On the Effects of the Lithostatic, Hydrostatic Pressures, and the Temperature on Plasma-Pulse Geo-Drilling (PPGD)

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\textsuperscript{2}Fraunhofer Institution for Energy Infrastructures and Geothermal Systems (IEG), Germany
Outline

Introduction

Plasma-Pulse Geo-Drilling (PPGD)

PPGD experiments under deep wellbore conditions

Conclusions and Outlook
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Conclusions and Outlook
Why cheaper drilling for Geothermal Energy

Temperature@1 km depth @Europe

[Chamorro et al. (2014)]
Why cheaper drilling for Geothermal Energy

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Why cheaper drilling for Geothermal Energy

Temperature@1 km depth @Europe

\[ \nabla T \sim 30^\circ C/km \]

[Chamorro et al. (2014)]

[Lowry et al. (2017)]: Calculated using the Well Cost Simplified (WCS) model from Sandia National Laboratories.
Why cheaper drilling for Geothermal Energy

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Temperature@1 km depth @Europe

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[Lowry et al. (2017)]: Calculated using the Well Cost Simplified (WCS) model from Sandia National Laboratories.
Why cheaper drilling: the case of AGS

AGS - case study

Impact of the drilling performance

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Current rotary</th>
<th>Ideal rotary</th>
<th>Target (any)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROP [ft/hr]$^2$</td>
<td>25</td>
<td>100</td>
<td>To be increased</td>
</tr>
<tr>
<td>Bit lifetime [hr]$^2$</td>
<td>50</td>
<td>200</td>
<td>To be increased</td>
</tr>
<tr>
<td>SpCC [USD/W$_e$]$^1$</td>
<td>145</td>
<td>37</td>
<td>2-5</td>
</tr>
</tbody>
</table>

SpCC: Specific Capital Cost  
USD equivalent to 2019USD  
Current rotary: assumes state-of-the-art mechanical rotary drilling  
Ideal rotary: assumes solving all challenges of state-of-the-art mechanical rotary drilling  
Target (any): assumes novel drilling technologies, e.g., PPGD, thermal spallation, laser, etc.

Thus, we need to increase the ROP and the bit lifetime to the values at which the SpCC reaches 2-5 USD/W$_e$, thereby enabling AGS to compete with other renewable energy resources.

$^1$[Malek et al. (2022)]  
$^2$[Lowry et al. (2017)]
How to reduce the drilling cost

\[ C_m = \frac{C_b + C_r (T_d + T_t + T_n)}{\Delta D} \]

<table>
<thead>
<tr>
<th>Cost parameter</th>
<th>Unit</th>
<th>Depends on</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_m )</td>
<td>Drilling cost</td>
<td>USD/m</td>
</tr>
<tr>
<td>( C_b )</td>
<td>Bit cost</td>
<td>USD</td>
</tr>
<tr>
<td>( C_r )</td>
<td>Rig cost</td>
<td>USD/hr</td>
</tr>
<tr>
<td>( T_d )</td>
<td>Drilling time</td>
<td>hrs, ROP</td>
</tr>
<tr>
<td>( T_t )</td>
<td>Tripping time</td>
<td>hrs, Bit lifetime</td>
</tr>
<tr>
<td>( T_n )</td>
<td>Non-rotating time</td>
<td>hrs, Mechanical failure and casing</td>
</tr>
<tr>
<td>( \Delta D )</td>
<td>Drilled depth</td>
<td>m, ROP and bit lifetime</td>
</tr>
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</table>

Contactless drilling technologies, i.e., PPGD, thermal spallation, laser, etc., are expected to:
- increase the ROP and the bit lifetime,
- eliminate most of the mechanical failure, and
- afford the drilling-with-casing approach.

[Lyons et al. (2012)]
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Plasma-Pulse Geo-Drilling (PPGD): Basic principal

Thus, PPGD requires short high-voltage pulses of rise time \( \leq 500 \) nanoseconds and amplitude \( \geq 200 \) kV, thereby forming plasma channels inside the rock, not in the drilling fluid.

Lightning in nature

\[
E > E_{DS,R}
\]

<table>
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<th>Applied voltage gradient</th>
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<tr>
<td>( E_{DS,R} )</td>
<td>Dielectric strength of the rock</td>
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<td>( E_{DS,DF} )</td>
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Plasma-Pulse Geo-Drilling (PPGD): Basic principal

Lightning in nature

\[ E > E_{DS,R} > E_{DS,DF} \]

- **E**: Applied voltage gradient
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Thus, PPGD requires short high-voltage pulses of rise time \( \leq 500 \) nanoseconds and amplitude \( \geq 200 \) kV, thereby forming plasma channels inside the rock, not in the drilling fluid.
InterPore2022, 30 May - 02 June, Abu Dhabi, UAE

Mohamed Ezzat et al. (mostamoh@ethz.ch) 30.05.2022

Geothermal Energy and Geofluids

PPGD: Proved concept

High voltage pulse

[Image of a graph showing pulse voltage over time]

[Ezzat et al. (2022b)]
Even though the research and investment in PPGD are incomparable (too little) to mechanical rotary drilling, comparative analysis has shown that PPGD may reduce the drilling costs by 17% from the costs of the mechanical rotary drilling (roller cone bit).
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[Anders et al. (2017)]

[PPGD: Proved concept]

High voltage pulse

Drill bit

Borehole

[High voltage electrode]

[Grounded electrode]

[Polyethylene Insulator]

[Ezzat et al. (2022b)]

[Ushakov et al. (2019)]

[Rossi et al. (2020)]
PPGD: Proved concept

Even though the research and investment in PPGD are incomparable (too little) to mechanical rotary drilling, comparative analysis has shown that PPGD may reduce the drilling costs by 17\% from the costs of the mechanical rotary drilling (roller cone bit).\[^1\] [Anders et al. (2017)].
PPGD phases (modeling approach)

- Phase-I: plasma formation in pores. [Lisitsyn et al. (1998)]
- Phase-II: Plasma pressure expand/induce microcracks.
- Phase-III: Plasma channel formation.
- Phase-IV: Plasma pressure damage rock.

Our simulations focus on the plasma simulation of Phase-I (i.e., increase in the pore pressure), which is the onset of the whole process. However, coupling this plasma simulation with a mature phase-field fracturing modeling is foreseen.

[Ezzat et al. (2022a)]
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PPGD experiments: Site

**Aim:** Investigates the PPGD performance in granite under deep wellbore conditions of up to 5 km depth.

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<td>bar</td>
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PPGD experiments @ Fraunhofer IEG, Bochum, Germany
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Control room

Safety Area

PPGD experiment

PPGD experiments @ Fraunhofer IEG, Bochum, Germany
PPGD experiments: Drilling cells

1- **Loading Frame Experiment** to study the lithostatic pressure effect

Apply lithostatic pressures up to 150 MPa simulating 5700 m depth.

[Ezzat et al. (2022b)]
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1- **Loading Frame Experiment** to study the lithostatic pressure effect

![Loading Frame Experiment](image1)

Apply lithostatic pressures up to 150 MPa simulating 5700 m depth.

[Ezzat et al. (2022b)]

2- **Mini-iBOGS Experiment** to study the hydrostatic pressure and temperature effects

![Mini-iBOGS Experiment](image2)

Apply hydrostatic pressures up to 50 MPa simulating 5000 m depth, and up to 80 °C.

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© Fraunhofer IEG/Börner
PPGD performance under elevated lithostatic pressure

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<td>Pulse voltage</td>
<td>200</td>
<td>kV</td>
</tr>
<tr>
<td>Rise time</td>
<td>&lt;100</td>
<td>ns</td>
</tr>
<tr>
<td>Electrode gap distance</td>
<td>15</td>
<td>mm</td>
</tr>
<tr>
<td>Number of pulses</td>
<td>10</td>
<td>#</td>
</tr>
<tr>
<td>Water electric conductivity</td>
<td>12-33</td>
<td>μS/cm</td>
</tr>
<tr>
<td>Hydrostatic pressure</td>
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[Ezzat et al. (2022b)]
PPGD performance under elevated lithostatic pressure

\[ Q \text{ [cm}^3\text{/pulse]} \]

\[ P_L \text{ [bar]} \]

[Graph showing the relationship between electric conductivity and confining pressure]

[Ezzat et al. (2022b)]
PPGD performance under elevated lithostatic pressure

Electric conductivity versus the confining pressure

Dominates the process at pressures less than 500 bars.

[Unlabeled graph showing electric conductivity versus confining pressure with data points and a polynomial fit]

[Detailed graph showing confining pressure strip free surface of the rock]

[Li et al. (2018)]

Dominates the process at pressures greater than 500 bars. [Ezzat et al. (2022b)]
PPGD performance under elevated lithostatic pressure

Electric conductivity versus the confining pressure

Dominates the process at pressures less than 500 bars. [Ezzat et al. (2022b)]

The confining pressure strip the free surface of the rock

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PPGD performance under elevated lithostatic pressure

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[Geinte Watanabe et al. 2015]

[Distilled water in the experiment]

The confining pressure strip the free surface of the rock

Domimates the process at pressures greater than 500 bars. [Li et al. (2018)]

[Plotted data and graphs showing conductivity and pressure relationships]
PPGD performance under elevated temperature

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PPGD performance under elevated temperature

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The rock’s electric conductivity dominates the performance until 500 bars, while the confining pressure dominates at higher pressures.
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The higher increase rate of the distilled water’s electric conductivity than that of granite decreases the PPGD performance by increasing the temperature.
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The higher increase rate of the distilled water’s electric conductivity than that of granite decreases the PPGD performance by increasing the temperature.

Outlook: Investigate the PPGD under coupled environment of elevated pressures, i.e., lithostatic and hydrostatic, and temperature.
PPGD may be a solution to reduce the drilling costs for geothermal energy, especially for the AGS.

<500 bars: The rock’s electric conductivity dominates. >500 bars: The confining pressure dominates.

Distilled water has a higher increase rate of electric conductivity with temperature than granite.

Thank you for your attention! Any Questions?

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Backup - PPGD: Pros

1- No mechanical abrasion

- Increases the ROP and elongates the bit lifetime.

2- No drilling string

- Minimizes the mechanical failures, which reduces the non-rotation time.

3- Fracture by tension as in (a)

- Tenth of the drilling specific energy of the rotary drilling.
Backup - PPGD: Research (challenges)

1- Understand the PPGD physics

   [Ezzat et al. (2022a)]

   to optimize the operating conditions.

2- Examine PPGD under HP/HT

   [Ezzat et al. (2022b)]

   to examine PPGD viability under the deep wellbore conditions.

3- Developing Compact generators

   [Anders et al. (2017)]

   to be installed in the drill head and withstand the deep wellbore conditions.

Geothermal Energy and Geofluid group, i.e., the PPGD project and this Ph.D. thesis, focus on topics 1 and 2. Nonetheless, other groups, e.g., Laboratory for High Power Electronic Systems, focus on topic 3.
Backup - PPGD experiments: Drilling cells

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![Loading Frame Experiment Diagram](image1)

Apply lithostatic pressures up to 150 MPa simulating 5700 m depth.

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Apply hydrostatic pressures up to 50 MPa simulating 5000 m depth, and up to 80 °C.

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[© Fraunhofer IEG/Börner]
Backup - Tested samples

T = 10°C

Lithostatic and hydrostatic pressures are equal 1 bar.
References I


