Seismic Traveltime Inversion with Quantum Annealing

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Abstract

This study demonstrates the application of quantum computing based quantum annealing to seismic traveltime inversion, a critical approach for inverting highly accurate velocity models. The seismic inversion problem is first converted into a Quadratic Unconstrained Binary Optimization problem, which the quantum annealer is specifically designed to solve. We then solve the problem via quantum annealing method. The inversion is applied on a synthetic velocity model, presenting a carbon storage scenario at depths of 1000-1300 meters. As an application example, we also show the capacity of quantum computing to handle complex, noisy data environments. This work highlights the emerging potential of quantum computing in geophysical applications, providing a foundation for future developments in high-precision seismic imaging.

Keywords: quantum computing, seismic inversion, borehole, carbon storage.

1. Introduction

Quantum computing is an emerging field with significant promise for various scientific and engineering disciplines. As we stand at the frontier of this technological revolution, early-stage research in quantum computing is crucial for the advancement of geophysics. Numerous studies have begun to explore the integration of quantum computing within this field, highlighting its immense and revolutionary potential (Moradi et al., 2018). For instance, quantum annealers can perform well in solving tomography optimization problems (Sarkar & Levin, 2018). Greer & O'Malley (2020) also demonstrated the application of quantum computing to binary-value full waveform inversion, addressing issues related to velocity variations. In the frequency domain, the seismic wave equation can be reduced to a system of linear equations, allowing for the application of quantum annealing

(Kumar, 2022). Furthermore, it has been shown that quantum annealing impedance inversion with L1 norm regularization can dramatically enhance accuracy and anti-noise capabilities (Wang et al., 2024).

A quantum annealer is a specific type of quantum computer designed to solve optimization problems (Yulianti & Surendro, 2022). The quantum annealing process in quantum annealers can find the minimum energy state of a system, corresponding to the optimal solution of a given problem (McGeoch, 2020). This process is achieved by utilizing quantum fluctuations, allowing the system to tunnel through energy barriers (Crosson & Harrow, 2016). While there are various types of models in quantum computing (Nimbe et al., 2021), this particular feature allows quantum annealing to efficiently explore complex energy landscapes, making them particularly well-suited for solving optimization problems.

Most previous attempts to address seismic problems using quantum annealers have primarily involved relatively simple models (Albino et al., 2022; Alulaiw & Sen, 2015; Greer & O'Malley, 2023). For conventional approach by classical computers, the cross-well seismic inversion between boreholes can be computationally expensive (McMechan, 1983), necessitating the development of new methods to tackle these challenges. Therefore, in this study, we aim to advance this line of research by applying quantum annealing to a complex problem: Seismic traveltime inversion of the velocity model between two boreholes. Our focus is on developing an inversion strategy that can accurately invert the velocity model with noisy data despite the limitation of the quantum hardware, specifically targeting carbon storage scenarios at depths of 1000-1300 meters. We use quantum annealer at D-Wave Advantage System, which has at least 5000 qubits (McGeoch & Farré, 2020). Clearly, this travel-time inversion method can be applied to other acquisition geometries and data such as surface seismic, vertical seismic profile (VSP), earthquake or micro seismic data.

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