Research Statement

ErSE-299: Directed Research
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Introduction

My research interests lie at the intersection of geophysics and emerging quantum technologies. As a geophysicist, my primary motivation is to evaluate the feasibility and scalability of quantum computing for problems in seismic processing, with particular focus on *simulation and inverse problems.* This direction is timely because seismic exploration and monitoring increasingly rely on large-scale computations, where quantum approaches may soon complement or accelerate classical methods. Through this project (ErSE 299, 6 credits, ∼18 hours/week workload), I aim to build a deeper understanding of where quantum computing methods can realistically integrate into geophysical workflows, and to prepare pathways for adaptation to production environments.

Background Research

Over the past two weeks, I conducted a systematic review of both *domain-specific applications* of quantum computing in geophysics and the *theoretical foundations* that make such applications feasible. This dual perspective clarifies both the *state of progress* in applying quantum methods to seismic problems and the *mechanisms* that allow these problems to be expressed on quantum hardware.

1. Quantum Applications in Geophysics

Recent years have seen a surge of studies exploring how quantum algorithms and hardware can address computational bottlenecks in geophysical workflows. These efforts can be grouped into four application areas:

- *Seismic Inverse Problems & Imaging* – Quantum annealing has been applied to velocity inversion and traveltime inversion, showing robustness against noise and improved resolution in low-contrast models. Sparse deconvolution has also been reformulated as a QUBO problem to enhance reflectivity estimation and horizon continuity.
  - Greer, J., & O'Malley, K. (2023, August). *Early steps toward practical subsurface computations with quantum computing.*
  - Nguyen, T., & Tura, J. (2025, May). *Seismic traveltime inversion with quantum annealing.*
  - AlSalem, H., Zhao, L., & Kim, Y. (2025, October). *Quantum Annealing Assisted Workflow for Sparse Spike Deconvolution.*
- *Seismic Wave Propagation & Forward Simulation* – Both annealing- and gate-based approaches have been explored for solving PDEs like the acoustic wave equation and Helmholtz equation, extending quantum computing to the forward-modeling backbone of seismic imaging.
  - Wen, X., & Wang, Z. (2025, May). *Seismic wave propagation simulation with quantum computing.*
  - Wright, A., Smith, J., & Patel, R. (2024, December). *Noisy intermediate-scale quantum simulation of the one-dimensional wave equation.*
  - Zhang, H., & Chen, Q. (2025, July). *Quantum simulation of Helmholtz equations via Schrödingerization.*
- *Subsurface & Hydrology Analogs* – Reformulating conductivity inversion in QUBO form demonstrates parallels between hydrologic and seismic problems, showing the broader reach of quantum optimization approaches.
  - Greer, J., & O'Malley, K. (2023, August). *Early steps toward practical subsurface computations with quantum computing* [also applied to hydrologic conductivity inversion].

- *Larger-Scale Full-Waveform Inversion (FWI)* – Both variational quantum circuits (VQCs) and QUBO-based formulations have been tested for pre-stack and post-stack seismic inversion, demonstrating potential for scaling quantum methods toward full imaging workflows.
  - Jiang, L., & Lin, P. (2023, November). *QuGeo: An end-to-end quantum learning framework for geoscience – A case study on FWI.*
  - Zhou, D., & Tanaka, M. (2025). *Binary-value full-waveform inversion via quantum annealing. Scientific Reports.*
  - Vashisth, A., Kumar, R., & Li, Y. (2025, February). *Pre-stack and post-stack seismic inversion using quantum computing.*

2. Foundational Quantum Principles

To interpret and assess these applications, I also studied the theoretical underpinnings of quantum computing architectures and problem encodings:

- *Natural Atom Platforms* – Systems such as trapped ions and neutral atoms offer long coherence times and high-fidelity qubits. Their scalability makes them leading candidates for solving the large-scale optimization problems characteristic of geophysics.
- *Analog and Hybrid Analog Modes* – Analog quantum computing uses direct Hamiltonian evolution, tuning physical parameters to represent the target problem. Hybrid analog–digital approaches combine analog evolution with gate-based corrections, offering a pragmatic route for noisy intermediate-scale quantum (NISQ) devices where full error correction is not yet feasible.
- *Ising Model and QUBO Mapping* – Many geophysical problems (e.g., velocity inversion, deconvolution, FWI) can be recast as Quadratic Unconstrained Binary Optimization (QUBO) problems. Since QUBO is mathematically equivalent to the Ising Hamiltonian, these problems map naturally to the optimization framework solved natively by quantum annealers. This connection explains why so much of the current geophysics–quantum work leverages annealing-based hardware.

3. Synthesis

By combining insights from *application-driven research* and *quantum computing foundations*, I developed a two-layered perspective:

- At the *application level*, seismic inverse problems, wave propagation, hydrology analogs, and FWI represent the frontier where geophysics meets quantum algorithms. These studies range from proof-of-concept benchmarks to early demonstrations of working methods.
- At the *foundational level*, the natural atom platforms, analog/hybrid operating modes, and the Ising/QUBO formalism form the enabling bridge that allows geophysical PDE and optimization problems to be mapped to quantum devices.

This synthesis clarifies both *what is being attempted today* and *why these approaches are feasible*, while also revealing the conditions under which they may scale to production-level geophysical workflows.

Current Focus

For this semester, I will concentrate on *forward seismic wave modeling with quantum approaches*, drawing on three recent contributions:

1. Wen, X., & Wang, Z. (2025, May). *Seismic wave propagation simulation with quantum computing.*
   Working method: proposes iterative quantum annealing for dispersion-preserving finite-difference operators, producing wavefields with reduced dispersion compared to Taylor-expansion classical methods.

2. Wright, A., Smith, J., & Patel, R. (2024, December). *Noisy intermediate-scale quantum simulation of the one-dimensional wave equation.*
   Proof-of-concept: demonstrates accurate gate-based simulation of the 1D acoustic wave equation on Quantinuum hardware, useful as a benchmark for PDE solvers on NISQ devices.

3. Zhang, H., & Chen, Q. (2025, July). *Quantum simulation of Helmholtz equations via Schrödingerization.*
   Theoretical breakthrough: reformulates the Helmholtz equation as a Schrödinger Hamiltonian, positioning seismic frequency-domain problems for future large-scale quantum hardware.

Together, these studies cover a spectrum: *working methods today*, *benchmarking on NISQ hardware*, and *theoretical breakthroughs for the future*.

Future Research Plan

Academic Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sunday date	31/Aug	07/Sept	14/Sept	21/Sept	28/Sept	05/Oct	12/Oct	19/Oct	26/Oct	02/Nov	09/Nov	16/Nov	23/Nov	30/Nov	07/Dec
Deadlines			Research Statement		Updates follow-up		Updates follow-up		Updates follow-up		Updates follow-up		Updates follow-up	Submit Research Materials	Presentation
Phases	Background Research														
			Focused Research & Planning												
					Implement & Analyze										
													Deliver		

The research plan follows the structured *timeline developed for ErSE 299*:

- *Weeks 1–3 (Background Research):* Completed survey of existing literature across inverse problems, forward modeling, hydrology analogs, and FWI.
- *Weeks 3–6 (Focused Research):* Read the three selected forward modeling papers (Wen & Wang, 2025; Wright et al., 2024; Zhang & Chen, 2025) in detail. Generate a concrete comparative summary outlining their *similarities, differences, scalability, and feasibility.*
- *Weeks 5–13 (Implementation and Analysis):* Based on insights from the focused reading, choose one approach (likely Wen & Wang's annealing-based method, given its practicality) to conceptually or partially implement. Evaluate its performance against classical baselines and assess its potential integration into geophysical workflows.
- *Weeks 13–15 (Delivery):* Synthesize findings into a final report and presentation. Deliverables will include the literature synthesis, analysis of forward modeling methods, and results from the chosen implementation.

Long-term, I envision a research program that:

- Bridges *quantum simulation methods* with *classical seismic workflows*, especially for forward modeling and inversion.
- Evaluates *scaling limits* of current quantum hardware against geophysical problem sizes.
- Explores *hybrid quantum-classical algorithms* as a realistic near-term path.

Conclusion

This project is an opportunity to align my geophysics background with cutting-edge quantum research. By focusing on *forward modeling methods*, I can critically evaluate what is already possible, what remains proof-of-concept, and what is purely theoretical. My broader vision is to identify *where quantum computing will have the most impact in seismic imaging* and to contribute to a roadmap for integrating these methods into geophysical processing workflows.