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Earth & Climate Science/Civil & Environmental Engineering Special Topics

PRACTICAL GEOTHERMAL GEOSCIENCE & ENGINEERING

Duke University Central Campus Geothermal Test Phase II

A Bass Connections Opportunity for Experiential Learning

ECS 590 / CEE 690 Class and Bass Connection Project Description

A Bass Connection associated ECS and CEE Special Topics 590 and 690 course will follow a geosciences-and-engineering investigation of a Duke University site's potential for Aquifer Thermal Energy Storage. ATES is a near-surface, geothermal-based, method of storing alternating heating and cooling water underground until needed.

During the course an original, Phase I, 120 m deep ATES test hole will be extended to 240 m. The 590/690 course will consist of a combination of field experience and weekly lectures on the basics of how one goes about establishing the potential for ATES energy resources. The field trips and lectures will prepare class participants to knowledgably follow the drilling of the shallow exploration well and its use in evaluating subsurface conditions.

The Topics to be covered in lecture are listed in the preliminary outline attached at the end of this syllabus. Guided visits to the drill site before, during, and after the 10-day drilling period will be conducted as major part of the class activities. Several opportunities to visit the drill site, drilling activities, and post drilling studies will be offered. A program of well logging is being developed and the basics of this subsurface characterization will be discussed.

Course evaluations will be divided into two options, one based on consistent field and lecture attendance and participation, the other on individual and group projects, including as part of a Bass Connection Team.

Through the Bass Connection Teams program, the course also offers the unique opportunity for collaborative projects and a second semester of focused study of the Phase II drilling results. Some of these projects will be guided toward publishable journal papers. A short list of the many possible projects - including ones covering social, economic, policy, as well as science and engineering - follow the lecture outline.

Meeting Times and Location

This course lectures will meet **Tuesdays from 3:05 - 4:20 PM** in LSRC A158. The intensive field experience is currently scheduled for Sept 25 to Oct 17. To take advantage of a practical geothermal investigation for energy sustainable development on Duke campus, the time commitment for this class will be front loaded on this field period.

Class Text Book Materials (In progress for RTI Publications): available on Sakai progressive drafts

Optimizing Geothermal Energy Development
P. E. Malin and J. F. Eppink

1. Geothermal Energy. The why, where, when, and how it fits.
    a. Why is geothermal considered a sustainable, abundant, resource?
    b. Where is cost-effective geothermal energy found now? Tomorrow?
    c. How geothermal energy fits into the Energy Transition
        i. A few hot wet rocks, many hot dry rocks
        ii. Cracking the Engineered Geothermal System nut
    d. The business case for geothermal energy
        i. The comparable market price – without climate change ?
        ii. The will to take the chance and pay the price
    e. Summary. The why, where, when, and how geothermal fits
2. Geothermal Above Ground. Engineering, business, policy, & the environment
    a. It is not Just for winter but summer too.
        i. Geothermal cooling and public heath
    b. The under-and-over ground cost and risk divide.
        i. Established engineering v known unknowns
        ii. Super-critical blowouts and leaky wells
        iii. Induced earthquakes: unfortunate cases
    c. Taking and mitigating the risks, public and private.
        i. Induced earthquakes – a non simple model
    d. The geothermal surface-patch:
        i. the other shakes, hums, rumbles, and scents
3. Geothermal Underground. Dealing with geological and financial uncertainty.
    a. Oil pools, geothermal flows.
        i. Exploring the energy ratios
    b. Heat extraction in complex rock systems.
        i. A confluence of channels, not voids
        ii. Horizontal wells
    c. The natural and policy limits and costs of current technologies
        i. Rock is a poor conductor
        ii. Rock is a good reservoir
    d. Simple ways to sort through the technology offerings.
        ii. The Peclet number
4. A Social License to Operate
    a. Access to the resource—the permitting conundrum
        i. The land access count down
    b. Facing the Flow Stimulation / Induced Earthquake knot
        i. NY: a case study in exception
    c. The development of advanced induced earthquake Traffic Light Systems.
        i. Forecasting, not predicting
    d. Potential for Public health, social equity, and environmental justice
        i. Geothermal as a community resource
5. The Challenges and a Way Forward
    a. Accelerating the adoption of geothermal energy
        i. The public Road Map
        ii. Balancing investments, permits, policies, and oversight with the benefits
        iii. Technology gaps and innovations
        iv. The work force transfer - From oil field to heat field?
    b. A final word: geothermal utilization will take more than a village and a bank

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About the Bass Connections Project Teams Opportunity

Class members selecting the Bass Connection Project Teams opportunity are expected to be more than a collection of individuals working in parallel. Instead, they should foster dynamic collaboration in which all members are exposed to the diverse aspects of each project and work together toward shared goals.

Bass Connections projects should provide students and faculty the opportunity to struggle collectively with a complex problem and produce meaningful deliverables - as defined by each individual team.

Students should not expect the project team to operate like a standard class. You will instead be asked to grapple with ambiguity and to help shape the trajectory of the project. That said, while this experience will differ from a standard class, **students receiving academic credit are expected to dedicate the same amount of time to their Bass Connections team as any other course (12 hours per week).**

Project Goals & Learning Objectives

The project goals and learning objectives will be identified by students after self-selecting into small teams. Students can choose from a variety of project types, and as a group will identify their project deliverables . See below for suggested project ideas.

OVERALL GOAL: To be able to employ geothermal efficiently in a variety of contexts .

Academic Crediting and Grading

Grading

Given the nature of the class and number of units offered - and being a seminar with an option for simply attending class and field trips, I am thinking of;

B-, B, B+ = making all the classes and field trips

A-, A, A+= completing or beginning a serious (potentially publishable) project, can extend to a second semester

Academic Honesty

Adherence to the Duke Community Standard is expected. To uphold the Duke Community Standard:

I will not lie, cheat, or steal in my academic endeavors;

I will conduct myself honorably in all my endeavors; and

I will act if the Standard is compromised.

Please visit the Duke Communitv. Standard website for information about the Standard and your obligation to act with respect to it.

Academic dishonesty, including lying, cheating (including plagiarism), or stealing, is a violation of university golicv.. Please visit Duke University Libraries for more information about properly citing sources and avoiding glagiarism .

Accommodations

Students with disabilities who believe they may need accommodations in this class are encouraged to contact the Student Disabilitv. Access Office at {919) 668-1267 or htt gs://access.d uke.edu/ students as soon as possible to ensure that such accommodations can be implemented in a timely fashion.

If you need special accommodations due to physical or learning disabilities, medical needs, religious practices, or other reasons, please inform us as soon as possible so we can work to accommodate those needs.

Team Leaders and Contact Information

Team Leaders

These faculty/staff will attend all team meetings and be available for students regularly.

Name	*Email*	*Affiliation*
Peter Malin**	Malin@ duke.edu	Nicholas School of the Environment - Earth and Climate Sciences
Paul Baker	gbaker@duke.edu	Nicholas School of the Environment - Earth and Climate Sciences
Laura Dalton	Laura.dalton@duke.edu	Pratt School of Engineering - Civil & Environmental Engineering
Heileen Hsu-Kim	hsukim@duke.edu	Pratt School of Engineering - Civil & Environmental Engineering
Brian McAdoo	Brian.mcadoo@duke.edu	Nicholas School of the Environment - Earth and Climate Sciences
Manolis Veveakis	Manolis.vevakis@duke.edu	Pratt School of Engineering - Civil & Environmental Engineering

** denotes team point-of-contact

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Fall Semester Schedule 2023

Tue 8/29/2023 3:05 PM - 4:20 PM

Tue 9/5/2023 3:05 PM – 4:20 PM
Topic 2: The big picture . Durham Basin and surrounding geology: Triassic Rifts, monoclines, relay ramps.

Mo 9/11/2023 to Mo 9/18/2023
ECS 590 / CEE 690 Questionnaire completion period – link sent and in Sakai

Tue 9/12/2023 3:05 PM – 4:20 PM
Topic 3: Geothermal heat flow: hydrothermal systems; critical state rock physics

Tue 9/19/2023 3:05 PM – 4:20 PM
Topic 4: Preparation for Field Weeks I & II: Drilling and well logging 101

Tue 9/26/2023 to Mon 10/02/2023
DU Central Campus Geothermal Test site
Topic 5: Field Week I - Geothermal assessment core drilling. In-field instruction.

Tue 10/03/2023 to Mon 10/17/2023
DU Central Campus Geothermal Test site
Topic 6: Field Week II - Geothermal core drilling continued; Geothermal well logging. In-field instructi on .

Tue 10/24/2023 1:05 PM - 2:20 PM
Topic 7: Geothermal Test preliminary results; post drilling project kick-offs.

Tue 10/31/2023 1:05 PM - 2:20 PM
Topic 8: Optimizing Geothermal Development.

Tue 11/7/2023 3:05 PM – 4:20 PM
Topic 9: Optimizing Geothermal Development.

Tue 11/14/2023 3:05 PM – 4:20 PM
Topic 10: Optimizing Geothermal Development.

Tue 11/28/2023
Topic 10 : Optimizing Geothermal Development .

Mo 12/04/2023 to Fr 12/08/2023
Topic 11 : Optimizing Geothermal Development

Tue 12/5/2023 1:05 PM - 2:20 PM
Last 590/690 Class: CCGT Phase II progress wrap up for 2023

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Some Suggested Potential Individual and Bass Connection Teams Experiential Learning Projects

- Science oriented topics
  - Drill site structural and lithological relations to the Durham basin
  - Rock core analysis
    - Lithology
    - Mineralogy
    - Fractures
  - Well logs
    - Physical characteristics - heterogeneous or homogeneous, iso- or anisotropic?
    - Relevance of critical state physics?
  - Water Chemistry
    - Equilibria
    - Geothermal thermodynamics
- Engineering
  - Ground water engineering modeling
    - Slug test and analysis, or equivalents for basic ground water characteristics
    - Basic ground water modeling - homogeneous, isot ropic, equivalent porous media
    - Basic chemistry
    - Stochastic ground water modeling
  - Geothermal engineering observation and modeling
    - Thermistor array, measurements, models, and implications
    - Basic hydrothermal modeling - homogeneous, isotropic, equivalent porous media
    - Stochastic hydrothermal modeling - heterogeneous, critical state media
  - Well treatments
    - Hydraulic stimulation - mini hydro fracture test
  - Potential and design for Aquifer Thermal Energy Storage:
    - System evaluation
    - System next step development
- Social
  - Daily blog on 1 or more social media accounts {last time we used twitter)
  - Social and administrative barriers to adaptation of Aquifer Thermal Energy Storage on Campus
  - Social and administrative barriers to adaptation of ATES for adjacent areas - e.g. downtown
- Economic
  - Level energy cost model:
    - Theoretical
  - Based on available measurements
    - Economic barriers to adaptation of Aquifer Thermal Energy Storage on Campus
  - Scalability
- Business model
  - Investors and stakeholders
- Policy
  - Permits!
  - Energy equity
  - Who will be affected by
    - Successful outcome of Phase II evaluation
    - Unsuccessful outcome of Phase II evaluation

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Proposal to The Duke Climate Research Innovation Seed Program

1.1 Proposal Title

Duke University Central Campus Geothermal Test - Phase II:

Characterizing Fractured Durham Basement Rock for ATES Cooling & Heating

1.2 Investigators

Paul Baker, Professor, Earth & Climate Science, Rm A116A, LSRC, pbaker@duke.edu, +1 919 684 6450

Laura Dalton Assistant Professor, Civil & Environmental Engineering, 121 Hudson Engineering Center, laura.dalton@duke.edu , +1 919 660-5421

Helen Hsu-Kim, Professor, Civil & Environmental Engineering, 118A Hudson Engineering Center, hsukim@duke.edu, +1 919 660-5109

Peter Malin, Professor (Emeritus), Earth & Climate Sciences, Rm A113A, LSRC, malin@duke.edu, +1 919 660 7418

Brian McAdoo, Associate Professor, Earth and Climate Sciences, Grainger Hall, brian.mcadoo@duke.edu, +1 919 680 1304

Manolis Veveakis, Associate Professor, Civil & Environmental Engineering, Rm 2456, FCIEMAS manolis.veveakis@duke.edu, +1 919 684 5867

1.3 Principal Investigator and Co-Principal Investigators

PI: Manolis Veveakis

Co PIs: Paul Baker, Laura Dalton, Helen Hsu-Kim, Peter Malin, Brian McAdoo

1.4. Primary research area:

Duke and Durham Energy Transformation

1.5. Secondary research area:

Duke and Durham Environmental and Climate Justice and Climate and Data

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2. Abstract. Cooling and Heating Duke and Durham with Geothermal ATES.

Duke and Durham are part of a rapidly growing, culturally diverse, urban area. Our Duke Central Campus Geothermal Test Phase II project seeks to establish if the fractured rocks found in our Phase I borehole can be use as local Aquifer Thermal Energy Storages for assisting with the cooling and heating of Duke and Durham buildings (see Appendix 5.4 for details on ATES systems). The goal of Phase II is to establish both (1) the useful thickness of the potential ATES rocks and (2) their capacity for cost-effective ATES. The Phase II borehole will also examine the potential for CO2 storage.

We drilled our 352 ft deep Phase I CCGT borehole with support from the NSOE Dean and Visiting Committee's Innovation Fund ($75k). The bottom 20 ft of this well penetrated fractured Carolina Terrane basement rocks which now appear to underlie campus and potentially the Durham area. If these water and fracture-rich rocks extend tens of feet deeper and are highly permeable, they many have potential for storing cold water for cooling and hot water for heating. (E.G. https://www.youtube.com/watch?v=rbPqMOtpkLs.)

To this end, our proposed CRISP project will build on our current results by extending the Phase I borehole to 700 ft and characterizing its rock for potential cost-effective ATES. We anticipate that, based on data collected in Phases I & II, we will be able to estimate the cost-effective ATES capacity of the fractured basement rocks by the end of 12-months.

3. Characterizing Fractured Durham Basement Rock for ATES Cooling & Heating.

3.1. Extending CCGT Phase I to Phase II: Rock Characterization for ATES & CO_2

Our objectives are to establish the (1) thickness and (2) potential cost-effective geothermal utilization of the fractured basement rocks found in our Phase I Central Campus Geothermal Test borehole. The fractured basement rocks appeared in the bottom 20 feet of the 352 ft deep Phase I borehole. They match fractured basement rocks that outcrop to the west of Duke and Durham (Fig 1). Based on their geological relationships and history, these rocks have been projected to underlie both the campus and city of Durham. Thus, their discovery in our Phase I borehole adds a direct demonstration of this relationship.

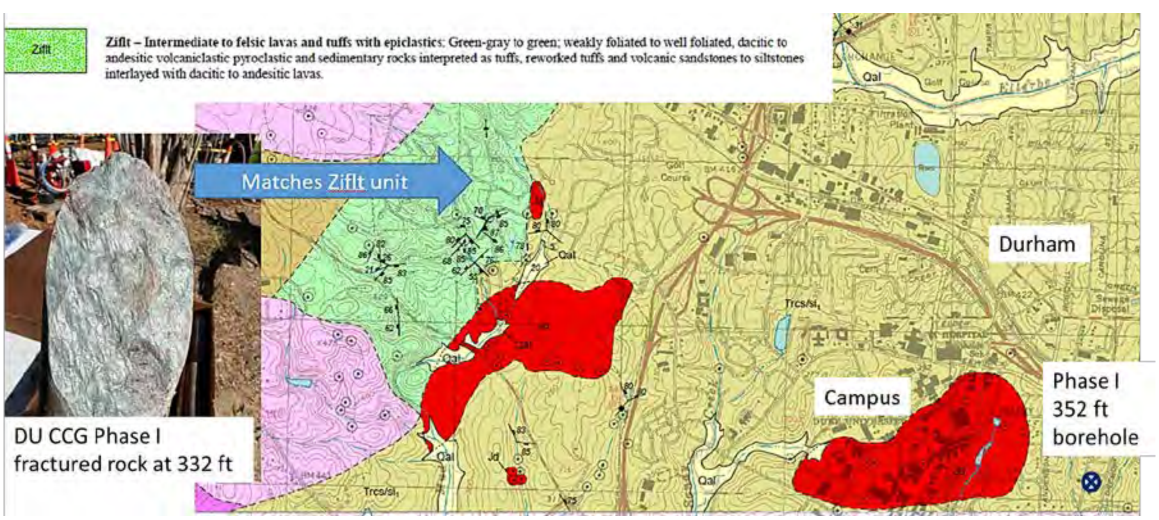

Fig 1. Map of fractured Ziflt rocks outcropping west of DU and found in Phase 1.

Significantly, if the thickness of these fractured rocks extends for several tens of feet deeper and hundreds of feet laterally – which would now appear to be the case – they may have potential for use in local Aquifer Thermal Energy Storage cooling and heating of Duke and Durham buildings, apartments, and houses. As described in Appendix 5.4, ATES is a closed loop method of heat storage. Cool water is stored for summer use, hot for winter.

This utilization also depends on the fluid-flow characteristics and distribution of the fractures in these rocks (Fig 2). If the density of connected, fluid filled fractures is sufficiently great, significant quantities of cool and hot water can be stored and retrieved for moderating the energy needed to run air conditioning and heating.

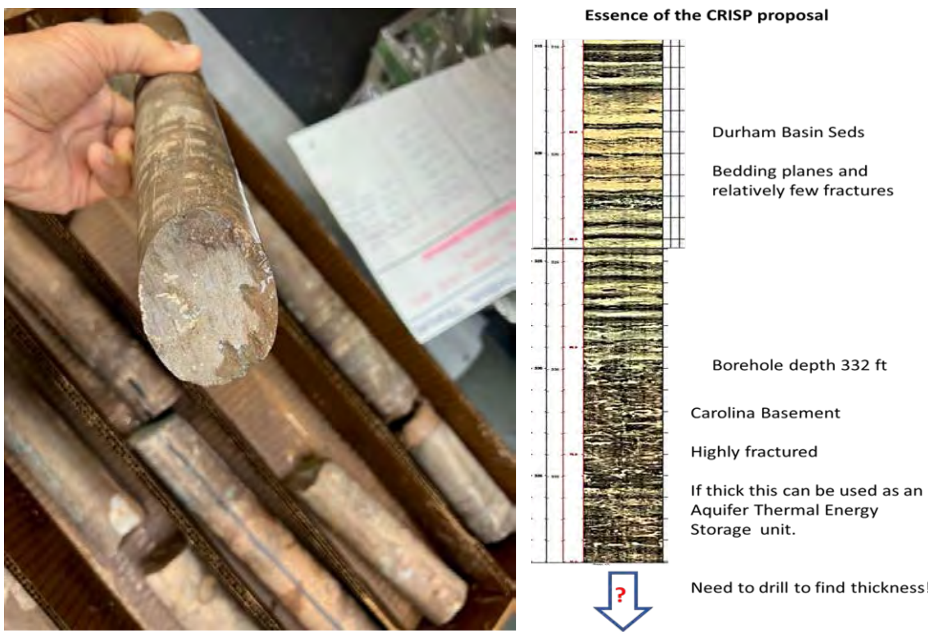

Fig 2. Left: Drill-core of the fractured rocks. Right: borehole televiewer log of fractures

3.2. DU Central Campus Geothermal Test, Phase I Results: Fractured Basement Rock.

3.2.1. NSOE Dean & Innovation Grant Committee: Phase I to Phase II plan.

The Duke Central Campus Geothermal Test borehole (CCGT) project was selected by the NSOE Dean and Board of Visitors for the Dean's Innovation Fund ($75k) in 2021. Project proponents were Paul Baker (co-PI), Peter Malin (co-PI), Dan Richter, Emily Klein, Brian McAdoo, Shineng Hu, Avner Vengosh, Gary Dwyer, Timothy Johnson, Dalia Patino Echeverri, Lincoln Pratson, Alex Glass, Henri Gavin, Manolis Veveakis. Edgard Ngaboyamahina joined later, and formed the project operations team with Baker, Malin, McAdoo, and Veveakis.

According to the Office of Sustainability, about half of campus energy usage is for cold and hot water. This thermal energy cannot be cost effectively produced 24/7 by solar and wind alone. If appropriately developed, an enhanced geothermal district cooling and heating system is an realistic option toward carbon neutrality at Duke within the foreseeable future. The CCGT project was the initial step toward this by showing that favorable geological condition exists.

After locating a site near the Duke Chiller Plant, obtaining permits and drilling bids, we drill-cored a 350 ft test borehole on Central Campus. At 330-334 ft we encountered a section of favorably fractured Carolina Terrane rocks beneath a blanket of mostly sealed Durham Basin sediments. If the fractured section continues for several tens or more feet, it has potential for developing of a Aquifer Thermal Energy Storage system for both seasonal cooling and heating. (E.G. see the 4 min video https://www.youtube.com/watch?v=rbPqMOtpkLs where it is cost-effectively used on a US military base in Georgia.)

Further, this project opened opportunities for fundamental research, advancing engineering, teaching, and entrepreneurial possibilities (e.g. see Appendix 5.5). It has provided a permanent laboratory for Duke students and potential outreach toward the greater Durham and Triangle community - especially the student participation in the drilling process as part of the *hands-on* Earth & Climate Sciences 590 Practical Geothermal Geosciences class that we ran in parallel with the drilling.

3.3. Description of the collaborative team and research setting(s)

Motivated by the goals of contributing to sustainable and equitable energy, the current Phase II Central Campus Geothermal Test CRISP proposal team assembled in order to (1) best carry forward the scientific, engineering, educational, and Duke community engagement and knowledge gained in Phase I, (2) continue to leverage the support of the technical, funding, and business community developed in Phase I, and (3) begin the steps toward extending our Phase I finding and expertise to the area and community beyond Duke campus. Further, the proponents of this CRISP proposal are only a subset of Duke faculty, staff, and students with vested interests and personal and professional stakes in continuing geothermal development on campus and beyond.

In terms of notable strengths and backgrounds, our proponent team brings the following high-lighted, unique, combination of expertise and experience:

PI Veveakis: geothermal engineering on CSIRO Perth Australia computer cooling

CoPI Baker: leading scientific & executive roles in scientific drilling (see 3.4)

CoPI Dalton: reactive, multiphase transport in nature; CO_2 sequestration

CoPI Hsu-Kim: impacts of energy production on water resources & global health

CoPI Malin: directing & teaching at follow-on New Zealand geothermal Institute

McAdoo: social & economic impacts of geology, climate & environment in Durham

Members of this team were also engaged in various educational aspects of the open enrollment ECS 590 Geothermal Geoscience class that was coordinated by Malin and run in parallel with, and made hands-on use, of the Phase I drilling effort (see Appendix 5.5).

3.4. Data Analysis & Core Archive at the US Continental Scientific Drilling Program

Duke has extensive geological, geochemical, geophysical, ground water, and engineering test facilities and supporting staff and students interested in the CCGT project. However, only limited number of test could be supported under our Phase I award from NSOE. Significantly, the materials and information collected in Phase I drilling – and to continue in Phase II – have also raised interest at the US Continental

Drilling Program based at the University of Minnesota. (See: https://cse.umn.edu/csd.) The Director of the CDP has proposed (and we have accepted) that the Phase I CCGT rock core be archived at CSD UoMN. The same offer has been extended to our proposed CRISP Phase II project if it should be funded. CSD also has offered to run special core analysis tests, tests that are not available at Duke.

3.5. Potential for sustained collaboration beyond the project term.

The proponents of our CRISP proposal have long associations relevant to geothermal energy development and in future-generation environmental education. They also have academic standings that lead to collaborations well beyond our circle within Duke. We see this diversity of our team as an asset for both further cooperative science and engineering and opportunities to increase support for geothermal applications at Duke and in Durham as pilots for our region and beyond.

A case in point is our relationships with the Cornell Earth Source Heat investigators (see the web links in the next section). Likewise with former students working in geothermal and environmental industries (e.g. see the geothermal project developed by Malin's student J. Eppink at https://arpa-e.energy.gov/technologies/projects/ambient-seismic-imaging-technology-low-cost-and-effective-geothermal-resource.) Hence the potential for our Phase II project to not only continued our collaboration but to expand it to a broader research and development community and industry engagement is high.

3.5.1. Highlighted work toward receiving external funding.

The PI and CoPI's have requested funding for similar, but deeper drilling, projects from ARPA-E, NSF Frontiers, and DoE EFRC. We also competed in the Research Triangle Institute's Forethought initiative for the future direction of collaborative with the Research Triangle Universities. Having received feedback from these various applications that, while the suggested work is impactful and well-presented technically, economically, and socially, a proof of concept with shallower pilot studies is first required before significant funding could be expected from these agencies.

We thus envision our CRISP proposal as seed funding to allow us access to gather sufficient information so that the team can be successful in further external funding. Ultimately, following the examples of Cornell University and University of West Virginia as described below, we ultimately aim securing Centre-level NSF/DoE funds.

Our differentiating factor is our focus on the energy, climate, economic, and social conditions of the southeastern US. In this region, cooling is a major concern, especially in rural communities. Because of it's localized, building-by-building technology, the ATES approach to cooling and heating may be a key road to equitable cooling solutions, both here and beyond.

There is president for this approach to geothermal development by other universities, specifically Cornell University and the University of WV. Given its northern climate, Cornell began its Earth Source Heating project several years ago (see: https://www.cornell.edu/ video/earth-source-heat-geothermal-energy-project-introduction). Cooperating with DoE and the International Continental Drilling Program in Potsdam German, Cornell was able to raise matching funds for a greater than 9,000 ft deep geothermal pilot test borehole: the CUBO Pilot well. (see: https://earthsourceheat.cornell.edu/).

3.6. Equitable Energy & Emission Reductions by Geothermal Modulation of Cooling

As short-and-longer term temperature extremes occur in many unexpected places around the globe, access to air conditioning and heating has become a public health issue. Currently, mostly electrically but also natural gas driven air cooling and heating are an energy, environmentally, and economically costly technologies. Even modest modulation of the energy required to create safe indoor temperatures would noticeably impact CO_2 and other climate change related gas emissions. This is especially true if this reduction could be realized at a local, building-by-building level, without resort to a central system requiring an extensive distribution system.

Given the appropriate geological conditions, Aquifer Thermal Energy Storage can provide this type local, incremental, building-by-building temperature modulation. A discussion of this technology, for which president exists in the Southeastern US, is presented in Appendix 5.4. The aim of our Phase II CCGT project is to see if the needed geological conditions exist under the Duke campus and in the Durham area.

4. Budgetary Documents.

4.1 CRISP Budget Form

Duke Climate Research Initiative Seed Program (CRISP) Budget Template

Cost Category	CRISP Funding Request	Notes - Name Activities Supported
Payroll-Allowable Categories		
RESEARCH ASSISTANTSHIP (PhD) (suggested range: $15–$18/hour + 11.3% fringe benefits*)	$	
RESEARCH ASSISTANTSHIP (Masters/professional) (suggested range: $12–$15/hour + 7.7% fringe benefits*)		
INSTRUCTION (Teaching)—PhD STUDENT (suggested range: $15–$18/hour + 11.3% fringe benefits*)	$	
POSTDOCTORAL (pay rate + 19.4% fringe benefits*) OR STAFF FTE (pay rate + 22.8% fringe benefits*)	$10,980	Malin - drill mngmt
Supplies & Materials		
INSTRUCTIONAL, RESEARCH, OR OFFICE SUPPLIES	$250	
COMPUTERS AND MINOR EQUIPMENT		
Travel Expenses		
TRAVEL—DOMESTIC	$2,250	UoMN core archive
TRAVEL—INTERNATIONAL	$2,250	Eu Geophy Union
General Operating and Other Costs		
ADVERTISING AND PUBLICITY	$	
CONTRACT WORK	$66,850	^drilling contract
PUBLIC RELATIONS (e.g., workshops or other related events)	$650	
MEETINGS—BUSINESS	$	
OTHER—MISC.	$16,750	#$14.75k Sci/Engin, +$2k drill contingency
TOTAL CRISP Request	**$99,980**	
Other Sources of Project Funds (Projects that leverage or match funds are encouraged and these funds [both awarded and proposed] should be noted so that we understand the comprehensive outlay for the project.)		
^ See attached bid for 350 ft of core drilling and logging by Hawston Drilling (picked from 6 bids).		
* includes water & rock chem, in situ fracture flow tests, rock mechanical properties; +potential drill changes or difficulties; residual to more depth.		

* Please refer here for additional details on fringe benefits:
https://resources.finance.duke.edu/resources/docs_sec/FbratesAnnounce_2223_May.pdf

4.2 Hawston Drilling Quotation

Hawkston, LLC
2410 Park Plus Drive
Columbia, TN 38401
931.486.4677

HAWKSTON

Estimate

ADDRESS
Mr. Peter Eric Malin
Duke University
308 Research Drive, Room
A115
Durham, North Carolina 27708
USA

ESTIMATE # 33-055
DATE 02/05/2023
EXPIRATION DATE 05/05/2023

ACTIVITY	QTY	RATE	AMOUNT
Mobilization/ Demobilization (lump sum)	1	7,000.00	7,000.00
ATV Drill Rig Support vehicle, crew, and equipment (Up to 10 hours onsite)	8	3,000.00	24,000.00
Rock Core Boxes Each	40	14.00	560.00
Skid Steer Per Day	8	325.00	2,600.00
Porta-Jon Lump	1	600.00	600.00
Per Diem Drill crew per diem or daily travel to/from site/yard	10	425.00	4,250.00
Environmental:Borehole Logging SPR, Gamma & Optical televiewer	1	9,000.00	9,000.00
Wireline Core Per Foot	350	42.00	14,700.00
Water Truck (week) (per week)	2	2,070.00	4,140.00

TOTAL **$66,850.00**

Accepted By

Accepted Date

5. Appendix Materials

5.1. Research schedule and milestones

DU CCGT Phase II - Drilling, Research, & Class Schedule and Milestones

Schedule and Milestones based on Phase I experience and Fall 2023 ECS 590 Class

Milestone	Date		Notes
	Start	**Finish**	
Permits			
Site permissions	1 May 23	31 Aug 23	John Noonen; Duke facilities review & MOU
Drilling Permit	1 May 23	29 Sep 23	NC water and/or monitoring well
DU Legal	1 Jun 23	31 Aug 23	Will Tricomi <will.tricomi@duke.edu>
NSOE Legal	1 Jul 23	31 Aug 23	Hunter Stokes <hunter.stokes@duke.edu>
Utilities	1 Aug 23	29 Sep 23	hydrant use etc as in drilling contract
driller license	1 Sep 23	29 Sep 23	TB Confirmed by drilling Company
Q1 Report	**1 Aug 23**	**1 Aug 23**	
Site Preparation			
Hydrant repair	1 Sep 23	29 Sep 23	drilling water source
site clear	1 Sep 23	29 Sep 23	vegetation/fire hazard
Drill pad	1 Sep 23	29 Sep 23	debris removal, leveling
Thermister removal	29 Sep 23	29 Sep 23	final Phase 1 measurements
Core Drilling Time Windows			
Rig mobilization	2 Oct 23	13 Oct 23	yard to site
Clearing Phase I	CMob +1 d	CMob +2 d	open hole to TD
Coring	CMob +3 d	CMob +12 d	core hole from 352 to 700
Contingency	CMob +13 d	CMob + 14 d	fishing and/or depth extension
Well Logging Time Window			
Logging tool mob	Cmob +15 d	10 Nov 23	Goler Associates or equivalent
Logging suite	LMob +1 d	LMob +3 d	run suite in and out of borehole
Q2 Report	**1 Nov 23**	**1 Nov 23**	
Hydraulic testing			
Standard	Logging +1	Logging +2	draw down, storage coef, permeability
Advanced	Logging +3	Logging +5	receptivity versus pressure; flow back
Q3 Report	**1 Feb 24**	**1 Feb 24**	
Water/Rock Chemistry, Mechanics, Mineralogy, Fracture Analysis			
Water	Hydro +6	26 Apr 24	solute chem for T&P percipitation in pipe
Rock	Core +15	26 Apr 24	rock strength; composition; poroperm
Q4 Report	**1 May 24**	**1 May 24**	
US Continental Drilling Facility Analysis and Archiving Window			
Core	CMob + 14 d	26 Apr 24	core scans; thermal conductivity
Aquifer Thermal Energy Storage Analysis, Summary Report, and Wrapup			
Analysis	Logging +6	26 Apr 24	parallel science & engineering measurments
Summary Report	**wk of 3 Jun 24**	**wk of 3 Jun 24**	CRISP presentation as appropriate
Wrapup	**wk of 3 Jun 24**	**wk of 3 Jun 24**	DU & Community seminar prep for CRISP use

5.2.Relevance to DU Climate Initiative & Energy Transformation priorities

This project fits squarely into DU's commitment for Carbon Neutrality. To achieve this important goal, we aim at evaluating the potential of the basin underneath DU's campus for clean, renewable, geothermal energy production and deep carbon storage. We have assembled an interdisciplinary science and engineering team to address the potential of well-established, cost-effectively scalable and equitably accessible Aquifer Thermal Energy technology to achieve this goal.

The CRISP web site states as its main aim is

Accelerating research on sustainable, equitable solutions to address the climate crisis, in keeping with the Duke Climate Commitment.

Given the geological conditions in Durham County, ATES cooling and heating promises to fulfill this aim. The Phase I results of the drilling at the Central Campus Geothermal Test well suggests that a fractured aquifer may extend to sufficient depths (332 ft to greater than at least 352 ft) and with temperatures exactly in the average of Durham's yearly high and low (0 C < ATES < 30 C Durham ATES ~ 15 C).

A critical feature of ATES is its local and incremental technology: one building at a time, with minimal infrastructure compared to district heating and cool. It can be used in conjunction with standard air conditioning/cool technology and direct use heating.

The Phase I CCGT results indicate that the fractured rock found at this drill site extend over large areas, including DU campus and Durham. Since ATES is a scalable technology, with sufficient subsurface exploration and sufficiently developed small- and large-scale heat exchangers, it can serve the range of single residences to apartment blocks to commercial malls.

ATES can also be coupled with solar and wind power to lower and raise feed stock temperatures for cooling and heating. Our Phase II seeks to establish the amount of fracture rock that can be used to store this thermal energy.

In the long run, after being established as technically viable, a critical key to ATES in the Duke and Durham area is the depth and lateral extent of fractured rock – and therefore the cost of drilling. This is where geological studies cross over into engineering, where shallow drilling technologies such as air and water hammer systems are significantly cutting costs.

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5.3 CV **<u>PAUL A. BAKER</u>**

Current Position: Professor, Earth and Climate Sciences, Duke University, Durham, NC

Interests: Geochemistry, Climate & paleoclimate, Marine geoscience, Origins of biodiversity

Degrees:

1973 B.A. Geology, University of Rochester
1975 M.S. Geology, Pennsylvania State University
1981 Ph.D. Scripps Institution of Oceanography, University of California

Professional Employment:

1973-1974 Graduate Teaching Assistant, Department of Geosciences, Pennsylvania State University
1974-1975 Graduate Research Assistant, Department of Geosciences, Pennsylvania State University
1975-1981 Graduate Research Assistant, Geological Research Division, Scripps Institution of Oceanography
1981-1987 Assistant Professor, Department of Geology, Duke University
1987-1994 Associate Professor, Department of Geology, Duke University
2015-2017 Dean, Geological Sciences and Engineering, Yachay Tech University
1994-present Professor, Earth & Climate Sciences, Duke University

Honors:

Fellow, American Geophysical Union
Fellow, The Geological Society of America

Other Relevant Professional Activities and Honors:

2006 Fulbright Scholar, UFPA, Belem, Brazil
2004-2011 Director, Global Environmental Change Program, Duke University 2006-2009 Member, AAAS Nominating Committee
2011-2014 National Ocean Sciences Accelator Mass Spectrometer Advisory Committee. R/V Marcus Langseth Scientific Oversight Committee
2012-2018 Member, National Geographic Society Committee on Research & Exploration.
2012-present Adjunct Professor (2012-present), Department of Ocean and Earth Dynamics, Universidade Federal Flumiense, Niteroi, Rio de Janeiro, Brazil Member, National Academy of Sciences, USNC/INQUA committee
2013-present Co-director of the Duke-Brazil Initiative
2014-2016 Co-director of the Global Brazil Humanities Laboratory 2015-2017 Chair, Andean Sustainable Development Solutions Network
Founding Dean, School of Geological Sciences and Engineering, Yachay Tech University, Ecuador
2016-2020 Member at Large, Geology and Geography Section, AAAS 2016-present Member, Board of Directors, Charles Darwin Foundation
2018 Elected Fellow, American Geophysical Union (AGU)
2020 Elected Fellow, Geological Society of America (GSA) 2020-present President, Continental Scientific Drilling Division, GSA

Current Grants

Biodiversity Conservation in the Binational Mira-Mataje River Basins-Building Biophysical and Socio-Environmental Bases for Conservation and the Adaptive Management of Ecosystem Services awarded by John D. and Catherine T. MacArthur Foundation 2017 – 23
Collaborative Research: Trans-Amazon Drilling Project awarded by National Science Foundation 2018 -23 2

Books:

Shukla, V. and Baker, P.A. (editors), 1988. Geochemistry and Sedimentology of Dolomite. Special Publication Number 43 of the Society of Economic Paleontologists and Mineralogists.

Dunbar, R.B. and Baker, P.A. (editors), 1988. Cenozoic Geology of the Pisco Basin. A guidebook to accompany an IGCP 156 Field Workshop.

Baker, P. and McNutt, M. (editors), 1998. Future of Marine Geology and Geophysics, Proceedings of a Workshop. Published by US NSF 264pp

Recent Refereed Journal Publications:

Liu, X., D.S. Battisti, R.H. White and P.A Baker, 2020. South American climate during the Early Eocene: impact of a narrower Atlantic and higher atmospheric CO_2. Journal of Climate, DOI 10.1175/JCLI-D-19-0170.1.

Cracraft, J.; Ribas, C.C.; d'Horta F.M.; Bates, J.; Almeida, R.P.; Boubli, J.P.; Campbell, K.E.; Cruz, F.W.; Ferreira, M; Fritz, S.; Grohmann, C.H.; Latrubesse, E.M.; Lohmann, L.G.; Musher,L.J.; Nogueira, A.; Sawakuchi, A.O., and Baker, P., 2020. The origin and evolution of Amazonian species diversity. In V. Rull, A. C. Carnaval (eds.), Neotropical Diversification: Patterns and Processes, Fascinating Life Sciences, https://doi.org/10.1007/978-3-030-31167-4_10, pp. 225-244.

Baker, P.A., Fritz, S.C., Battisti, D.S., Dick, C.W., Vargas, O.M., Asner, G.P., Martin, R.E., Wheatley, A., Prates, I., 2020. Beyond Refugia: New insights on Quaternary climate variation and the evolution of biotic diversity in tropical South America. In V. Rull, A. C. Carnaval (eds.), Neotropical Diversification: Patterns and Processes, Fascinating Life Sciences, https://doi.org/10.1007/978-3-030-31167-4_10, pp. 51-70.

Latrubesse, E.M., Fernando M. d'Horta, Camila C. Ribas, Florian Wittmann, Jansen Zuanon, Edward Park, Thomas Dunne, Eugenio Y. Arima, Paul. A. Baker, 2020. Vulnerability of the biota in riverine and seasonally flooded habitats to damming of Amazonian rivers. Aquatic Conservation: Marine and Freshwater Ecosystems, 2020: p. 1–14, https://doi.org/10.1002/aqc.3424.

Benito, X., Melina Feitl, Tobias Schneider, Sherilyn C Fritz, Paul A Baker, Eric J Pedersen, Pierre Gaüzère, Majoi de Novaes Nascimento, Mark Bush, Albert Ruhi, 2020. Ecological resilience in Andean lakes: a paleolimnological perspective. Limnology & Oceanography.

Luethje, M., Benito, X., Schneider, T., Mosquera, P., Baker, P., and Fritz, S.C., 2020. Paleolimnological response of Ecuadorian lakes Fondococha and Piñan to local and regional stressors over the last two millennia, Journal of Paleolimnology

Guédron, S.; J. Tolu, C. Delaere, P. Sabatier, J. Barre, C. Heredia, E. Brisset , S. Campillo, R. Bindler, S. C. Fritz, P.A. Baker and D. Amouroux. 2020. Two millennia of copper and silver metallurgy in the Lake Titicaca region: historical reconstruction and ores fingerprinting using lead isotopes, Anthropocene

Bruno, M.C.; José M. Capriles; Christine A. Hastorf; Sherilyn C. Fritz; Marie Weide; Alejandra I. Domic; Paul A. Baker, 2020. The rise and fall of Winaymarka: rethinking cultural and environmental interactions in southern basin of Lake Titicaca. Human Ecology

Jiskra, M. S. Guédron, S., Tolu, J., Fritz, S.C., Baker, P., Sonke, J.E., 2020. Climate and anthropogenic factors driving mercury stable isotopes in a Holocene record of Lake Titicaca

Ferreira, F., Silva, C., Sandes, A., Chiessi, C., Kern, A., Baker, P, Dwyer, G., Rigsby, C., Huang, E., Tian, J., 2020. Biochronostratigraphy of the western equatorial Atlantic for the last 1.93 Ma. Quaternary International

5.3 Laura Elizabeth Dalton

Professor Dalton joined Duke University in August 2022 after obtaining her PhD from North Carolina State University, MS and BS from West Virginia University. Dr. Dalton is an experimentalist and her research interests include studying and understanding reactive, multiphase transport in porous media. She is particularly interested in understanding and manipulating chemical and physical processes that occur during reactive, multiphase transport in both engineered (cementitious) and natural (geological) porous materials. To this end, she uses quantitative imaging approaches such as X-ray computed tomography (CT), neutron tomography, and electrical imaging modalities including electrical capacitance tomography (ECT). She is interested in using hybrid and simultaneous imaging modalities because complementary and temporal information can be obtained using these approaches to better understand complex processes such as developing innovative methods to sequester CO_2.

APPOINTMENTS AND AFFILIATIONS

- Assistant Professor in the Department of Civil and Environmental Engineering

CONTACT INFORMATION

- Office Location: 165 Hudson Hall, Durham, NC 27708
- Office Phone: (919) 660-5421
- Email Address: laura.dalton@duke.edu
- Websites:
    - Dalton Research Group

EDUCATION

- Ph.D. North Carolina State University, 2022

RESEARCH INTERESTS

4D Imaging; Carbon sequestration in porous materials; sustainable material development; structural integrity of carbon capture and storage wells; reactive transport in porous materials

COURSES TAUGHT

- EGR 201L: Mechanics of Solids

IN THE NEWS

- Laura Dalton: How Mass Moves Through Rocks and Other Hard Places (Oct 29, 2022 | Pratt School of Engineering)
- Laura Dalton: Watching Mass Move Through Rocks and Other Hard Places (Aug 17, 2022 | Duke Engineering News)

REPRESENTATIVE PUBLICATIONS

- Wang, H; Dalton, L; Guo, R; McClure, J; Crandall, D; Chen, C, *Application of unsupervised deep learning to image segmentation and in-situ contact angle measurements in a CO2-water-rock system*, Advances in Water Resources, vol 173 (2023) [10.1016/j.advwatres.2023.104385] [abs].
- Dalton, LE; LaManna, JM; Jones, S; Pour-Ghaz, M, *Does ITZ Influence Moisture Transport in Concrete?*, Transport in Porous Media, vol 144 no. 3 (2022), pp. 623-639 [10.1007/s11242-022-01826-z] [abs].
- Wang, H; Dalton, L; Fan, M; Guo, R; McClure, J; Crandall, D; Chen, C, *Deep-learning-based workflow for boundary and small target segmentation in digital rock images using UNet++ and IK-EBM*, Journal of Petroleum Science and Engineering, vol 215 (2022) [10.1016/j.petrol.2022.110596] [abs].
- Guo, R; Dalton, L; Crandall, D; McClure, J; Wang, H; Li, Z; Chen, C, *Role of heterogeneous surface wettability on dynamic immiscible displacement, capillary pressure, and relative permeability in a CO2-water-rock system*, Advances in Water Resources, vol 165 (2022) [10.1016/j.advwatres.2022.104226] [abs].
- Dalton, LE; Crandall, D; Pour-Ghaz, M, *Supercritical, liquid, and gas CO2 reactive transport and carbonate formation in portland cement mortar*, International Journal of Greenhouse Gas Control, vol 116 (2022) [10.1016/j.ijggc.2022.103632] [abs].
- Guo, R., L. E. Dalton, M. Fan, J. McClure, L. Zeng, D. Crandall, and C. Chen. “The role of the spatial heterogeneity and correlation length of surface wettability on two-phase flow in a CO2-water-rock system.” Advances in Water Resources 146 (December 1, 2020). https://doi.org/10.1016/j.advwatres.2020.103763.
- Fan, M., J. E. McClure, R. T. Armstrong, M. Shabaninejad, L. E. Dalton, D. Crandall, and C. Chen. “Influence of Clay Wettability Alteration on Relative Permeability.” Geophysical Research Letters 47, no. 18 (September 28, 2020). https://doi.org/10.1029/2020GL088545.
- Harbert, W., A. Goodman, R. Spaulding, I. Haljasmaa, D. Crandall, S. Sanguinito, B. Kutchko, et al. “CO2 induced changes in Mount Simon sandstone: Understanding links to post CO2 injection monitoring, seismicity, and reservoir integrity.” *International Journal of Greenhouse Gas Control* 100 (September 1, 2020). https://doi.org/10.1016/j.ijggc.2020.103109.

5.3 **Heileen Hsu-Kim**

Education, Training, & Certifications

- Ph.D., University of California - Berkeley 2004
- M.S., University of California - Berkeley 1999
- B.S., Massachusetts Institute of Technology 1998

Previous Appointments & Affiliations

- Sternberg Family Professor of Civil & Environmental Engineering, Civil and Environmental Engineering, Pratt School of Engineering 2020 - 2021
- Addy Professor, Civil and Environmental Engineering, Pratt School of Engineering 2019 - 2020
- Associate Professor in the Department of Civil and Environmental Engineering, Civil and Environmental Engineering, Pratt School of Engineering 2013 - 2019
- Mary Milus Yoh and Harold L. Yoh, Jr. Associate Professor, Civil and Environmental Engineering, Pratt School of Engineering 2014 - 2019
- Assistant Professor, Environmental Sciences and Policy, Nicholas School of the Environment 2011 - 2014
- Assistant Professor of Civil and Environmental Engineering, Civil and Environmental Engineering, Pratt School of Engineering 2005 - 2013

Selected Grants

- **Customized Approaches for Evaluating and Reducing Chemical Exposures from Home Building Materials awarded by Department of Housing and Urban Development 2022 - 2024**
- **Duke University Program in Environmental Health awarded by National Institutes of Health 2019 - 2024**
- **HHEAR Program awarded by National Institutes of Health 2019 - 2024**
- **AOI 1: Characterization of Arsenic and Selenium in Coal Fly Ash to Improve Evaluations for Disposal and Reuse Potential awarded by Department of Energy 2019 - 2024**
- **Convergence RAISE: Harnessing Extracellular Vesicle Mediated Interkingdom Communication awarded by National Science Foundation 2019 - 2023**

Selected Publications

- Koenigsmark, Faye, Michelle Chiu, Nelson Rivera, Alexander Johs, Jeremy Eskelsen, Donovan Leonard, Boakai K. Robertson, et al. "Crystal lattice defects in nanocrystalline metacinnabar in contaminated streambank soils suggest a role for biogenic sulfides in the formation of mercury sulfide phases." *Environmental Science. Processes & Impacts*, January 2023. https://doi.org/10.1039/d1em00549a.
- Hower, J. C., J. G. Groppo, S. D. Hopps, T. D. Morgan, H. Hsu-Kim, and R. K. Taggart. "Coal Feed-Dependent Variation in Fly Ash Chemistry in a Single Pulverized-Combustion Unit." *Minerals* 12, no. 9 (September 1, 2022). https://doi.org/10.3390/min12091071.
- Berky, Axel J., Emily Robie, Susy Navio Chipa, Ernesto J. Ortiz, Emma J. Palmer, Nelson A. Rivera, Ana Maria Morales Avalos, Joel N. Meyer, Heileen Hsu-Kim, and William K. Pan. "Risk of lead exposure from wild game consumption from cross-sectional studies in Madre de Dios, Peru." *Lancet Regional Health. Americas* 12 (August 2022): 100266. https://doi.org/10.1016/j.lana.2022.100266.
- Kose-Mutlu, Borte, Heileen Hsu-Kim, and Mark R. Wiesner. "Separation of rare earth elements from mixed-metal feedstocks by micelle enhanced ultrafiltration with sodium dodecyl sulfate." *Environmental Technology* 43, no. 7 (March 2022): 1013–25. https://doi.org/10.1080/09593330.2020.1812732.
- Kessler, M. L., J. E. Kelm, H. E. Starr, E. N. Cook, J. D. Miller, N. A. Rivera, H. Hsu-Kim, and J. L. Dempsey. "Unraveling Changes to PbS Nanocrystal Surfaces Induced by Thiols." *Chemistry of Materials* 34, no. 4 (February 22, 2022): 1710–21. https://doi.org/10.1021/acs.chemmater.1c03888.
- Neal-Walthall, Natalia, Udonna Ndu, Nelson A. Rivera, Dwayne A. Elias, and Heileen Hsu-Kim. "Utility of Diffusive Gradient in Thin-Film Passive Samplers for Predicting Mercury Methylation Potential and Bioaccumulation in Freshwater Wetlands." *Environmental Science & Technology* 56, no. 3 (February 2022): 1743–52. https://doi.org/10.1021/acs.est.1c06796.
- Gerson, Jacqueline R., Natalie Szponar, Angelica Almeyda Zambrano, Bridget Bergquist, Eben Broadbent, Charles T. Driscoll, Gideon Erkenswick, et al. "Amazon forests capture high levels of atmospheric mercury pollution from artisanal gold mining." *Nature Communications* 13, no. 1 (January 2022): 559. https://doi.org/10.1038/s41467-022-27997-3.
- Mello, Danielle F., Laura L. Maurer, Ian T. Ryde, Dong Hoon Songr, Stella M. Marinakos, Chuanjia Jiang, Mark R. Wiesner, Heileen Hsu-Kim, and Joel N. Meyer. "*In Vivo* Effects of Silver Nanoparticles on Development, Behavior, and Mitochondrial Function are Altered by Genetic Defects in Mitochondrial Dynamics." *Environmental Science & Technology* 56, no. 2 (January 2022): 1113–24. https://doi.org/10.1021/acs.est.1c05915.

5.3 CV NATIONAL SCIENC FOUNDATION FORMAT RESUME,

EDUCATION, EXPERIENCE, GRANTS, RELEVANT MAJOR PUBLICATIONS & ACTIVITIES

PETER ERIC MALIN

EDUCATION

INSTITUTION	LOCATION	MAJOR/AREA OF STUDY	DEG	YEAR
STANFORD	PALO ALTO, CA	GEOPHYSICS	BS	1971
STANFORD	PALO ALTO, CA	GEOPHYSICS/MARINE	MS	1972
PRINCETON	PRINCETON, NJ	GEOPHYSICS/SEISMOLOGY	PHD	1978
UNIV SO CAL	LOS ANGELES, CA	POST DOC, SEISMOLOGY		1978-1981

EXPERIENCE

From - To	Position Title, Organization and Location
AUG 20 - PRES	PROFESSOR (EMERITUS), DUKE UNIV., DURHAM, NC
MAY 07 - JUL 20	ADJUNCT PROF., DUKE UNIV., DURHAM, NC
JUN 15 - SEP 19	RESEARCH PROF., GERMAN GEOSCI CENTER GFZ, POTSDAM, GR AND ADJUNCT PROF SOUTHERN METHODIST UNI. GEOTHERMAL LAB.
MAY 07-MAR 15	DIRECTOR, INST EARTH SCI & ENG, UNI AUCKALND, AUCKLAND, NZ (FOLLOW-ON FOR THE GEOTHERMAL INSTITUTE OF NZ)
APR 97- OCT 07	PROFESSOR, DUKE UNIV., DURHAM, NC
SEP 91 - MAR 97	ASSOCIATE PROFESSOR, DUKE UNIV., DURHAM, NC
AUG 85 - AUG 91	ASSOC. RES. GEOPHYS & LECTURER, UCSB, SANTA BARBARA, CA
JUN 81 - JUL 85	ASSIS. RES. GEOPHYS & LECTURER, UCSB, SANTA BARBARA, CA
JUN 78 - MAY 81	RESEARCH ASSOC, UNIV. SOUTHERN CALIFORNIA, LOS ANGELES, CA
JUN 70-AUG 72	MARINE GEOPHYSICIST, USGS, MARINE BRANCH, MENLO PARK, CA

CURRENT AND PENDING GRANTS

2023 Ambient Seismic Imaging Technology for Low Cost and Effective Geothermal Resource Exploration, Development, and Management**.** US Department of Energy, ARPA-E SEED SBIR to Enegis LLC. Principal Investigator Jeffrey F. Eppink. Principal Geothermal Technology Consultant (1/4 time) Peter E. Malin; 1 year Geothermal R&D at Newberry Volcano Geothermal Field, Deschutes Co, OR

No pending grants.

MAJOR RELEVANT JOURNAL PUBLICATIONS

2022 Kwiatek, G., Martínez-Garzón, P., Davidsen, J., **Malin**, P., Karjalainen, A., Bohnhoff, M., Dresen, G. (2022). Limited earthquake interaction during a geothermal hydraulic stimulation in Helsinki, Finland. J of Geophys. Res.: Solid Earth, 127, e2022JB024354. https://doi. org/10.1029/2022JB024354

2021 Lamb, O.D., Lees, J.M., **Malin**, P.E. et al. Audible acoustics from low-magnitude fluid-induced earthquakes in Finland. SciRep 11, 19206 (2021). https://doi.org/10.1038/s41598-021-98701-6

2020 P. **Malin**, P. Leary, L. Cathles, & C. Barton, Observational and Critical State Physics Descriptions of Long-Range Flow Structures, Geosciences 10, 50; doi:10.3390/geosciences10020050

2020 Bohnhoff, M., **Malin**, P., Borehole Seismic Networks and Arrays. - In: Gupta, H. K. (Ed.), Encyclopedia of Solid Earth Geophysics, (Encyclopedia of Earth Sciences Series), Cham : Springer International Publishing, 1-9.https://doi.org/10.1007/978-3-030-10475-7_268-1

2020 **Malin**, P., Fault Zone Guided Waves. Springer Nature Switzerland AG 2020 H. K. Gupta (ed.), Encyclopedia of Solid Earth Geophysics, Encyclopedia of Earth Sciences Series, https://doi.org/10.1007/978-3-030-10475-7_269-1

2020 Hillers, G., T. A. T. Vuorinen, M. R. Uski , P. E. **Malin**, et al., The 2018 Geothermal Reservoir Stimulation in Espoo/Helsinki, Southern Finland: Seismic Network Anatomy and Data Features, Seismol. Res. Lett. 91, 770–786, doi: 10.1785/ 0220190253.

2020 Ader, T., Chendorain, M., Free, M. **Malin**, P., et al. Design and implementation of a traffic light system for deep geothermal well stimulation in Finland. J Seismol 24, 991–1014 (2020). h□ ps://doi.org/10.1007/s10950-019-09853-y

2019 C. Sicking & P. **Malin**, Fracture seismic: Mapping subsurface connectivity, Geosciences 9, no. 12, pp.1–34, doi: 10.3390/geosciences 9120508

2019 G. Kwiatek, T Saarno, P. **Malin,** & OTN Science Team, Controlling Induced Seismicity During a 6.1-km-Deep Geothermal Stimulation in Finland, Science Advances 5, 5,

2018 P. **Malin**, M. Bohnhoff, F .Blümle, G. Dresen, P. Martínez-Garzón, M. Nurlu, U. Ceken, F. Kadirioglu,R. Kartal, T. Kilic, & K. Yanik, Microearthquakes preceding a M4.2 Earthquake Offshore Istanbul, Nature Reports, 8:16176 | DOI:10.1038/s41598-018-34563-9.

2018 Bohnhoff, M., P. **Malin**, J. ter Heege, J-P Deflandre and C. Sicking, Suggested best practice for seismic monitoring and characterization of non-conventional reservoirs. First Break V36 1 Feb 2018

2017 Leary, P., P. **Malin**, and R. Niemi, “Fluid Flow and Heat Transport Computation for Power-Law Scaling Poroperm Media,” Geofluids, vol. 2017, Article ID 9687325, 12 pages, 2017. https://doi.org/10.1155/2017/9687325.

2017 Leary, P.; **Malin**, P.; Saarno, T.; Kukkonen, I. Prospects for Assessing Enhanced Geothermal System (EGS) Basement Rock Flow Stimulation by Wellbore Temperature Data. Energies 2017, 10, 1979 DOI: 10.3390/en10121979

2014 B. Voight, S. Sparks, P. **Malin** & SEA-CALIPSO Team, The SEA-CALIPSO volcano imaging experiment at Montserrat. Wadge, G., Robertson, R., Voight, B. (eds.) Eruption of Soufrière Hills volcano 2000 to 2010. London, GB, Geological Society of London, Memoirs 39. doi:10.1144/M39.15

MAJOR SYNERGISTIC ACTIVITIES

Leader, James Henare Maori Research Center NZ - Invited Presentations & Workshops w So Pacific Comm
Chancellor's Gold Prize for Geothermal Technology R&D & Transfer, Uni. of Auckland, Auckland, NZ.
US DoD Geothermal Program Recognition for Contributions to Geothermal Science
Editorial Board, Geology, Geological Society of America
Seismology Editor, EOS: Transactions of the American Geophysical Union

5.3 CV Brian MCADOO

Division of Earth and Climate Sciences
Nicholas School of the Environment
Duke University
3115 Grainger Hall
9 Circuit Dr
Durham, NC 27708 USA
Tel: +1 845 249 9561

Institution and Current Position

Associate Professor of Earth and Climate Sciences 2021-present
Nicholas School of the Environment, Duke University, USA

Employment History

Associate Professor of Earth and Climate Sciences 2021-present
Duke University

Professor of Environmental Science 2012-2021
Inaugural College Rector (administration)
Yale-NUS College, Singapore

Assistant, Associate and Full Professor of Earth Science 2011-2015
Vassar College, USA

Blaustein Visiting Professor 2008-2009
School of Earth Sciences, Stanford University, USA

Visiting Professor 2004-2005
Institute of Geology, ETH-Z, Zürich, Switzerland

Academic Qualifications

PhD in Earth Sciences 2000
University of California, Santa Cruz

Post-Graduate Diploma in Science, Geology 1993
University of Otago, New Zealand

BSc in Geology 1991
Duke University

Publications (Top 5 relevant publications in the last 5 years)

Van Gevelt, T., **McAdoo**, B.G., Yang, J., Li, L., Williamson, F., Scollay, A., Lam, A., Chan, K.N., Switzer, A.D. (2023). “Using virtual simulations of future extreme weather events to communicate climate change risk.” *PLOS Climate* 2(2): e0000112.

Sudmeier-Rieux, K., B. **McAdoo**, et al. (2021), Scientific evidence for ecosystem-based disaster risk reduction, *Nature Sustainability*.

McAdoo, B.G., M. Quak, K.R. Gnyawali, B.R. Adhikari, S. Devkota, P.L. Rajbhandari, and K. Sudmeier-Rieux (2018), Roads and landslides in Nepal: how development affects environmental risk, *Nat. Hazards Earth Syst. Sci.*, 18, 3203-3210.

Monecke, K., E. Meilianda, D-J Walstra, E. Hill, **B. McAdoo**, Q. Qiu, J. Storms, A. Masputri, C. Mayasari, M. Nasir, I. Riandi, A. Setiawan, and C. Templeton (2017), Postseismic coastal development in Aceh, Indonesia- Field observations and numerical modeling, *Marine Geology* 392.

Research Grants Awarded and Relevant Research Projects

2023-2025 Duke University Climate x Health Data (**$100K USD**), Climate Change and Emergency Care in the SE US and Brazil, (**P.I.**)

2019-2021 Singapore Ministry of Education **($25K SGD**), Plastics in Tonle Sap, Cambodia, (**co-P.I.**)

2013-2021 Singapore Ministry of Education (**$180K SGD**), The Tsunami Project: Transdisciplinary approaches to disaster risk reduction (**P.I.**)

2014-2019 National Science Foundation (**$700K USD**), Sustainable Adaptive Gradients in the Coastal Environment (SAGE): Reconceptualizing the Role of Infrastructure in Resilience (**co-PI**; P.I. Elisabeth Hamin, U. of Massachusetts)

2007 National Science Foundation (**$25K USD**). Rapid response to the 1 April 2007 Solomon Islands tsunami, (**P.I.**)

2005-2010 National Science Foundation (**$2.4M USD**): Developing International Protocols for Offshore Sediments and their Role in Geohazards (**co-P.I.**)

2003-2004 National Science Foundation (**$25K USD**): Surface Geomorphology from 3D Seismic and Multibeam Bathymetry: Implications for Cascadia Seismicity (**P.I.**)

2001-2002 National Science Foundation (**$34K USD**): Surface Geomorphology from 3D Seismic, Nankai Accretionary Prism, Japan (**P.I.**)

Summary of the most relevant research outcomes from all previous grants

My work is centered around using Earth and Climate Sciences to inform Disaster Risk Reduction. Our work in Indonesia after the 2004 Indian Ocean Tsunami was the first to determine the penultimate events (Monecke et al., *Nature* 2008), critical information for planning for the next disaster. McAdoo and Paravisini (*Nature Geoscience*, 2011) argued for understanding the historical politics that lead to the environmental degradation of the Haitian countryside and subsequent urban migrations prior to the 2010 earthquake. Finally, Hamin et al. (*Sustainability*, 2018) develops an interdisciplinary framework for understanding solutions to coastal resilience, and is being implemented in communities in the US Eastern seaboard.

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Duke | PRATT SCHOOL *of* ENGINEERING

5.3. Lead Principal Investigator’s Curriculum Vitae

EMMANOUIL (MANOLIS) VEVEAKIS

Associate Professor, Department of Civil and Environmental Engineering
Duke University, Box 90287, Durham, North Carolina, 27708-0287 Ph.: (919) 660-5205, Fax: (919) 660-5219, email: manolis.veveakis@duke.edu,

EDUCATION AND TRAINING:

Postdoctoral Fellow (2010-12), National Technical University of Athens, Greece
Ph.D. (2010) in Geomechanics, Department of Mechanics, School of Applied Mathematical and Physical Sciences, National Technical University of Athens
M.Sc. (2007) Theoretical and Applied Mechanics, School of Applied Mathematical and Physical Sciences, National Technical University of Athens, Greece
BS and M.Sc. (2005) Applied Mathematical and Physical Sciences, National Technical University of Athens, Greece

RESEARCH AND PROFESSIONAL EXPERIENCE: *Academic Appointments*

2021-today **Associate Professor,** Civil and Environmental Engineering, Duke University
2018-2021 **Assistant Professor,** Civil and Environmental Engineering, Duke University
2015-2018 **Senior Lecturer,** School of Petroleum Engineering, UNSW Australia
2012-2018 **Research Scientist,** CSIRO Earth and Resource Engineering

Adjunct/Honorary Positions
2014-today **Visiting Senior Research Scientist,** CSIRO Energy and Minerals Sector

2013-today **Adjunct Senior Lecturer**, School of Mathematics and Statistics, UWA

SELECTED PUBLICATIONS:

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1. Mielniczuk, B., T. Hueckel and **E. Veveakis**, 2020. A prototype device for the quantification of the mechanisms driving desiccation cracking, Provisional Technology submitted for patent. Duke Reference Number: T-007379-2021.
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SYNERGISTIC ACTIVITIES:

1. **Editor in Chief** for *Geomechanics for Energy and the Environment*, Elsevier (I.F. 4.604), since June 2022

2. **Guest Editor** for *Environmental Geotechnics (ICE):* Cecinato F. and E. Veveakis (Guest Eds). Special issue *"Recent advances on coupled multiphysical effects in environmental geotechnics", 2017*

3. **Guest Editor** for *Physics of the Earth and Planetary Interiors (I.F. 2.82):* D. Yuen, Y. Wang, S. Ni, X. Chang, M. Veveakis (Guest Eds). *Microseismicity from all scales, Vol 261, Part A., 2016*

4. **Associate Editor** for *Landslides,* Springer (I.F. 6.153), since Sep 2013

5. **Co-Organiser of**: The 6th GEOPROC Conference, Paris 5-7 July 2017; Modelling of instabilities and bifurcation in Geomechanics, ALERT School, 6-8 October 2016. Aussois France

CURRENT GRANTS AND PROJECTS:

NSF CMMI "CAREER: An integrated dissipative modeling framework for the long-term assessment of Geohazards", CMMI-2042325, Total Award Amount $580.158. Role: PI

5.4. The Basics of Aquifer Thermal Energy Storage for Local Cooling and Heating Systems

The geological setting of Duke and Durham are not considered favorable to geothermally generated electrical power: the thermal energy generated in the North Carolian area by the opening of the Atlantic Ocean some 200 M years has long disappeared and no new episodes of volcanism or uplifted heat have replaced it. In a sense, the result is that the energy to replace this local, sustainable, low environmental and CO2 impact resource is either being imported on electrical wires, oil tankers, gas pipelines, or generated locally, as one example, by facilities such as the Sharon Harris nuclear power plant.

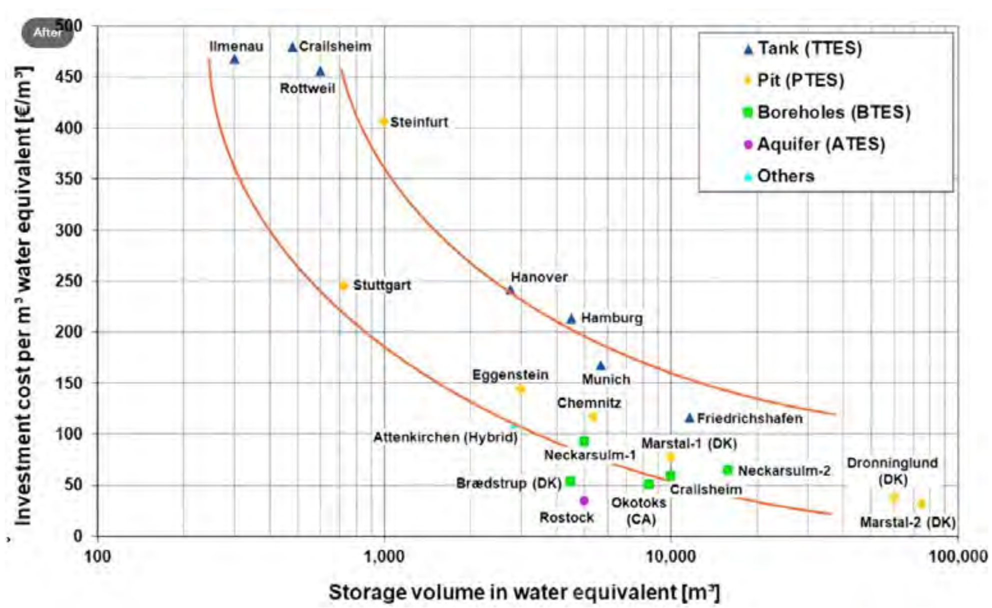
However, the preliminary results of our Phase I drilling project suggests that the local geology might provide a cost-effective way to moderate these imports and distribute local sources more broadly and fairly. In Phase I drilling the highly fractured top of basement rocks to the Durham basin was encountered at 342 ft depth. These rocks continued to the 352 ft deep well bottom.

In geothermal applications, fractured rock is the key to cost-effective energy delivery: while energy rich fossil fuels pool and can be economically drawn out at gallon per minute rates, the equivalent in geothermal water needs to flow at gallon per second rates. Moreover each gallon has to be at temperatures more than 2 times that of boiling to make a make even a few tens of kilowatts of electrical power. Rocks with such temperatures lie deep beneath Duke campus and Durham County, far from current economically feasible use.

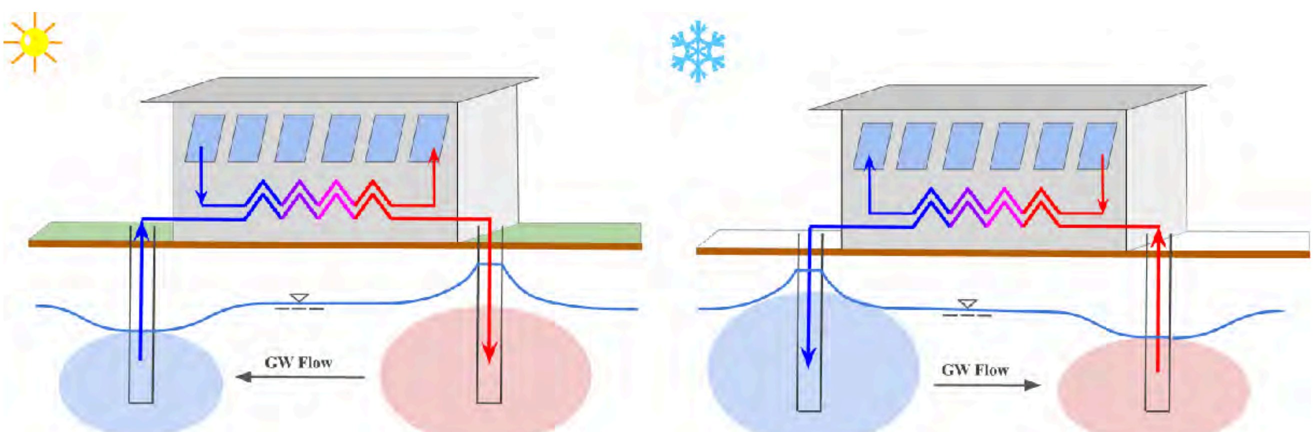
There is however the potential beneath Duke and Durham for thick layers of highly fractured rock, rock where significant volumes of cooled and heated water could be stored and retrieved as needed to moderate both the import and generation of less environmentally sustainable energy.

This moderation can be realized with Aquifer Thermal Energy Storage: storing cold water in winter and hot water in summer.

The basic essence of ATES technology as it applies to Duke and Durham can be quickly grasped either by watching the first 4 minutes of https://www.youtube.com/watch?v=rbPqMOtpkLs or reviewing the diagrams on the next page. Or more broadly reading https://celsiuscity.eu/thermal-energy-storage/. ATES has been used and evaluated in a number of locations where subsurface temperatures do not allow for direct or electrical power production. The Figure below compares tank storage costs to pit, borehole, and ATES systems.



A block cut diagram showing the basic surface and subsurface features of ATES. Two wells are sunk into fracture rich rock, one that will be come a storage for cool water, one for warm. Above ground a standard air conditioning fan system makes use of the stored water to moderate the energy need to heat and cool the building. In summer cool water is pumped from the former through the fan system to drop the temperature of the cooling fluid, which enters the building. Having absorbed heat from the building the warm water is pumped into the warm side well. In winter this process is reversed.



A schematic Figure showing the principle of ATES in cooling and heating. Note that subsurface waters do not enter into the building and are only used in the heat exchanger to lower or raise the initial temperatures of the actual heat exchanger system. In other words by using the relative temperature of the underground stored water to either lower or raise the heat exchanger fluid the energy consumption of the exchanger is lowered.

5.5 Media coverage of the Central Campus Geothermal Test and Student Participation

5.5.1 Classes that go Deeop

PUBLISHED NOVEMBER 26, 2022 IN RESEARCH, CAMPUS

CLASSES THAT GO DEEP

Central Campus drilling project explores geothermal energy potential beneath Durham

BY GREG PHILLIPS. PHOTOS BY JARED LAZARUS AND BILL SNEAD

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On a nondescript Central Campus corner lot this fall, a hole was drilled 350 feet into the earth.

Less than three inches wide, and visible only as a capped-off pipe a foot or two off the ground, the deep borehole is a window into the region's geologic past, an enquiry into the geothermal energy that sits below the surface of the earth, and a classroom for learning about both.

"It's a laboratory," said Paul Baker, a professor at the Nicholas School of the Environment and principal investigator on the research side of the project. "This is fantastic for students to see."

The geothermal dig site, located on Central Campus

Geothermal energy is the clean and renewable source of heat contained in rock beneath the earth's surface. That heat emanates from the planet's core, which burns at 1,000 degrees Celsius. The remnants of that radiant heat closer to the surface can be used to heat and cool buildings, and to generate electricity through steam.

It's used most widely in places like Iceland, where sources of high heat are close to the surface. But it can be accessed elsewhere by drilling.

Duke sits atop a Triassic basin, a lowland trench created by the split of land masses about 220 million years ago and subsequently filled with sediment runoff from higher ground. The drilling project taking place this fall was funded through the Dean's Research Venture Initiative at the Nicholas school, and will begin the process of measuring how much geothermal energy is present in the rocks beneath Durham, exploring whether it is plentiful enough – and sufficiently warm – to be of potential use on campus.

"I don't think there's a huge possibility of a resource here, but it's still worth exploring," Baker said. "Exploration is important. We want students to see this."

Exploration is the crux of the project's classroom aspects. The practical experience in geothermal geoscience and drilling class is taught by Peter Malin, professor emeritus at the Nicholas School.

Professor emeritus Peter Malin shows students a drawing of the drilling core

Malin said he wants to equip students with the knowledge needed to spearhead geothermal projects.

"My hope is that someday in the future, they will be leading in some small community and be asked to determine the geothermal potential that might exist in their community, and have practical experience that they can start out knowing with confidence that they would be able to deliver for their citizens and fellow community members," he said.

Brian McAdoo, an associate professor at Nicholas, is also using the project as part of an experiential class examining natural resources in North Carolina that can contribute to a more sustainable future.

"The only way to learn that stuff for real is to do it," McAdoo said. "This was an extraordinary opportunity for the students to see what it takes to actually drill a hole in the ground somewhere. And it's not easy."

The borehole reached through the ancient sediment into the underlying rocks. Malin called it a pilot drill that's a necessary first step in any deep geothermal project.

"The next stage for a Duke commitment toward geothermal would be an equivalent pilot boring into these deeper rocks," he said.

In his basement lab at the Pratt School of engineering, Associate Professor Manolis Veveakis and his students are analyzing the rocks removed from all levels of the hole. The cylindrical cores tell the geological story of the last couple hundred million years in Durham.

In studying the mineralogic composition of the samples, Veveakis and his students will assess whether the rocks are sufficiently permeable to carry the water used to transfer geothermal heat to the surface. Because the Triassic basin runs all the way up the East Coast, the findings will be useful for geothermal projects far beyond Durham.

"For me, the most exciting thing is the combination of advanced teaching and research," Veveakis said. "The fundamental thing is to have the data and understand what you're dealing with."

Students are also testing groundwater samples and assessing changes in underground temperature. The hole will remain in place, its caps secured, so students and researchers can continue to gather data from it.

Students have the opportunity to work with samples as soon as they are brought up

"We can come back and measure these things over time," Baker said.

Anya Gupta, a junior studying earth, climate science and environmental science, said she's enjoyed learning about the drilling process and how renewable energy projects are initiated. But the highlight, she said, is piecing together the geologic history of the area from the cores removed from the drill hole.

"It's really neat to be able to piece together an evolutionary history of the Durham Basin and understand what depositional climates were like millions of years ago, what minerals were present, and be able to understand the subsurface geology of this region of North Carolina," Gupta said.

The new class reflects Duke's Climate Commitment, the goals of which include making students fluent in sustainability. The drilling project was possible only thanks to the battery of geological knowledge among Duke faculty.

The new class reflects Duke's Climate Commitment, the goals of which include making students fluent in sustainability. The drilling project was possible only thanks to the battery of geological knowledge among Duke faculty.

"We have all the complementary expertise here at Duke," Veveakis said. "That's unique."

Students have hands-on access at drill site

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614 Chapel Drive, Box 90563, Durham, NC 27708-0563(919) 684-2823

5.5.2 Media coverage of the Central Campus Geothermal Test and Student Participation

NEWS | UNIVERSITY

Students, researchers to drill 400-foot hole on Duke campus for geothermal research

Researchers will study Durham's geology and preliminarily assess the geothermal potential while graduate students will get hands-on geoscience experience.

Photo by Karianna Klassen | The Chronicle

By Karianna Klassen
October 3, 2022 | 11:14pm EDT

Researchers are about to start drilling a 400-foot deep hole on Duke's campus to explore geothermal possibilities and conduct geological research.

Geothermal energy, a renewable energy source which harnesses the heat of Earth's core, is typically accessed by drilling into the Earth's crust.

The drilling project is integrated with the fall 2022 graduate course ECS 590: Special Topics in Earth and Climate Sciences taught by Peter Malin, professor emeritus at the Nicholas School of the Environment.

Malin said that the 75-millimeter wide borehole will be drilled in early October on what was formerly Central Campus.

Researchers will study Durham's geology and preliminarily assess the geothermal potential while graduate students will get hands-on geoscience experience.

In addition to lectures on geosciences and trips to the active drill site, students will participate in projects like testing groundwater chemistry, analyzing rock samples, or measuring changes in underground temperature, according to Malin. For their final projects, students will write a position paper on whether Duke should pursue geothermal energy.

The U.S. Department of Energy announced plans to invest in domestic geothermal energy development in July. Malin believes students will benefit from a practical drilling education, because he sees this recent announcement as a "vote of confidence" in geothermal resources.

"We need to investigate more opportunities for decarbonizing our electricity and this is one example of how we can use our campus as a laboratory for doing so," Toddi Steelman, Stanback dean of the Nicholas School, wrote in an email.

Steelman approved the funding for the drilling project through the Dean's Research Venture Initiative, which aims to support "innovative, early-stage environmental research."

"Our students will be the next generation of leaders in the world," she wrote. "It is important that this generation be fluent in the challenges posed by climate change and the steps we can take to address it."

Katie Owens, a second-year graduate student enrolled in the course, expressed excitement to learn about the costs and complications of pursuing geothermal energy.

"We're going to need a lot of innovation in our lifetime to figure out the energy challenge that we have ahead of us, so this is a great opportunity to learn about how to manage [geothermal] implementation practices," Owens said.

Malin said that the entire length of the borehole will be cored, meaning that whole cylindrical samples of rock will be collected as drilling commences.

Analysis of these cores could give researchers insight into Durham's geological history. While student researchers plan to run tests on the cores independently, Malin said that additional funding could help send the cores to scientists at the U.S. Continental Scientific Drilling facility for more thorough analysis.

Paul Baker, professor of earth and climate sciences at the Nicholas School, is the project's principal investigator. He hopes that drilling 400 feet is deep enough to reach a magmatic rock layer formed by volcanic eruptions 201 million years ago.

Studying this rock will reveal more about the history of the Durham Basin and could have implications for potential geothermal energy development, according to Baker.

According to Baker and Malin, if drilling reveals rock with properties conducive to extracting geothermal energy and ground temperature measurements are promising, Duke could investigate campus use of geothermal energy.

Baker and Malin were aware of geothermal possibilities when choosing to drill close to Duke's Central Campus Chiller Plant, which supplies chilled water for air conditioning on campus. If geothermal viability is found, the plant might be able to supplement its fossil fuel usage with geothermal energy.

The project is a beginning step in evaluating geothermal energy as a means to lower Duke's carbon footprint. Both this drilling project and the ECS class align with Duke's recently announced Climate Commitment and the University's larger goals of sustainability and sustainability education.

Editor's Note: This story was updated Tuesday morning to clarify that the facility the cores could be sent to is the U.S. Continental Scientific Drilling facility.