



ENGINE

ENhanced Geothermal Innovative Network for Europe

Workshop 4

**Drilling cost effectiveness and feasibility
of high-temperature drilling**

2 - 5 July 2007

ISOR, ICELAND GEOSURVEY - REYKJAVÍK - ICELAND



Workshop Abstracts

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ABSTRACT SUMMARY

SESSION 1 Case histories of EGS and high-temperature drilling	7
Drilling EGS wells at Soultz-Sous-Forêt HETTKAMP T., TEZA D., BAUMGÄRTNER J., GANDY T.....	9
Drilling into deep sedimentary geothermal reservoirs – case study Groß Schönebeck BRANDT W., HUENGES E., ZIMMERMANN G., MOECK I., SAADAT A., HOLL H-G.	11
A Snapshot of the Drilling and Completion Practices in High Temperature Geothermal Wells in the Philippines SARMIENTO Z.....	14
Experiences on geothermal drilling in El Salvador MONTERROSA M., MAYORGA H.	15
From an ENhanced Geothermal Innovative Network for Europe to an European Geothermal Drilling Program? LEDRU P., HUENGES E., FLOVENZ O.	16
Geothermal drilling in some parts of Asia and Russia ABANES R.	18
The Iceland Deep Drilling Project (IDDP) FRIDLEIFSSON G. O., ELDERS W.	19
SESSION 2 Innovative technology and drilling effectiveness.....	21
InnovaRig - an Instrument for a European Geothermal Drilling Program HUENGES E., WOHLGEMUTH L., PREVEDEL B.	23
Geothermal drilling with modern highly automated rigs - a drilling contractor's perspective STEFÁNSSON A.	25
High Temperature Wells - Cost Analysis INGASON K., MATTHÍASSON M.	26
The GeneSys-Project: Coast Efficient Single-Well-Concepts for Deep Geothermal Energy from the Northern German Basin JUNKER R., TISCHNER T., KEHRER P., JATHO R., WESSLING S., HOFMEISTER K., EVERS H., SULZBACHER H.	28
Spallation Drilling for Deep Heat Mining ROTHENFLUH T., RUDOLF VON ROHR P.	29
An illustration of VSP efficiency in crystalline rocks to plan the deviation of a geothermal well while drilling PLACE J., NAVILLE C., LE GARZIC E., GERAUD Y., DIRAISON M.	30
SESSION 3 Well design and cementing.....	31
Challenges faced in drilling high-temperature geothermal wells in Iceland THORHALLSSON S.	33
Iceland Deep Drilling Project (IDDP) casing design for extremely high temperatures MATTHÍASSON M., INGASON K.	34

Top-down cementing of geothermal wells in Iceland BIRKISSON S., THORHALLSSON S.	36
The casing scheme ... most important factor for the success of a deep well? SPERBER A.	38
Corrosion Testing for Hot Dry Rock Geothermal Wells in Soultz-sous Forêts-Preliminary Results MULLER J., BILKOVA K., SEIERSTEN M.	40
Evaluation of cement integrity using distributed temperature sensing HENNINGES J., BRANDT W.	41
Development and Application of Metal Casing Packers KLEE G., RUMMEL F., BAUMGÄRTNER J.	42
Well stimulation using explosives GARCIA-NOCEDA C.	43
High Temperature, high precision, temperature measurement probe LEBERT F.	44
SESSION 4 Reservoir assessment, stimulation, testing and logging.....	45
Reservoir engineering in two geothermal field in El Salvador MONTERROSA M.	47
The PT borehole simulator HEX-B MÉGEL T., KOHL T.	48
Conventional logging – geothermal wells SCHULTE T., HOLL H-G.	49
High temperature logging ASMUNDSSON R.	50
Hydraulic fracture operation in the hydrocarbon industry - Lessons for geothermal applications FOKKER P.	51
Why coring should be part of any exploratory high-temperature drilling project, as illustrated by the case histories of the Salton Sea Scientific Drilling Project (SSSDP) and the planned Iceland Deep Drilling Project (IDDP): an appeal for technology development ELDERS W.	52
Chemical stimulation of the Soultz wells SCHINDLER M., NAMI P., TISCHNER T.	58
AUTHORS' INDEX.....	59

SESSION 1

Case histories of EGS and high-temperature drilling

ENGINE - ENhanced Geothermal Innovative Network for Europe
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Drilling EGS wells at Soultz-Sous-Forêt

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In the last 20 Years four new deep wells were drilled to develop a scientific HDR/EGS prototype at Soultz sous Forêts, three old oil wells were deepened into the granite to observe seismicity during hydraulic stimulations and one additional seismic observation well was completely new drilled. In 1997 the upper reservoir or the “stimulated down hole heat exchanger” was tested at app. 3.5 km depth using a doublet in between GPK1 and GPK2. After the deepening of GPK2 and the drilling and stimulation of the wells GPK3 and GPK4 the deeper reservoir at 5 km was investigated using a triplet with two production wells. The first step in every drilling operation is the choice of the right size of the drilling rig with a good safety margin and fitting the wellbore planning. During all drilling operations at Soultz this was the case. During times with high oil prices the availability of drilling rigs is not sufficient anymore, therefore, sometimes bigger rigs than necessary are used and the drilling costs are rising unnecessarily. In Soultz always standard oil field hole sizes were drilled (for example drilling 17 ½” and running 13 3/8” casing or drilling 12 ¼” and running 9 5/8” casing) to reduce the costs and to maximize the availability of spare parts or additional (fishing) tools.

Massive hydraulic stimulation is the key to develop and run an HDR/EGS power plant at economical costs because the natural permeability is not high enough within the deep granite at Soultz. Therefore the wells need to be able to resist the thermal cycles while cooling during injection and while heating during production. The wells at Soultz were completed with an uncemented internal casing which is only supported at the bottom by open hole casing copper nickel packers and a short cementation. Thermal expansion and contraction, of the otherwise self-supporting pipes (during injection and production experiments), are compensated in the well head assembly using high temperature Aflas or Viton ring seal pack-offs. Both the casing packers and the wellhead seals were developed and improved in Soultz during the last years in order to obtain a usable well completion at reasonable cost.

The used bottom hole assemblies and drilling bits at Soultz were improved during the last years therefore longer life times at the same penetration rates of the used drilling equipment could be performed. During directional drilling with a mud motor no improvement of the drilling performance was observed. Therefore the amount of motor runs was minimized to the risk of the high “lost in hole” prices. The abrasiveness of the Soultz granites as well as the fact that it varies on short distances in grain size, alteration and number of fractures per meter PDC-bits were not used. The friction within the highly abrasive granite did not allow using integral blade stabilizers for hole size control. Roller reamers were used instead to control the well path with a slick, packed or pendulum bottom hole assembly. The weak point during directional drilling within the Soultz granite was the number of failures of the MWD equipment. While mud circulation within the granite there is only minor cooling of the formation observed, because the matrix porosity of the granite is zero. The combination of

temperature and the vibration of the drill string reduced the life time of the electronic boards within the down hole equipment of the MWD used.

The granite within the Rhine Graben is highly fractured and a natural water convection exists down to a depth of probably around 10 km. While drilling within these fractures losses and gains were observed in the drilling mud system. A low cost clear brine water mud was used to avoid losses and gains balancing the mud and formation fluid densities up to the second digit behind the Komma.

Drilling into deep sedimentary geothermal reservoirs – case study Groß Schönebeck

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Deeply buried aquifers in the North German Basin with formation temperatures of up to 150°C are investigated to develop stimulation methods to increase the permeability by enhancing or creating secondary porosity and flow paths. The final goal is to test the generation of geothermal electricity from such low-enthalpy reservoirs using a doublet of boreholes, one to produce deep natural water and the other to re-inject the utilized water. For these purposes, an in-situ downhole laboratory was established in Groß Schönebeck, north of Berlin, Germany.

This article describes the challenges and experiences of drilling the geothermal research well into a deep sedimentary geothermal reservoir. The lessons learnt covers drilling large diameter in sheet silicate bearing rocks, directional drilling through and beneath salty formations, and various mud concepts with the goal of minimized formation damage.

At present, two 4.3 km deep boreholes have been drilled. The first well GrSk 3/90, originally completed in 1990 as a gas exploration well and abandoned due to non-productivity, was re-opened in 2000 and was hydraulically stimulated in several treatments between 2002 and 2005. In 2006, the second well GrSk 4/05, planned for extraction of thermal waters, was drilled in order to realize a doublet system with two hydraulically connected boreholes. It is planned to stimulate in the second well both, the Lower Permian sandstones and the underlying volcanic rock. The resulting engineered reservoir should have an increased productivity being operated with minimized auxiliary energy to drive the thermal water loop and should have a minimized risk of a temperature short circuit of the system during a planned 30-year utilization period. The forthcoming phase is designed to demonstrate sustainable hot water production from the reservoir between the two wells through a long-term circulation experiment.

The new well GrSk 4/05 is located at the same drill site as GrSk 3/90, the surface distance of both wells is about 27 m. Drilling operation begun in April 2006 and were finished in January 2007 at 4400 m depth.

Drilling operations

The design and drilling of the second well considered the following issues (1) to (3): (1) the deep static water table of the reservoir and the respective withdrawal during production (housing for the submersible pump), which requires a large hole diameter, (2) the distance between the two wells of the doublet in the target horizon and the opportunities of increasing the inflow conditions by an inclined well and later by implementation of multiple fracs, by using the directional drilling techniques, and (3) a drilling mud concept, which avoids formation damage of the reservoir as much as possible.

The following chapters focus on the encountered drilling experiences ranging from circulation loss during cementation via collapsing of casings within Upper Permian evaporites up to the occurrence of acid gas indications. Finally the entry into the reservoir is described.

The drilling started with the large hole diameter (23") with difficulties in clay dominated depth sections. Therefore, sufficient pumping capabilities beyond 4000 l/min were required. A complete casing cementation was necessary, because during hot water production thermally induced stress might cause casing damage on the non-cemented pipes.

A total fluid loss and uncontrolled hydrofracturing occurred during the bottom up cementation of the combined 16" x 13 3/8" casing, performed with a mean slurry density of 1450 kg/m³. Therefore, squeeze cementation was performed from top of the well to the former cement infiltration zone. The successful placement of the cement was controlled by thermal logging.

After drilling 1600 m thick Upper Permian evaporates counterbalanced with a mud density of 2000 kg/m³, a the 9 5/8" liner was installed which - despite of a strength with a safety factor of 1.8 - collapsed in the bottom region after reduction of the mud density back to 1060 kg/m³. Presumably, additional stress components from anisotropic stress by the well inclination of about 20° in connection with temperature induced high ductile rocksalt (temperatures of 110°C in 3800 m depth) caused this failure. Stress concentration in interbedded anhydritic layers might have increased anisotropic stresses. The collapsed 9 5/8" liner was replaced with a combined 7"x 7 5/8" liner after sidetracking. The latter caused further challenges as the setting of the mechanical anchor of the whipstock required a modification of the anchor for a reliable operation in mud with 40% baryte content. Furthermore, the borehole design needed to be adjusted due to the loss of one casing dimension.

Therefore, the borehole was deepened with 5 7/8" diameter drilling into the geothermal reservoir of the Lower Permian section.

In order to avoid induced permeability decreases through invaded drilling mud, this reservoir below 3900 m was drilled with a near balanced mud density of 1030 kg/m³. However, borehole wall breakouts at 3940 m forced a cleaning run and an elevation of mud pressure to 1100 kg/m³. This specific mud pressure was provided by a geomechanical study that investigated the initiation of borehole breakouts in the reservoir successions under low mud pressures.

Another reason for increasing the near-balanced mud weight was the occurrence of HC - gas with H₂S - content below the 7 5/8" casing shoe (within fissured lowermost Upper Permian). To prevent this gas inflow, the mud density had to be increased up to 1200 kg/m³.

We used a marble flour based mud (OptiBrigde™) to minimise fluid losses into the productive sandstone formations of the target horizon. Due to the danger of differential sticking and formation damage the mud weight was slightly decreased in the further drilling operations. Fluid losses were not significantly observed during the rest of drilling and casing operations.

The well followed its foreseen path and target and a combined 5" liner with a non-cemented section of pre-perforated pipes at the bottom was installed in the lowermost section at 4400 m depth.

Conclusions

In the North East German Basin, 4000 m deep Lower Permian sandstones and volcanic rocks have been explored for geothermal energy production. Within this context, the gained drilling experiences show (1) that drilling a large hole diameter (23") is feasible but challenging especially in clay dominated layers, (2) that directional drilling can be applied as a standard operation, and (3) that a variable mud concept needs be applied in order react to unforeseen operational requirements such as formation damage, breakouts, or inflows. In this project, technical and scientific challenges were successfully met and the lessons learnt provide essential know how for developing future drilling strategies in deep sedimentary geothermal systems, especially in the Central European Basin System.

A Snapshot of the Drilling and Completion Practices in High Temperature Geothermal Wells in the Philippines

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Well drilling in the Philippines currently account for 66% of the cost of a steamfield development and 33% of the total project cost. A key element which directly influences the drilling cost is associated with the problems on unrecoverable loss of circulation and collapsing formations which hindered drilling progress. Considering its significant impact in the pricing of steam, and the need to make the geothermal electricity price more competitive, geothermal operators in the Philippines continue to search for innovations to test new technologies that would speed up drilling operations. Recent drilling results indicate an emerging and better performance that was previously subsumed to be unpredictable, based on a wide scatter in the Cartesian plot of the total depth (TD) drilled versus duration.

Considerations applied in well design, drilling practices and completion technology in the Philippines are discussed in this paper. Downhole logging, to determine static formation temperatures while drilling, aides in setting the production casing at desired temperatures. Right-sizing of casing allows wellbore output optimization and, thus reduces total well requirements for highly permeable reservoirs. Hydro-fracturing, thermal fracturing and acidizing have been effective in improving production and injection capacities of wells. Under-balanced drilling using aerated mud and water in an under-pressured reservoir significantly improved drilling performance and led to attainment of drilling targets and successful completion of wells. The completion of >2500 meter well in less than 30 days had been achieved through the use of portable top drive equipment, high performance polycrystalline diamond bits (PCD), high temperature mud motors and the implementation of improved drilling practices.

Experiences on geothermal drilling in El Salvador

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The drilling of geothermal wells in El Salvador started in the late 60's when 3 deep exploratory wells were drilled (AH-1, CH-1 and TR-1) present 96 commercial casing wells have been drilled in the whole country. The standard casing programme is 9 5/8" for production casing and 7" or 7 5/8" for slotted linner, in some cases 13 3/8 and 9 5/8 also have been used. In the late 90's, in order to reduce the formation damage air, aerated mud or foam was used at the Berlin field, where almost 300°C is measured. The use of directional wells was also implemented mainly to reduce the environmental impacts of the civil works. The rock formation is andesite lavas, tuff and clays, however hydrothermal alteration is normally found in the shallow or deeper zones. The main constraints or problems during the drilling operation are the loss of circulation in the preliminary stages, several permeable zones at different depths in the same hole, blow out in shallow thermal aquifers and formation collapses or large severity that normally could cause stuck of the pipe string, the use of lubricating fluids, back reaming or back off operation must be necessary to recover the pipe or also the complete hole. In spite of the normal problems during the drilling operations, the wells are the unique way to get out the fluid and energy from the reservoir and an alternative to convert in reality the use of the geothermal energy in El Salvador.

From an ENhanced Geothermal Innovative Network for Europe to an European Geothermal Drilling Program?

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The European Commission support for geothermal energy research has been constant since the end of the eighties but has significantly increased within its 6th R&D Framework Program. The ENGINE Coordination Action (ENhanced Geothermal Innovative Network for Europe) is aimed at co-ordinating present R&D initiatives for Enhanced Geothermal Systems (EGS), ranging from the resource investigation and assessment stage to exploitation monitoring. Thirty five partners are involved in ENGINE, representing 15 European Countries plus Mexico, El Salvador and Philippines. By mid-term, the project has organised 2 conferences and 4 specialised workshops. Already after one year, the material available on the web site <http://engine.brgm.fr> reveals a strong motivation of the scientific community to update the framework of activities, preparing a Best Practice Handbook and defining new ambitious research projects.

Due to the increasing price of energy and the need to reduce greenhouse gas emission, there is a noticeable increase in interest in geothermal energy from the industry in Europe. A Stakeholder Committee has been created to enhance links between R&D teams and stakeholders, i.e. private or public firms and authorities either already involved in geothermal energy, or will possibly be in the near future. The aim of this committee is to provide information about on going R&D efforts in Europe about Enhanced Geothermal Systems and give insight into the newest achievements made by industrial projects. Strategic guidance to the Executive Group and to Contractors in general is expected through suggestions and recommendations of the Committee. Several points of convergences are already underlined.

The general question of demonstrating the efficiency of a wide range of geothermal applications has been raised. If all R&D teams and stakeholders are convinced, an effort of communication in Europe still has to be done to promote the geothermal energy as a cost-efficient alternative source of energy, whether from high-enthalpy fields like in Tuscany (Italy); Iceland or Guadalupe (France) or from very low enthalpy in Norway or Switzerland where geothermal heat pumps are widely spread. This is the first point of convergence and a communication plan to be proposed. Several stakeholders express their interest for such an organisation as ENGINE that aims at co-ordinating present research and development initiatives for Enhanced Geothermal Systems. Thus, the need for good synthesis of the knowledge and collection of existing data for modelling and assessment of the resources, prior to drilling is emphasized. R&D teams have, on their own, underlined the need of a sustainable support of industrial partners and public bodies to ambitious research projects. This is the second point of convergence that fully justifies the existence of such Stakeholder Committee. From this convergence of interest, and in agreement with its main objectives, ENGINE should play the role of a scientific exchange platform for promoting past and on-going experiences by making them visible and reproducible. The needs for research expressed by the stakeholders are in general aimed at specific obstacles for improving cost-

efficiency of existing technologies like improvement of submersible pumps, better combination of heat and power generation and control of scaling in surface installations. The main challenging problem that they have addressed is the investigation of the possible links between geothermal energy and CO² capture, sequestration and storage. For R&D teams involved in EGS, the proceedings of the mid-term conference reveals a wide spectrum of themes like the reduction of the geological risk during exploration of deep resources, development of new stimulation strategies and the mitigation of the induced seismicity... These differences in establishing priorities are related to the fundamentally different missions of R&D and industrial projects. However, as mentioned above, the development of a scientific exchange platform is of common interest for both. Definition of research projects supported by the stakeholder committee should be a target for this platform that could be presented to the EU commission as a possible contribution for the future work programme of the FP7.

Stakeholders and R&D teams consider that the development of enhanced geothermal systems still requires the definition of an ambitious research program at the scale of Europe that will federate the research capacity and limit the financial risk by sharing the investment. Such a program, that could be for example an European Geothermal Drilling Program requires an unified approach of both scientists and stakeholders and constitutes a third point of convergence. To achieve this goal, ENGINE, or another collaborative action after the end of ENGINE, must become a "political" platform that will have the technical and economic background to propose and support new projects. Among these new projects, the evaluation of the potential of former oil and gas field could also be one way to limit the risk and start new demonstration projects. Such a European geothermal drilling program could be promoted in parallel at the level of policy makers for implementing incentive politics for supporting geothermal energy as a contribution to achievements of EU objectives for renewable energies and greenhouse gas reduction.

Geothermal drilling in some parts of Asia and Russia

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The drilling activities in some parts of Asia and Russia were studied and analyzed and presented with emphasis on its problems and some solutions applied. In some of the wells drilled in the identified areas there is no apple to apple comparison in terms of weather, formation drillability, well design and equipment utilized. It is also worth mentioning that because of confidentiality of data in these companies conducting the drilling operation there is very limited information available. But for purposes of presentation it is endeavored in this material that all information is thoroughly explained to be able to share the experiences of geothermal drilling in these areas and come up with a recommendation in our effort to reduce geothermal drilling cost and contribute to the cost reduction objective of ENGINE in the application of EGS.

The common problems in the Geothermal Drilling operation, i.e. lost circulation, equipment failure, improper drilling practices, cementing problems, casing problems, logistical problems and all other geothermal drilling activity related problems, will be dealt with based on what was experienced. Solutions applied to these problems will likewise be discussed.

Because drilling is a major component in the overall EGS activity it should be able to contribute to the cost reduction effort of ENGINE in order for the project to be successful and economical.

Summary

The presentation focuses in the drilling performance of some of the wells drilled in the Philippines, Papua New Guinea and Mutnovsky in Russia. The areas identified are the countries with available published data that we can use as basis in our effort to identify and recommend to the body (ENGINE) actions to be taken in order to attain its objective of reducing the cost of drilling geothermal wells and be competitive in the power industry and direct use of geothermal heat . It is hoped that this presentation will contribute in the cost reduction effort of ENGINE in the implementation/execution of EGS.

The Iceland Deep Drilling Project (IDDP)

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A status report on the IDDP was presented at the Engine Workshop 2 in Volterra in April 2007. Since then, two important developments have occurred. Last month, the two PIs of IDDP reluctantly recommended that the first deep IDDP well should be rotary drilled to target depth (4.5 km) rather than continuously core drilled between 3.5-4.5 km. Secondly, an international aluminium company, Alcoa, has now joined as a partner in the IDDP. As a result, we now anticipate that drilling into a supercritical reservoir in Krafla, NE-Iceland, will be realized late summer or autumn next year, 2008.

To compensate for the lack of continuous core, a reasonable number of spot cores should be collected below 2.4 km to target depth. From the scientific viewpoint continuous coring is much more preferable to spot coring as it provides much better information about the reservoir, about the nature of the fracture system, about water-rock reactions, and allows measurement of physical properties necessary for calibration of geophysical interpretations. If total loss of circulation occurs during drilling, coring it is the only way to get rock samples as drill cuttings will not be obtained. Accordingly, spot coring is recommended in the event of total circulation loss.

A balance needed to be struck between scientific rewards, costs, and safety. Continuous coring is inherently slower and more expensive than rotary drilling and we have extremely limited experience of continuous coring at very high temperatures. Questions have been raised about the cooling of the bottom hole assembly and its integrity at high temperatures, that are still being debated amongst drilling engineers. It is likely that these issues can only be addressed by actual experience in continuous coring at high temperature. At present, however, the chief goal of IDDP is to drill into supercritical fluid and to get it up to the surface for testing. Thus, in order to lower the risk in drilling the hole and complete it sooner for flow testing, we reluctantly recommended to IDDP to delete the planned continuous coring in the first IDDP well. There is a need for improved core drilling technology, especially to improve the rate of penetration which would result in lower drilling cost, and to improve the cooling efficiency to meet hostile environments of rock temperatures of 500-600°C. Continuous coring should still be seriously considered in the 2nd and/or the 3d IDDP well, which will be drilled at Hengill and Reykjanes in SW-Iceland before 2010.

The main financial supporters of IDDP constitute the Icelandic energy consortium, which is composed of three leading Icelandic energy companies together with the government of Iceland. Last month negotiations with Alcoa proved positive for participation in the energy consortium, Alcoa now becomes the fourth industrial partner in IDDP. In addition, the International Continental Drilling Program (ICDP) and the US National Science Foundation (NSF), have since 2005, allocated funds for scientific studies by supporting considerable core drilling in the deeper parts of the IDDP well(s). The plan is to seek additional funds to the EC-FP7 for developing the engineering pilot plant test of the supercritical fluid for power production, likely to be needed in 2009-2010.

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Workshop 4, Drilling cost effectiveness and feasibility of high-temperature drilling
Reykjavík, 2 - 5 July 2007, Iceland

The poster shows the IDDP drillhole design, drilling schedule and time plan. Drilling a fully cased and cemented well to about 3.5 km is scheduled for immediate deepening to ~4.5 km in 2008. After heat-up period of unknown length, the drilling will be followed by a major flow test and detailed chemical study of the deep supercritical reservoir fluid, provided we will find such fluid below 3.5 km depth. Most likely, a mechanical and chemical engineering pilot test will be needed before power production from supercritical resources is realized. Discussions for involving more international industrial partners in IDDP are underway.

SESSION 2

Innovative technology and drilling effectiveness

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InnovaRig - an Instrument for a European Geothermal Drilling Program

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The GeoForschungsZentrum Potsdam, the national German center for Geosciences within the Helmholtz Association, offers an especially build rig for scientific drilling. Lessons learnt from the International scientific continental deep drill program (ICDP) and from geothermal drilling showed the lack of an instrument for scientific purposes such as:

- to have an opportunity for applying various drilling processes within the frame of usual industry safety standards,
- sufficient equipment for sample recovery (cores, cuttings, mud, gas),
- reliable installations to support various stimulation procedures (chemical, mechanical, and thermal),
- installations to make logging easier respectively to reduce its preparing time,
- support for comprehensive data acquisition from drilling, logging, testing, and monitoring,
- and additional technical options derived from special scientific requirements.

These items were considered in the recently realized construction and the rig is now ready to enter into the operation phase. InnovaRig is designed to address significant cost reduction in comparison to conventional rigs requiring less personal using a semi-automatic operation and minor mob-demob-time due to the container based construction.

Let's bring some advantages of the new rig: The operator can choose between a power supply from the electric grid or by generator. A so called skid-system allows with one setup to realize two drilling points by hydraulically shifting the rig by 10 m.

Two top drive systems allow spot-coring as well as wireline coring. Additional drill pipe and blowout preventer components are available together with the rig. The new instrument InnovaRig provides the opportunity to join in a scientific co-operation with the GeoForschungsZentrum Potsdam, like:

- innovative geothermal concepts or challenges to future geothermal drilling,
- especially the application of time consuming tests of new methods within the concept of enhanced geothermal systems saving additional capital costs for rig time,
- and providing experimental facilities for service companies to test new technologies outside of commercial drilling operations.

Therefore, the geothermal community has now the chance to design projects to improve geothermal drilling by addressing new approaches in particular within the goal to cut the costs for geothermal drilling and to follow the concept of enhanced geothermal systems.

In a nut-shell:

InnovaRig basics:

- Mast and Hoist System with hydraulically driven double cylinder system and – 3500 kN hook load (~ 5000 m depth capacity).
- Pipe Handling System with semi-automatic hands-off-technology and combined pipe connector bridge, pipe handler and iron roughneck.
- Four Drilling Techniques integrated such as rotary drilling, standard coring, wireline coring and air drilling based on two new top drive systems (rotary drilling & wireline coring).
- Mud System, Pumps and Tanks adjustable to drilling procedure.

InnovaRig for Science:

- Coring Technique adjustable to all kinds of drilling methods due to a double top drive systems, an integrated wireline winch and wireline pump, and modified mud tank system for wireline coring.
- Fast Logging operation by pre-installed storage racks for logging sondes and special equipment for the logging cable guidance.
- Scientific Sampling by a special collector for cutting sampling, a new mud gas analysis device (mass spectrometry), and a science container for field lab investigations.
- Data Management on site with online data acquisition integrated into ICDP Drilling Information System (DIS).

Geothermal drilling with modern highly automated rigs - a drilling contractor's perspective

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The company Jardboranir hf. has been leading in the harnessing of geothermal energy in Iceland. It works on the international market providing rigs and project management and prides itself to provide a service in an safe, efficient and a dependable manner. Today practically all drilling work in high temperature geothermal wells in Iceland are done by Jardboranir with about 7000 wells drilled. Today about 4% of high temperature geothermal wells in the world was drilled by Jardboranir.

The lecture will give an overview of the company history, its operations both in Iceland and abroad and the organizational structure of the company. Emphasis will be put on giving a thorough overview of the management of the company with special attention on how we maintain a high standard in worker safety and environmental protection.

Jardboranir specializes in geothermal drilling with modern highly automated rigs. The new fleet of rigs have made it possible to shorten the average time for drilling an 2200m well from 45 days to about 35 days. Jardbornanir is a drilling contractor that is able to offer a comprehensive service with rigs that have a drilling capacity down to over 4000 m depth and can drill both vertical and deviated wells. Since last year the company can also offer under balance drilling that has increased the drilling speed because of a better return of drilling fluid to the surface and therefore reducing the likelihood of the rig getting stuck in the well. An overview will be given of the main technical specification of Jardboranir fleet of rigs with special attention to the newest addition and how they with automation of rigs have increased speed, accuracy and safety in the drilling process. Finally the Jardboranir vision to the future will be explained.

High Temperature Wells - Cost Analysis

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In the following the cost of high temperature geothermal wells is analysed. This includes the preparation, the drilling and the completion of the well. In high temperature geothermal wells the temperature of the reservoir can be up to 300°C. The analysis is based on experience gathered in Iceland for the past ten years.

The total cost of geothermal power plant has been roughly divided in drilling, steam supply system, el-mech and buildings. The cost of drilling is 30–40% of the total cost. Usually this is for example higher than the cost of turbine generator unit. The feasibility of a geothermal power plant is therefore highly dependent on how successful the drilling is. Preferably the wells should be productive and at the same time inexpensive.

We divide the total drilling cost in three main parts:

- Preparation i.e. building a drilling pad, water supply system and drilling and running a surface casing.
- Drilling of the high temperature well, including casing material
- Completing the well after drilling i.e. wellhead, silencer, drainage system and a house for the wellhead.

The percentage of the different parts of the drilling cost will vary some what depending on the type of well being drilled but the drilling itself is always by far the largest. The total cost of drilling 2000 m deep vertical well having ø8 1/2" production part is approximately 225 MISK (2,6 MEUR). This is excluding VAT. Design and supervision is however included.

The production parts in high temperature wells in Iceland is drilled either by using ø8 1/2" drilling bit or ø12 1/4" drilling bit. The larger diameter production part is generally considered more feasible where the enthalpy is low and the smaller diameter where the enthalpy is high. Well 20 in Krafla Geothermal Power Plant was the first directionally drilled high temperature well in Iceland. This was back in 1982. For the past ten years directional drilling is becoming more and more common and now every 3 or 4 wells out of 5 are directionally drilled. While a directionally drilled well is more expensive than a vertical one they have important advantages. Wells can be made to cut promising fissures, parts of the reservoir inaccessible from directly above become accessible and several wells can be drilled from each drilling pad.

The total cost of drilling different types of wells have been compared. The comparison is based on 2000 m deep wells. Included is the preparation, drilling and completing the well after drilling. If one would also include the cost of the steam supply system the difference between vertical and directionally drilled wells would be less.

For the past year aerated drilling has been tried in Iceland and more than ten high temperature wells have been drilled using this technique. The result has been positive with respect to drilling but it is still too early to confirm that the productivity of these wells is higher than the productivity of conventional wells. The trial aerated drilling carried out for the past year adds 7–12% to the total cost of drilling.

The drilling cost has been divided into drilling, other work carried out during drilling and material. This is only the drilling cost i.e. neither preparation before drilling or completion after drilling is included. It is concluded that for high temperature drilling the cost of work is 70–80% and the cost of material is 20–30% .

The drilling cost as a percentage of the drilling cost of each well and the well depth has been studied. The cost of drilling the last 500 m (from 1500–2000 m) is approximately 15% of the drilling cost. By extrapolation one can conclude that the drilling cost would be increased by 15% if a 2000 m well would be drilled to 2500 m.

A primitive study has been carried out for evaluating how the drilling cost of high temperature wells in Iceland has developed for the past eight years. Reservation must be made regarding the method used and how accurately it represents the drilling cost. It is also questionable if the cost index used in the comparison, the Icelandic “byggingavísitala”, gives the correct indication of general price increase. According to the study the cost of drilling was more or less the same until 2003. Since then it has decreased by over 20%. The large drilling contracts which have been made in the past years are the primary explanation why the cost has decreased. Because of those it has been easier for the drilling contractor to organize the drilling work and the drilling rigs are now working all year round and not only in the summer time as before. Bearing in mind how important the drilling cost is in the total cost of geothermal power plants it is obvious that the price development in the past years will affect geothermal power plants feasibility in a positive way.

The GeneSys-Project: Coast Efficient Single-Well-Concepts for Deep Geothermal Energy from the Northern German Basin

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Within the GeneSys-Project, the BGR (Federal Institute for Geoscience and Resources) and GGA-Institute (Leibnitz Institute for Applied Geoscience) aim at the extraction of deep geothermal energy (3500-4000 m) from the tight sediments of the Northern German Basin. Therefore three new concepts for geothermal heat extraction using a single-well-concept have been developed, since drilling costs are a crucial point to the efficiency of geothermal plants.

All concepts have been developed for the use in low-permeable sediments to provide small to medium-sized consumers with geothermal heat in the order of 2 MWth. Key technology to all concepts is the water-frac-technique, which is used to create large fractures in the sedimentary rocks.

- Deep circulation concept: Via a hydraulic fracture a highly permeable geologic fault is connected to the well. Hot water can be withdrawn from the formation.

- "Huff-Puff"-concept: A hydraulic fracture is created, which acts as a storage reservoir for injected cold water. The cold water heats-up and can be produced as necessary. The cycles of injection and production can be adapted to the needs of the consumer – e.g. injection during weekend and production during working days or injection in summer and production in winter.

- Two-strata concept: A hydraulic fracture connects two strata of sandstones. Both strata are connected to the well. A tubing passing a packer gives access to the lower stratum while the upper stratum is linked via the annulus of the same well. Water is injected into the lower sandstone, heats-up while migrating through the fracture and is produced from the upper sandstone layer. A persisting circulation is established.

The Huff-Puff and the Two-Strata concept have been successfully applied at the geothermal research well Horstberg Z1 in the Mittlere Buntsandstein formation. By the end of 2007 a 3800 m deep well will be drilled in the town of Hannover to supply office and laboratory buildings of the GEOZENRUM with geothermal heat by using a coast efficient single-well concept.

Spallation Drilling for Deep Heat Mining

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By 2050 at least 100 GW of electricity could be generated by geothermal power plants in the U.S. for a maximum investment of 1 billion US Dollars in research and development[1]. These numbers show clearly the enormous potential of geothermal power. However, temperatures high enough in terms of electricity production are commonly only found in holes reaching down to 4-10 km below the earth's surface. The MIT report[1] shows that drilling costs increase exponentially with depth. New drilling technologies are therefore needed to reduce costs for geothermal wells. Apart from conventional mechanical drilling by means of a rotary drilling bit, there is a technology called "Spallation Drilling". Therein, a flame jet or laser is directed to the rock to cause fragmentation. In simple terms, spalling is a form of crackling caused by an unequal expansion of rock crystals. While this technology, also known as "thermal rock fragmentation", is already used in Russia and the Ukraine to drill large diameter holes in surface mining, in our laboratory we aim to investigate the possibility of using this technology to drill deep holes for geothermal power plants. Beyond 3000 meters supercritical conditions for water are found. Our theoretical and experimental experience with hydrothermal flames is used and shall allow spallation in this supercritical environment. Fundamental experimental and theoretical research will be done on heat transfer, transport of spalled material and burner nozzle design. Ignition and stability of the flame are further investigated, as these are main conditions for the operation downhole. These data then allow the design of a pilot facility for geothermal application.

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An illustration of VSP efficiency in crystalline rocks to plan the deviation of a geothermal well while drilling

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At the Soultz-sous-Forêts geothermal site and in general in Enhanced Geothermal Systems, the fluid flow paths between the injection and the production boreholes are mainly composed by a set of permeable structures. The aim of our work is to document the efficiency of multi-component VSP (Vertical Seismic Profiling) to define while drilling the architecture of these potential flow paths within the heat exchanger and to save drilling costs.

The test of 3C VSP efficiency at Soultz EGS in GPK1 (Place et al, 2007) is considered successful, as major permeable fault zones intersected by the well can be investigated far away from the well. Their structural parameters (dip and azimuth) can be indeed inferred from this VSP data set, and are in accordance with the results of logging data (UBI, ARI, FMI...). In addition, some fractured corridors are well imaged but are not drilled.

Thus, we focus our work on two main tasks:

- First, we propose to go into detail in the interpretation of this 3C VSP data processed in an isotropic way, in order to deduce as much structural information as possible; the aim is to assess what can be reasonably learnt about the granite from the observed (and non observed!) seismic arrivals, P-P, P-S, S-S, S-P mode conversions.
- Second, in an opposite approach, we show the kind of structural information which can be rapidly given by a VSP interpreter if a VSP survey is carried out while drilling. Even just after pre-processing (i.e. full and long processing is not required) some arrival can be exploited to locate some major structures affecting the reservoir. Thus, the VSP can complement with benefit 2D or 3D reflection seismic images in order to deduce the position of the well relatively to permeable targets.

Thus, we expose how a VSP survey can help the deviation of a borehole while drilling to reach a permeable target for geothermal application. As a result, drilling cost can be significantly reduced thanks to such a fast multi-component VSP analysis; then, after drilling, the same data set processed in isotropic way can provide precious information for fluid flow to help to manage the geothermal resource of the reservoir.

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SESSION 3

Well design and cementing

ENGINE - ENhanced Geothermal Innovative Network for Europe
Workshop 4, Drilling cost effectiveness and feasibility of high-temperature drilling
Reykjavík, 2 - 5 July 2007, Iceland

Challenges faced in drilling high-temperature geothermal wells in Iceland

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Now, in the year 2007, ten high-temperature geothermal areas in Iceland have been explored by deep drilling and the generation is 420 MWe and 450 MWt are at six sites. The drilling effort has accelerated in the last few years as the geothermal industry has found a new market in selling electricity to large aluminium smelters. Previously the local market for district heating, electricity and steam to industry was the driving force.

Drilling into high-temperature geothermal reservoirs in Iceland started in 1940. Some 200 HT wells have been drilled which fit the definition of exceeding 200°C at 1000 m depth. Intensive drilling started half a century ago and now four drilling rigs are active drilling such wells to depths of 2000-3000 m, half of them directional. These wells are of two basic designs, either having 9-5/8" or 13-3/8" production casing. There are a total of four overlapping casing strings, each one cemented in place, and the open hole either has a slotted liner or is „barefoot“. The depth of each casing string overlaps roughly about 1/3 of the intended depth for the interval being drilled for safety. Most wells are very productive, capable of yielding 5-15 MWe of electricity, but the best ones 20 MWe. The latest power plants, at Hellisheiði 90 MWe and at Reykjanes 100 MWe, require only 6 and 10 production wells respectively. All or part of the wastewater is reinjected into wells at all sites, each one capable of accepting up to 250 l/s.

Initially, there was not much knowledge available on HT drilling initially, but over the years the technology has improved and lessons have been learned. The presentation will focus on the successes as well as the most serious difficulties that relate specifically to the geothermal environment such as: blow-outs inside the well or outside, casing damages, wellhead failures, cementing, material selection, coring. Case histories are presented. The successes in geothermal drilling have to do with much faster drilling and good well outputs. The time to drill a well has been reduced by the use of modern drilling rigs and equipment, mud motors and aerated drilling fluids and less time is spent on cementing loss zones. The structure of the drilling contracts, standardization of well design and professionalism of the drilling crews are important factors in reducing the time to drill a well. A drilling contract was awarded with 50 wells, based on international tendering. Geothermal utilization in Iceland has thus become an industry where reproducable results are obtained and risks have been reduced. It now takes some 35 days to drill down to 2500 m, including the time for rig transport.

The HT wells typically encounter temperatures well above 300°C without drilling problems, even with mud motors and MWD equipment, as the well temperature stays below 100°C due to mud/water circulation. There is rapid heating-up once the circulation stops but there is usually a time-window within which logging tools can be run. As the rigs are reaching ever greater depths the temperature can be expected to increase and now the Iceland Deep Drilling Project (IDDP) will target zones where supercritical temperatures are to be expected (>374°C for fresh water, higher for saline). Drilling in temperatures of 400-500°C poses a new challenge.

Iceland Deep Drilling Project (IDDP) casing design for extremely high temperatures

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The aim of the Iceland Deep Drilling Project (IDDP) is to drill a 4-5 km deep exploration well into a high-temperature geothermal system in order to reach 400-600°C hot supercritical hydrous fluid. The main purpose of the IDDP is to find out if it is economically feasible to extract energy and chemicals out of hydrothermal systems at supercritical conditions.

- The IDDP design premises were initially assessed on basis of the presumed deep temperature and pressure values at the depth of 5,000 m. Two possibilities were considered, viz.:
Linear extrapolation from the established temperature and pressure values pertaining to the critical point in fresh water (374.15°C and 22.12 MPa)¹, and considered to exist at a depth of 3,500 m. Linear extrapolation to 5,000 m depth yields a temperature of about 550°C and 25 MPa pressure.
- Estimation based upon “Isochor” behaviour would on the other hand yield 391°C and 26.7 MPa at a depth of 5,000 m.

Three alternative temperature and pressure cases are selected for assessing load and stress conditions in the upper part of the anchor casing, the wellhead flange and the wellhead master valve.

Flowing well:

T= 500°C and P= 19,5 MPa (Linear)
T= 340°C and P= 14,5 MPa (Isochor)

Closed well:

T= 400°C and P= 22 Mpa
T= 20°C and P= 26.7 MPa

The casing design is based on the ASME Boiler and Pressure Vessel Code, Section VIII, Div 2, Alternative Rules. Addenda July 1, 2003, and ANSI and API standards for flanges and valves. The design consisted of the following:

- Design of anchor and production casings; ensuring strength integrity; materials and couplings selection.
- Selection of materials and pressure class for wellhead master valve.
- Selection materials and pressure class for wellhead master valve flanges.

The conclusion was to use thick K-55 grade steel for the casings, except for the top 300 m of the anchor casing where T-95 would be used due to its creep resistance. The connections are Hydril 563 couplings and threads for the anchor and production casing, Wellhead and valves are to be of ANSI pressure Class 2500.

Top-down cementing of geothermal wells in Iceland

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Cementing of casing strings in geothermal wells is one of the most critical operations to insure safety and long life of the wells. In high temperature wells there are usually three or four casing strings that are cemented for the full length, the deepest ones typically in Iceland from surface and reaching down to 700-1300 m. The purpose of the cement is to support the casing, isolate the formation and provide corrosion protection. If the cement bond is inadequate the casing thermal expansion, normally constrained by good cementing, will result in elongation that may exceed what the wellhead is designed for. If the cement is poor steam seepage to surface outside the well may become a problem. A special case is collapse in the casing due to external pressure that occurs if water or poor cement becomes trapped in the annulus but this can also occur deep in the well during the cementing operation.

The cementing operations in Iceland are carried out by the drilling contractors and their drilling crews. The inner-string cementing method is the rule and frequently topping up when no returns are received or the cement level goes down. This is due to losses of cement to the formation or through normal losses or through fracturing. The loss of circulation policy, while drilling the cased portion of the wells in Iceland, is only to stop the drilling and cement large loss zones (>10 l/s). The smaller losses are drilled past and attempts made to heal with loss of circulation material (LCM). If a large loss zone is near the target depth, they are not cemented. The first cementing attempt is to pump the cement slurry through the drill string (inner-string method) and up the annulus to surface. Based on Cement Bond Logs (CBL) the cement is topped-up by squeeze cementing or through a „spaghetti“ string where two small-diameter pipes extend to the top of cement. In case of large loss zones the well is as a first step cemented up to the loss zone and the loss kept open by clean water pumped simultaneously down the annulus. After a short time for the original cement to set, the next step is to „squeeze cement“ by pumping the cement down to the loss zone. Repeated CBL logs have shown this procedure to result in continuous cement support for the whole casing string.

The conventional procedure places great pressure on the formation, with the danger of creating new fractures. Another problem is the collapse force on the casing from the slurry having a density of 1.65 g/cm³. In most cases this collapse force during inner-string cementing is what determines the required casing thickness. Most wells have relatively large losses when it comes time to pump the cement slurry (5-20 l/s). Adding LCM and the large expanded perlite particles frequently does a good job of healing the losses, especially the ones caused by thermal fractures that tend to open up while the well is being cooled and running of the casing.

To overcome many of these problems two tests were made at Reykjanes in 2004 with what is referred to as top-down cementing or reverse circulation cementing. Then all of the cement slurry is pumped down the annulus and the displaced water allowed to flow up inside the

casing and out through a cement head on the top of the casing. This flow is throttled by two choke valves to match the cement slurry volume being pumped. Water meters were placed on the return flowlines and there is also a totalizer on the cement pump to allow proper control of the chokes. There is therefore no „free fall“ of the slurry and a backpressure built gradually up at the cement head from the weight of the cement column, as is to be expected in this U-tube arrangement. The cement slurry is pumped to the annulus through the kill-lines on the wellhead with the annular BOP's closed in order that no air is sucked in. A casing shoe without a float valve is used to allow return flow and no drill string was used as in the inner-string method. A milk tracer is used to give notice that the cement had reached the casing shoe. Reversing of the pressure build-up at the wellhead also reveals when the cement has reached the shoe and starts traveling up inside the casing. Both of these experiments were successful and required small topping up jobs. For a very short period early in the cementing job, until the choke was properly adjusted, there was more water coming out through the choke valves than cement slurry being pumped in. Balance was quickly regained so the vacuum break did not last long (suction in the annulus). As the pressure on the wellhead goes up as the job progresses the choke needs to be adjusted to insure that the volumes are in balance. Instrumentation is required to allow proper flow control. A CBL log showed good cement bond, except for a short section in the annulus between the two casings. As there can be no external water in this part and the cement density was adequate, no explanation has been found. This may be an inherent problem with the way the CBL is made, for example the casing was not pressurized while the log was run.

Longer casings will have to be run in the future and loss zones are frequently encountered. Therefore it is likely that the reverse circulation method will find wider use. The main benefits for geothermal wells are the following:

- Wells with loss zones can be cemented as gravity aids the flow and less pressure is exerted on the formation.
- Less collapse pressure exerted on the casing as compared to inner-string cementing. This is because the cement column pressure is partly being balanced inside the casing by the wellhead pressure. The wells can thus be designed with thinner walled casings.
- Long casing strings can be cemented without reverting to 2-stage cementing.
- Cement slurry will be in the annulus between the two casing strings. The slurry tail can be of high density to insure that there be no free water which can result in a casing collapse.
- No float equipment (float shoe and float collar) is required.
- Less time spent on cementing as the drill string does not have to be tripped in for an inner-string job.
- Low pressure cement slurry pumps can be used as there is no pressure build-up (no pressure or suction in the annulus).
- There is less heating-up of the cement slurry, allowing longer pumping times or less use of retarders.

The casing scheme ... most important factor for the success of a deep well?

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A proper borehole design (the drilling & casing scheme) is an important factor to successfully drill a deep well, in drilling for hydrocarbons as well as for recovery of geothermal energy. Selection of a casing scheme has also a high impact on overall borehole costs.

With the oral presentation an overview on following aspects will be given:

- how to plan the casing scheme of a deep well properly,
- which pressures (external, internal) and loads (weight, tension, bending, compression) are stressing the casing strings,
- how to design (calculate) casing strings for different pressure and load situations,
- the influence of temperature and temperature changes on casing,
- the impact of well design on the capability of proper cementation of casing strings,
- the influence of borehole design on well costs.

Summary

Planning of a well starts at final depth with desired hole and/or casing diameter and moves upwards stepwise. The needed number of casing/liner strings strongly depends on the geology. Casing strings are run to

- secure drilled hole sections (e.g. in unstable formation)
- separate hole sections/formations with different pressure gradients
- seal formations against fluids (gas, oil, water) from last or next section.

A “Golden rule” says: drill as small as possible, but as large as necessary (due to cost reasons). Despite the fact that bit diameters and casing (pipe) diameters are (more or less) “standardized”, there are still some options to optimise well design and to minimise costs by choosing a “standard clearance casing scheme” or a “slim clearance casing scheme”. However, advantages and disadvantages should be evaluated thoroughly in each case.

“Clearance” (= diameter difference between open hole and casing) and “stand-off” (= concentricity of casing in open hole) have a high impact on the quality of a casing cementation, particularly in deviated wells. New techniques and equipment can help to

improve cementation quality even in narrow clearance applications and contribute to a reduction in overall well cost by allowing the use of a “slim clearance casing scheme”.

Corrosion Testing for Hot Dry Rock Geothermal Wells in Soultz-sous Forêts- Preliminary Results

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Corrosion risk for some materials proposed for Soultz project at 200°C was evaluated for different steels with and without protective coating. The preliminary experiments were performed at autoclave which could house specimen of various geometries and which allowed electrochemical measurements. In some cases the testing was performed using a corrosion inhibitor. For uncoated steels the corrosion tests showed erosion at 2 mm/y at 200°C. The corrosion products formed on the surface did not provide any corrosion protection. All the tested coatings performed very well. They effectively reduced the corrosion and they did not deteriorate during the test. The chosen inhibitor did not give any significant inhibitor effect.

Evaluation of cement integrity using distributed temperature sensing

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The cement sheath mainly serves to support the borehole casing and seal the annulus to flow along the axis of the well. Especially geothermal wells require a high-quality cement sheath because they are subject to strong mechanical stress resulting from high temperature changes. Moreover expansion of trapped fluid behind the casing can lead to unintended fracturing of the formation or casing collapse. Temperature logs have traditionally been used to determine the top of cement, while more recently acoustic and nuclear measurements have been added to the methods used for cement sheath evaluation. Using distributed temperature sensing (DTS) continuous temperature profiles can be recorded with high temporal and spatial resolution. In contrast to conventional wireline logging, the complete evolution of the well temperature profile over time can be monitored. The fiber-optic sensor cables can be permanently installed behind the borehole casing allowing for continuous monitoring during operation and production without well intervention. Here we report on a set of DTS measurements performed during a stinger cementation in an 800m deep well which was drilled in a saline aquifer in the Northeast-German basin within the framework of the CO2SINK project. From the evolution of the well temperature profile over time the position and quality of the cemented sections was determined. Apart from information during construction and completion, important data for the operation of a well and for monitoring of processes inside the reservoir causing temperature changes can be collected using the installed DTS cable.

Development and Application of Metal Casing Packers

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Early hydraulic borehole tests as well as borehole completion operations at the HDR geothermal test site at Soultz-sous-Fôrets were characterized by several technical problems due to conventional (rubber-based) packer technology at temperatures exceeding 120 to 140°C, and high gas- and salt content of the borehole fluids. After extensive investigations with aluminum, copper, and even stainless steel as packer material for different applications such as hydraulic / hydrofrac testing at great depth or permanent borehole sealing for nuclear waste storage, casing packers consisting of soft metal shells of salt water resistant copper - nickel alloy mounted on a mandrill of 7" or 9-5/8" casing were developed during the past years to overcome these problems. After numerous laboratory prototype tests, the new casing packer technology was successfully used during the extension of borehole GPK-2 and the completion of the boreholes GPK-3 and GPK-4.

Well stimulation using explosives

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The results of several experiences of ground-water stimulation wells using explosives are presented. The results of this kind of experiences can contribute with interesting information for the geothermal wells and they allow to value with great detail the produced effects. The interpretation of this type of experiments also allows to define lines of investigation for situations of greater depth and therefore with greater risks and costs. The difficulties, not only normative but also technical, using explosives for the stimulation of wells don't allow to predict big expectations as for their future utilization if one keeps in mind their scarce effectiveness in the increment of productivity of the wells.

High Temperature, high precision, temperature measurement probe

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High precision temperature measurements allow establishing accurate temperature logs and characterizing geological events in geothermal wells (localization of geological change or of water flow from rocks fractures). In the framework of the European HITI project, BRGM wants to transfer his experience from low temperature domain (0-130 °C) to high temperature domain (up to 320 °C).

Proposed wireline logging tool aim an accuracy better than 0.1°C and a sensitivity better than 0.005°C in a range of 0 to 320°C.

Summary

The poster presents:

Examples of use of a high precision temperature measurement wireline logging tool that BRGM used in eighteen's and nineteen's, Specifications of the projected probe.

SESSION 4

Reservoir assessment, stimulation, testing and logging

ENGINE - ENhanced Geothermal Innovative Network for Europe
Workshop 4, Drilling cost effectiveness and feasibility of high-temperature drilling
Reykjavík, 2 - 5 July 2007, Iceland

Reservoir engineering in two geothermal field in El Salvador

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Over the last 15 years two geothermal fields have been under commercial exploitation in El Salvador, the Ahuachapán and Berlin fields. They are located to the western and the eastern part of the country, respectively. In order to achieve the requirement of energy production and to contribute in the sustainable development, the reservoir engineering is undertaking several activities. The monitoring is the main source of information and the first view that is happening into the geothermal system and reservoir. Mass flow rate, enthalpy, wellhead pressure, fluid chemistry are only a few parts of the continuous monitoring that has to be done. Pressure declining is the most common effect when the reservoir yield mass. The Ahuachapán field declined 15 bar at the beginning, but during the last 10 years the decline was 2-3 bar, however Berlin was declined around of 14 bar for the last 15 years. Boiling and dilution seem to be the largest process happening in the reservoir. Thermal breakthrough due to injection is not evident yet in both fields, spite of some pressure recharge which has also been observed at the neighboring wells. Numerical modeling is another important issue for the reservoir management Several models are normally used and they are continuously up dated for more confident forecasting. The reservoir engineering is contributing to produce at least 1,150 GWhe per year, equivalent to 20% of the total electricity consumption in El Salvador.

The PT borehole simulator HEX-B

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The numerical borehole simulator HEX-B has been developed with the specific aim to calculate the injectivity and productivity of open hole sections in deep wells. The calculation requires the monitoring of wellhead data, such as the history of salinity, flow rate, temperature and pressure but also the geometrical situation of the borehole (casing diameter, cementation, ...). After different phases of development HEX-S is now also suited to forecast downhole pressure data.

As such, the transient pressure profiles during stimulation of wells GPK2 (June 2000) and GPK3 (May 2003) were calculated based on measured wellhead data. A comparison of the time-history of near-borehole events during the GPK2 test and downhole pressure development in the open-hole sections of this borehole indicated that use of a heavy (or dense) brine helped stimulate the bottom part of the well. The corresponding analysis for the GPK3 test showed that the failure pressure of the fractures in the bottom part of the wellbore was never exceeded when injecting the heavy brine.

Conventional logging – geothermal wells

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In order to decide about the overall feasibility of EGS projects some key parameters have to be investigated: downhole temperature, downhole pressure, brine chemistry and the potential maximum flow rate which can be achieved. Wireline logging operations are performed in EGS wells in order to help answering these key questions.

We look into the characteristics of these wireline logging programs performed in various classes of EGS projects in typical and representative geological settings: deep sedimentary structures, deep granites, shallow volcanics and shallow metamorphics. Characteristics of these EGS classes regarding the wireline tools applied and typical evaluation procedures used are going to be covered.

We ask the question where adjustments to typical wireline logging programs can contribute to a further increase in drilling cost effectiveness of EGS wells and search for the potential of further standardisation and “streamlining” of wireline logging programs within EGS projects. Finally we look into the need for further research and development.

High temperature logging

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High temperature logging has to this date mostly involved temperature and pressure measurements using mechanical and digital memory tools. Other physical parameters for reservoir evaluation have been obtained during drilling when the well can be cooled down using cooling water at the drill site. With more frequent high temperature geothermal utilisation and drilling to even higher temperatures (e.g. supercritical), the need to upgrade existing instruments and methods for extended tolerance to even more volatile conditions has become more urgent. Such instruments and methods could then be operated without the need of cooling and can in some cases be the only methods available for use if a well cannot be cooled down, due to excessive heat or lack of cooling medium. A brief overview of the current status of high temperature logging conditions will be given, along with discussions on the required parameter space, which can depend on factors such as formation types and well fluid chemistry. Tool manufacturing limitations are discussed (material, connections and electronics) along with wellhead design considerations, that would allow logging even at high wellhead temperatures and pressures.

Hydraulic fracture operation in the hydrocarbon industry - Lessons for geothermal applications

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Hydraulic fracturing is commonly applied in the hydrocarbon industry to stimulate the production. From the literature in the hydrocarbon industry, guidelines can be distilled on the selection of wells that are most suitable for such treatments, for a proper operation of the treatment, and for an adequate assessment of the result. In this presentation, some of the operational lessons learnt in the hydrocarbon industry will be transferred to geothermal applications. Many issues have similar characteristics, like the economics, the geomechanics, and the productivity assessment. There are, however, also differences. Important differences can be found in the temperature effect, the dual-porosity characteristics of geothermal reservoirs, the type of fluids used, and the required coupling of hydraulic and geomechanical properties of the reservoir. The presentation will focus on hydraulic fracture treatments and address reservoir and geomechanical issues, and present some operational guidelines for testing and evaluation. In particular the recent hydrocarbon experience with very low-permeability reservoirs will be addressed.

Why coring should be part of any exploratory high-temperature drilling project, as illustrated by the case histories of the Salton Sea Scientific Drilling Project (SSSDP) and the planned Iceland Deep Drilling Project (IDDP): an appeal for technology development.

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In March 1986 a research borehole of the Salton Sea Scientific Drilling Project reached a depth of 3,220 m in the Salton Sea geothermal system of Southern California as part of the first major research drilling project of the U.S. Continental Scientific Drilling Program (Elders and Sass, 1988). The principal goals of the SSSDP were to investigate the physical and chemical processes of a high-temperature, high salinity, magmatically driven, hydrothermal system at depths approximately twice as deep as the usual existing production wells in that geothermal field.

In mining exploration and in scientific drilling in the oceans continuous core drilling is the norm. However based on the advice of a drilling consultant the idea of continuously coring the SSSDP borehole was abandoned because of the difficulties expected at the high temperatures anticipated (Ross and Forsgren, 1992). Instead it was decided to follow standard oilfield practice and use rotary drilling but to attempt to core about 10% of the drilled depth: 1 million USD of the budget was assigned to that task. Plans called for setting aside 250 hours of rig time for logging and downhole fluid sampling, but, because of the difficulties experienced, these tasks actually required 487 hours. A broad suite of geophysical logs was obtained from the upper part of the borehole, but at depths where formation temperatures exceeded 300°C, the inability to cool the borehole sufficiently severely limited the logging program (Paillet and Morin, 1988). The demands of the logging program required that the amount of coring be reduced and, when the borehole reached final depth, only 224 m (or 7%) of the borehole had been cored (Ross and Forsgren, 1992).

The borehole encountered temperatures of up to 360°C and produced metal-rich, alkali-chloride brines containing up to 25 wt% of total dissolved solids. The rocks penetrated exhibited a progressive transition from unconsolidated lacustrine and deltaic sediments to hornfelses, with lower amphibolite facies mineralogy, with locally abundant ore minerals. A key finding from study of the cores, with implications for commercial development of the resource, was that at shallower levels permeability is controlled by secondary porosity formed by the incongruent dissolution of carbonate cement in sandstones. With increasing temperatures this porosity is destroyed in hornfelsesediments where permeability is entirely dominated by partially mineralized fractures. Flow tests of the deeper part of the borehole yielded flow rates of up to 370,000 kg/h at 250psig (1,724 kPa or ~17bar) wellhead pressure, sufficient to provide enough steam to generate at least 12 MWe, thus demonstrating the commercial potential of the deeper reservoir.

Even although the cores recovered were limited, they made possible pioneering studies of petrophysical properties, sedimentary and evaporitic facies analysis, resolution of the source of the dissolved salts, evaluation of structural relationships, identification of igneous-intrusive units, resolution of mineral-paragenesis, and of vein-deposition sequences related to emplacement of ore-bodies. Detailed petrography and isotope analyses of the cores permitted identification of the sources of sulphur in the ore mineralization. Two distinct types of vein mineralization could be seen in the cores, (a) an earlier a carbonate + sulphide (sphalerite, galena, chalcopyrite, pyrite, pyrrhotite) + epidote assemblage, and (b) a later epidote + hematite + anhydrite + sulphide + quartz assemblage. The type (a) veins appear to be older and the deeper production is associated with type (b) veins. Laboratory petrophysical measurements of porosity, density, and P-wave velocity improved calibration and interpretation of downhole and surface geophysics (Elders and Sass, 1988).

The IDDP

The aim of the IDDP is to explore the potential of producing supercritical hydrothermal fluids as an energy source (Fridleifsson and Elders, 2005). Superheated steam produced from a fluid initially in the supercritical state will have a higher enthalpy than steam produced from an initially two-phase system, but, in addition, large changes in physical properties of fluids occur near the critical point. Orders of magnitude increases in the ratio of buoyancy forces to viscous forces occur that can lead to very high and fluctuating rates of mass and energy transport. Similarly, because of major changes in the solubility of minerals above and below the critical state, supercritical phenomena play a major role in high temperature water/rock reaction and the transport of dissolved metals (Fournier, 1999). Hitherto, study of such supercritical phenomena has been restricted to either small-scale laboratory experiments or to investigations of "fossil" supercritical systems exposed in mines and outcrops. Furthermore mathematical modelling of the physics and chemistry of supercritical fluids is hampered by a lack of a reliable thermodynamic database over the range of temperatures and pressures of the supercritical state, particularly for saline fluid compositions.

Drilling to produce supercritical fluids at depths of 4-5 km and temperatures of 500-600°C is, with one exception, almost unprecedented in the worldwide geothermal industry. The only precedent was another example of collaboration between government, industry and the scientific community that also aimed to extend conventional geothermal resource investigations into new regimes of temperature and make direct observations and sample the processes that couple magmatic and hydrothermal processes. That project, funded by the Agency of Industrial Science and Technology (AIST) of Japan, and involving scientists and engineers of the New Energy and Industrial Technology Organization (NEDO – a government agency), the Japan Metals and Chemicals Co., and university scientists was a 3.7 km deep exploratory core hole at Kakkonda, in the Hachimanti Geothermal Field, Iwate Prefecture, Japan (Muraoka, et al., 1998). This well penetrated an entire shallow hydrothermal convection zone, an entire contact metamorphic aureole, and part of a neo-granitic pluton (tonalite with a K-Ar age of 0.19 Ma), a cooling granitic intrusion that is the heat source for the hydrothermal system. The shallow hydrothermal system is developed in Holocene to Miocene volcanic and intrusive andesitic rocks and shows a boiling point controlled temperature profile down to 3100 m depth, where a 380°C temperature occurs. At that depth and temperature, a transition from brittle to ductile conditions was observed and the temperature gradient became conductive. Temperatures reached >500°C at 3729 m (Muraoka, et al. 1998). At the bottom of the borehole the permeability was very low and the

borehole was subject to plastic deformation. For this reason the drill hole was completed as a production well in the shallow hydrothermal system. The Kakkonda deep borehole represented a number of firsts that extended the range of geothermal investigations worldwide. The bottom hole temperature of $>500^{\circ}\text{C}$ is the highest so far measured in any drilling project, except for the rare occasions when still-molten lavas have been drilled at about 100 m depth. The borehole at Kakkonda reached temperatures higher than the boiling point depth curve and entered a subsolidus cooling pluton. It was also the first geothermal well to penetrate the brittle-ductile transition (Muraoka, et al. 1998). It is theorized that, in very high-temperature geothermal systems, the main constraint on the maximum depth of hydrothermal convection is the control on permeability exerted by the transition from brittle to ductile behaviour (Fournier 1999).

History of the Drilling Plan Adopted by IDDP

Given this background, from the outset, the IDDP, recognized that the success would involve solving difficult technical and scientific problems and welcomed the inclusion of basic scientific studies. The project invited participation from the international scientific community (Fridleifsson and Albertsson, 2000). The first concern was to decide how best to drill into, test and study supercritical geothermal reservoirs in Iceland. Two international workshops in 2002 funded by the International Continental Scientific Drilling Program (ICDP) were held. The workshop, held in March 2002 brought together more than 50 international experts to develop the optimum strategy of meeting the difficult technical challenges of drilling and sampling wells to depths of up to 5 km with temperatures of $>450^{\circ}\text{C}$. The workshop led to a clearer definition of the range of conditions likely to be encountered and developed the guidelines for planning drilling and sampling.

The drilling workshop considered different options for obtaining cores in a high-temperature geothermal production well. Fruitful discussions were held among panel participants with a diversity of experience in drilling in countries and different environments, and with representatives of organizations that have developed different approaches to drilling and coring. The workshop considered four options for obtaining cores in two different sizes of production wells, A and B. Well profile A has a 9 5/8 inch production casing to 3500 m, whereas Well profile B has a 9 5/8 inch casing to 2400 m with a 7 inch production casing to 3500 m. The upper part of Profile B (to 2400 m) is the design currently used in standard production wells used in the geothermal fields of the Reykjanes Peninsula in Iceland. The two different options for coring considered were continuous wireline coring and spot coring. It was estimated that drilling, coring and reaming to a nominal depth of 5000 m would take about 250 days. The preferred plan suggested was to use a wireline coring system attached to the platform of a conventional rotary rig to continuously core the well in two stages, the first down to 3.5 km depth, followed by reaming, and then continuous coring to the supercritical zone expected beyond that depth.

The second workshop held in October 2002 brought together approximately seventy international experts on geothermal systems. It continued the discussion on technical issues of drilling into and sampling supercritical geothermal reservoirs. In addition, panels were held on studies of geology, fluid chemistry and reservoir properties. There was a strong agreement that there was a crucial need for drill cores. Studies of fossil supercritical geothermal systems exposed in mines and outcrops, that formed in similar environments to those expected in Iceland, indicate that supercritical fluids have pervaded every cubic

centimetre of their basaltic host rocks. It is not known if this occurs by diffusion from spaced-out fractures, or by microfracturing and fluid advection on a sub-millimetre scale. Core samples from deep wells will give first-hand look at the process. Similarly, the thermodynamics of supercritical solutes is poorly known, as the transition from sub- to supercritical conditions at the magma-hydrothermal interface is accompanied by substantial changes in the physical-chemical characteristics of the reservoir fluids. The paired samples of fluids and rocks from the IDDP well will be extremely valuable for testing and improving numerical models of reservoir properties, of fluid-rock reactions, and of controls on the compositions of both fluids and minerals under supercritical conditions. This requires obtaining as much core as possible in and near the supercritical transition. Study of the coupling of the chemical and mineral alteration, fracture propagation, pressure solution, and fluid flow will be based on analysis of data on mineral chemistry, isotopes, geothermometry, and fracture geometry. The costs of the many man years of laboratory studies and interpretation are a major contribution by the scientific team to the IDDP. Similarly the science program is contributing more than 3.6 million USD to the coring program. More than half the IDDP science projects proposed by the science team would be impossible or severely compromised without drill core. Coring is a part of all major scientific drilling projects today. The philosophy is that utilization of core will increase as science progresses in the future and cores constitute a robust archival record.

There are also practical reasons for coring. Nowadays, the usual practice in Iceland is to drill with downhole motors, for their high rate of penetration, and this produces very fine-grained drill cuttings. Irrespective of the cutting size, unravelling the nature and chronology of fracture failure and vein in-filling and detection of time serial fracture events and determination of constitutive rock properties is impossible without drill cores. Similarly understanding the nature and formation of permeability requires study of cores. Measurements of mechanical and thermal properties of core as a function of temperature are necessary to quantify processes related to brittle-ductile behaviour. The permeability and thermal diffusivity of fractured and intact, fresh and altered, basalt comprise essential baseline information for fluid circulation models. Furthermore, as indicated above lost circulation during drilling, which is common in highly permeable zones in Iceland, would prevent recovery of drill cuttings. Similarly the use of borehole viewers and most other logging tools is impossible because of high temperatures. Furthermore, recognizing when the supercritical conditions are reached during drilling will best be done by studying mineral assemblages and fluid inclusions in cores as they are recovered.

However, the estimated costs of continuous coring followed by reaming to the diameter of the well to production size escalated considerably at that time. Because continuous coring is slower and therefore more expensive than conventional drilling, a compromise was proposed and adopted to reserve continuous coring for the supercritical zone below 3.5 km depth and to take only spot cores in the upper part of the well.

These recommendations were reviewed and refined in the two year long feasibility study funded by Deep Vision (Fridleifsson et al., 2003). Meanwhile the science team has obtained awards of 3 million USD from the US National Science Foundation, and 1.5 million USD from the ICDP to obtain drill cores and data for scientific studies as part of the IDDP. Given the extremely competitive nature of funding for science projects and the limited budgets available, these are very large awards. This is an indication of the global significance of the IDDP project. In 2003 an Icelandic energy company, a member of the IDDP consortium,

offered one of its planned exploratory wells on the Reykjanes peninsula, in southern Iceland, to the IDDP for deepening. This well reached 3.1 km in February 2005, and research on the downhole samples began. Unfortunately the well became plugged during a flow test and was abandoned in February 2006 after attempts to recondition it failed. This led to the IDDP deciding to move the site for the first deep borehole to Krafla, near the northern end of the central rift zone of Iceland, within a volcanic caldera that has had recent volcanic activity. The Krafla geothermal system has higher temperature gradients than at Reykjanes. The drill site chosen is near an existing well that encountered 340°C at only 2.5 km depth. Drilling is expected to occur in 2008.

An informational workshop concerning the IDDP was held in Reykjavik in March 2007 to review the current situation, to reconsider goals and plans in view of new circumstances, and to make recommendations. It became apparent that there was increased interest in the IDDP on the part of the Icelandic energy industry. It now seems likely that in the next few years deep (> 3.5 km) exploratory boreholes will be drilled in each of three major geothermal fields in Iceland. Because deep drilling plans are furthest along at Krafla, it was decided to focus on that field first.

However a prime concern is the recent even larger escalation of cost estimates for drilling, coring, fluid sampling and testing of a deep geothermal well. As indicated above, continuous coring is much more preferable in terms of characterizing the nature of the resource. However Icelandic drilling engineers had serious reservations about the performance of a wireline coring system at high-temperatures and raised questions about the difficulty of cooling the bottomhole assembly in a narrow diameter corehole. Another concern is the cost of changing drilling rigs necessary for the different tasks of rotary and core drilling and the difficulty and cost of reaming the corehole to production size. Continuous coring is inherently more expensive than rotary drilling and there is limited experience of continuous coring at very high temperatures. It is likely that these issues can only be addressed by actual experience in continuous coring at high temperature.

Given the present circumstances, unless in the immediate future a technically and fiscally viable option for continuous coring can be found by 2008, the principal investigators reluctantly concluded early in June 2007 that the first deep IDDP well, should be rotary drilled to target depth (4.5 km) while taking a reasonable number of spot cores, depending on the budgetary constraints. Depending on the temperature gradient the supercritical conditions may be encountered at less than 4.5 km depth. In the future, based on the knowledge that will be gained from study of these deep wells, the IDDP should seek funds for continuous coring through the supercritical zone in a geothermal system in Iceland.

The economic potential for developing deep high-temperature geothermal resources in Europe has not yet been thoroughly assessed. However the potential for making a major contribution of sustainable energy in the region may be very large, not only in Iceland and Italy, but also in the Azores, Canaries, Turkey, Greece, Guadeloupe, Russia, and elsewhere (Elders, 2007). Our limited knowledge of the nature of such geothermal systems is a handicap in exploring for and developing these deep unconventional geothermal resources (DUGR's). Given the present state of our knowledge, it is therefore desirable to carry out detailed scientific investigations of different classes of high-temperature systems and the study of drill cores is an essential part of such studies. Hence the plea to the ENGINE

drilling community for advice on improving the technology and economics of both spot core drilling, and of continuous wireline coring at high temperatures.

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Summary

The purpose of this presentation is to make the case that coring should be part of any program of high-temperature drilling, except perhaps in the case of infilling production wells in already explored reservoirs. A review of the SSSDP will be used to illustrate the desirability and practicality of obtaining as much core as possible within relevant technical and budgetary limitations. Then a discussion of the evolution of planning for the IDDP will be used to illustrate these technical and budgetary limitations. Finally, a plea will be made for improving the technology and economics of core drilling, particularly continuous wireline coring at high-temperatures.

Chemical stimulation of the Soultz wells

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All three deep Soultz wells were subjected to chemical stimulations as a complementary method to hydraulic fracturing. The finding of fractures filled with calcite constituted the starting point of chemical stimulation in Soultz. Further, the potential improvement of the near wellbore performance without seismic events has been considered as advantage of chemical treatments. In 2003, the first deep well (GPK2) was stimulated by injection of hydrochloric acid. A significant reduction of near wellbore friction losses was observed immediately after the acid front reached the open hole section. Nevertheless, the improvement is important only at high flow rates (30 l/s), whereas at lower rates (15 l/s) only a minor improvement remains. It is likely that turbulent friction losses inside the wellbore, where a fish is stuck, were reduced due to the acid injection. No clear indications were found for an improvement in the formation around the well GPK2.

During a circulation test between GPK2 and GPK3 in 2003, hydrochloric acid was injected in GPK3 over a limited time period of 12 hours. No reduction of the injection pressure was observed during or after the acid injection. Three years later a so called organic clay acid (OCA) was pumped into the well. Two injection tests before and after the OCA-job showed almost no improvement of the well productivity due to OCA injection.

The failing of the acid stimulations in GPK3 coincides with the existence of a large infinite conductive fracture as the dominant outlet. There is no potential to improve the well by dissolving minerals from these fracture faces. A series of chemical treatments were applied in GPK4, starting with the injection of HCl in 2005. This operation improved the wells injectivity by 50%, but it is questionable whether this improvement was achieved in the open hole or through leakages in the casing. The following chemical operations were injection of RMA (Regular Mud Acid), NTA (chelating agents) and OCA. While the RMA operation improved the wells injectivity further, the NTA reduced it again, probably by plugging fractures. The final OCA application led to an increase of the productivity by 25% up to 0.5 l/s/bar (determined after two days of injection). The origin of the improvements due to acid injections (HCl, RMA, OCA) can be twofold: Microseismicity was observed during these operations and is located only at the casing leakages at (4100 m and 4400 m TVD) which suggests, in combination with new flow logs, the stimulation of this leakage during the chemical treatments. On the other hand, the recent open hole flow profile ends at 4780 m TVD and does not allow an interpretation of the deeper flow distribution in the last 200 m of the open hole. Thus, the achieved productivity enhancement at GPK4 can not clearly be attributed to an improvement of the reservoir below the casing.

AUTHORS' INDEX

ENGINE - ENhanced Geothermal Innovative Network for Europe
Workshop 4, Drilling cost effectiveness and feasibility of high-temperature drilling
Reykjavík, 2 - 5 July 2007, Iceland

ENGINE - ENhanced Geothermal Innovative Network for Europe
 Workshop 4, Drilling cost effectiveness and feasibility of high-temperature drilling
 Reykjavík, 2 - 5 July 2007, Iceland

ABANES Roberto	18	LEDRU Patrick	16
ASMUNDSSON Ragnar	50	MATTHÍASSON Matthías	26, 34
BAUMGÄRTNER Jörg.....	9, 42	MAYORGA Herbert.....	15
BILKOVA Katerina.....	40	MÉGEL Thomas.....	48
BIRKISSON Sturla.....	36	MOECK Inga.....	11
BRANDT Wulf.....	11, 41	MONTERROSA Manuel	15, 47
DIRAISON Marc	30	MULLER Jiri.....	40
ELDERS Wilfred	19, 52	NAMI Patrick.....	58
EVERS Hermann.....	28	NAVILLE Charles	30
FLOVENZ Olafur	16	PLACE Joachim.....	30
FOKKER Peter	51	PREVEDEL Bernhard	23
FRIDLEIFSSON Gudmundur Omar	19	ROTHENFLUH Tobias.....	29
GANDY T.....	9	RUDOLF VON ROHR Philipp.....	29
GARCÍA-NOCEDA Celestino	43	RUMMEL Fritz.....	42
GERAUD Yves	30	SAADAT Ali.....	11
HENNINGES Jan	41	SARMIENTO Zosimo.....	14
HETTKAMP Thomas	9	SCHINDLER Marion	58
HOFMEISTER Knut.....	28	SCHULTE Thomas	49
HOLL Heinz-Gerd.....	11, 49	SEIERSTEN Marion.....	40
HUENGES Ernst	11, 16, 23	SPERBER Axel.....	38
INGASON Kristinn	26, 34	STEFÁNSSON Ari	25
JATHO Reiner	28	SULZBACHER Hans	28
JUNKER Ralf.....	28	TEZA Dimitra.....	9
KEHRER Peter	28	THORHALLSSON Sverrir	33, 36
KLEE Gerd	42	TISCHNER Torsten	28, 58
KOHL Thomas.....	48	WESSLING Stefan.....	28
LE GARZIC Edouard	30	WOHLGEMUTH Lothar	23
LEBERT François.....	44	ZIMMERMANN Günter	11

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