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

M. Ezzat[1], J. Börner[2], D. Vogler[1], V. Wittig[2], M. O. Saar[1]

[1]Geothermal Energy and Geofluids (GEG) group, ETH Zurich, Switzerland

[2]Fraunhofer Institution for Energy Infrastructures and Geothermal Systems (IEG), Germany

PPGD Project

Outline

Outline

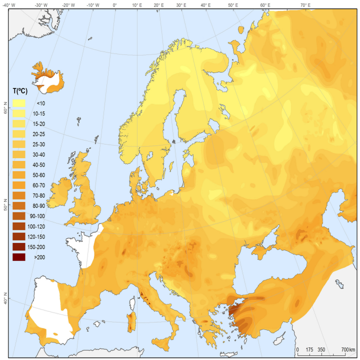
Introduction

Plasma-Pulse Geo-Drilling (PPGD)

PPGD experiments under deep wellbore conditions

Conclusions and Outlook

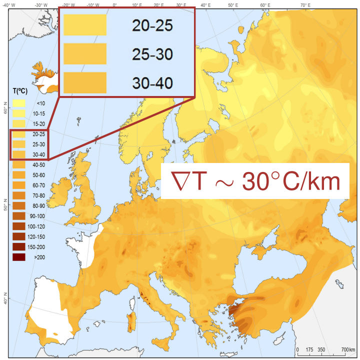
Why cheaper drilling for Geothermal Energy



Temperature@1 km depth @Europe

[Chamorro et al. (2014)]

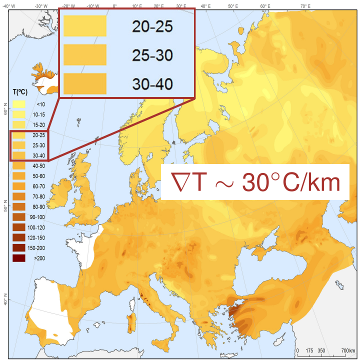
Why cheaper drilling for Geothermal Energy



Temperature@1 km depth @Europe

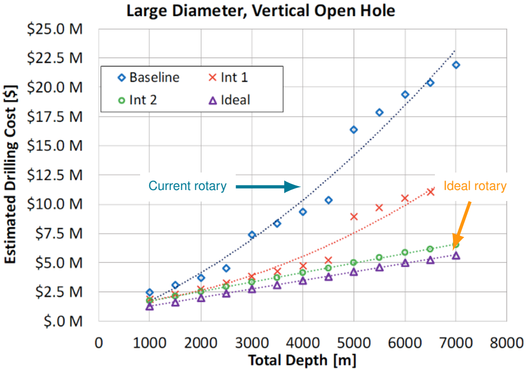
[Chamorro et al. (2014)]

Why cheaper drilling for Geothermal Energy



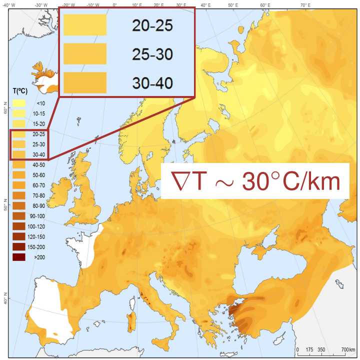
Temperature@1 km depth @Europe

[Chamorro et al. (2014)]



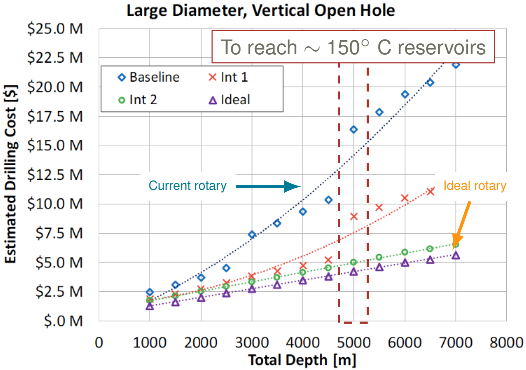
[Lowry et al. (2017)]: Calculated using the Well Cost Simplified (WCS) model from Sandia National Laboratories.

Why cheaper drilling for Geothermal Energy



Temperature@1 km depth @Europe

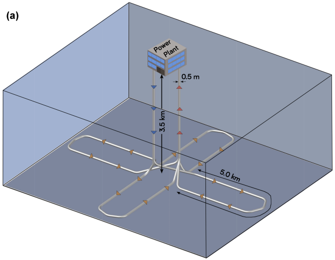
[Chamorro et al. (2014)]



[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[1]



Impact of the drilling performance

Scenario	Current rotary	Ideal rotary	Target (any)
ROP [ft/hr][2]	25	100	To be increased
Bit lifetime [hr][2]	50	200	To be increased
SpCC [USD/W_e][1]	145	37	2-5

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

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

	Cost parameter	Unit	Depends on
C_m	Drilling cost	USD/m	
C_b	Bit cost	USD	
C_r	Rig cost	USD/hr	
T_d	Drilling time	hrs	ROP
T_t	Tripping time	hrs	Bit lifetime
T_n	Non-rotating time	hrs	Mechanical failure and casing
ΔD	Drilled depth	m	ROP and bit lifetime

[Lyons et al. (2012)]

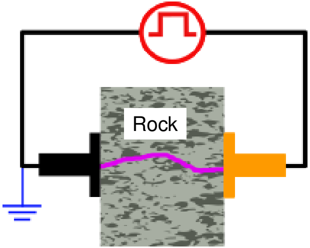
Contactless drilling technologies, i.e., PPGD, thermal spallation, laser, etc., are expected to:

- increase the ROP and the bit lifetime,
- eliminate most of the mechanical failure, and
- afford the drilling-with-casing approach.

Outline

Plasma-Pulse Geo-Drilling (PPGD): Basic principal

Lightning in nature

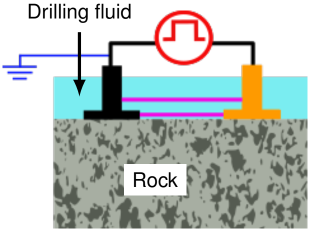


$E > E_{DS,R}$

E	Applied voltage gradient
$E_{DS,R}$	Dielectric strength of the rock
$E_{DS,DF}$	Dielectric strength of the drilling fluid

Plasma-Pulse Geo-Drilling (PPGD): Basic principal

Lightning in nature



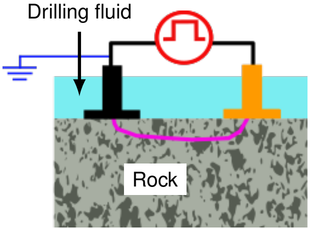
$E > E_{DS,R} > E_{DS,DF}$

E	Applied voltage gradient
$E_{DS,R}$	Dielectric strength of the rock
$E_{DS,DF}$	Dielectric strength of the drilling fluid

Plasma-Pulse Geo-Drilling (PPGD): Basic principal

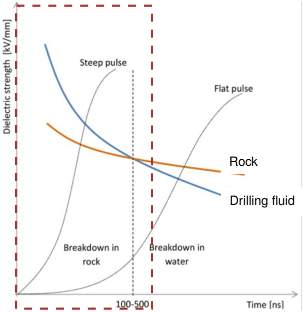
Alexander Vorobyev

(1909-1981) TPU



$E > E_{DS,R} > E_{DS,DF}$

Rise time $\tau_R < 500$ ns

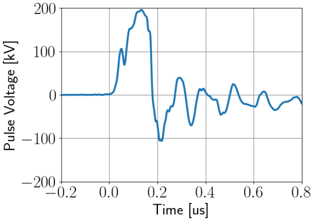


[Ushakov et al. (2019)]

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.

PPGD: Proved concept

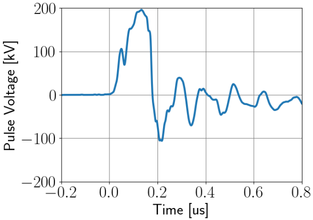
High voltage pulse



[Ezzat et al. (2022b)]

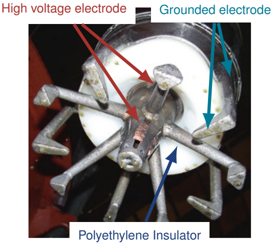
PPGD: Proved concept

High voltage pulse



[Ezzat et al. (2022b)]

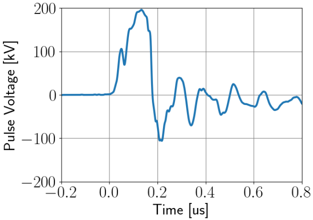
Drill bit



[Ushakov et al. (2019)]

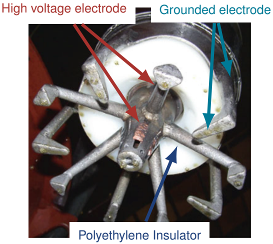
PPGD: Proved concept

High voltage pulse



[Ezzat et al. (2022b)]

Drill bit



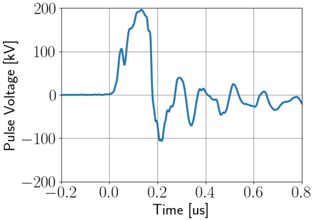
[Ushakov et al. (2019)]

Borehole

[Rossi et al. (2020)]

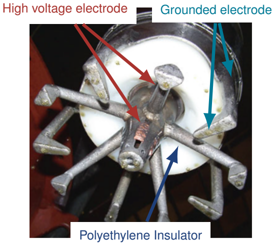
PPGD: Proved concept

High voltage pulse



[Ezzat et al. (2022b)]

Drill bit



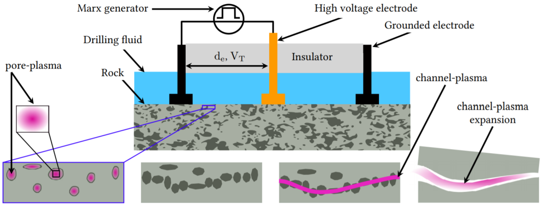
[Ushakov et al. (2019)]

Borehole

[Rossi et al. (2020)]

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%[1] from the costs of the mechanical rotary drilling (roller cone bit). [1] [Anders et al. (2017)].

PPGD phases (modeling approach)



(a) Phase-I (b) Phase-II (c) Phase-III (d) Phase-IV

- 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)]

Outline

PPGD experiments: Site

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

parameter	unit	range
Lithostatic pressure	bar	1 - 1500
Temperature	℃	7 - 80
Hydrostatic pressures	bar	1 - 500

PPGD experiments @ Fraunhofer IEG, Bochum, Germany

PPGD experiments: Site

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

parameter	unit	range
Lithostatic pressure	bar	1 - 1500
Temperature	°C	7 - 80
Hydrostatic pressures	bar	1 - 500

PPGD experiments @ Fraunhofer IEG, Bochum, Germany

PPGD experiments: Site

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

parameter	unit	range
Lithostatic pressure	bar	1 - 1500
Temperature	°C	7 - 80
Hydrostatic pressures	bar	1 - 500

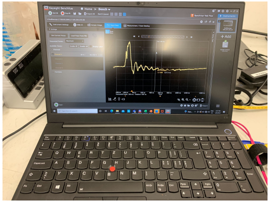
PPGD experiment

PPGD experiments @ Fraunhofer IEG, Bochum, Germany

PPGD experiments: Site

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

parameter	unit	range
Lithostatic pressure	bar	1 - 1500
Temperature	℃	7 - 80
Hydrostatic pressures	bar	1 - 500



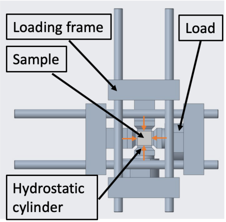
Control room

PPGD experiment

PPGD experiments @ Fraunhofer IEG, Bochum, Germany

PPGD experiments: Drilling cells

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



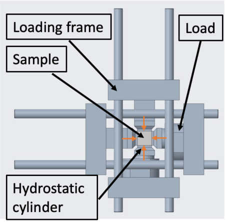
© Fraunhofer IEG/Börner

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

[Ezzat et al. (2022b)]

PPGD experiments: Drilling cells

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

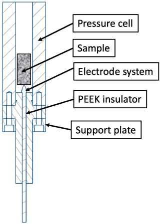


© Fraunhofer IEG/Börner

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

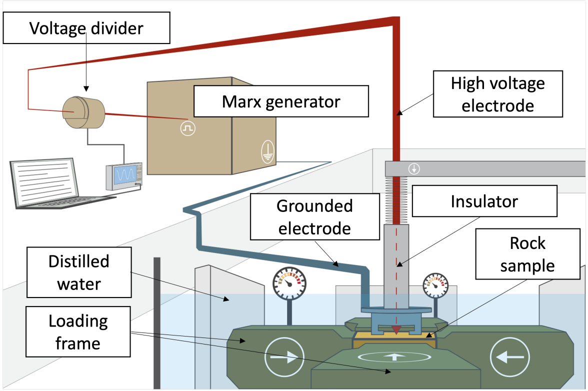


© Fraunhofer IEG/Börner

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

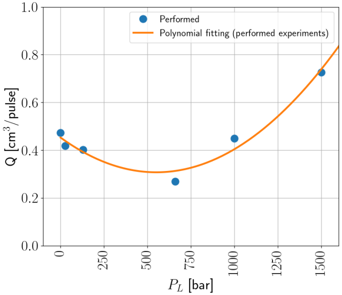
PPGD performance under elevated lithostatic pressure

parameter	value	unit
Pulse voltage	200	kV
Rise time	<100	ns
Electrode gap distance	15	mm
Number of pulses	10	#
Water electric conductivity	12-33	μS/cm
Hydrostatic pressure	1	bar
Temperature	10	°C
Lithostatic pressure	1 - 1500	bar



[Ezzat et al. (2022b)]

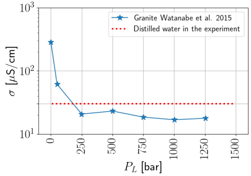
PPGD performance under elevated lithostatic pressure



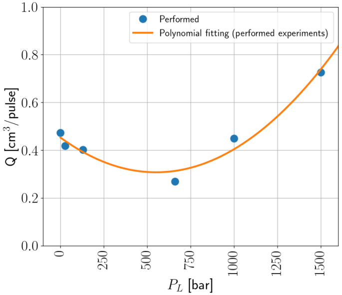
[Ezzat et al. (2022b)]

PPGD performance under elevated lithostatic pressure

Electric conductivity versus the confining pressure



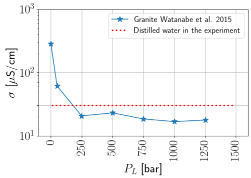
Dominates the process at pressures less than 500 bars.



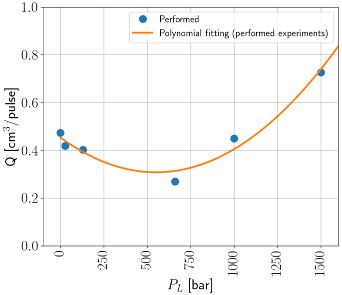
[Ezzat et al. (2022b)]

PPGD performance under elevated lithostatic pressure

Electric conductivity versus the confining pressure

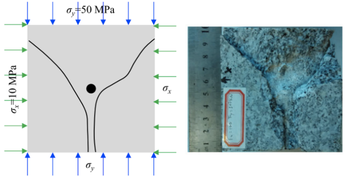


Dominates the process at pressures less than 500 bars.



[Ezzat et al. (2022b)]

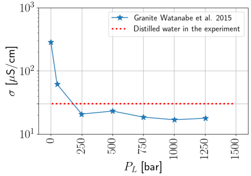
The confining pressure strip the free surface of the rock



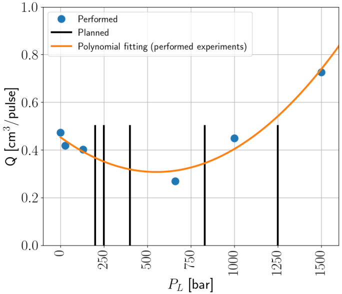
Dominates the process at pressures greater than 500 bars. [Li et al. (2018)]

PPGD performance under elevated lithostatic pressure

Electric conductivity versus the confining pressure

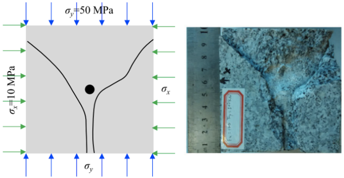


Dominates the process at pressures less than 500 bars.



[Ezzat et al. (2022b)]

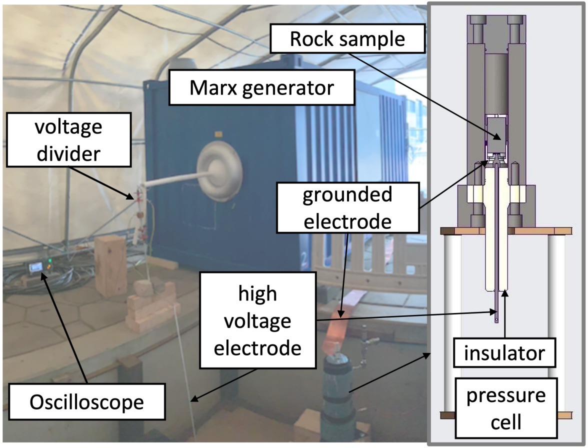
The confining pressure strip the free surface of the rock



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

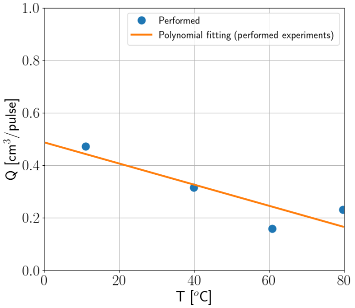
PPGD performance under elevated temperature

parameter	value	unit
Pulse voltage	200	kV
Rise time	<100	ns
Electrode gap distance	15	mm
Number of pulses	10	#
Water electric conductivity	12-33	μS/cm
Hydrostatic pressure	1	bar
Lithostatic pressure	1	bar
Temperature	11 - 80	°C



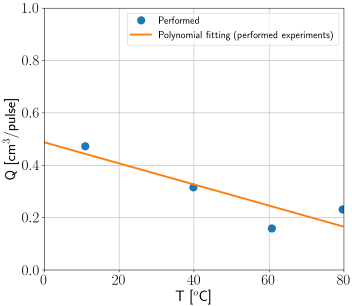
[Ezzat et al. (2022b)]

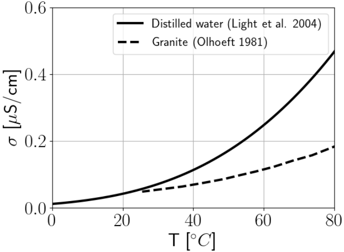
PPGD performance under elevated temperature



[Ezzat et al. (2022b)]

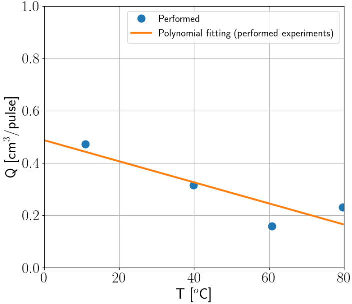
PPGD performance under elevated temperature

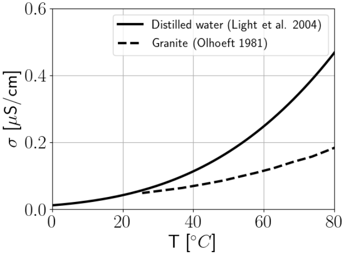




[Ezzat et al. (2022b)]

PPGD performance under elevated temperature

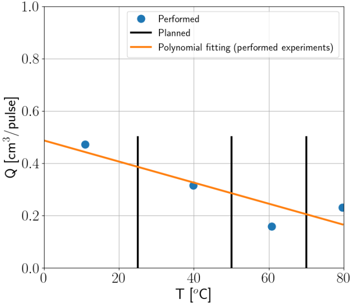


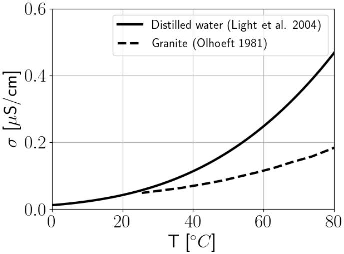


The rate of increase of the distilled water electric conductivity with temperature is greater than that of the granite. Consequently, the discharge is more likely to occur in water reducing the performance with temperature.

[Ezzat et al. (2022b)]

PPGD performance under elevated temperature





The rate of increase of the distilled water electric conductivity with temperature is greater than that of the granite. Consequently, the discharge is more likely to occur in water reducing the performance with temperature.

[Ezzat et al. (2022b)]

Outline

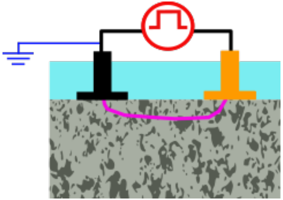
Introduction

Plasma-Pulse Geo-Drilling (PPGD)

PPGD experiments under deep wellbore conditions

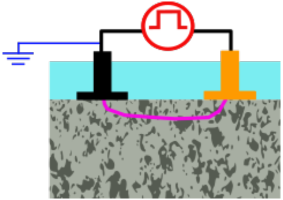
Conclusions and Outlook

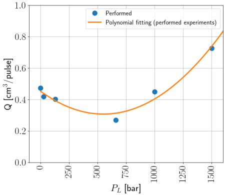
Conclusions and Outlooks



PPGD may be a solution to reduce the drilling costs for geothermal energy, especially for the AGS.

Conclusions and Outlooks

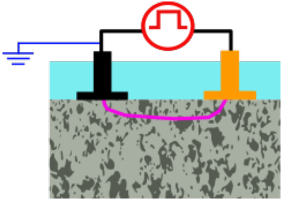




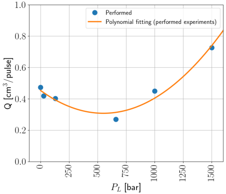
PPGD may be a solution to reduce the drilling costs for geothermal energy, especially for the AGS.

The rock's electric conductivity dominates the performance until 500 bars, while the confining pressure dominates at higher pressures.

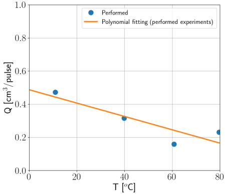
Conclusions and Outlooks



PPGD may be a solution to reduce the drilling costs for geothermal energy, especially for the AGS.

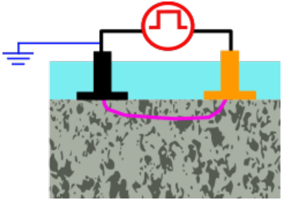


The rock's electric conductivity dominates the performance until 500 bars, while the confining pressure dominates at higher pressures.

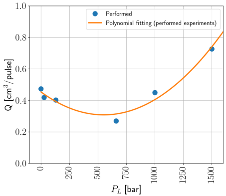


The higher increase rate of the distilled water's electric conductivity than that of granite decreases the PPGD performance by increasing the temperature.

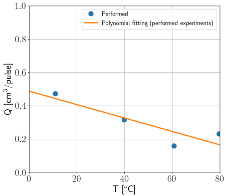
Conclusions and Outlooks



PPGD may be a solution to reduce the drilling costs for geothermal energy, especially for the AGS.



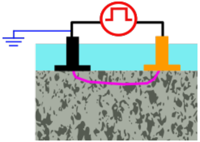
The rock's electric conductivity dominates the performance until 500 bars, while the confining pressure dominates at higher pressures.

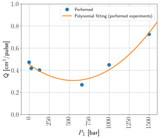


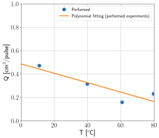
The higher increase rate of the distilled water's electric conductivity than that of granite decreases the PPGD performance by increasing the temperature.

Outlook: Investigate the PPGD under coupled environment of elevated pressures, i.e., lithostatic and hydrostatic, and temperature.

Conclusion







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.

GEO
Fraunhofer IEG
SwissGeoPower
Innosuisse
Grant No. 28305.1 PFIW-IW

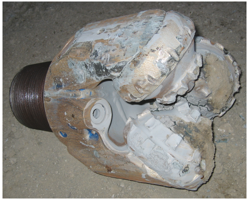
Scan for the PPGD Project

Thank you for you attention! Any Questions?

mostamoh@ethz.ch

Backup - PPGD: Pros

1- No mechanical abrasion



⇓

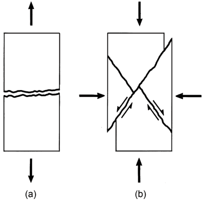
Increases the ROP and elongates the bit lifetime.

2- No drilling string

⇓

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

3- Fracture by tension as in (a)

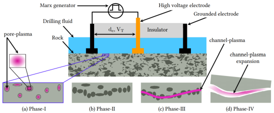


⇓

Tenth of the drilling specific energy of the rotary drilling.

Backup - PPGD: Research (challenges)

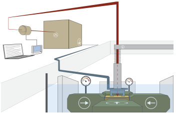
1- Understand the PPGD physics



[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

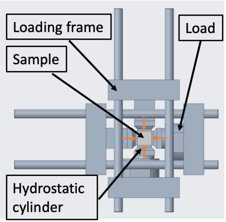
[Anders et al. (2017)]

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

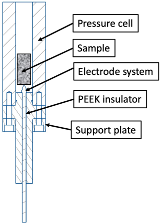
1- **Loading Frame Experiment** to study the lithostatic pressure effect



© Fraunhofer IEG/Börner

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

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



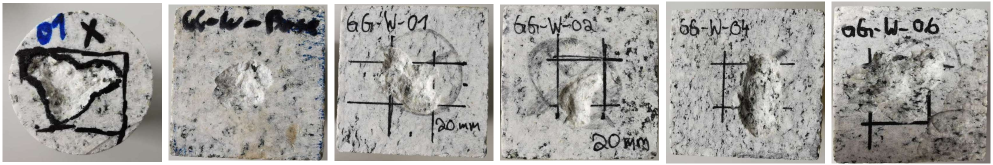
© Fraunhofer IEG/Börner

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

[Ezzat et al. (2022b)]

Backup - Tested samples

T= 10°C



(a) 1 bar (b) 27 bar (c) 330 bar (d) 660 bar (e) 1000 bar (f) 1500 bar

Lithostatic and hydrostatic pressures are equal 1 bar.

(a) 10^{o}C (b) 40^{o}C (c) 60^{o}C (d) 80^{o}C

References I

Anders, E., Voigt, M., Lehmann, F., and Mezzetti, M. (2017). Electric impulse drilling: The future of drilling technology begins now. In *36th International Conference on Ocean, Offshore & Arctic Engineering*, volume 8, Trondheim, Norway. OMAE.

Chamorro, C. R., García-Cuesta, J. L., Mondéjar, M. E., and Pérez-Madrazo, A. (2014). Enhanced geothermal systems in europe: An estimation and comparison of the technical and sustainable potentials. *Energy*, 65:250–263.

Ezzat, M., Adams, B. M., Saar, M. O., and Vogler, D. (2022a). Numerical modeling of the effects of pore characteristics on the electric breakdown of rock for plasma pulse geo drilling. *Energies*, 15(1):250.

Ezzat, M., Börner, J., Vogler, D., Witting, V., Adams, B. M., and Saar, M. O. (2022b). Experimental investigation of the lithostatic pressure effects on plasma pulse geo drilling. *In prep.*

Li, X., Wang, S., and Wang, S. (2018). Experimental investigation of the influence of confining stress on hard rock fragmentation using a conical pick. *Rock Mechanics and Rock Engineering*, 51(1):255–277.

Lisitsyn, I. V., Inoue, H., Nishizawa, I., Katsuki, S., and Akiyama, H. (1998). Breakdown and destruction of heterogeneous solid dielectrics by high voltage pulses. *Journal of Applied Physics*, 84(11):6262–6267.

Lowry, T. S., Finger, J. T., Carrigan, C. R., Foris, A., Kennedy, M. B., Corbet, T. F., Doughty, C. A., Pye, S., and Sonnenthal, E. L. (2017). Geovision analysis: Reservoir maintenance and development task force report (geovision analysis supporting task force report: Reservoir maintenance and development). Technical report, Sandia National Lab.(SNL-NM), Albuquerque, NM (United States).

References II

Lyons, W., Carter, T., and Lapeyrousse, N. J. (2012). Chapter one - basic equations. In Lyons, W., Carter, T., and Lapeyrousse, N. J., editors, *Formulas and Calculations for Drilling, Production, and Workover (Third Edition)*, pages 1–35. Gulf Professional Publishing, Boston, third edition edition.

Malek, A. E., Adams, B. M., Rossi, E., Schiegg, H. O., and Saar, M. O. (2022). Techno-economic analysis of advanced geothermal systems (ags). *Renewable Energy*.

Rossi, E., Adams, B., Vogler, D., Rudolf von Rohr, P., Kammermann, B., and Saar, M. O. (2020). Advanced drilling technologies to improve the economics of deep geo-resource utilization. In *2nd Applied Energy Symposium: MIT A+ B (MITAB 2020)(virtual)*, page 148. ETH Zurich, Geothermal Energy & Geofluids.

Ushakov, V. Y., Vajov, V. F., and Zinoviev, N. T. (2019). *Electro-discharge Technology for Drilling Wells and Concrete Destruction*. Springer, Cham, Switzerland.