Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Coring at Extreme Temperatures, Design and Operation of a Core barrel for the Iceland Deep Drilling Project (IDDP)

Alister Skinner[1], Paul Bowers[2], Sverrir Þórhallsson[3], Guðmundur Ómar Friðleifsson[4], Hermann Guðmundsson[3]

[1] ACS Coring Services, 3 Riccarton Drive, Currie, Edinburgh, EH14 5PN, Scotland, UK,
[2)] Rok-Max Drilling Tools Ltd., P.O. Box 87, Truro, Cornwall, TR3 7ZQ, UK,
[3)] Iceland Geosurvey (ISOR), Grensasvegur 9, Reykjavik, IS-108, Iceland,
[4)] HS Orka hf, Brekkustígur 36, 260 Reykjanesbær, Iceland.

acscs@blueyonder.co.uk, paulbowers@rokmax.com, s@isor.is, gof@hs.is, hg@isor.is

Keywords: core bit, bit cooling, coring, core tube data logger, high temperature core barrel, International Continental Drilling Project (ICDP), Iceland Deep Drilling Project (IDDP), Reykjanes Ridge, SW Iceland, RN-17, scientific coring, spot coring, supercritical

1. ABSTRACT

The science program of the Iceland Deep Drilling Project (IDDP) requested that as much coring as possible should be done in the transition zone to supercritical and inside the supercritical zone (>374ºC), in the depth interval 2400-4500 m. Early ideas were to employ a hybrid mining-type wireline coring system and do continuous coring. This was abandoned in favour of taking spot cores (10 m in length) at selected depths in a production size hole of 8½" (215.9 mm). The coring system selected is of conventional design, non-wireline with a 7¼" (184.15 mm) OD and capable of collection of a 4" (101.6 mm) diameter core using an 8½" (215.9 mm) OD core bit. This system incorporates materials, clearances and bearings which are compatible with the operation of the core barrel at high temperatures. This is important as the projected temperatures in the IDDP scientific borehole before cooling could be as high as 450ºC. Special attention was given to the volume of flushing which could be applied to the core barrel and through the bit while running in/out and while coring and this in turn impacts on internal core barrel design of waterways and bearing configuration. Before the deployment in the IDDP it was decided to test the new core barrel and bit design. In November 2008 a very successful spot coring was performed at 2800 m depth in the production well RN-17 B at Reykjanes, where the formation temperature is 315ºC. Well RN-17B was being reconditioned by sidetracking it out of well RN-17 at 930 m depth below the production casing, to become an inclined exploration/production well. The core trial was performed in the open hole at 35º inclination. The main benefit of the core barrel is its unique feature to enable high water flow rates for cooling during coring, of up to 40 l/s. A core tube data logger was also designed and placed inside the inner barrel to monitor the effectiveness of cooling. The temperature could be maintained at 100ºC while coring but it reached 170ºC for a very short period while tripping in. The effective cooling is attributed to a top drive being employed which allows circulation while tripping in or out, except for the very short time when a new drill pipe connection is being made. A 9.3 m hydrothermally altered hyaloclastite breccia was cored with 100% core recovery, in spite of it being highly fractured. Unfortunately unexpected geological conditions in well IDDP-1 has precluded further use of the core barrel in this borehole and further operational results will have to await further developments in the IDDP program.

2. INTRODUCTION

2.1 Background Events

Prior to the RN-17 Borehole being occupied for the test spot coring various IDDP committee meetings and workshops had determined that a deep borehole would be scientifically examined by the collection of core and logs. Cost constraints led to the conclusion that continuous coring would not be possible and that a series of spot cores at selected and strategic intervals would have to be collected.

Further costing analyses indicated that it may be beneficial for IDDP to purchase a core barrel for the work rather than hire from an oilfield-type service company. This possibility could also allow for 'non-standard' design which could better address hot temperatures and rate of penetration issues. A tender specification was drawn up and tenders issued for the supply of equipment or a service supply (or both) to a number of companies in Russia and Europe. The responses indicated that it would indeed be cost efficient to purchase a core barrel for the work and that specific requirements for operation in deep, hot boreholes could be incorporated into the design.

A recommendation was made, and accepted by IDDP, that specific core barrels and core bits be made for the project. Included in the cost schedule it was proposed that allowance be made for a full spot core test in a 'borehole of opportunity' to allow proper appraisal of the finished products before committing to a 5 km deep scientific borehole. The placing of contracts for core barrels and core bits followed and the resulting core barrel and spot core test results are the subject of this paper.

2.2 Geological Setting

As shown in Figure 1, three areas in Iceland have been targeted for scientific study of high temperature supercritical fluid zones. Although the first designated scientific borehole (IDDP 1) is scheduled for Krafla, an opportunity arose to carry out a spot coring test at Reykjanes.

In late 2003 a member of the IDDP consortium had offered one of its planned exploratory wells, RN-17, located on the Reykjanes peninsula for deepening by the IDDP (Friðleifsson and Elders, 2005). It was drilled to 3.1 km depth where it was planned to deepen it further some 2 km, partly by continuous wireline coring. The 3.1 km deep well was flow tested in November 2005, and collapsed during that test. In February 2006 the well had to be abandoned after several attempts at reconditioning it failed. In 2008, the field operator decided to side track this well southwards.

During that operation the request by IDDP came up to allow test-coring in this well with the new IDDP coring equipment. The request was met by HS Orka hf, leading to this paper.

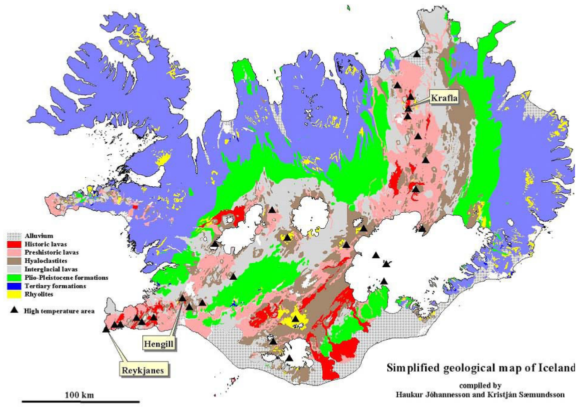

Figure 1: The geological setting of the high-temperature geothermal fields of Reykjanes, Hengill (Nesjavellir), and Krafla, being considered for deep drilling by IDDP.

3. CORE BARREL

The advisory groups of IDDP (SAGA and Deep Vision) determined that a core barrel be obtained for the project and a tender exercise was carried out to evaluate rental from a service company or procurement of a specialist core barrel for IDDP. The result of the tender returns based on the specification below indicated that a specialist core barrel could be cost effective for the project and it was agreed to follow this route.

3.1 Core Barrel Specification for Deep Geothermal Borehole

The specification drawn up for international tender for a core barrel and core bits can be summarised as follows:

A conventional core barrel is required for spot coring work in a deep scientifc geothermal borehole. See http://www.iddp.is. Temperatures in the borehole are expected to exceed 500°C but with cooling and other measures currently employed in drilling shallower geothermal boreholes it is hoped to keep coring temperatures below 200°C. (see Figure 2) but they could be as high as 250°C. The temperatures shown in Figure 2 are extrapolated from real data and indicate the hole temperature, over time, when continually flushing while drilling or coring and are the typical temperatures the corebarel could experience at the drilled depths shown. Data is verifiable to 2500 m from current drilling.

The project is cost limited and has also to take place in a borehole being drilled for ultimate energy production as well as obtaining detail on supercritical fluids. Technical and safety procedures and precautions need to be in place and to a certain extent impinge on the corebarrel design and its mode of operation. This is explained in the specification requirement detail below.

3.1.1. Outer Core Barrel

Double walled core barrel 7” OD with API thread and bit connections and overall length of maximum 10 m. This overall length should be broken down to allow efficient transportation and assembly and incorporate top and bottom stabilisers, possibly a central stabiliser and the opportunity to run a 5 m or 10 m assembly.

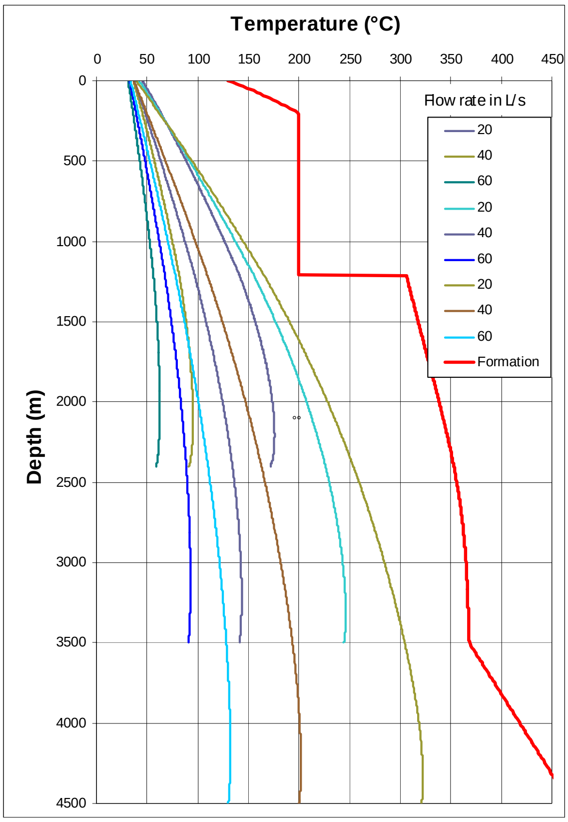

Figure 2: The anticipated temperature scenarios which any core barrel design has to meet.

Rig configuration limits tubular handling operations and thus the maximum possible corebarrel length to an effective 10 m core run. Stabilisers on the corebarrel need to be compatible with coring operations with an 8½” core bit. Corebarrel head or crossover sub dimensions will be finalised when all rig tubular details are also known.

3.1.2 Inner Core Barrel

Preferred core size 101.2 mm (4”).

Core barrel sections to suit the full or part length of corebarrel being used.

Bearing assembly to be water cooled and have no components susceptible to failure in heat to around 250°C – barrel adjustments and tolerances must make allowance for heating of corebarrel while in operation which can only be limited by the water flushing. Figure 2 suggests that a minimum flushing capacity of 30-40 litres per second will have to be maintained for all of the tripping time and preferably for at least some of the coring time.

Conventional core spring type catcher and screw on shoe essential. Other catcher options can also be considered as additions. Consideration may also need to be given to keeping the catcher shoe cool so it does not expand and interfere with core pasage through it?

Single or limited re-use inner core barrels will be considered if this is thought beneficial for annular clearances for flow requirements and the wall thickness is too weak for robust useage but sufficient for core collection and stability.

3.1.3 Core Barrel Flush

Core barrel to be able to pass a minimum of 30–40 litres/second while running string and should be able to perform coring at 30 litres per second while coring – i.e. there must be sufficient annulus to allow this.

Because of the danger of blowout in the borehole there will be check valves in the string which will not allow steel balls to be deployed to the corebarrel prior to coring. In any event this would also preclude pumping at higher flushing rates should the string be held downhole for longer than anticipated when the core barrel is attached.

3.1.4 Core Bits

These require to be designed for the corebarrel, have 8½" OD have (possibly) peripheral and face discharge to accommodate the volumes of flush required without undue pressure or flushing loss at the bit cutting face. Only spot coring will be undertaken and this is anticipated to be carried out only at drill bit changes or at other places where the geology may dictate – such as in a lost circulation zone where rock alteration properties would be investigated.

The formation is most likely to be basalt or dolerite or gabbro as the borehole progresses. It may be fractured and have alteration zones in areas where there may be lost circulation. The rig top drive is well instrumented and has good bit weight control. It is also capable of 140-200 RPM but using this speed may not be possible due to API string harmonics and 70-100 RPM may be a more likely useable range. WOB can be well-controlled and an appropriate BHA to suit the bit can be made up, including uphole stabilisers (see below).

Information gained from previous large diameter coring suggests that surface set diamond bits performed well and PDC bits less well due to breaking although the penetration rate was good until this happened. Smaller diameter core bits using impregnated diamond bits perform very well and are robust. Provided the rig can accommodate the rotary requiremetnts of such bits they should also be considered for this spot coring exercise.

3.1.5 Contrary Coring Practice

Due to borehole depths (>3500 m) and slow drillstring trip times with singles it is not possible, within the scientific budget available, to carry out the custom, or best practice, or tradition, of cleaning the hole after drilling and before coring, unless it is demonstrated that there is significant metal junk in the hole when it would have to be done. Neither is it intended to drill a pilot hole to stabilise the coring bit at start. The core barrel and core bit should therefore be sturdy and aggressive enough to withstand some difficult conditions while establishing the coring regime. However, if the core bit can achieve this, and make good penetration rate for 10m of core then this will suffice and the bit can be changed if necessary for the next spot core. In order for the project to be financially viable a penetration rate, given suitable operating parameters, of 2.5 m/hr while coring should be aimed for as a minimum in the formations indicated above.

3.2 Manufacture

The core barrels were made by ROK-MAX Drilling Tools Ltd. and the core bits were made by GEOGEM Ltd., both UK companies with a good track record in making specialist coring equipment.

The core barrel is of all steel construction using components such as bearings heat treated and plated to withstand an extremely harsh in-hole environment together with high operating temperatures. No rubber or plastic seals are used in its construction and special high temperature grease is used to lubricate the bearings and threaded components. It comprises an 11.6 metre non-wireline conventional double tube corebarrel, with non-rotating inner tube assembly. It is specifically designed to take spot cores of 4" (101.6 mm) diameter x 10 metres long and to give maximum flow through the core barrel of at least 40 l/s flush for cooling. Special attention was given to the volume of flushing which could be applied to the core barrel and through the bit while running in/out and while coring and this in turn impacts on internal core barrel design of waterways and bearing configuration.

3.2.1 The Core Bits

The core barrel bits for use with the system were designed with large waterways and a rounded profile crown to allow an element of hole cleaning when spudding in and maximum cooling when down hole. The composition is impregnated diamond with natural diamond and carbide gauging on both OD and ID. Matrix composition is designed for high end temperatures and fast wear to allow clean fast cutting over the whole life of the bit. The design of the bit and matrix allows for a rotational speed (RPM) between 70 and 160 RPM. The weight on bit (WOB) should be between 12000 to 25000 lbs or 5.45–11.36 tonnes. Generally speaking the higher RPM used the lower the weight on bit, or vice versa, always within the given parameters. A close-up of bit and core catcher is shown in Figure 3, below.

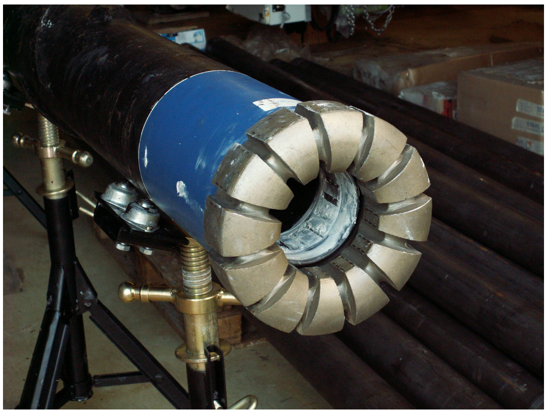

Figure 3: The Core Bit and Core Catcher assembly.

The results shown in Figure 4 were also established from the hydraulic testing

3.2.2 Outer Core Barrel Assembly

Stabilizers and core bit are currently designed for 8½" (215.9 mm) hole size. The outer core barrel assembly comprises bit, lower stabilizer section, lower outer barrel body, middle stabilizer section, upper outer barrel body, top stabilizer section and core barrel head. There are no landing, latching or stabilizing rings for the inner core barrel interconnected with the outer assembly. All materials, manufacture and threads on the core barrel are to API specification but some internal core barrel threads are modified. The box thread and diameter on the core barrel head section of the outer core barrel is directly compatible with the drill collars being used and two types were manufactured to accommodate 6¾" (171.5 mm) and 8"

203.2 mm) drill collar types. The core barrel, ready for transportation, is shown in Figure 5.

HYDRAULICS INFORMATION

8 1/2" x 4" Impregnated Corehead

INPUT DATA	1	2	3	4	5
Diameter of Bit (ins)	8.5	8.5	8.5	8.5	8.5
Flow Rate (gpm)	264	330	396	462	528
Mud Weight (lb/g)	10.4	10.4	10.4	10.4	10.4
Number of Nozzles	12	12	12	12	12
Dia of Nozzles (ins)	0.563	0.563	0.563	0.563	0.563
TFA	3.012	3.012	3.012	3.012	3.012
OUTPUT DATA					
Bit Pressure Drop, P (psi)	7.305	11.414	16.436	22.371	29.220
Jet Velocity, V (fps)	28.048	35.060	42.072	49.084	56.096
Bit Hydraulics Horsepower, HHP	1.125	2.198	3.797	6.030	9.001
Impact Force, ft lbs	39.859	62.280	89.683	122.069	159.437
Hydraulic Horsepower / sq ins	0.020	0.039	0.067	0.106	0.159
Flow Rate (Ltr / sec)	20	25	30	35	40

Figure 4: Core Bit Information from Hydraulics Testing.

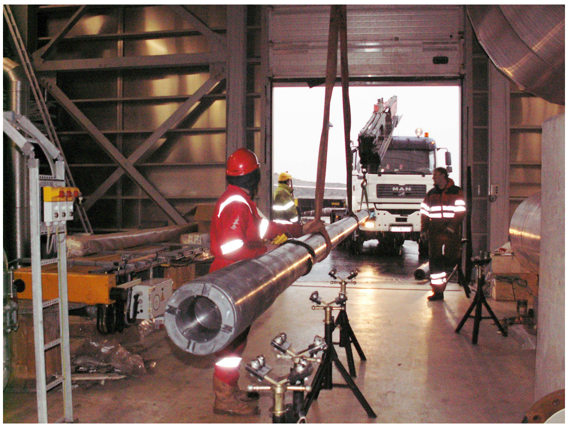

Figure 5: The assembled Core Barrel ready for shipping to the Rig site.

3.2.3 Inner Core Barrel Assembly

The inner core barrel comprises lower shoe which contains the core catcher or core spring, upper shoe, lower inner barrel stabilizer, lower core barrel section, middle stabiliser section, upper core barrel section and core barrel bearing assembly. The bearing assembly housing screws into the outer core barrel head and is the only fixed point of contact with the outer core barrel. The bearings allow the inner barrel assembly to rotate freely within the outer tube and adjustment on the bearing shaft ensures that the correct inner to outer spacings are set. The stabilizer sections keep the inner barrel central to the outer tube and the lower shoe. When the inner core barrel assembly length is adjusted via the bearing shaft the face of the lower shoe sits inside the core bit throat with sufficient clearance for flush but not too much to hamper core ingress to the barrel. The core catcher design is 'conventional' spring catchers operating on a 'wedge' principle for competent formations.

3.2.4 Temperature Sensor

Hermann Guðmundsson of ISOR designed and fitted a digital temperature probe in a pressure housing at the top of the inner barrel core chamber. Also within the pressure housing a selection of temperature recording wax 'spots' were inserted to allow a backup temperature reading to be recorded. Because this probe projects into the core chamber it is not possible to take a full 10 m core run as it could be crushed if full core recovery was achieved. Figure 6 shows the fitting of the temperature probe.

Figure 6: The Temperature Probe assembled in its housing is attached to the inner core barrel head assembly.

4. SPOT CORING OPERATIONS

A Spot Core Test was thought prudent as part of the operational planning for IDDP-1 at Krafla in order to try to maximize operational information and train the drilling crew in coring procedures. The main aims were as follows:

Core Aspects:

- Learn what may be the percentage core recovery, the core condition, information on core washing, bit performance and wear.
- Approve the bit design based on grading of the used bit, so the additional bits can be ordered (up to 10 pcs). Monitor the function of the core catcher and the bit cooling:
- Inspect the core barrel for adverse temperature effects. Read from temperature logger and temperature indicating strips/paint placed inside the core barrel.
- Determine how to optimize the bit cooling procedure with the top-drive while tripping in. How much and how long to circulate at each stand?

Core barrel handling:

- Are any parts missing or able to be modified to speed up the handling of the core barrel.
- How to maximize tripping speed. Train the crew
- Train the drillers and core hands in the proper coring procedures. Collect information that can be put into a handbook for IDDP.
- Collect information relative to "risk assessment".
- Work with the drillers during the coring run to establish best parameters of rotation, weight on bit and sensitivity of recording of parameters on

the console so that a profile can be built up and added to the procedures to be followed for the spot coring on the full scale IDDP-1 project in Krafla next summer.

The rig Tyr, which is the largest of the Jarðboranir Iceland Drilling company rigs was used for the spot coring and is the same rig that will operate at Krafla for the deep Scientific Borehole.

Figure 7: The Drilling Rig Tyr at Borehole RN-17.

It is a Soilmech HH300 Drilling rig with variable speed top drive, automated pipe handling and all safety features necessary for high pressure, high temperature geothermal well drilling. All rig tubulars are to API specification and the rig crew are extremely competent in the handling and maintenance of all of the tools and machinery.

Safety and procedural documentation was prepared and reviewed by key personnel prior to the approval for the test being given by SAGA and then before the interfacing to the rig was finally determined. The rig crew were briefed on the Core Barrel and the operating parameters in a 'tool box talk' at shift changeovers so that both shifts were prepared for whatever may be occurring on their shift. The Tool Pusher and Operations Superintendent agreed the bottom hole assembly with S. Þórhallsson and A. Skinner prior to the start of the operation. All core barrel assembly, adjustment and delivery to the rig was carried out by the coring team of Herman Guðmundsson, Paul Bowers and Alister Skinner.

Full data recording of all drilling parameters was logged and is available for future analysis. Various graphs can be produced and there is a graphical output of drilling parameters available to the driller while he is operating the rig. Figure 8, below is a graph of the data recorded by A. Skinner in paper form as he monitored progress while the driller varied parameters to try to maintain steady and even progress. Compare this to the detailed graphs of Figures 9 and 10. While the detailed graphs give exact information there is a danger in using the information they display too quickly because there can be other reasons for the marked abrupt changes. For example, when bit weight is applied there is immediate string hysteresis which indicates (incorrectly) that extremely rapid progress is suddenly being made and if this were taken note of too quickly there would be an immediate requirement to reduce bit weight again to avoid bit blocking or core jamming. However over a few tens of seconds the pattern is clear and monitoring rate of progress against time in increments of 2-5 minutes gives a good indication of how things are progressing. Note however that the TREND of the logged data is consistent with this but that trend is not seen on any of the data screens, only the absolute values or their graphical representation. Nevertheless the recorded information is consistent and helpful – if one views torque and RPM then it is clear that increased torque reduces RPM for the same bit weight and applied power. Monitoring of this inter-relationship allows a good indication of coring and potential core blocking problems. Given the power available on the rig it is unlikely that the RPM would have fallen to a stall position but definite sticking points can be seen and on later observation of the core collected there is one section of core cut eccentrically suggesting core barrel instability and there are numerous inclined fractures where core jamming could have occurred temporarily. However, good steady penetration and sufficient core barrel clearance between cut core and tube wall seems to have greatly assisted in allowing a full core barrel penetration to be achieved without having any refusal to penetrate further.

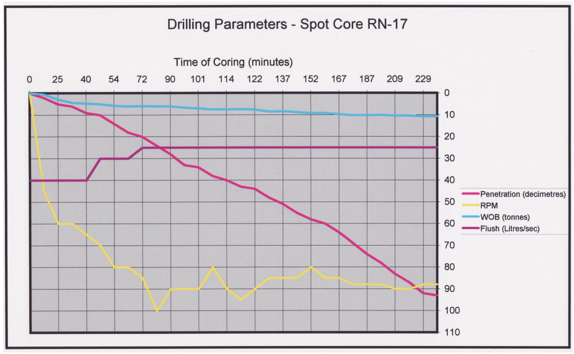

Figure 8: Smoothed Drilling Parameters recorded during the Coring Run (yellow: RPM. Blue: WOB, Dark purple; flush, Light Purple: penetration).

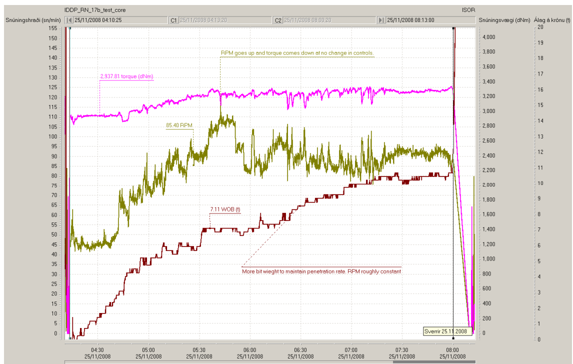

Figure 9: Weight on bit (WOB) (tonnes), Torque (dNm) and revolution (RPM) diagram during the test coring operation.

The flush rate while coring was varied to observe what would happen while coring. Bear in mind that the flush rates available while coring were very high compared to other core barrels and it is a known fact that high flush rates can affect both core recovery and penetration rates by washing away of core and lifting bit off cutting contact with the bottom, respectively. 40 litres per second was used while spudding in and for the first five minutes, it was then cut down to 30 litres per second and after a few more minutes was reduced to 25 litres per second for the remainder of the coring run. No marked changes in either bit weight or penetration rate were observed and provided the formation is competent it would appear that there should be no problems in trying to core with full flush capability in boreholes which have a higher ambient temperature, such as that anticipated at Krafla. This suggests that the bit design allows for full flow through the waterways and then uphole without causing undue pressure build up at the bit face or in the core barrel head ports.

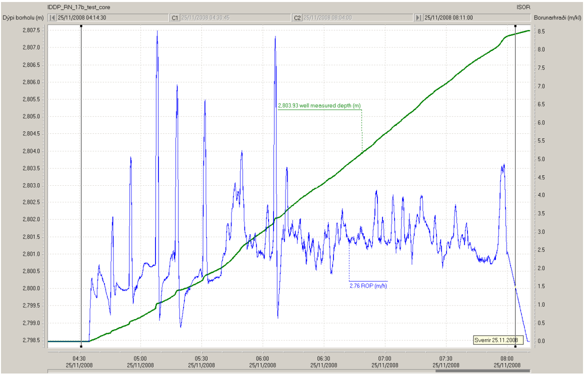

Figure 10: Time-coring rate (m/h) diagram – 27 November 2008, 4:34-8:00 – at 2800 m depth. Core recovery was close to 100% of 4" core. Average coring rate 2.6 m/h. The green curve shows increasing depth.

It was not possible to reach and maintain high RPM (>100) on the drill string without excessive vibration and string movement. This could be due to a number of factors but certainly the vertical to inclined borehole configuration would have something to do with this. However rotation without excessive vibration or string movement was possible within the operating bit parameters given by Geogem and applied here. Generally if low-end RPM has to be used then high-end bit weights have to be applied to maintain acceptable penetration and smooth operation.

5. SPOT CORING RESULTS

All of the indications while coring suggested that core was being collected but it was not until the pull-off force at the base of the coring run increased markedly then dropped back that it could be said that there was core caught inside the core barrel which had to be broken off. Then it was not until the string was tripped out, the core barrel dismantled and the core pumped out of the inner tubes that the full measure of the success of the core run was established.

Core recovery was excellent and this despite the fact that the core barrel was being run in an inclined borehole and the rock was fractured with many wedge shaped planar fractures which could have easily caused core jamming. Figures 11 and 12 shows the nature of the core collected.

Figure 11: Core Bit with Core securely held in Catcher.

Figure 12: Core removed from Core Barrel and boxed for examination.

The cored section consisted of a hyaloclastite breccia, thoroughly altered to greenschist facies mineralogy. Apparently, this breccia was deposited in shallow marine environment, despite the fact it is now at 2.500 m depth below the surface. The age of this breccia is one of the key questions to be unraveled to allow estimation of the subsidence rate in the middle of the Reykjanes rift zone. The drill core is now being studied by the IDDP science team and some of the results will be presented at the WGC-2010 (Friðleifsson and Richter, 2010).

6. CONCLUSION

The core barrel was designed for a vertical borehole. RN-17 test hole was inclined at 35 degrees so the inner core barrel stabilizers could not operate properly as centralizers since wear was always on the side 'lying down'. Although this did not materially affect the coring it induces more refurbishment of stabilizers than would otherwise occur and it may be that for inclined coring (not routinely planned) a set of stabilizer rings may have to be incorporated into the outer core barrel sections.

The work was carried out to an agreed plan, schedule and extremely tight timescale. The successful outcome is in large measure due to the thought put into the core barrel and bit designs by Rok-Max and Geogem and to the efforts of Hermann Guðmundsson regarding site management of equipment, logistics and suitable location to set up and service the core barrels. The IDDP committees of SAGA and Deep Vision approved the case for core barrel procurement which was overseen by Bjarni Palsson of Landsvirkjun. At site the Iceland Drilling Project Manager Steinar Mar Þórisson worked with us and both shift crews of 'TYR' to allow an excellent test with a good outcome.

REFERENCES

Elders, W.A. and Friðleifsson, G.O.: Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24-29 April 2005.

Friðleifsson, G.Ó. and Richter, B.: The Geological Significance of two IDDP-ICDP Spot Cores from the Reykjanes Geothermal Field. Proc. World Geothermal Congress, Bali, Indonesia, April 25-29 (submitted), (2010)