Plasma Drilling (PPGD): Introduction and Modeling

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

Innosuisse Grant No. 28305.1 PFIW-IW

PPGD Project

Outline

Outline

Background

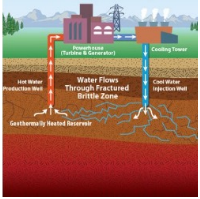
Plasma-Pulse Geo-Drilling

Modeling of the PPGD

Take-Home Message

Background - Geothermal Systems

Conventional geothermal system

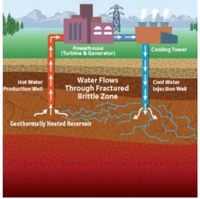


[©GreenFire Energy Inc.]

Shallow reservoirs $\sim$ 1-2 km
Temperature gradient $\geq$ 70 °C/km.
In permeable rock layers
Specific geological locations

Background - Geothermal Systems

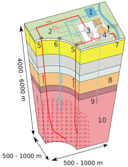
Conventional geothermal system



[©GreenFire Energy Inc.]

Shallow reservoirs ~ 1-2 km
Temperature gradient ≥ 70 °C/km.
In permeable rock layers
Specific geological locations

Enhanced geothermal system

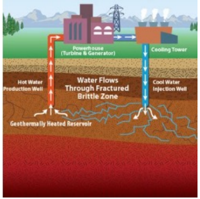


[Schiegg et al. (2015)]

Deep reservoirs ~ 3-5 km
Temperature gradient ≥ 40 °C/km.
Fracturing in the impermeable rocks
Everywhere

Background - Geothermal Systems

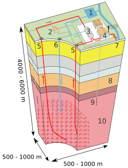
Conventional geothermal system



[©GreenFire Energy Inc.]

Shallow reservoirs $\sim$ 1-2 km
Temperature gradient $\geq$ 70 °C/km.
In permeable rock layers
Specific geological locations

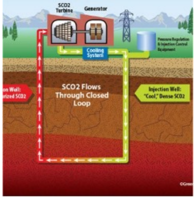
Enhanced geothermal system



[Schiegg et al. (2015)]

Deep reservoirs $\sim$ 3-5 km
Temperature gradient $\geq$ 40 °C/km.
Fracturing in the impermeable rocks
Everywhere

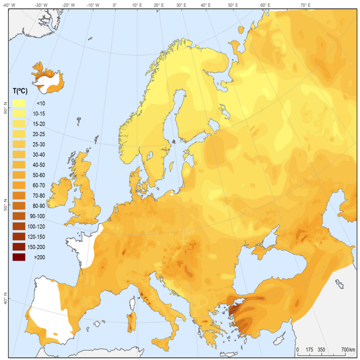
Advanced geothermal system



[©GreenFire Energy Inc.]

Extremely deep reservoirs $\geq$ 5 km
Temperature gradient $\sim$ 30 °C/km.
Closed loop system
Everywhere

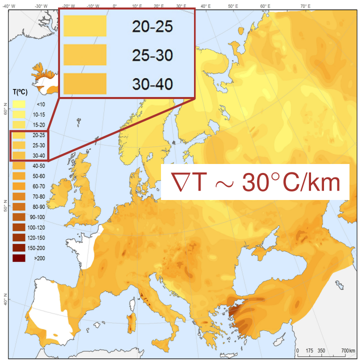
Background - Drilling Costs



Temperature@1 km depth @Europe

[Chamorro et al. (2014)]

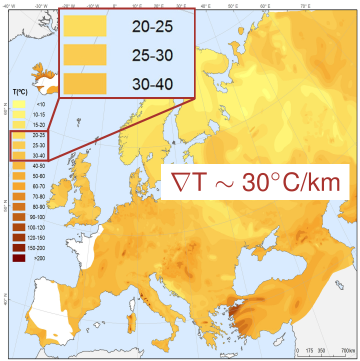
Background - Drilling Costs



Temperature@1 km depth @Europe

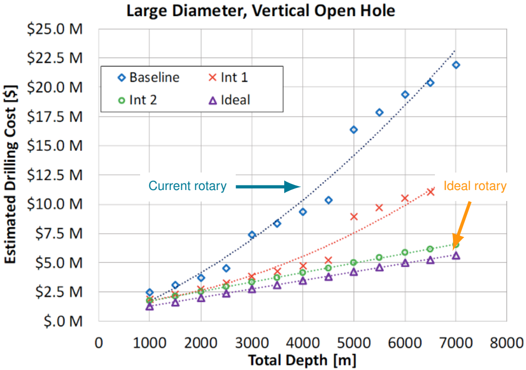
[Chamorro et al. (2014)]

Background - Drilling Costs



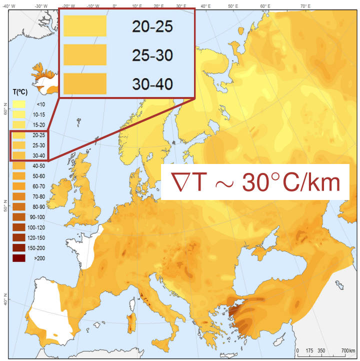
Temperature@1 km depth @Europe

[Chamorro et al. (2014)]

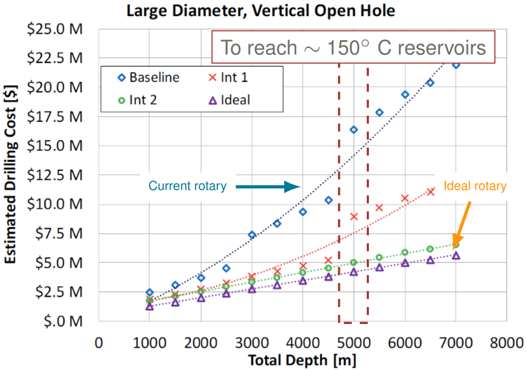


[Lowry et al. (2017)]: Calculated using the Well Cost Simplified (WCS) model from Sandia National Laboratories.

Background - Drilling Costs



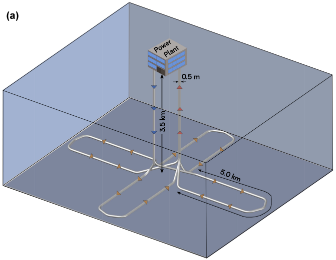
Temperature@1 km depth @Europe
[Chamorro et al. (2014)]



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

Background - Drilling Costs for AGS

AGS - case study[1]



Impact of the drilling performance

Scenario	Current	Ideal	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)]

Background - Drilling Costs Reduction

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

	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)]

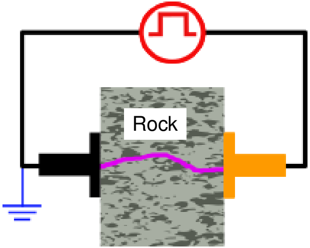
Contactless drilling technologies, i.e., PPGD, thermal spallation, laser, etc., are expected to:

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

Outline

PPGD - Concept

Lightning in nature

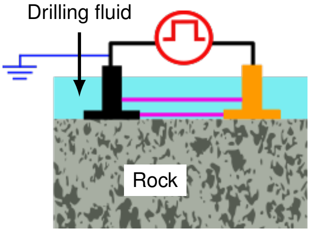


$E > E_{DS,R}$

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

PPGD - Concept

Lightning in nature



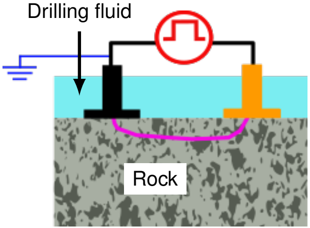
$E > E_{DS,R} > E_{DS,DF}$

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

PPGD - Concept

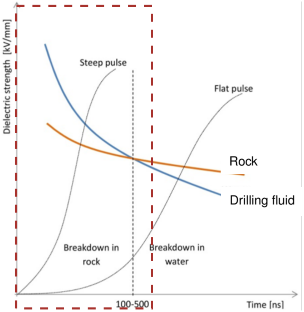
Alexander Vorobyev

(1909-1981) TPU



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

Rise time $\tau_R < 500$ ns

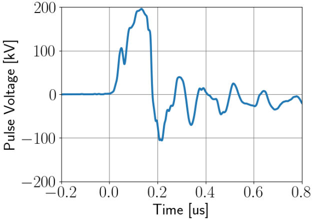


[Ushakov et al. (2019)]

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 - on the Lab Scale

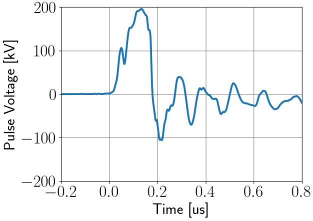
High voltage pulse



[Ezzat et al. (2022b)]

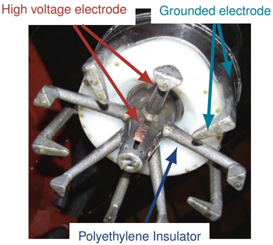
PPGD - on the Lab Scale

High voltage pulse



[Ezzat et al. (2022b)]

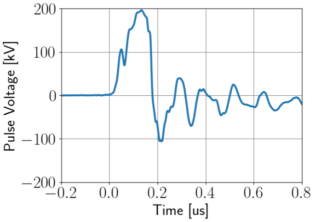
Drill bit



[Ushakov et al. (2019)]

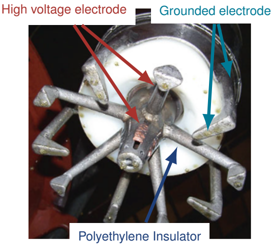
PPGD - on the Lab Scale

High voltage pulse



[Ezzat et al. (2022b)]

Drill bit



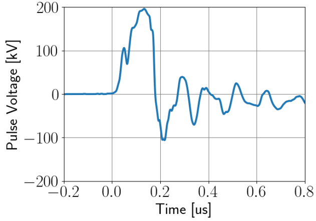
[Ushakov et al. (2019)]

Borehole

[Rossi et al. (2020)]

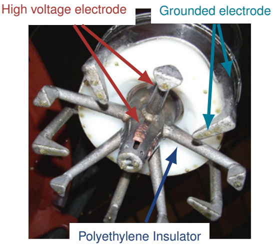
PPGD - on the Lab Scale

High voltage pulse



[Ezzat et al. (2022b)]

Drill bit



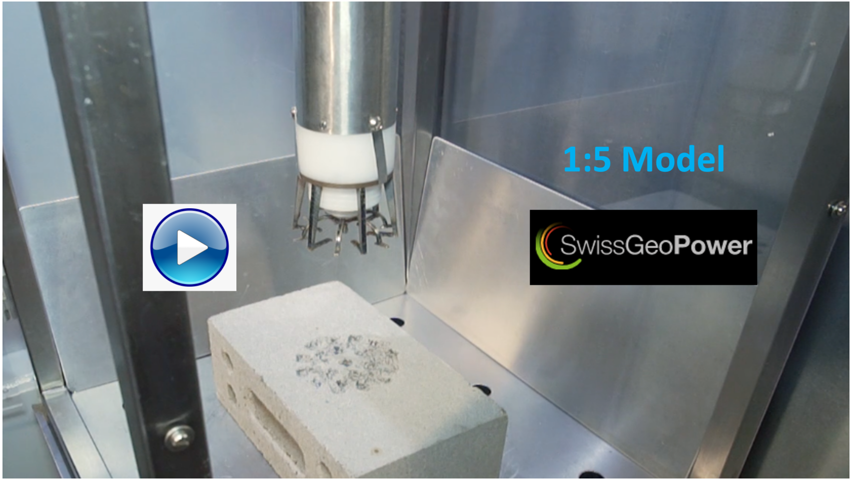
[Ushakov et al. (2019)]

Borehole

[Rossi et al. (2020)]

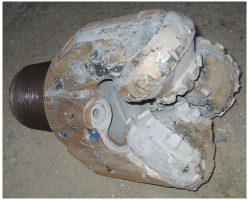
Even though the research and investment in PPGD are incomparable (too little) to mechanical rotary drilling, comparative analysis has shown that PPGD may reduce the drilling costs by 17%[1] from the costs of the mechanical rotary drilling (roller cone bit). [1] [Anders et al. (2017)].

PPGD - 1:5 Prototype by SwissGeoPower



PPGD - Pros

1- No mechanical abrasion

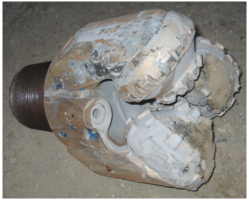


⇓

Increases the ROP and elongates the bit lifetime.

PPGD - Pros

1- No mechanical abrasion



⇓

Increases the ROP and elongates the bit lifetime.

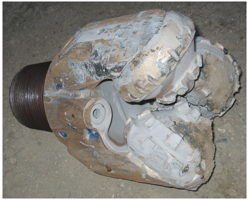
2- No drilling string

⇓

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

PPGD - Pros

1- No mechanical abrasion



⇓

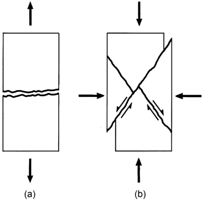
Increases the ROP and elongates the bit lifetime.

2- No drilling string

⇓

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

3- Fracture by tension as in (a)



⇓

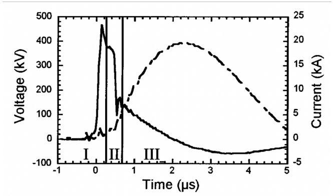
Tenth of the drilling specific energy of the rotary drilling.

PPGD - More pros

- Easier directional drilling
  ⇒ By controlling the operated electrodes.
- Simultaneous casing
  ⇒ Borehole diameter is larger than than the drill bit diameter.
- Make bigger covens from a small borehole
  ⇒ Nuclear waste storage or tunnel excavation.
- No need for the drilling rig to exert vertical pressure.
- Usable for mining exploration and mineral separation.

PPGD - Cons

1- High voltage impulses

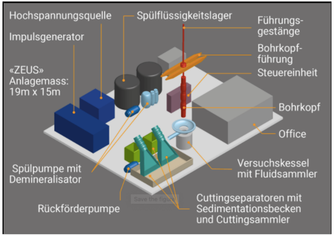


[Lisitsyn et al. (1998)]

2- Operation Environment

At $\sim$ 5 km depth,
150 MPa (i.e., 1500 atm) and
150 ^oC.

3- Pulse generator volume



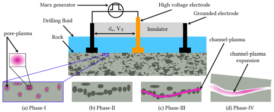
[©SwissGeoPower.ch]

PPGD - More cons

- Demoralized water is necessary
  $\Rightarrow$ Developing a cheaper drilling fluid of high dielectric strength is necessary
- Relatively big cutting size for circulation to be transported to the surface
  $\Rightarrow$ Use higher energy pulses or optimize the electrode configuration would solve the problem.

PPGD - Challenges (Research Areas)

1- Understand the PPGD physics

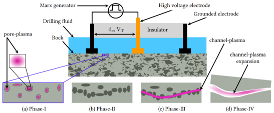


[Ezzat et al. (2022a)]

to optimize the operating conditions.

PPGD - Challenges (Research Areas)

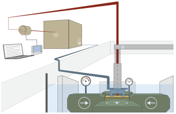
1- Understand the PPGD physics



[Ezzat et al. (2022a)]

to optimize the operating conditions.

2- Examine PPGD under HP/HT

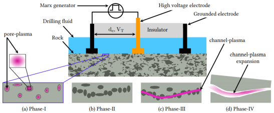


[Ezzat et al. (2022b)]

to examine PPGD viability under the deep wellbore conditions.

PPGD - Challenges (Research Areas)

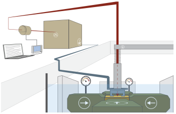
1- Understand the PPGD physics



[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.

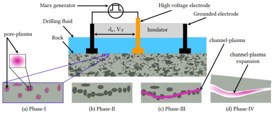
3- Developing Compact generators

[Anders et al. (2017)]

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

PPGD - Challenges (Research Areas)

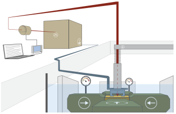
1- Understand the PPGD physics



[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.

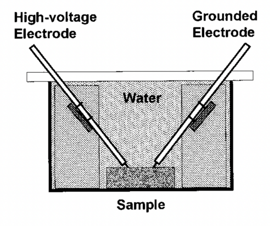
Geothermal Energy and Geofluid group, i.e., the PPGD project and this Ph.D. thesis, focus on topics 1 and 2. Nonetheless, other groups, e.g., Laboratory for High Power Electronic Systems, focus on topic 3.

Outline

Modeling of the PPGD

Lisitsyn et al. (1998) Experiment:

Experimental Setup



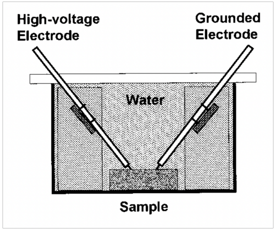
So, fracture onset occurs in the rock pores.

[Lisitsyn et al. (1998)]

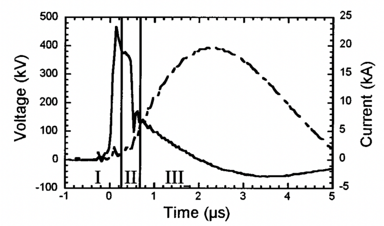
Modeling of the PPGD

Lisitsyn et al. (1998) Experiment:

Experimental Setup



Pulse profiles



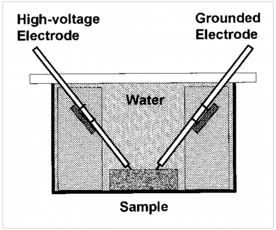
So, fracture onset occurs in the rock pores.

[Lisitsyn et al. (1998)]

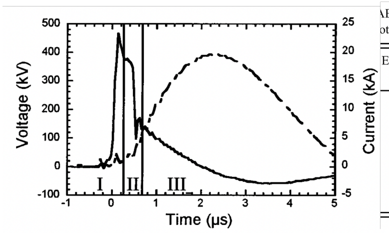
Modeling of the PPGD

Lisitsyn et al. (1998) Experiment:

Experimental Setup



Pulse profiles



Results

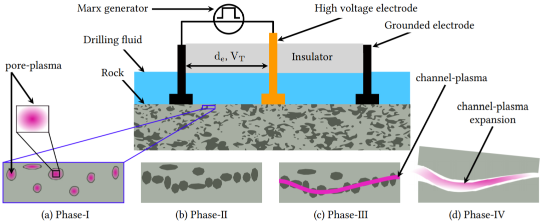
ABLE I. Destroyed volume in the experiment with granite samples (thr
ots).

Experiment number	Destroyed volume, cc dry granite	Destroyed volume, cc water-saturated granite
1	2.75	0
2	2.73	0
3	0	0
4	3.00	0
5	1.91	0
6	8.27	0
Average	3.11 ± 2.75	0 ± 0

So, fracture onset occurs in the rock pores.

[Lisitsyn et al. (1998)]

Modeling of the PPGD

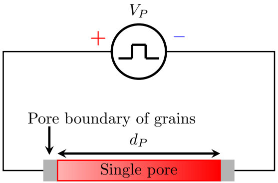


- Phase-I: plasma formation in pores. [Lisitsyn et al. (1998)]
- Phase-II: Plasma pressure expand/induce microcracks.
- Phase-III: Plasma channel formation.
- Phase-IV: Plasma pressure damage rock.

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)]

PPGD Modeling - Plasma Formation in Pores

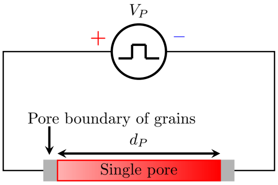


We use ZAPDOS application to simulate the plasma formation in a single pore and calculate the deposited electric power in the pore.

An open-source MOOSE Framework application for the simulation of plasma.

Then, we use the ideal gas low to calculate the increase in the pore pressure, i.e., final plasma pressure. [Ezzat et al. (2021)]

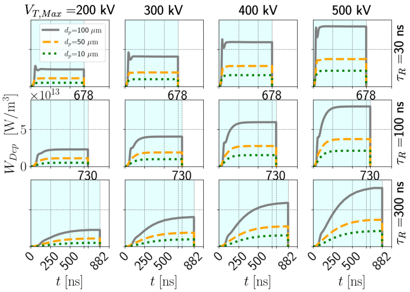
PPGD Modeling - Plasma Formation in Pores



We use ZAPDOS application to simulate the plasma formation in a single pore and calculate the deposited electric power in the pore.

An open-source MOOSE Framework application for the simulation of plasma.

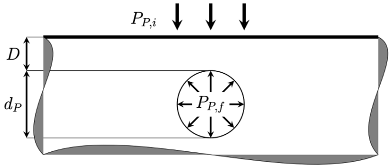
Deposited electric power density



Then, we use the ideal gas low to calculate the increase in the pore pressure, i.e., final plasma pressure. [Ezzat et al. (2021)]

PPGD Modeling - Plasma Formation in Pores

(a) Pressure concentration

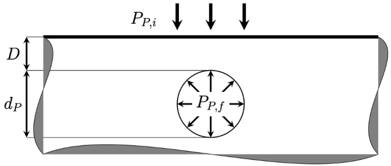


- Single pulse is enough to cause damage in rock of 100 um pore size (e.g., tuff or sandstone). However, A few pulses are necessary to cause damage in rock of pore sizes smaller than 100 um pore size (e.g., granite). Shown experimentally by [Lisitsyn et al. (1998)].

[Ezzat et al. (2021)]

PPGD Modeling - Plasma Formation in Pores

(a) Pressure concentration



$$P_{P,C} = \sigma_{Max}\left[1 + \frac{D/d_P}{(D/d_P)^2 + (D/d_P)^3}\right]^{-1} \quad (1)$$

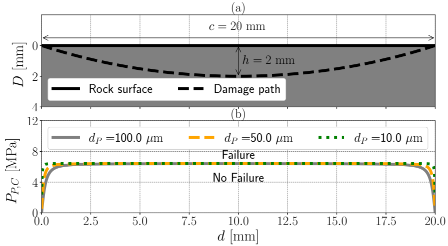
- Single pulse is enough to cause damage in rock of 100 um pore size (e.g., tuff or sandstone). However, A few pulses are necessary to cause damage in rock of pore sizes smaller than 100 um pore size (e.g., granite). Shown experimentally by [Lisitsyn et al. (1998)].

[Ezzat et al. (2021)]

PPGD Modeling - Plasma Formation in Pores

(a) Damage path (based on experimental work)

(b) Failure criterion



[Ezzat et al. (2021)]

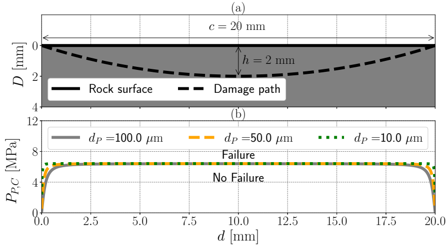
PPGD Modeling - Plasma Formation in Pores

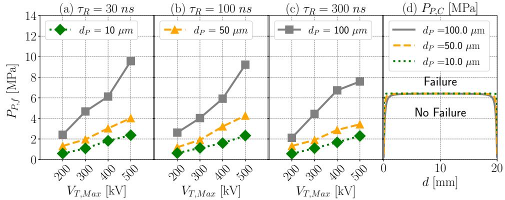
(a) Damage path (based on experimental work)

(b) Failure criterion

(a, b, c) Plasma pressure for different rise times.

(d) Failure criterion



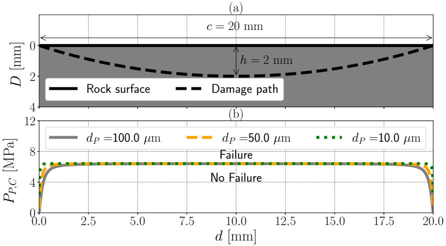


[Ezzat et al. (2021)]

PPGD Modeling - Plasma Formation in Pores

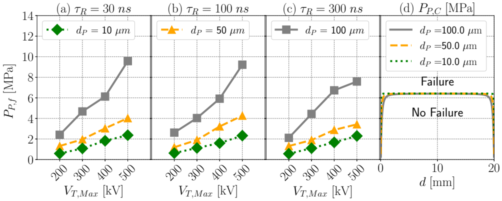
(a) Damage path (based on experimental work)

(b) Failure criterion



(a, b, c) Plasma pressure for different rise times.

(d) Failure criterion

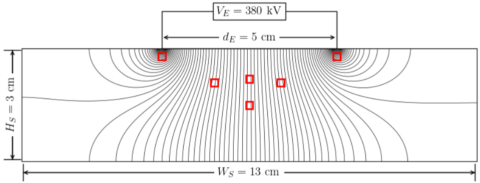


Single pulse is enough to cause damage in rock of 100 um pore size (e.g., tuff or sandstone). However, A few pulses are necessary to cause damage in rock of pore sizes smaller than 100 um pore size (e.g., granite). Shown experimentally by [Lisitsyn et al. (1998)].

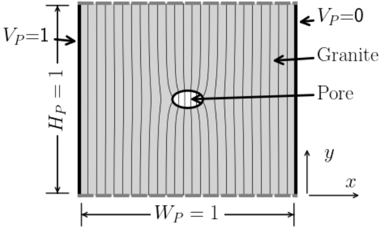
[Ezzat et al. (2021)]

PPGD Modeling - Pore Characteristics Effect

Sample model schematic



Pore model schematic

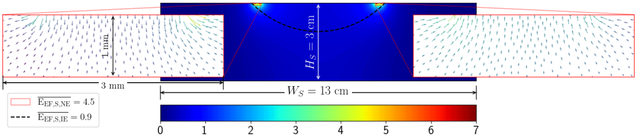


We use this model to calculate the electric field distribution: (1) across the sample to distinguish which regions have the highest electric field values and (2) across one single pore of different fluids, shapes, sizes, and orientations.

[Ezzat et al. (2022a)]

PPGD Modeling - Pore Characteristics Effect

Sample model schematic



We used Poisson Equation to calculate the electric field distribution ($E_S(x, y)$).

$$\nabla \cdot (\varepsilon \nabla V_S) = \rho_e, \qquad (2)$$

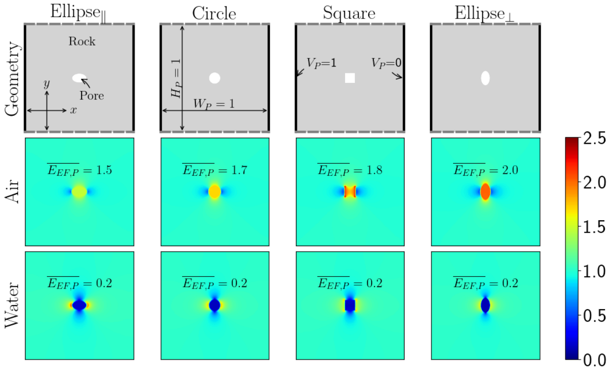
$$E_{EF,S} = E_S / E_E, \qquad (3)$$

ε	Electric permittivity
$V_S(x, y)$	Voltage distribution
$E_S(x, y)$	Electric Field
$E_{EF,S}$	Enhancement Factor of E_S

[Ezzat et al. (2022a)]

PPGD Modeling - Pore Characteristics Effect

Enhancement factor for the pore's electric field.



$$\nabla \cdot (\varepsilon \nabla V_P) = \rho_e, \quad (4)$$

$$E_{EF,P} = E_P / E_E, \quad (5)$$

ε	Electric permittivity
$V_P(x, y)$	Voltage distribution
$E_P(x, y)$	Electric Field
$E_{EF,P}$	Enhancement Factor of E_P

[Ezzat et al. (2022a)]

PPGD Modeling - Pore Characteristics Effect

Paschen's Law:

Breakdown Voltage (for gases):

$$V_{DS,a}(P_P, d_P) = \frac{B P_P d_P}{\ln(A P_P d_P) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{sec}}\right)\right]} \quad (6)$$

Dielectric strength (for gases):

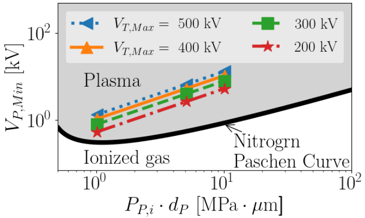
$$E_{DS,a}(P_P, d_P) = \frac{B P_P}{\ln(A P_P d_P) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{sec}}\right)\right]} \quad (7)$$

($d_P > 10\ \mu$ m, $P_P < 2.5$ MPa)

[d_P limit: Husain and Nema (1982) & P_P limit: Hopf et al. (2015)]

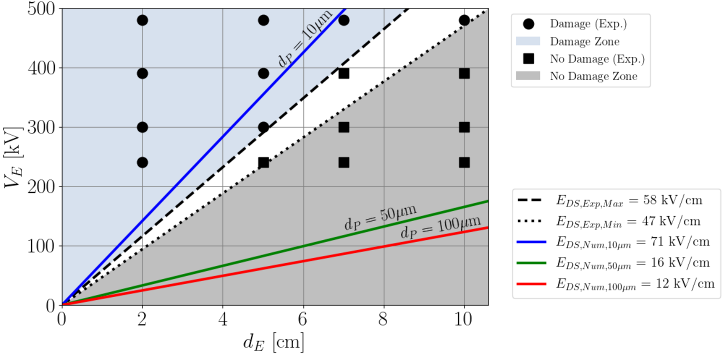
[Ezzat et al. (2021)]

Paschen Curve:



PPGD Modeling - Pore Characteristics Effect

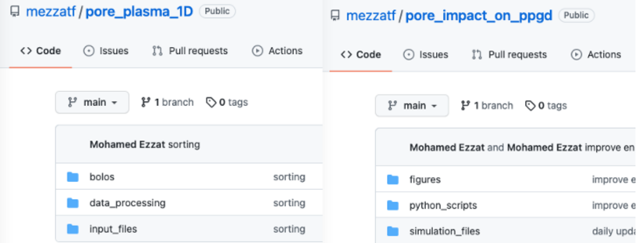
Predicted VS Measured Dielectric Strength of the Granite:



[Ezzat et al. (2022a)]

PPGD Modeling Repositories

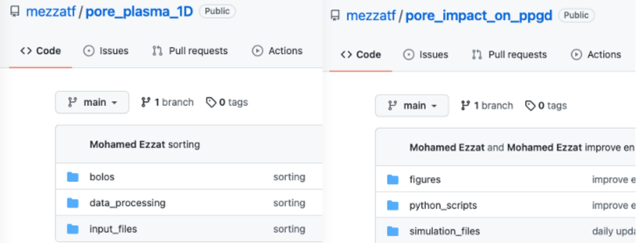
Our models are open source:



https://github.com/mezzatf

PPGD Modeling Repositories

Our models are open source:

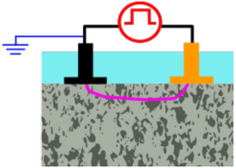


https://github.com/mezzatf

You can learn, ask questions, modify and collaborate.

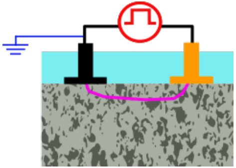
Outline

Take-Home Message

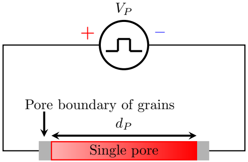


PPGD may be a solution to reduce the drilling costs for geothermal energy, especially for the AGS.

Take-Home Message

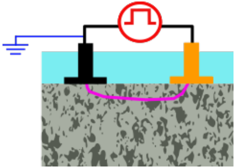


PPGD may be a solution to reduce the drilling costs for geothermal energy, especially for the AGS.

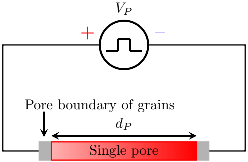


Pore pressure increase due to Plasma Formation is sufficient to induce fracturing in granite.

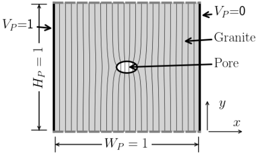
Take-Home Message



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

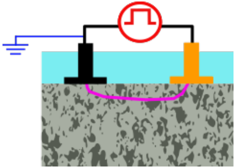


Pore pressure increase due to Plasma Formation is sufficient to induce fracturing in granite.

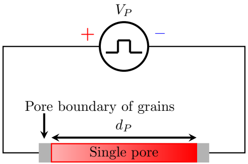


The Pore characteristics, i.e., pressure, fluid, size, and orientation, are critical for the PPGD process.

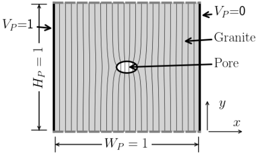
Take-Home Message



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



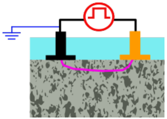
Pore pressure increase due to Plasma Formation is sufficient to induce fracturing in granite.



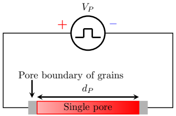
The Pore characteristics, i.e., pressure, fluid, size, and orientation, are critical for the PPGD process.

Outlook: (1) Include the electrodynamic effects and (2) couple the plasma and the rock fracturing models. [Ezzat et al. (2021, 2022a)]

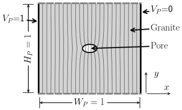
Take-Home Message



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



Pore pressure increase due to Plasma Formation is sufficient to induce fracturing in granite.



The Pore characteristics, i.e., pressure, fluid, size, and orientation, are critical for the PPGD process.

Geothermal Energy & Geofluids
Fraunhofer IEG
SwissGeoPower
Innosuisse
Grant No. 28305.1 PFIW-IW

Thank you for you attention! Any Questions?

mostamoh@ethz.ch | m.ezzatf@icloud.com

Scan for the PPGD Project

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.*

Ezzat, M., Vogler, D., Saar, M. O., and Adams, B. M. (2021). Simulating plasma formation in pores under short electric pulses for plasma pulse geo drilling (ppgd). *Energies*, 14(16).

Hopf, A., Rossner, M., Berger, F., and Prucker, U. (2015). Dielectric strength of alternative insulation gases at high pressurestreamer influence on paschen's law at high pressure. In *Electroenergetica glasamy molodeshny*, pages 394–399.

Husain, E. and Nema, R. S. (1982). Analysis of paschen curves for air, n2 and sf6 using the townsend breakdown equation. *IEEE Transactions on Electrical Insulation*, EI-17(4):350–353.

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.

References II

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).

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.

Schiegg, H. O., Rødland, A., Zhu, G., and Yuen, D. A. (2015). Electro-pulse-boring (epb): Novel super-deep drilling technology for low cost electricity. *Journal of Earth Science*, 26(1):37–46.

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