the areal extent of the geothermal plays the actual gas sampling locations may vary from the proposed sampling grid to accommodate the highest probability areas for a geothermal resource. During the field sampling, sample locations are adjusted based on evaluation of the surface geologic features, structural features, presence of geothermal indicia, accessibility in terms of drilling, plant construction and transmission line logistics. Within the final sampling areas MMR gas sampling locations are identified and sample density is based on enough sample points to represent the selected areas allowing for non-usable points.

**3.1 MMR gas sampling**

The MMR gas and geologic exploration techniques have been used at 17 sites in four countries and the United States at potential geothermal source locations. The site results discussed in this paper were used to determine 1) the location and volume off the geothermal resource 2) surface geophysics station locations 3) siting information for new drill pads and 4) safe location of production wells. MMR gas samples are collected using the following steps:

Step 1. Where competent rock is encountered at the surface a one-in diameter pilot hold is drilled using a rotary hammer drill to a depth of one meter. Where unconsolidated regolith is encountered a pilot hole is created using a hammer drill by driving five eights inch diameter solid rods to a maximum depth of three meters.



**Figure 3. Rotary hammer drilling with auger bit in competent rock for gas sampling pilot hole.**

Step 2. Drive a hollow gas recovery rod with tubing attached to the gas recovery point into the pilot hole with a hammer drill or slide hammer.



**Figure 4. Inserting hollow sampling rod and tubing in the pilot hole for gas collection.**

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Step 3. Seal the borehole annulus to reduce atmospheric air contamination.



**Figure 5. Sealing of the sampling rod annulus with bentonite.**

Step 4. Connect copper sampling tube and hand vacuum pump to the sample tubing and purge the tubing and copper tube.



**Figure 6. Purging of the sample tubing and copper tube.**

Step 5. Collect subsurface gases in copper tubes or Giggnebach bottles.



**Figure 7. The collecting of gases into a copper tube.**



**Figure 8. The collecting of gases into Giggenbach bottle.**

. Step 6. Remove hollow gas sampling rod and tubing and abandon borehole



**Figure 9. The removal of the gas sampling rod and tubing with a modified jack.**

### 3.2 MMR Gas Analysis and General Analysis Results

MMR gas samples collected in Giggenbach bottles and/or copper tubes are analyzed at the Volcanic and Hydrothermal fluids analyses laboratory at the University of New Mexico, or at the Ohio State Noble Gas Lab.

#### 3.2.1 Analytical Techniques for MMR Gas Samples

The analytical system consists of two instruments connected to a high vacuum system. The first instrument is a Pfeiffer Quadrupole Mass Spectrometer (QMS) with mass range 0 to 120 AMU. This instrument is used for the elemental analyses of He, Ar, N<sub>2</sub> and O<sub>2</sub> using Secondary Electron Measurement (SEM) and operated in dynamic mode. The second instrument is a Gow Mac gas chromatograph equipped with a Discharge Ionization Detector (DID), Haye Sep D and Mole sieve columns and run with ultra-pure and purified helium carrier gas. The GC is used for the elemental analyses of N<sub>2</sub>, Ar + O<sub>2</sub>, H<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub>, CO and H<sub>2</sub>S. Calibration of both instruments is performed using calibration gas mixtures purchased from Air Liquide. Calibration gas mixtures have an analytical accuracy of  $\pm 5\%$ . Except for low-level (few 10's of ppm) helium, the QMS has a precision of better than 0.1 % for all species. The precision of the GC has not been systematically determined but based on repeated measurements is  $\pm 2\%$ . Agreement between duplicate samples collected in two separate copper tubes at the same site is excellent. The vacuum system consists of high accuracy MKS Baratron gauges (total range is ambient to  $10^{-5}$  torr), a Bayer-Alpert (ion) gauge, a diffusion pump and a roughing pump to back the diffusion pump and to obtain low vacuum. The QMS is connected to a turbo pump that is backed with a second roughing pump. The design of the vacuum line insures low blanks due to  $10^{-5}$  torr line pressure and highly accurate calibrations due to the large range of the two MKS Baratron gauges.

#### 3.2.2 General Analytical Results

The MMR gas samples from all sites show compositions that are dominated by the air components N<sub>2</sub>, O<sub>2</sub>, Ar, which is typical of soil gas samples, because of the shallow sample depths. MMR gases in the samples may include CO<sub>2</sub>, He, CH<sub>4</sub>, H<sub>2</sub>S, H, N<sub>2</sub>, Ar and CO that may exist out of the range of air if they are associated with hydrothermal geothermal sources. Ratio geothermometer applications must be treated with caution and the CO<sub>2</sub>-CH<sub>4</sub> geothermometer, which could potentially be affected by disequilibrium reactions as the gases travel from a deep source to the surface. <sup>3</sup>/<sup>4</sup>He, <sup>40</sup>/<sup>36</sup>Ar and <sup>12</sup>/<sup>13</sup>C isotope values may be used to assist in determining the origin of He, Ar and C gases which increase their reliability as geothermometers. The ratio geothermometers typically used are: CO<sub>2</sub>-CH<sub>4</sub>, H<sub>2</sub>-Ar, CO<sub>2</sub>-N<sub>2</sub>, and CO<sub>2</sub>-Ar also used is the H<sub>2</sub>S geothermometer. Temperatures for these geothermometers have ranged from 32°C to 411°C. The presence or absence of geothermometer anomalies is based on a comparison to the base line geothermometers. Each site has its own unique base line geothermometer results.

All MMR temperatures need to be treated with caution, but if supported with other data they represent shallow to deep conditions in a liquid hydrothermal system feeding springs, fumaroles and surface soils.

#### 4. SELECTED SITES FOR THE MMR EXPLORATION TECHNIQUES

Geothermal desk top studies are conducted at the potential geothermal sites to: reduce the risk of continuing geothermal exploration at a site with no thermal energy at depth, reduce the risk of improper siting of surface geophysics studies and locate geothermal exploration drilling. This desk top study determines a go or no-go for field exploration.

The sample locations points were set up in a grid pattern within an area based on the desktop study report. Because of field discoveries, location of geothermal indicia and logistics, some sample points were moved to accommodate these discoveries. All gas samples were collected from a depth of 1 to 3 meters below ground surface, or at steaming ground and fumaroles. Gas head space samples were collected from lakes, springs and wells.

In the last eight years the site locations explored are: Atacama Desert (Chile), New Mexico, Colorado, Central Tukey, Caribbean, and Northern Sumatera. These locations consisted of multiple potential geothermal sources or proven resources. These sites are described and categorized as: no further action site, or a geothermal resource with recommended locations for surface geophysics and exploration boreholes. At proven geothermal resources recommendations have been made for new production pads and safe location of production wells on existing drilling pads.

All sites were analyzed for CO<sub>2</sub>, CH<sub>4</sub>, CO, He, N<sub>2</sub>, O<sub>2</sub>, Ar and H<sub>2</sub> gases. The presence of a potential geothermal source was in part determined by locating high temperature gas geothermometer anomalies.

##### 4.1 Atacama Desert Sites

The five potential geothermal sites investigated in the Atacama Desert in Chile covered an area of 1000 square kilometers in total. Fifteen and sixteen gas samples were collected at the yellow east and green west site respectively, fifteen gas samples were collected at the red site and thirteen gas samples were collected at the south and north sites.

Factors that pertain throughout the Atacama Desert geothermal sources are:

Heat flow density models and empirical data of the volcanic arc within the Atacama Desert sites indicate presence of shallow magma bodies (at depths of 4 to 6 Km) producing temperatures in the range of 250°C to 300°C with a heat flow range of greater than 100mW/m<sup>2</sup>

- Base line temperature ranges for the CO<sub>2</sub>-N<sub>2</sub> and H<sub>2</sub>-Ar geothermometers ranged from 41°C to 53°C and from 39°C to 59°C respectively in the potential geothermal source areas
- Background temperature range for the Atacama Desert exploration areas ranged from 6°C to 26°C.

The green west site and the yellow east site are the preferred drilling sites in the Atacama Desert geothermal source based on the following:

##### Yellow East Site

- At the yellow site the MMR gas geothermometers show a cluster of five temperatures ranging from 159°C to 192°C.
- The yellow site MMR gas geothermometers show confirmation from the first through the third trip.
- At the yellow site the deep geothermometers with high ranging temperatures are found at a juncture of three fault traces and a suspected structural basin.
- Drilling and construction access is available and should not interfere with the tourism.
- The yellow east site contains some of most reliable values for the CO<sub>2</sub>-CH<sub>4</sub> geothermometers, which are temperatures in 140°C -190°C range. A geothermometer of 125°C is also detected using H<sub>2</sub>-Ar geothermometer and is quite consistent with the lower end of the CO<sub>2</sub>-CH<sub>4</sub> geothermometers.

##### Green West Site

- At the green site the deep high temperature locations are on the edge of the suspected clay cap, which is where they would be suspected to be if the up flow of gases was refracted by the clay cap to the edge of the clay cap.
- Drilling and construction access is available and should not interfere with the tourism.

The red site is the secondary drilling site in the Atacama Desert geothermal resource, even though the thermal energy-in-place is greater than the yellow east site based on the following:

- This site is a secondary drilling site, because of the difficulty limited drilling and construction access, because of tourism traffic.
- The MMR gas geothermometers show four temperatures ranging from 116°C to 198°C.
- The MMR deep gas geothermometers trend along a fracture trace.

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- The calculated thermal energy is the highest in the Atacama Desert and was based on an increase in average temperature and area.
- The elevated geothermometers were not replicated during the second and third resampling trips.

The north and south sites were not recommended as primary or secondary drilling sites based on the following:

- The MMR high gas geothermometer anomalies at the south site show three temperatures, ranging from 155°C to 205°C, with no trends or groupings.
- The MMR high gas geothermometer at the north site show one temperature of 150°C.
- There is no other MMR high gas geothermometers at the north site.
- None of the existing high geothermometer temperatures have been replicated to date by adjacent MMR points sampling and analysis.

#### **4.2 Southern New Mexico Sites**

Two sites were investigated in southern New Mexico for a potential geothermal source, site one consisted of 41 square kilometers and site two consisted of 70 square kilometers. Seventeen MMR gas samples were collected at site one and twenty-two MMR gas samples were collected at site two. In conjunction with the MMR gas sampling, geologic exploration was conducted to further evaluate potential geothermal source areas by identifying geothermal indicia, sampling and analyzing gas and water from existing wells and locating faults and fault traces. The faults and fault traces are targets for: 1) surface geophysical exploration to determine the extent of fractures, 2) temperature gradient and geothermal exploration wells to determine fluid phases, yields and pressures and 3) MMR gas sampling and analysis.

The results of the site investigations were as follows:

##### **General Results**

- The MMR gas samples in this report represent a mixture of gas components, pore space air and other gas components (CO<sub>2</sub>, H<sub>2</sub>, and He).
- The intermediate to deep gas components represent inputs from: a) the mantle/magma and b) hydrothermal fluids that move upward from deep crustal regions.

##### **Site One**

- The fault trace areas had the highest absolute values of MMR gases associated with a geothermal source.
- The aqueous geochemical analysis showed the general chemistry of an existing well to be a dilute chloride fluid.
- The well head space gas analysis produced a geothermometer anomaly of 127.8 °C.
- The well's aqueous geochemistry suggests the fluids are either an umbrella-shaped perched fluid condensate zone overlying a low temperature geothermal system, or an outflow zone on the margins of the geothermal inferred resource.
- The well water indicated potential scaling or minor corrosive potential depending on the interaction of the fluids with the country rock.
- The highest area of concentration of intermediate to deep MMR gas geothermometer anomalies were found at site one and ranged from 85.3 to 91.6 °C.

The fault trace, well analysis and correlation with the MMR geothermal anomalies identified site one as an inferred geothermal resource and was recommended for further geothermal investigation.

##### **Site Two**

The recommendation for Site Two was for no further geothermal investigation.

#### **4.3 Southern Colorado Site**

One, 1.7 square kilometer, Site was investigated in southern Colorado the site consisted of thirty- seven MMR gas samples over three areas within the site (west area 1, south area 2 and east area 3). The existence of thermal energy in-place at the southern Colorado site was based on the following factors determined from the on-site exploration of the southern Colorado site, the MMR gas analysis, geothermometry, surface geophysics and previous works on the geothermal history of the southern Colorado site:

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- Reservoir fluid temperatures for all geothermometers at the west area one of the southern Colorado site ranged from 42°C to 90°C. In the west area one a single geothermometer anomaly (90°C) and a gas geothermometer from an adjoining spring (150°C) were near an identified fault juncture.
- Reservoir fluid temperatures for all geothermometers at the south area two ranged from 34°C to 69°C. No grouping of geothermometer anomalies were found at this location.
- Reservoir fluid temperatures for all geothermometers at east area three of the property ranged from 26°C to 105°C. A grouping of geothermometer anomalies (95°C to 105°C) were located along an identified fault in east area three.

The results presented in this study based on the MMR gas and other gas geothermometers, surface geophysics, geologic exploration of the site and previous works indicate an inferred geothermal resource in Precambrian basement rock primarily in east area three and secondarily at west area one. Temperature gradient holes were drilled at the three areas a few feet into basement rock. The highest measured temperature gradient hole at east area three was 60°C. The evidence for a geothermal resource is present, but it is likely in the basement rock at a substantial depth.

Currently no further exploration was recommended at this site.

#### **4.4 Caribbean Island Arc Volcano Site**

A desktop study and two geologic field explorations were completed on an island arc volcano (20 square kilometers) in the Caribbean. The first field event consisted of twenty-three MMR gas samples and a second field event consisted of eighteen MMR gas samples and a time-domain electro-magnetic survey (TDEM) of fault traces identified in the first field study. A third field event a MT survey based on the first two field events was successful in verifying data from the first two field events.

In the first field study the areas on the volcano investigated were the northeast, north and southwest slopes of the volcano. The second field study focused on the southwest slope of the volcano, which had the best geothermal potential based on the first field study.

The volcano is currently ranked as a qualified indicated geothermal resource based on the following data:

The volume of the geothermal resource at the volcano site was based on an area determined by the gas collection of gases of magmatic origin, geothermometry, fault identification, recent geothermal indicia.

- The area of the projected geothermal resource is approximately 4.9 square kilometers with an estimated thickness of 500 to 1000 meters.
- Estimated average reservoir fluid temperature on the southwestern flank of the volcano 196°C based on the average of the cut off temperature and the volcano crater CO<sub>2</sub>-CH<sub>4</sub> fumarole gas geothermometer temperature of 282°C.
- Estimated deep reservoir fluid temperature beneath volcano crater is 282°C based on CO<sub>2</sub>-CH<sub>4</sub> geothermometer temperature.
- Cut off temperature estimated at 110°C.
- Base temperature estimate (the lowest temperature that will be reached in the reservoir as a part of the extraction injection process) 110°C plus (gas geothermometer).
- Pressure is atmospheric as currently determined from the water supply wells, but at depth may be enough for artesian flow.
- Permeability as hydraulic conductivity in fractured andesite lithology is estimated at 1.0E<sup>+1</sup> to 1.0E<sup>-3</sup> m/day.
- Geochemistry of water from existing water supply wells and previous works slightly acidic with moderate SO<sub>4</sub> and CO<sub>2</sub> content.

The two field assessments of the volcano geothermal source demonstrated that part of the volcano's southwest slope has been upgraded to a qualified indicated geothermal resource with probable reserves. This was based on direct TDEM results and MMR gas analysis, indicating geothermometer temperatures and resource dimensions such that the thermal energy in place can be estimated with a reasonable level of confidence.

#### **4.5 Sumatera, Indonesia Sites**

Three geothermal sites were investigated in northern Sumatera they consisted of site one a production pad and two new proposed drilling sites, site two and site three (both approximately 33,000 square meters).

At site one (14,000 square meters) a subsurface investigation was conducted, because of the destabilization of the second production well's preliminary casing and cementing due to gas and fluid influx from the geothermal resource. The investigation consisted of sixteen MMR gas samples, a CO<sub>2</sub> surface flux study (approximately 300 measurements) a refraction micro tremor survey (four transects) and a review of the previous geotechnical production pad construction reports to assist in determining the stability of the drilling pad and if any further production wells could safely be completed.

The findings at the site one production pad showed that the site one production pad is located on an area of spatially variable fractured pyroclastic bedrock. The fractures are approximately vertical providing preferential pathways for direct upwelling of total fluids (dry gases, steam and aqueous fluids) through the rock fractures from a liquid dominated hydrothermal reservoir that contains either a vapor phase at the top or has undergone boiling due to pressure releases from drilling. The gasses may continue to increase destabilization of the unconsolidated drill pad material providing preferential pathways for venting from the unconsolidated material to the surface unless they are controlled and redirected away from the drilling zone.

Based on the MMR gas analysis, CO<sub>2</sub> surface flux study, previous pad geotechnical reports and the Refraction Micro tremor survey conducted on and around site one some minor liquefaction potential within the drill pad sediments during a magnitude 7.0 earthquake may occur. On site one the number of production wells were reduced from seven to three and locations for the last two production wells were selected based on the MMR gas and geophysical investigation results. The remaining production wells were then successfully completed.

At each of the proposed sites (site two and site three) three MMR gas samples were collected and analyzed to determine their potential as geothermal production sites. The results of the MMR gas survey at the proposed drilling pads at site two and site three indicated that further exploration should be considered only at site three where a geothermometer of 152°C was recorded and the gas ratios and absolute gas results were found to be significantly outside the range of air and shallow soil gas.

#### **4.6 Central Turkey Sites**

Two sites were investigated in central Turkey, site one (28 square Kilometers) consisted of fourteen MMR gas samples and site two (34 square kilometers) consisted of seventeen MMR gas samples. At the two sites investigated the most favorable geothermal resource is located within the site one area. At the site one area the depth of the resource is estimated to be between 3,500 and 4,000 meters below land surface and the thickness is estimated to be 500 meters based on MT results, previous works, MMR studies and surface geologic exploration. The current estimated Geothermal Resource data is as follows:

- Average resource temperature in a portion of site one is 139 °C.
- Maximum resource temperature is extrapolated to be in the 200°C plus range and is based on the highest MMR gas geothermometer considered to be reliable.
- Cut-off temperature is estimated to be 100 °C (Australian Geothermal Lexicon, 2010).

Based on the geologic setting, depth of the resource, geothermometry, an estimated volume of the resource area at site one the geothermal resource is expected to be a convective moderate to low temperature self-discharging geothermal resource. Site one area has been recommended for seismic exploration and temperature gradient wells.

Site two has not been recommended for further exploration.

#### **5. CONCLUSIONS**

Based on the MMR gas exploration body of work the application of MMR gas exploration and accompanying techniques can be used at potential geothermal sources both in fractured rock or regolith lithologies to locate, qualify and initially quantify geothermal sources thereby, reducing exploration and production costs and risks. Also, gas data, geothermometers, source volumes (GeothermEx, 2004) and proposed depths at these geothermal sources can be used to locate exploration wells and surface geophysics more efficiently and effectively and evaluate production pad stability and safety.

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