FINAL REPORT

Mapping Interaction between Magmatic and Hydrothermal System with Fluid Inclusion Analysis

Project ID:	10-03-013
Coordinator:	Anette K. Mortensen
Start date:	1. September 2011
Duration:	2 years
Partners:	Landvirkjun, Háskóli Íslands, USGS, Ormat

1 Project summary

The GEORG project 10-03-013 "Mapping Interaction between Magmatic and Hydrothermal System with Fluid Inclusion Analysis" was a two-year research project that commenced in September 2011. The project encountered several setbacks, which has resulted in that not all the milestones outlined in the project proposal have been achieved. This final report includes an overview of what have been achieved in the project as well as outlining complications and delays encountered during the project.

The objective of GEORG project 10-03-013 "Mapping Interaction between Magmatic and Hydrothermal System with Fluid Inclusion Analysis" was to investigate chemical changes and rock alteration in vicinity to magma near the roots of active geothermal systems by studying alteration in cuttings, applying several analytical techniques in studying fluid inclusions and finally modelling interaction between geothermal and magmatic system based on results from mapping changes in alteration and fluid inclusion composition near this interphase along with fluid chemistry from wells drilled in vicinity to magmatic conditions.

Originally the project plan entailed four steps as outlined in the grant agreement:

1) Characterisation of hydrothermal alteration in the deep sections of 5-7 production wells in Krafla and two wells at Þeistareykir with petrographic and microprobe analysis
2) Fluid inclusion analysis (Th and Tm) of 5-7 wells in Krafla and two wells in Þeistareykir geothermal field in order to characterise changes in temperature and salinity with depth
3) Laser Ablation ICP-MS of individual fluid inclusions to measure the fluid composition, origin and magmatic contribution (major, trace elements, gases and isotopes (e.g. He and Ar isotopes)) (Hofstra et al., 2009), at depths in the wells selected from fluid inclusion analysis (T_h and T_m) and FIS gas analysis.
4) Modelling of fluid-magma and fluid-rock interaction in the deeper parts of geothermal reservoirs, where high temperatures and high magmatic impact occur through interpretation of results of alteration zonation and fluid inclusion analysis (LA ICP-MS and FIS) in comparison with chemical analyses of fluid samples from the wells.

Initially the objective of the project was to take outset in two active geothermal systems: Krafla and Þeistareykir in NE-Iceland. However, during the project focus centred on studying Krafla geothermal system as changes that could be associated with the interphase between the geothermal and magmatic system was more prevailing in data from that system.

In the following sections results of the studies at Krafla geothermal system and Þeistreykir geothermal system will be summarized.

1.1 Þeistareykir geothermal system – fluid inclusion study of well ÞG-3

At Þeistareykir was carried out a study of fluid inclusion analyses (T_h ~ homogenisation temperature) in well ÞG-3 at three depth intervals between 2000-2500 m depth, but in well ÞG-3 superheated temperature conditions had temporarily been measured in November 2006, when the well was recovering in temperature after drilling completion (figure 1). The study included fluid inclusion analyses of both alteration minerals (mainly quartz) and rock-forming minerals (plagioclase). The results revealed that temperature was mostly at or below the boiling point at the depths that were sampled except at 2100 m depth, where high temperatures up to 370-385°C were recorded. When homogenization temperatures are higher than the boiling point, it is typically interpreted to reflect localized boiling in the reservoir. In ÞG-3 it is associated with the upper part of an interval dominated by intrusions with low permeability. The disclosure of temperatures higher than the boiling point in ÞG-3 both from temperature logging and fluid inclusion analysis could point towards that the well is approaching the transition zone from the geothermal to the magmatic system.

Despite of these findings it was decided not to carry out additional analyses with single fluid inclusion analysis techniques because of the low number of fluid inclusions exhibiting superheated homogenisation temperatures. Instead it was decided to focus the detailed study of single fluid inclusion analysis on samples from Krafla, where inclusions with high homogenisation temperatures were much more abundant increasing the likelihood of an outcome of the single inclusion analyses methods, as such analyses commonly require analysis of several inclusion before obtaining reliable results.

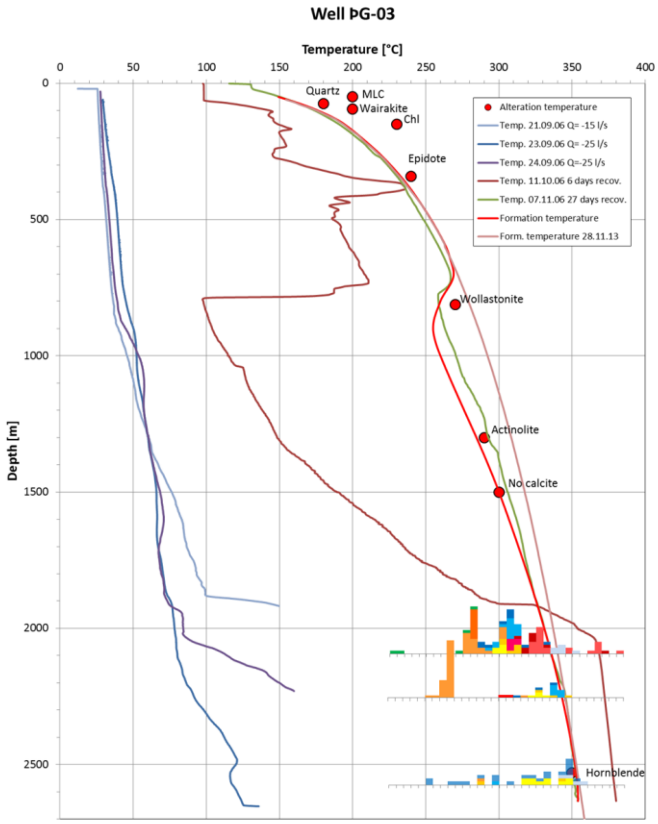


Figure 1. *Measured temperature, alteration temperature and homogenisation temperature in well ÞG-3 (unpublished data).*

1.2 Krafla geothermal system

At Krafla geothermal system a drilling campaign was carried out in 2007-2009 where wells were drilled into different parts of the reservoir with the purpose of expanding the field. Several wells encountered corroding fluid conditions, which have been attributed to superheated conditions. Two wells even drilled into magma of rhyolitic composition e.g. KJ-39 and IDDP-1. The shallow level of magma within Krafla Caldera has provided an opportunity to study and characterise the interface between the hydrothermal and magmatic system.

During this project studies focused on characterising the changes observed in vicinity to the magmatic or superheated conditions. Four wells were studied in detail: KJ-38, KJ-39, KG-25 and IDDP-1.

1.2.1 Master´s project: Hydrothermal alteration and fluid inclusion analysis of well KJ-38, KJ-39 and KG-25

The two first milestones of the project were carried out as part of the M.Sc. study of Margrét Th. Jónsdóttir. She did a detailed fluid inclusion study of the four wells measuring the homogenisation temperature (T_h) at 2-4 depth intervals in each well. The fluid inclusion analyses have revealed that while the temperature is following the boiling point curve with depth, then some of the fluid inclusions are recording higher temperatures, which seems to reflect boiling conditions (figure 2). At the same time the fluid inclusion study revealed that secondary one phase inclusions become pronounced in the lowermost part of the wells (KG-25, KJ-39, IDDP-1), but these inclusions consist both of vapour rich inclusions and melt inclusions. In well IDDP-1 it was only possible to find one-phase vapour-rich inclusions or melt inclusions, which excluded further fluid inclusion analyses of this well under the study of the master´s student.

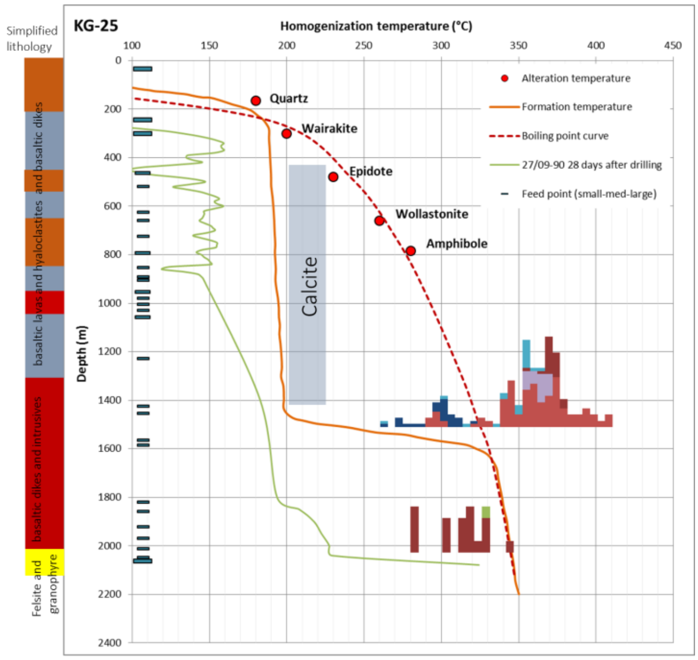
Further the M.Sc. study included a petrographic and mineralogical study of alteration minerals in the deeper parts of three of the wells; KJ-38, KJ-39 and KG-25. The main conclusions of that part of the study was that epidote-chlorite-actinolite alteration minerals characterise well KJ-38 and KJ-39 at 2200 m depth while no epidote was identified in KG-25 at 2085 m indicating a higher temperature grade reflected by the actinolite alteration zone has been attained near the bottom of this well. Few other conclusions were drawn from this part of the study except that presence of hematite suggests that oxidizing conditions form in vicinity of intrusives. The study did not reveal whether contact metamhorphic conditions had developed in vicinity to the transition zone from hydrothermal to magmatic system as in particular the study of alteration in well KG-25 was hoped to reveal given the results of fluid inclusion analyses.

Margrét Th. Jónsdóttir completed her master´s degree in late summer 2014 one years later than originally was planned. The scope of the M.Sc. project was modified during the project. Originally it was planned that the study should entail more wells, but it was necessary to reduce the extend of this work as fluid inclusion analyses proved more time consuming than expected because of the small grain size of the cuttings.

The M.Sc. study was further extended as the student requested reduced study load due to family related issues. This meant that the output of study diminished and thus required more time to complete the study. To ensure that the student completed her study more money was allocated to the M.Sc. student that otherwise had been allocated to analytical work and chemical modelling at ÍSOR.

Karl Grönvold, Árný E. Sveinbjörnsdóttir and Níels Óskarsson at University of Iceland were supervising and assisting with the mineralogical study of the M.Sc. study including SEM image and probe analyses of selected samples from three of the wells. During this part of the project communication with the project coordinator and supervisor at ÍSOR was ignored. For some reason that has never been clarified the co-supervisors at University of Iceland intended to let the student graduate without including the project coordinator and supervisor at ÍSOR in the second part of the master´s project as well as the thesis evaluation process. It was not until within a week or two from the expected graduation date that the project coordinator was informed about the status. On request of the project coordinator the graduation was delayed to allow time for review, and eventually Margrét Th. Jónsdóttir graduated in with M.Sc. degree in the fall 2014.

Following this incident, the role of the M.Sc. student committee has been strengthened at University of Iceland as well as the regulations surrounding the graduation procedure, so hopefully such an incidence of neglect of communication will not occur again.



(Jónsdóttir, 2014)

Figure 2. *Measured temperature, alteration temperature and homogenisation temperature in well KG-25 (Modified from Margrét Th. Jónsdóttir, 2014).*

1.2.2 Fluid inclusion bulk gas analysis and single inclusion geochemical analysis.

The third milestone of the project was further analysis of the fluid inclusions both through fluid inclusion bulk gas analysis and single inclusion geochemical analysis of vapour-rich inclusions and melt inclusions.

Fluid inclusion bulk gas analysis was carried out by Lara Owens at New Mexico Tech (currently at Ormat). She did fluid inclusion bulk gas analysis of four wells in Krafla (KJ-17, KG-25, KG-26 and KJ-39), but the analyses can be used to outline the fluid stratigraphy of the geothermal system in vicinity to the analysed wells.

The fluid inclusion bulk gas analyses of well KG-25 revealed that the subdivision of the reservoir is noticeable with this method, but the upper reservoir is characterised by depressed CO_2 geothermometer temperatures signifying cooling of aquifer fluids (figure 3). The transition into the lower reservoir with boiling conditions at 1500 m depth is characterised by a large range in homogenisation temperature of liquid-rich inclusions ranging between 260-410°C suggesting an interval characterised by changing conditions affected by boiling. The fluid inclusion bulk gas analysis of well KG-25 were particularly interesting as they indicated that the lower reservoir can be further subdivided. Between 1500-1800 m depth the CO_2 and H_2 geothermometer temperatures are comparable reflecting temperatures near the boiling point, while fluid inclusion bulk gas analyses reveal that below 1800 m depth the reservoir is characterised by a vapour-rich zone showing gradual increase in total gas with depth, which is coinciding with an increased ratio of insoluble/soluble gases such as CO_2/Total gas and H_2/H_2S.

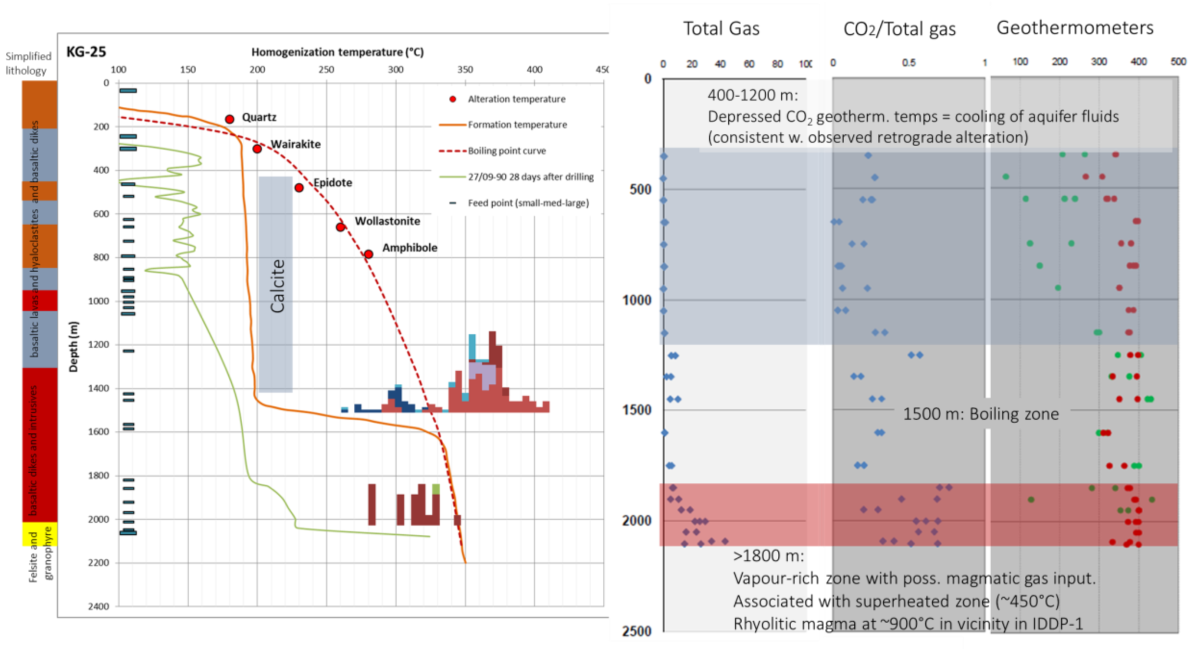


Figure 3. *Fluid inclusion analyses from well KG-25. Left: Stratigraphy, formation temperature, temperature based on selected alteration minerals and fluid inclusion thermometry. Right: Fluid inclusion bulk gas stratigraphy.*

Selected samples that had been analysed by Margrét Th. Jónsdóttir as part of her master´s project were sent to Al Hofstra for single fluid inclusion analysis at the laboratory that he leading at USGS in Denver, USA, but through these analyses the objective was to obtain further analyses of the composition of fluids and gasses in the inclusions. They attempted to analyse samples from well KJ-38, KJ-39, KG-25 and IDDP-1, but it was only possible to get results from inclusions from well KJ-39 and KG-25.

The single fluid inclusion analyses revealed that the inclusions observed in the deeper parts of these four wells consisted mainly of vapour-rich fluid inclusions similar to what is observed in steam reservoirs. In well KG-25 analyses of single fluid inclusions below 2000 m depth showed that the vapour-rich inclusions had exsolved from rhyolite melt (figure 4) and from Laser Raman spectrometry it was confirmed that the vapour-rich inclusions contained CO_2.

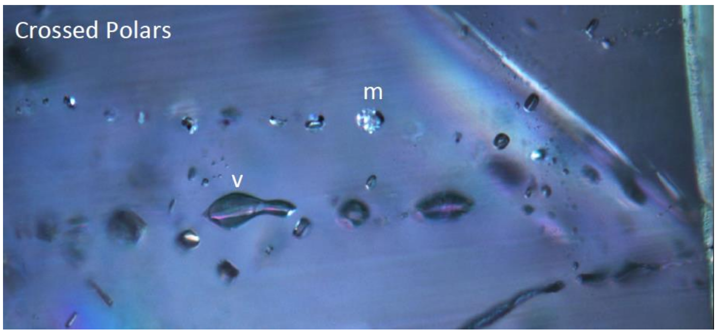


Figure 4. *Fluid inclusions in quartz from 2020 m depth in well KG-25. The inclusions consist of co-genetic melt inclusions (m) and vapour-rich inclusions (v) indicating the vapour exsolved from the rhyolite melt, when in was intruded at this depth.*

In well KJ-39 three types of fluid inclusions were identified; primary basalt melt inclusions and vapour-rich inclusions in plagioclase and secondary rhyolite melt inclusions and vapour-rich inclusions. LA-ICP-MS analyses of the melt inclusions were calibrated against published geochemical analyses of rhyolites and basalts from Krafla for multi-element data reduction. The result of the multi-element data reduction is that rhyolite melt inclusions in well KJ-39 are of similar composition to the rhyolite glass from well IDDP-1 (figure 5), which have been published by Zierenberg et al. (2002).

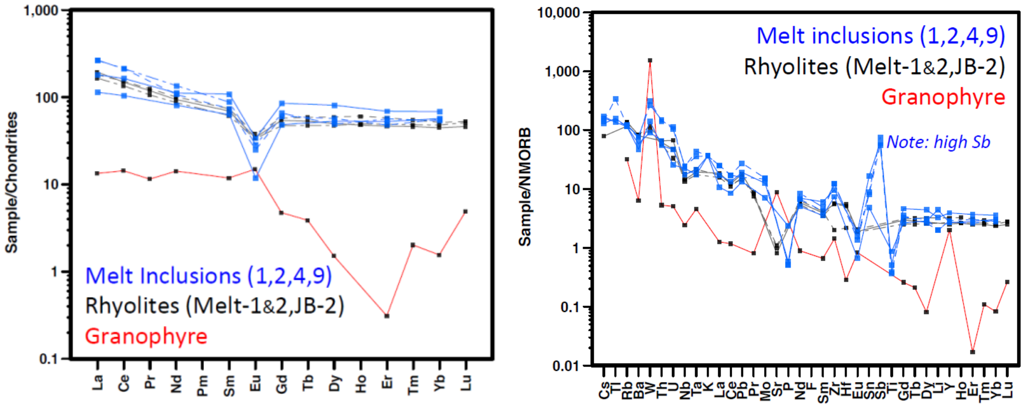


Figure 5. *Fluid inclusions in quartz from 2020 m depth in well KG-25. The inclusions consist of co-genetic melt inclusions (m) and vapour-rich inclusions (v) indicating the vapour exsolved from the rhyolite melt, when in was intruded at this depth.*

Some of the conclusions from the detailed study of fluid inclusions near the transition from hydrothermal to magmatic system is that the transition zone is characterised by a vapour-rich zone with signs of increased magmatic gas input. The thickness of the zone is variable, but in vicinity of well KG-25 it is up to 200-300 m thick.

Further, the study has revealed that the rhyolite magma in KJ-39 is similar in composition to the rhyolite encountered in IDDP-1, which point towards that the rhyolite may have formed in the same event or under similar conditions, and that the size of the rhyolite magma may be larger than initially anticipated, but the distance between KJ-39 and IDDP-1 is more than 1,5 km and magma was encountered 400 m deeper in the crust in well KJ-39.

In the spring of 2013 most data analyses had been completed and the last milestone of chemical modelling and publication of the results remained to be completed. At that time the project was on schedule for completion with one year delay. However, in the late summer 2013 did the project coordinator resign from ÍSOR. Subsequently ÍSOR formally maintained the role of project coordinator, while allowing the original project coordinator to complete the remainder of the project at her wish. Despite intensions to complete the project objectives this has been hampered by new obligations. The last couple of years the results of the project have been presented at meetings and workshops organised by GEORG in Iceland, but eventually the results were not presented at an international conference as originally planned. The status of the project at this time of closure is that the results of the study are sufficient for a publication. An outline draft for an article has been made and it is still the intension to publish some of the results of this study though the project is now completed.

2 Project Management

Project management and distribution of responsibility has followed the guidelines outlined in the project agreement. Anette K. Mortensen was the project coordinator until the end of 2013, when she resigned from ÍSOR. Subsequently ÍSOR formally maintained the role of project coordinator, while allowing the original project coordinator to participate and partly manage the remainder of the project at her wish. The role of the project coordinator in this project was to ensure that the goals of this scientific study was achieved, by managing the number of study areas and number of individual wells to be studied based on analytical progress while maintaining within the project budget.

Supervision of the M.Sc. student was carried out in collaboration with University of Iceland, but analytical work in the master´s project was partly carried out at ÍSOR and partly at University of Iceland. As mentioned in chapter 1.2.1 then communication was not maintained between the supervisors at University of Iceland and the project coordinator for some time, but eventually issues were solved so that the master's student could graduate.

As the industry partner in the project Landsvirkjun provided access to valuable data and expertise of Krafla geothermal field and advice on the parts of the field that were most valuable to study.

There were two international partners in the project. Al Hofstra´s team at USGS in Denver, USA, assisted in providing analyses of single fluid inclusions, a technique that is currently not available in Iceland. Lara Owens from University of New Mexico Tech (now at Ormat) provided fluid inclusion bulk gas analyses, which is also a technique that is currently not available in Iceland. They both provided analytical services and expertise knowledge of these analytical techniques and their interpretation and collaboration with these partners were good.

3 Student involvement

One M.Sc. student was supported by this project, Margrét T. Jónsdóttir. She graduated from University of Iceland (Háskóla Íslands) with a M.Sc. degree in the fall 2014. The name of her master's thesis is "Alteration and fluid inclusion temperature in well KJ-38, KJ-39 and KG-25 in Krafla (Ummyndun og vökvabóluhiti í borholum KJ-38, KJ-39 og KG-25 í Kröflu).

4 Publications and disseminations

The results of the research in this project has been disseminated mainly at meetings and workshops arranged by GEORG, but list of disseminations is outlined below:

1. Mortensen, A. K., 2012. Mapping Interaction between Magmatic and Hydrothermal System with Fluid Inclusion Analysis. GEORG Open House, 22.11.2012. Presentation
2. Jónsdóttir, M.T., 2012. Mapping Interaction between Magmatic and Hydrothermal System with Fluid Inclusion Analysis; 3rd European Geothermal Ph.D. day in Pisa, Italy; Conference poster
3. Jónsdóttir, M.T., 2014. Ummyndun og vökvabóluhiti í borholum KJ-38, KJ-39 og KG-25 í Kröflu. Meistararitgerð, Jarðvísindadeild, Háskóli Íslands, 101 bls.
4. Mortensen, A. K., Jónsdóttir M. Th., Owens L., Hofstra A., 2016. Fluid-rock Interaction between magmatic and hydrothermal system with fluid inclusion analysis. The Deep Roots of Geothermal Systems, Open Conference, Reykjavík Energy Headquarters 18.-19. February 2016. Presentation

5. Mortensen, A. K., Jónsdóttir, M. Th., Owens L., Hofstra A., Guðmundsson Á. 2016 Mapping interaction between magmatic and hydrothermal System with fluid inclusion analysis. GGW2016 - GEORG Geothermal Workshop, 24. November 2016. Abstract for Poster presentation.

5 Cost statement

An overview of anticipated and actual costs of the project is presented in table 1. The actual cost of the project almost equals the original estimated cost, however as the cost of some parts of the project was higher than anticipated, then the scope of other parts of the project had to be reduced.

The main discrepancies are the additional time it required for the student to finish her master´s degree. Then analytical costs were higher or required more time or samples than originally was accounted for. Furthermore, the unit price of specialists increased during the project period.

To ensure that the cost of the project remained within the allocated budget, then this resulted in that time allocated for a specialist at ÍSOR to analyse, do model calculations and presenting the project at meetings was greatly reduced in the second part of the project and for similarly reasons there was no participation in an international conference to present the results of the project.

Table 1. *Cost statement for the project showing anticipated and actual costs.*

Salaries including overhead	BUDGET				ACTUAL COST			
	Unit cost	Man-months	hours	Total	Unit cost	Man-months	hours	Total
ISOR	1200	2,5	350	3.000	1320	2,39	335	3.154
ISOR	1250	2,5	350	3.125	1375	0,98	137	1.346
LV	1250	2	280	2.500	1375	2,00	280	2.750
UI	1250	2	280	2.500	1375	2,00	280	2.750
USGS	1500	1	140	1.500	1500	1,00	140	1.500
Ormat	1250	1	140	1.250	1250	0,71	100	893
MSc stud. task 1-2	500	9	1260	4.500	500	12,61	1765	6.304
		20	**2800**	**18.375**		**21,69**	**3037**	**18.696**
Operational exp.								
Laser ablation ICP-MS analysis 5 days of $500 pr. day				275				286
Microprobe analysis 24 days of 10.000 pr. day				240				678
Fluid inclusions stage and microscope, 40 thin sections				460				500
				975				**1.464**
Travel expences								
Conference participation				800				0
				800				**0**
Total cost				**20.150**				**20.160**
GEORG support				**9.975**				**9.975**
Own financing				**10.175**				**10.185**