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DEVELOPMENT OF METRIC FOR MEASURING THE IMPACT OF RD&D FUNDING ON GTO'S GEOTHERMAL EXPLORATION GOALS

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ABSTRACT

The Department of Energy's Geothermal Technology Office (GTO) provides RD&D funding for geothermal exploration technologies with the goal of lowering the risks and costs of geothermal development and exploration. The National Renewable Energy Laboratory (NREL) was tasked with developing a metric in 2012 to measure the impacts of this RD&D funding on the cost and time required for exploration activities. The development of this cost and time metric included collecting cost and time data for exploration techniques, creating a baseline suite of exploration techniques to which future exploration cost and time improvements can be compared, and developing an online tool for graphically showing potential project impacts (all available at http://en.openei.org/wiki/Gateway:Geothermal). This paper describes the methodology used to define the baseline exploration suite of techniques (baseline), as well as the approach that was used to create the cost and time data set that populates the baseline. The resulting product, an online tool for measuring impact, and the aggregated cost and time data are available on the Open Energy Information website (OpenEI, http://en.openei.org) for public access.

INTRODUCTION

Due to the risk that is associated with geothermal exploration, obtaining funding for an exploration program is typically a difficult task for potential developers. The GTO has funded research projects that could potentially reduce the risk of early development, lower the levelized cost of electricity, and increase the impact that an activity has on accelerating the development of the 30 GW_e of undiscovered hydrothermal resources within the U.S. as estimated by the U.S. Geological Survey (USGS) geothermal resource assessment (Williams, 2008).

In 2012, the GTO sponsored the development of a metric to measure the impact a new or improved exploration technique or technology could have on the cost and time required to complete a set of exploration techniques. The metric was developed by NREL and the framework was based on previous work at the University of Kansas, a "screening protocol to assess potentially prospective geothermal resources" (Walker et al., 2005). Walker et al.'s 2005 GRC publication, *Development of Genetic Occurrence Models for Geothermal Prospecting*, defines a generic exploration plan that is based on the genetic occurrence of individual techniques in exploration programs. NREL's metric uses a similar layout to define a baseline exploration suite against which the GTO can use to evaluate the impact of future RD&D efforts.

COST AND TIME DATA SET

NREL started building the cost and time data set by creating a list of 127 exploration techniques that one might consider as part of an exploration program. The costs associated with each exploration technique were collected from exploration vendors in the United States, and from Australian and Canadian companies that have conducted geothermal exploration in the United States.All of the techniques were allocated to one of the eight categories listed in Table 1.

Table 1: Eight categories of geothermal exploration and their corresponding number of techniques per category.

Exploration Categories	# of Methods
Data and Modeling	7
Downhole	32
Drilling	10
Field	11
Geochemistry	3
Geophysics	29
Lab Analysis	17
Remote Sensing	18

Information on cost and time requirements for each of these 127 techniques were solicited from industry. The data collected came from geothermal, oil/gas, and mineral exploration vendors in the United States, Canada, and Australia that have performed exploration in the United States. The data were limited to cost and time information applicable to the western United States. Limiting the data set to a particular geographical region was intended to prevent cost and time anomalies due to relocation and/or geology that do not represent the current geothermal market in the U.S. The largest challenge in creating the cost and time database was collecting enough data to populate the baseline. During the time NREL collected data, 102 exploration vendors were contacted. 71 of the 102 (69%) vendors were either non-responsive or were not interested in the project. During collection, cost data were collected for 66 of the 127 exploration techniques; time data were collected for 51 of the 127 techniques.

Data were collected using a triangular distribution by asking vendors to quote "Low", "Typical", and "High" values for the exploration techniques they perform. Each vendor was asked to briefly explain what factors would typically increase or decrease both cost and time of an exploration method. From the data collected, the absolute minimum, absolute maximum, and average of the typical values were used to create a single data set, as seen in Appendix A. An example of how the data set was created is shown in Table 2 and Table 3.

Table 2: MT Data inputs from 4 vendors

MT survey	Low $	Typical $	High $	Unit
Company A	$704.76	$1,404.76	$2,297.62	Station
Company B	$522.22	$1,055.56	$1,694.44	Station
Company C	$1,000	$2,000	$2,000	Station
Company D	-	$2,495	-	Station

Table 3: Aggregated MT data that is visible to public.

	Low $	Typical $	High $	Unit
MT survey	$522.22	$1,738.83	$2,297.62	Station

The data collected have been posted on OpenEI, but have been aggregated, as shown in Figure 1, to protect the identity of the participating vendors. All of the exploration techniques that NREL addressed as well as the techniques that still require industry input can be found in the Geothermal Energy page of OpenEI (http://en.openei.org/wiki/Exploration_Techniques). An example of data that is currently available on OpenEI is shown in Figure 1.

Exploration Technique Information	
Exploration Group	Geophysical Methods
Exploration Sub Group	Magnetic Methods
Information Provided by Technique	
Lithology:	
Stratigraphic/Structural:	map subsurface clay structure
Hydrological:	
Thermal:	
Cost/Time Dependency:	Location, Size, Resolution, Terrain, Weather
Cost Information	
Low-End Estimate (USD):	522.22 / station
Median Estimate (USD):	1,738.83 / station
High-End Estimate (USD):	2,297.62 / station
Time Required	
Low-End Estimate:	1.67 days / 10 stn
Median Estimate:	3.77 days / 10 stn
High-End Estimate:	7.50 days / 10 stn

Figure 1: MT data shown as an example of the data interface currently available on OpenEI.org

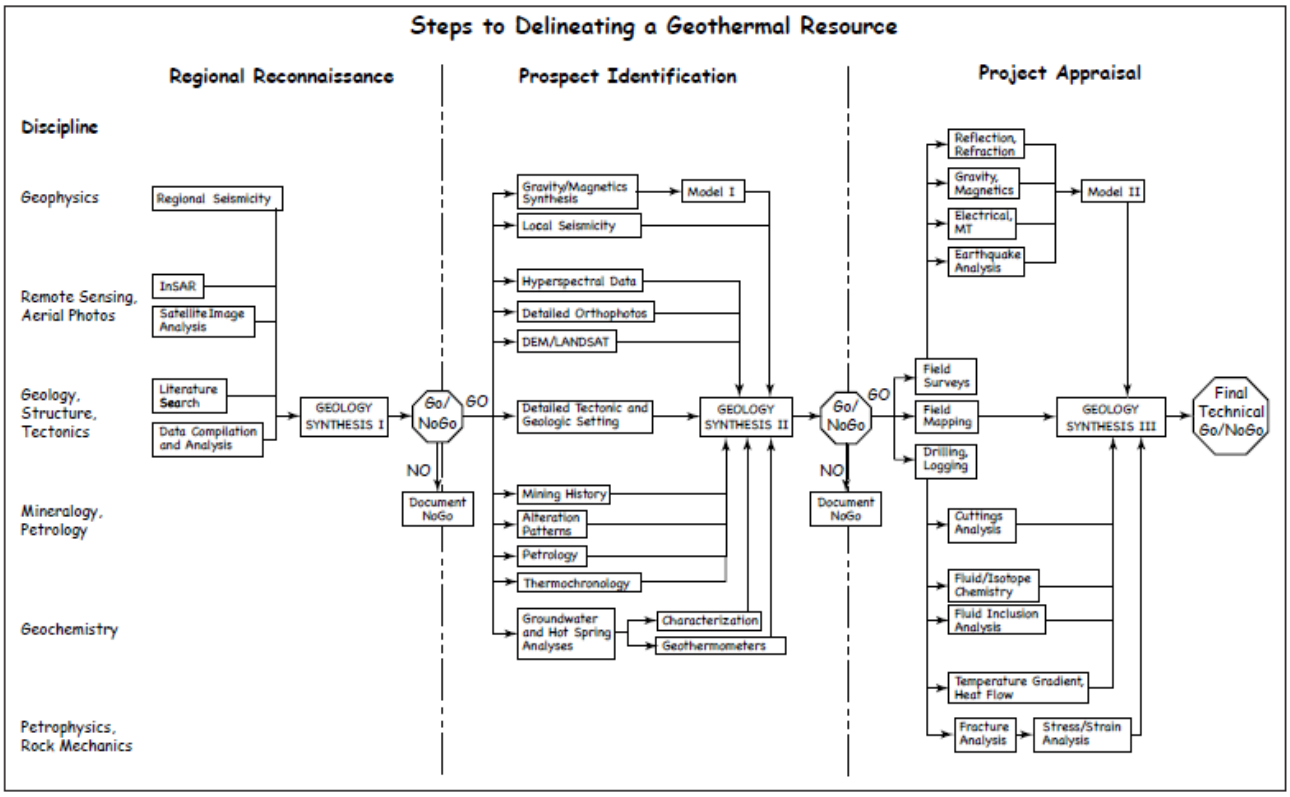

Figure 2: Graphical representation of the tools, data, and geologic features that can be assessed prior to drilling, as defined by Walker et al., (2005).

CREATION OF BASELINE

After the cost and time database was initiated, the second objective was to define which techniques would be used in the baseline suite for exploration of a typical 30MW$_e$ hydrothermal resource, and the manner in which they would be grouped. NREL used Walker et al. (2005) delineation of a geothermal resource plan (Figure 2), as the starting point for the baseline. Their approach was organized into three pre-drilling phases consisting of Regional Reconnaissance, Prospect Identification, and Project Appraisal, as shown graphically in Figure 2. NREL also added a fourth phase–Initial Drilling.

The Walker et al. (2005) GRC paper, *Development of Genetic Occurrence Models for Geothermal Prospecting*, was used as a starting point for defining the baseline suite of exploration techniques. Walker et al. (2005) defined three pre-drilling phases in geothermal exploration: regional reconnaissance, prospect identification, and project appraisal. The NREL cost and time baseline utilizes these three phases and adds a fourth phase, Initial Drilling. Together, these four phases consist of 22 pre-production-drilling techniques including literature review, field techniques, geochemistry, geophysics, petrography, remote sensing, and shallow/small diameter drilling. The individual techniques, the order in which they are conducted, and their corresponding costs have been reviewed by geothermal developers and exploration experts, with the conclusion that the baseline suite is a reasonable starting point for an exploration program, and it is therefore suitable for comparison of future exploration projects.

Our list of techniques departs from the list defined by Walker et al. (2005), as NREL's method uses techniques based on their cost and level of permitting required. The baseline suggests that it is common to perform techniques that have the least permitting requirements in the early stages of a project.[1] It is also industry practice to use the least expensive techniques early in the project. The baseline only represents the typical costs and time that are associated with one site. According to conversations

[1] The level of permitting required differs at each location. Due to these inconsistencies, the baseline should not be used as a permitting guide. In some instances, permitting will be required at all stages and should be confirmed with the respective agencies.

with industry experts, developers commonly evaluate 5-10 sites in the initial phases and only perform exploratory drilling on 1-2 of the initial sites. The number of sites to be explored differs due to individual financing, company portfolios of exploration projects, and risk assessments. For this reason NREL chose not to suggest the number of sites per phase. The four phases and their descriptions are defined in Table 4**Error! Reference source not found.**.

While the NREL baseline includes the same pre-drilling phases as Walker et al. (2005), the NREL suite does not mention any of the decision points that Walker et al. describe. This does not imply that the NREL model does not require decision points, rather that the quantity and location of decision points needs to be determined by the developer. Typically, the decision points are based on the developer's risk assessment plan, and will likely vary from one developer to the next.

VALIDATION OF BASELINE

NREL elicited expert input to determine if the baseline exploration technology suite and the proposed order and quantity of measurements were considered reasonable and consistent with industry practice. NREL interviewed four geothermal exploration experts and had each of them individually critique the baseline from a technical and financial perspective. Each expert felt that the baseline was reasonable, meaning that the list of techniques selected comprise common criteria used in typical geothermal exploration activities. The difference in exploration plans between each expert was not significant for the first three phases; however, opinions varied on the fourth phase, Initial Drilling. The reasons for the variation can be traced to individual models and ideologies that are intended to reduce the uncertainty and risk associated with the exploration well drilling, as well as definitions and terminology used in drilling. The latter was mitigated by using explicit definitions for exploration drilling, such as bottom-hole diameter, depth, type of casing, and the type of rig used to drill the well (i.e., rotary hole, core hole, etc.).

Of the four experts, three agreed that NREL's costs were reasonable with the estimates provided. The fourth expert's cost assumptions differed specifically in Phases 3 and 4, with Phase 3 adjusted to $250k,

Table 4: Pre-drilling exploration phases used in the NREL baseline suite, the expected level of permitting for a typical site, and the expected cost associated with the entire phase.

Phase	Title	Permits Required	Description	Typical Cost Range
1	Regional Reconnaissance	No	Regional Reconnaissance is reserved for a literature review and low-cost expenditures (e.g., geochemical sampling) to cover a large area with minimal site visits. As such existing data for an area such as geophysics, geology (including but not limited to mining history, regional and local tectonics, etc.), fluid and rock geochemistry, and hydrology are reviewed at this stage.	up to $50k
2	Prospect Evaluation	No	Prospect Evaluation is reserved for innexpensive techniques that require more time on site. Techniques such as hyperspectral imaging, detailed geothermometry (all known water wells and surface manifestations), elemental and compound analysis of ground water/soil composition/etc., and initial field mapping and structural analysis are typical.	$50-$100k
3	Project Appraisal	Yes	Project appraisal is reserved for initial geophysical surveys at a site. The first two phases will have justified exploration techniques such as refelection seismic, magnetotellurics, magnetics, gravity, and resistivity surveys, as well as detailed mapping and conceptual models.	$250-$500k
4	Project Appraisal, Initial Drilling	Yes	Initial drilling is reserved for the drilling techniques that take place before the first production sized well. techniques such as thermal gradient holes (TGH), core holes, slim holes, and their associated analysis are typically performed.	$6-7M

and Phase 4 adjusted to $1.5M-$2.5M. This reduction in cost would result in fewer exploration techniques being used, potentially increasing the risk of drilling an unsuccessful well, but significantly lowering exploration costs. This is an example of how individual risk assessments can impact the outcome of an exploration program.

Table 5 is a representation of the final baseline defined by NREL. The 22 techniques include desktop analysis of previous exploration literature and data, geochemistry, structural field mapping, geophysical surveys, thermal gradient drilling, and any modeling and simulation that would be required. The techniques that were selected for each phase were selected based on their corresponding costs, as well as the level of permitting that is typically required.

COST & TIME METRIC TOOL

Once the exploration baseline was established, a tool was created to graphically show the cumulative impact on exploration cost and time from one or more RD&D efforts. This impact can be used as a metric that GTO can use to evaluate potential exploration RD&D applications, to quantify the impact of a particular completed RD&D project, and to measure the cumulative impact of its exploration RD&D portfolio. The tool is designed to emphasize the change in exploration costs and time instead of only the total cost and time for a given set of exploration techniques. The baseline is represented as a bar chart in the tool, and the impact on cost is visualized as a waterfall chart. Every change that is made to the baseline shows a decrease or increase in cost while a second bar chart represents the final cost associated with each change. The time change is shown in a similar fashion but instead of a waterfall chart, the total project time is shown as individual points that are connected by a line. For both cost and time, each change that is made is also shown in a data table below the chart, broken down by technique. Figure 3 shows an example of the user interface with a change in two techniques in Phase 1. Figure 3 is a hypothetical scenario to show a visual representation of the tool output.

Any changes made in the tool can be saved and printed for future reference and sharing. At present,, there is only one baseline input into the tool. However, it was designed so that multiple baselines can be created if necessary. The tool is available on OpenEI (http://en.openei.org/wiki/Exploration_Cost_and_Time_Metric).

Table 5: Final baeline exploration plan - This plan is based off of a typical 30 MWe hydrothermal exploration program. This is intended to reflect the cost portion for only one exploration site.

	Method	Unit Cost	Unit	Cost Source	# of Units	Well Multiplier	Total Cost
Phase I (no site visit)	Regional Reconnaissance						
	Geothermal Literature Review	$ 200.00	hour	Database	80		$ 16,000.00
	Geothermometry	$ 30.00	sample	Database	20		$ 600.00
	Multispectral Imaging	$ 370.23	sq. mile	Database	40		$ 14,809.00
	Data Acquisition-Manipulation	$ 250.00	hour	Database	60		$ 15,000.00
						Phase 1 Total $	$46,409
Phase II (no permit required)	Prospect Evaluation						
	Hyperspectral Imaging	$ 1,337.56	sq. mile	Database	40		$ 53,502.58
	Compound and Elemental Analysis	$ 30.00	compound	Database	50		$ 1,500.00
	Geothermometry	$ 30.00	sample	Database	50		$ 1,500.00
	Field Mapping	$ 600.00	hour	Database	40		$ 24,000.00
	Modeling-Computer Simulations	$ 195.00	hour	Database	40		$ 7,800.00
						Phase 2 Total $	$88,303
Phase III (permit required)	Project Appraisal						
	Ground Gravity Survey	$ 68.31	station	Database	500		$ 34,155.56
	Aeromagnetic Survey	$ 167.34	mile	Database	200		$ 33,467.20
	Magnetotellurics	$ 1,738.83	station	Database	75		$ 130,412.20
	Reflection Survey	$ 44,946.67	sq. mile	Database	6		$ 269,680.00
	Field Mapping	$ 600.00	hour	Database	40		$ 24,000.00
	Modeling-Computer Simulations	$ 195.00	hour	Database	40		$ 7,800.00
						Phase 3 Total $	$499,515
Phase IV (Initial Drilling)	Project Appraisal						
	Thermal Gradient Holes	$ 16.50	foot	Database	500	20	$ 165,000.00
	Core Hole Drilling	$ 200.00	foot	Interview	3500	5	$ 3,500,000.00
	Cutting Analysis	$ 4,000.00	100 feet cut	Database	15		$ 60,000.00
	Core Analysis	$ 10,000.00	30 foot core	Database	10		$ 100,000.00
	Slim Holes	$ 169.90	foot	Database	7000	2	$ 2,378,530.00
	Compound and Elemental Analysis	$ 30.00	compound	Database	50		$ 1,500.00
	Modeling-Computer Simulations	$ 195.00	hour	Database	80		$ 15,600.00
						Phase 4 Total $	$6,220,630
						Phase I-IV Total Cost	$ 6,854,856.53

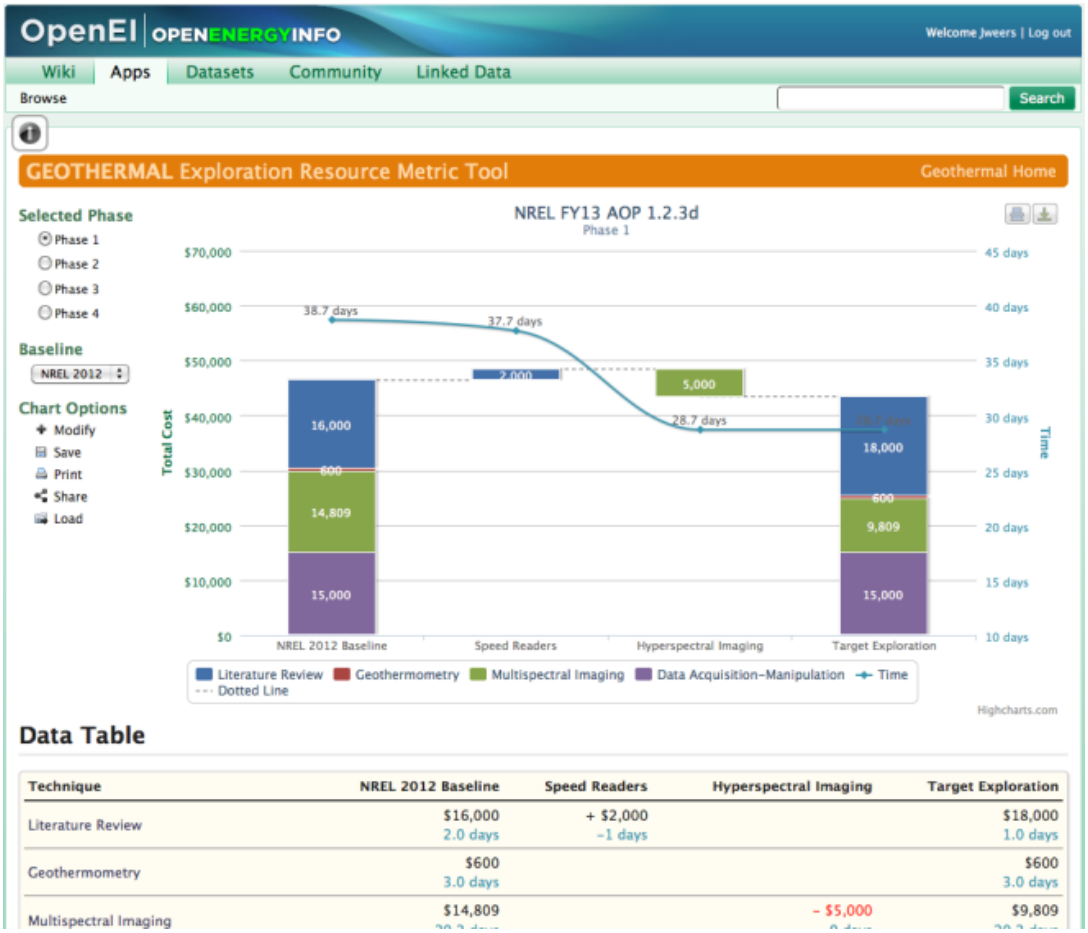

Figure 3: Example chart of the user interface for the Exploration Cost and Time Metric Tool.

CONCLUSION

The GTO funded NREL's efforts in the creation of a database that includes cost estimates and timeframes for techniques that may be used in a hydrothermal exploration program. The database is currently available in aggregated form on OpenEI.org (http://en.openei.org/wiki/Exploration_Techniques). It is intended to be available as an open data source so it can be updated and utilized by industry as necessary.

The cost and time database was used in the development of a baseline exploration technology suite that was validated by industry experts as an acceptable representation of a typical 30MW$_e$ geothermal exploration program. It is intended to be used as a reference point for comparison to innovative exploration techniques and programs.

An exploration metric tool has been developed to graphically display the cumulative impact to exploration cost and time from one or more exploration RD&D efforts. The baseline is used within the tool to represent current cost and time, factors which RD&D projects may impact. The intent is for GTO to use the tool in evaluating the impact of its RD&D funding opportunities. It allows users to quantify the impact that a particular technique, or set of techniques, will have on the cost or time required to complete an exploration program. The tool is available on OpenEI. (http://en.openei.org/wiki/Exploration_Cost_and_Time_Metric).

REFERENCES

Walker, J. D., Sabin, A. E, Unruh, J. R, Combs, J., Monastero, F. C., (2005), "Development of Genetic Occurrence Models for Geothermal Prospecting." Transactions-Geothermal Resources Council, p. 309-314

Williams, C. F., Reed, M. J., Mariner, R. H., DeAngelo, J. and Galanis, S. P. J. (2008), "Assessment of Moderate- and High-Temperature Geothermal Resources of the 16 United States." Fact Sheet 2008-3082. U.S. Geological Survey, http://pubs.usgs.gov/fs/2008 /3082.

APPENDIX A: NREL COST AND TIME DATA SET.

Cost/Time Database 9/19/12								
Techniques	Min $	Avg $	Max $	$ Unit	Min Time	Avg Time	Max Time	Time Unit
2-M Probe Survey	200.00	300.00	500.00	station	1.50	2.00	3.00	hours
Acoustic Logs	1.00	4.63	16.00	foot	8.39	16.08	32.17	days
Aerial Photography	100.36	240.54	2360.00	sq. mile	0.10	0.26	2.00	days/sq. mile
Aeromagnetic Survey	22.53	167.34	1126.30	mile	0.26	0.86	2.33	days/100 mile
Airborne Electromagnetic Survey	48.27	317.38	1609.00	mile	0.11	0.98	4.66	days/100 mile
Airborne Gravity Survey	86.89	274.17	933.22	mile	4.00	37.33	164.00	weeks
Airborne Resistivity Survey	128.72	486.72	1609.00	mile	1.68	2.59	5.70	days/100 mile
Audio-Magnetotellurics	1118.26	8900.03	25000.00	mile	4.56	14.17	28.12	days/10 mile
Caliper Log	0.40	0.78	3.00	foot	0.35	0.46	0.69	days
Cement Bond Log	0.85	1.25	3.00	foot	0.35	0.46	0.69	days
Compound and Elemental Analysis	15.00	30.00	50.00	compound	-	-	-	-
Controlled Source Audio MT	1866.44	11696.63	25000.00	mile	3.97	11.64	28.12	days/10 mile
Controlled Source Frequency-Domain Electromagnetics	2928.38	4505.20	7079.60	mile	9.12	16.89	27.35	days/10 mile
Controlled Source Frequency-Domain Magnetics	12000.00	18000.00	25000.00	mile	1.00	11.00	56.00	days
Core Analysis	2000.00	10000.00	25000.00	30 foot core	1.00	4.00	8.00	weeks
Cutting Analysis	1000.00	4000.00	10000.00	100 feet cut	1.00	3.00	8.00	weeks
Data Acquisition-Manipulation	60.00	250.00	500.00	hour	5.00	7.50	10.00	days
Density Log	0.40	0.68	0.80	foot	0.69	0.69	1.39	days
Direct-Current Resistivity	4827.00	16109.00	45000.00	mile	-	-	-	-
Field Mapping	400.00	600.00	1000.00	hour	2.00	6.00	16.00	weeks
FLIR	241.35	643.60	1609.00	mile	0.25	1.03	3.89	days/sq. mile
Fluid Inclusion Analysis	17.57	17.57	26.78	sample	2.00	2.00	4.00	weeks
FMI Log	--	5000.00	--	well	-	-	-	-
Gamma Log	0.25	0.38	0.75	foot	0.35	0.69	0.69	days
Geodetic Survey	250.00	600.00	1500.00	point	5.00	15.00	20.00	days
Geographic Information System	70.00	80.00	150.00	hour	0.00	0.00	0.01	days/sq. mile
Geothermal Literature Review	60.00	200.00	250.00	hour	-	-	-	-
Geothermometry	30.00	30.00	30.00	sample	-	-	-	-
Ground Gravity Survey	35.00	68.31	300.00	station	0.13	0.25	0.67	days/10 stn
Ground Magnetics	160.90	2835.68	18000.00	mile	0.60	3.09	8.63	days/10 mile
Hyperspectral Imaging	8.63	1337.56	10759.45	sq. mile	1.13	21.24	92.00	days
LiDAR	300.00	850.00	1300.00	sq. mile	9.00	19.00	53.00	days
Macrophotography	220.00	220.00	500.00	hour	1.00	1.00	5.00	days
Magnetotellurics	522.22	1738.83	2297.62	station	1.67	3.77	7.50	days/10 stn
Microgravity-Hybrid Microgravity	50.00	61.67	115.00	station	0.30	0.36	1.20	days/10 stn
Modeling-Computer Simulations	85.00	195.00	500.00	hour	-	-	-	-
Mud Logging	1300.00	1450.00	2000.00	day	1.00	1.00	1.00	days
Multispectral Imaging	10.00	370.23	1312.50	sq. mile	1.50	29.20	135.00	days
Multispectral Thermal Infrared	10.00	146.88	259.38	sq. mile	0.03	0.03	0.08	days/sq. mile
Near Infrared Surveys	450.00	800.00	1350.00	sq. mile	6.00	16.00	30.00	weeks
Optical Televiewer	1.00	1.50	3.00	foot	-	-	-	-
Petrography Analysis	275.00	420.00	625.00	sample	-	-	-	-
Pressure Temperature Log	0.60	1.48	2.50	foot	1.23	1.46	2.39	days
PSInSAR	20.72	103.60	259.00	sq. mile	16.00	54.00	120.00	weeks
Radiometrics	8.05	4609.55	16000.00	mile	0.05	1.12	4.02	days/10 mile
Reflection Survey	26763.33	44946.67	120000.00	sq. mile	1.36	4.45	12.46	days/sq. mile
Refraction Survey	6206.80	10877.33	25000.00	mile	12.73	36.18	115.27	days/10 mile
Resistivity Log	0.40	0.68	1.00	foot	0.35	0.35	0.69	days
Resistivity Tomography	60.98	76.22	106.71	foot	1.00	2.00	3.00	days
Rock Density	10.00	30.00	50.00	sample	1.00	10.00	21.00	days
SAR	10.44	59.57	673.40	sq. mile	21.00	40.00	96.00	days
Self Potential	907.48	6473.05	18000.00	mile	15.02	23.33	42.91	days/10 mile
Single-Well and Cross-Well Seismic	30.49	54.88	106.71	foot	1.00	2.00	3.00	days
Slim Holes	100.00	169.90	200.00	foot	75.30	100.13	111.90	feet/day
Sonic Mapping & Caliper	0.40	0.85	1.25	foot	-	-	-	-
Spontaneous Potential	0.40	0.48	1.00	foot	-	-	-	-
SRT	0.00	0.00	0.00	process	2.00	2.00	2.00	days
Static Temperature Survey	0.25	0.35	0.75	foot	-	-	-	-
Stereo Satellite Imagery	259.00	282.31	362.60	sq. mile	-	-	-	-
SWIR	450.00	800.00	6000.00	subject	1.00	1.00	5.00	days
Thermal Gradient Holes	5.00	16.50	50.00	foot	-	-	-	-
Time-Domain Electromagnetics	62.35	8609.42	25000.00	mile	0.26	8.48	27.77	days/10 mile
Trace Element Analysis	15.00	18.00	106.00	element	-	-	-	-
Vertical Electrical Soundings	45052.00	50415.33	62214.67	mile	3.00	5.65	15.50	days
Verticle Seismic Profiling	60.98	76.22	106.71	foot	1.00	2.00	3.00	days
Z-Axis Tipper Electro Magnetics	4827.00	6206.14	17239.29	mile	-	-	-	-