FLUID-INDUCED SEISMICITY

The characterization of fluid-transport properties of rocks is one of the most important, yet difficult, challenges of reservoir geophysics, but is essential for optimal development of hydrocarbon and geothermal reservoirs. Production of shale oil, shale gas, heavy oil and geothermal energy, as well as carbon-dioxide sequestration, are relatively recent developments where borehole fluid injection is often employed to enhance fluid mobility. Unlike active seismic methods, which present fundamental difficulties for estimating the permeability of rocks, microseismicity induced by fluid injection in boreholes provides the potential to characterize physical processes related to fluid mobility and hydraulic-fracture growth in rocks.

This book provides a quantitative introduction to the underlying physics, application, interpretation, and hazard aspects of fluid-induced seismicity with a particular focus on its spatio-temporal dynamics. It presents many real-data examples of microseismic monitoring of hydraulic fracturing at hydrocarbon fields and of stimulations of enhanced geothermal systems. The author also covers introductory aspects of linear elasticity and poroelasticity theory, as well as elements of seismic rock physics and of the mechanics of earthquakes, enabling readers to develop a comprehensive understanding of the field. *Fluid-Induced Seismicity* is a valuable reference for researchers and graduate students working in the fields of geophysics, geology, geomechanics and petrophysics, and a practical guide for petroleum geoscientists and engineers working in the energy industry.

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Preface

Characterization of fluid-transport properties of rocks is one of the most important, yet one of most challenging, goals of reservoir geophysics. However, active seismic methods have low sensitivity to rock permeability and mobility of pore fluids. On the other hand, it would be very attractive to have the possibility of exploring hydraulic properties of rocks using seismic methods because of their large penetration range and their high resolution. Microseismic monitoring of borehole fluid injections is exactly the tool that can provide us with such a possibility. Borehole fluid injections are often applied for stimulation and development of hydrocarbon and geothermal reservoirs. Production of shale gas and heavy oil as well as CO_2 sequestration are relatively recent technological areas that require broad applications of this technology. The fact that fluid injection causes seismicity has been well established for several decades (see, for example, Pearson, 1981, and Zoback and Harjes, 1997). Current ongoing research is aimed at quantifying and controlling this process. Understanding and monitoring of fluid-induced seismicity is necessary for hydraulic characterization of reservoirs and for assessments of reservoir stimulations.

Fluid-induced seismicity covers a wide range of processes between the two following limiting cases. In liquid-saturated hard rocks with low to moderate permeability (10^{-5}–10^{-2} darcy) and moderate bottom hole injection pressures (as a rule, less than the minimum absolute value of the principal compressive tectonic stress) the phenomenon of microseismicity triggering is often caused by the process of linear relaxation of pore-pressure perturbations (Shapiro *et al.*, 2005a,b). Note that we speak here about the linearity in the sense of corresponding differential equations. In porodynamics this process corresponds to the Frenkel–Biot slow wave propagation (see Biot, 1962, and a history review by Lopatnikov and Cheng, 2005, as well as an English translation of Frenkel, 2005). In the porodynamic low-frequency range (hours or days of fluid-injection duration) this process reduces to a linear pore-pressure diffusion. Then, the linear pore-pressure diffusion defines features of the rate of spatial growth, geometry and density of clouds of microearthquake hypocenters (Shapiro *et al.*, 2002, 2003, 2005a,b; Parotidis *et al.*, 2004). In some cases, spontaneously triggered natural seismicity, like earthquake swarms, also shows similar diffusion-like signatures (Parotidis *et al.*, 2003, 2004, 2005; Hainzl *et al.*, 2012; Shelly *et al.*, 2013).

Another extreme case is a strong non-linear fluid–solid interaction related to the hydraulic fracturing of sediments like a tight sandstone or a shale with extremely low permeability (10^{-9}–10^{-5} darcy). In this case a fluid injection leads to a strong enhancement of the permeability. Propagation of a hydraulic fracture is accompanied by opening of a new fracture volume, fracturing fluid loss and its infiltration into reservoir rocks, as well as diffusion of the injection pressure into the pore space of surrounding formations and inside the hydraulic fracture (Economides and Nolte, 2003). Some of these processes can be seen from features of spatio-temporal distributions of the induced microseismicity (Shapiro *et al.*, 2006b; Fischer *et al.*, 2008; Dinske *et al.*, 2010). The initial stage of fracture volume opening as well as the back front of induced seismicity (propagating after termination of the fluid injection) can be observed. Evaluation of spatio-temporal dynamics of induced microseismicity can help to estimate physical characteristics of hydraulic fractures, e.g. penetration rate of the fracture, its permeability as well as the permeability of the reservoir rock. Therefore, understanding and monitoring of fluid-induced seismicity by hydraulic fracturing can be useful for describing hydrocarbon and geothermal reservoirs and for estimating the results of hydraulic fracturing.

Seismicity induced by borehole fluid injections is a central topic of this book. It describes physical fundamentals of interpretation of fluid-induced seismicity. The first two chapters of the book provide readers with an introduction to the theoretical background of concepts and approaches useful for understanding fluid-induced seismicity. An application-interested reader can probably skip these two chapters and just go directly to Section 1.4 and then Chapters 3–5, using Chapters 1 and 2 mainly as reference material.

In Chapter 1 the book starts with a brief introduction to the theory of elasticity and seismic-wave propagation. This chapter also includes elements of fracture mechanics and of the geomechanics of faulting. Then there is an introductory description of earthquake sources of the seismic wavefield. Finally, the chapter contains a brief schematic description of methodical approaches of microseismic monitoring. Many important processing-related methodical aspects of microseismic monitoring remain outside of the scope of this book.

Chapter 2 provides a detailed introduction to the theory of poroelasticity. The main physical phenomena responsible for fluid-induced seismicity and discussed in this book in detail are fluid filtration and pore-pressure relaxation. They are closely related to slow waves in porous fluid-saturated materials. The dynamics of slow wavefields is the focus of this chapter. The chapter also includes a discussion of some non-linear effects related to deformations of the pore space. They are relevant for characterizing poroelastic coupling and for formulating models of the pressure-dependent permeability. Such models will be used for the considerations of non-linear pressure diffusion in subsequent chapters. The topic of thermo-poroelastic interaction is not discussed in the book.

In Chapters 3–5 of this book we describe the main quantitative features of different types of fluid-induced microseismicity. Different properties of induced seismicity related to reservoir characterization and hydraulic fracturing are addressed, along with the magnitude distribution of seismicity induced by borehole fluid injections. Evidently, this is an important question closely related to seismic hazard of injection sites. Many corresponding aspects of the book are also applicable to induced tectonic seismicity.

This book attempts to contribute to further elaboration of the seismicity-based reservoir characterization approach (see also Shapiro, 2008).

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[1] Here, and in the following, the affiliations are given for the time periods during which the access to the data was made possible.