Chapter 1

Introduction

1.1 Seismic monitoring of fluid flow

I believe one of the next major breakthroughs in Geophysics will be *seismic time-lapse monitoring of subsurface fluid flow*. Seismic time-lapse monitoring consists of recording multiple seismic surveys at a single site, repeated over time intervals in which interesting subsurface fluid movement can take place. Integrated with fluid-flow simulation, geology, rock physics and geophysics, spatial estimates of fluid-flow paths, permeabilities and phase-front movement in the subsurface may be inferred from the time-lapse seismic monitor data. Seismic monitoring offers us the exciting possibility of being able to estimate where and how fluids are flowing in the Earth, and may help us assess the role of fluids in crustal processes.

1.2 Why is monitoring of fluid-flow important?

Seismic monitoring of subsurface fluid flow has immense potential for impact in: enhanced recovery of natural energy resources, groundwater and environmental studies, global climate issues, and an improved understanding of plate tectonic mechanisms.

1.2.1 Energy resources

Hydrocarbons fuel the world's economy, including transportation, power generation, and the manufactured goods that our society depends upon. Most of the Earth's potential oil and gas reserves have already been found and are currently being rapidly depleted. Because we do not understand the complexity of flowpaths and flow barriers in hydrocarbon reservoirs, we leave behind at least as much oil as we produce in each reservoir due to suboptimal production strategies (?). I believe that seismic monitoring will become an interactive diagnostic tool, coupled with fluid-flow simulation and production history matching, that will help us to better understand reservoir fluid flow, and eventually lead us to double our recoverable oil and gas reserves. The detailed case studies of seismic fluid-flow monitoring presented in this thesis are focused on enhanced recovery of hydrocarbons.

1.2.2 Groundwater and environmental issues

Groundwater is becoming a precious resource. High-resolution shallow seismic surveys might be useful in monitoring water table fluctuations with time over large surface areas to better understand aquifer depletion and recharge. Also, it is becoming increasingly important to monitor contaminant plumes at hazardous spill sites to make sure clean water is not polluted. While seismic data cannot "see" most contaminants in water, the closely related electromagnetic surveying technique called Ground Penetrating Radar (GPR) can image contaminant plumes by electrical conductivity differences and could be useful for fluid-flow monitoring.

1.2.3 Methane hydrates and global climate

Methane hydrates are ice-like deposits which contain huge amounts of trapped methane gas. Methane hydrate deposits have been found at continental margins on a worldwide basis (?). It is estimated that the amount of methane gas trapped in the ice is at least as large as all the conventional oil and gas reserves found to date! This means that methane hydrates may be an important future energy resource when their in situ physical properties and formation mechanisms are better understood.

Methane is a greenhouse gas, and plays an important role in global climate. Monitoring the rate at which these deposits accumulate or dissolve could provide very useful information to climate models, and help understand the possible buffering role of methane hydrates. For example, in periods of global cooling, the accompanied drop in sea level could decrease hydrostatic pressure enough to allow massive subsea hydrate deposits to start dissolving. Dissolution of hydrates would add free methane gas to the atmosphere, which could buffer global cooling by starting a greenhouse effect. At present, these massive deposits of methane have not been accounted for in global climate models and their role is not well understood. Seismic monitoring of methane hydrate deposits could add useful insight.

Finally, many methane hydrate deposits have been found near offshore plate subduction zones. I believe there may be some relation between the location of these deposits and the fluids that are being heated, pressurized and driven out of the saturated downgoing slab. Monitoring subduction-zone hydrates might give a clue to the fluid flow system in a subducting plate, and how that is related to subduction rates, depth and magnitude of earthquakes, and chemistry of upwelling magma at subduction-zone volcanic chains.

1.2.4 Earthquake mechanisms and prediction

Earthquake seismologists believe that fluid flow plays an important role in the magnitude and frequency of earthquakes. Fluids can lubricate fault surfaces making it easier for an earthquake to occur. Highly pressurized pore-fluid in a fault region might indicate that an earthquake is about to occur. Pore pressure increases which cause seismic velocity decreases might be monitorable over time. I can imagine a seismic monitoring experiment consisting of a small array of geophones on one side of the San Andreas, and a shot location on the other. Repeated shots could be fired at reasonable time intervals (1 week?) and the seismic arrivals at the geophone array could be analyzed to see if the velocity (pore pressure) in the fault zone is decreasing (increasing). A similar experiment has recently been performed by Nadeau et al. (**?**). This type of seismic monitoring might help to better understand the earthquake mechanism along a fault, and perhaps be useful as a tool to predict when an earthquake is about to occur.

1.3 An overview of this thesis

In this thesis, I explicitly develop the link between fluid flow, rock physics and seismic analysis. The thesis is organized in four main parts: mathematical aspects of seismic monitoring theory, feasibility analysis of monitoring fluid flow at a given site, data processing issues related to time-lapse seismic monitor data, and integrated interpretation of monitoring data combining fluid-flow, rock physics, seismic modeling and seismic analysis.

Chapter 2 discusses the mathematical relationships between fluid flow, rock physics, seismic modeling, seismic imaging and velocity analysis. Chapter 3 discusses feasibility analysis with a case study from the Troll Field offshore Norway. The goal is to predict whether gas coning from a horizontal oil depletion well could be monitored from surface seismic data under realistic conditions using the available reservoir description, fluid-flow simulations, and core measurements. Chapter 4 discusses data processing issues with a study of six 3-D seismic surveys recorded over a steam injection site at the Duri Field in Sumatra, Indonesia. Chapter 5 makes an integrated interpretation of the Duri 4-D data by combining aspects of fluid-flow, rock physics, seismic modeling, velocity analysis, and seismic imaging.

1.4 Acknowledgment

Many of the ideas presented in this thesis concerning seismic fluid-flow monitoring have been inspired and shared by collaborations with Professors Jon Claerbout and Amos Nur, and friends at Stanford who are equally excited about the future role of seismic fluid-flow monitoring.