Geothermics 76 (2018) 149–163

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Sensitivity of seismic properties to temperature variations in a geothermal reservoir

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A R T I C L E I N F O

Keywords:
Sensitivity
Temperature
Seismic properties
Geothermal

A B S T R A C T

Geophysical characterization plays a key role for the definition of the deep structures of geothermal reservoirs and the consequent assessment and validation of the geothermal conceptual model. Seismic methods may provide a valuable contribution for this purpose. This involves a deep and reliable understanding of the sensitivity of seismic-wave propagation to physical and temperature variations, with complex interactions. We present the theory and sensitivity analysis based on rock's mechanical Burgers model including Arrhenius temperature equations, integrated with Gassmann model for fluid saturated porous rocks, pressure effects for bulk and shear moduli, as well as permeability and squirt flow effects. Assuming a temperature gradient model, the analysis applied at low seismic frequencies compares the interpretation of the sensitivity effects for different typical seismic elastic quantities, showing the different performance in relation to physical effects, including melting, supercritical conditions, and observability obtained in different temperature regions. With a quantification of the physical properties, the results of the study show that in deeper zones the main expected contributions in terms of variations in seismic velocity, moduli and seismic attenuation due to temperature come from melting transition, while in shallower porous fluid-saturated formations the trends are governed by pressure effects, with minor contributions of permeability and possible effects related to soft porosity. The new calculated elastic moduli are complex-valued and frequency-dependent, and temperature dependent through the fluid properties. In this complex scenario, not always the increments in the velocity and elastic wave moduli correspond to an increment in the temperature. Moreover, with mobility decreasing as a function of depth, the analysis shows that the shear quality factor is sensitive to permeability, which introduces moderate effects for velocity and attenuation of shear waves. The analysis applies to active exploration seismic and passive seismology.

1. Introduction

Seismic methods may provide a valuable contribution for the geophysical characterization of geothermal reservoirs, either using exploration approaches (Batini et al., 1983; Niitsuma et al., 1999) or passive seismology to image the subsurface, obtain velocity information and monitor the geothermal reservoir (e.g., Blanck et al., 2016; Majer et al., 2007). This task requires a deep and reliable understanding of the sensitivity for seismic-wave propagation to physical and temperature variations, with complex interactions of the interrelated effects. This is relevant in particular for deep-drilling projects, where supercritical fluid conditions can be encountered (Farina et al., 2016; Dobson et al., 2017; Reinsch et al., 2017) and prediction, for example by reverse VSP (RVSP) (Poletto et al., 2011; Poletto and Miranda, 2004) may play a key role.

Several works consider seismic wave propagation in hot geothermal rocks worldwide (e.g., Cermak et al., 1990; Kristinsdóttir et al., 2010; Vinciguerra et al., 2006), in the presence of temperature and fluids. Jaya et al. (2010) analysed petrophysical experiments on Icelandic geothermal rock samples at simulated in situ reservoir conditions to delineate the effect of temperature on seismic velocity and attenuation, with the goal to predict the effect of the saturating pore fluid on seismic velocity using a modified Gassman equation. In their study the temperature dependence follows solely from the thermophysical characteristic of the saturating fluid in porous rock. Iovenitti et al. (2013) and Tibuleac et al. (2013), studied the seismic-temperature distribution to test the seismic component of an exploration method calibrated by integrating geological, geophysical and geochemical experimental data, including empirical temperature – P-wave velocity relationships and sensitivity analysis after removing the effects on depth, using a

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https://doi.org/10.1016/j.geothermics.2018.07.001
Received 20 September 2017; Received in revised form 2 May 2018; Accepted 1 July 2018

geostatistical approach. More recently, seismic rheological analysis of the brittle ductile transition (BDT) and seismic propagation modeling in presence of temperature was performed by Carcione and Poletto (2013), with temperature and fluids by Carcione et al. (2014, 2017), Farina et al. (2017), including melting and supercritical condition. The numerical algorithms developed in these studies (Carcione and Poletto, 2013; Carcione et al., 2014, 2017; Farina et al., 2016, 2017) can be used for seismic simulation in arbitrary geological media at variable geothermal conditions, including temperature and tectonic effects at depth. After understanding the seismic behavior in geothermal environments, a model-based analysis of sensitivity for the elastic quantities together with the experimental study is essential for seismic characterization.

In particular, this work is part of the ongoing characterization of geothermal formations by full-waveform seismic modelling including temperature, planned and performed in the framework of the European Union Horizon 2020 GEMex Project (GEMex, 2016), for the study of high-temperature geothermal zones and geothermal systems in Mexico: for engineered geothermal system (EGS) development at Acoculco and for a super-hot resource near Los Humeros (e.g., Urban and Lermo, 2013). GEMex includes the analysis of the distribution of rock modulus of elasticity and correlation to temperature, namely: comparing the spatial distribution of rock modulus of elasticity with the temperature distribution data derived from the thermo-mechanical models with the purpose to estimate deep formation temperatures from seismic and gravity surveys (GEMex, 2016).

In this work, we present the theory and numerical sensitivity analysis based on rock's mechanical Burgers model including creep-flow by Arrhenius temperature equations, integrated with Gassmann model to account for fluid saturated porous rocks, and pressure effects for bulk modulus. The analysis includes permeability effects and squirt-flow, which may introduce unrelaxed effects at frequencies higher than the seismic frequencies. The analysis presented in the second part of the paper is applied at low seismic frequency, assuming a constant-gradient model for temperature. It compares the interpretation of the characteristic sensitivity effects for different typical seismic elastic quantities, showing the different performance in relation to physical effects, including melting and supercritical, and investigates results in different temperature regions in sample-case examples. Main results are related to interpretation of differences in sensitivity calculated with attenuation and propagation velocity, with interpretation of melting, fluid saturation and pressure effects in the sensitivity curves.

The scope of this work is to provide a first basis for the seismic sensitivity analysis with temperature by numerical simulation. The analysis is representative of the wave propagation behavior at different conditions.

2. Theory

2.1. The Burgers model for brittle–ductile behavior

Carcione and Poletto (2013) observed that the Burgers model is suitable to describe the transient viscoelastic creep for arbitrary media, because there is experimental evidence that linear viscoelastic models are appropriate to describe the behavior of ductile media. Gangi (1981, 1983) obtained exponential functions of time using linear viscoelastic models to fit data for synthetic and natural rocksalt. Chauveau and Kaminski (2008) described the effect of transient creep on the compaction process on the basis of the Burgers' model. The viscosity can be expressed by the Arrhenius' equation, accounting for thermodynamic effects, and the constants that appear in the creep rate expressions describe the properties of a specific arbitrary material at given physical conditions. For this study, we assume isotropic materials, however anisotropy is considered in Carcione and Poletto (2013), which can be further developed for sensitivity analysis purposes. For more details on the derivation of the constitutive equations the reader may refer to previous works (Carcione and Poletto, 2013; Carcione et al., 2014, 2017).

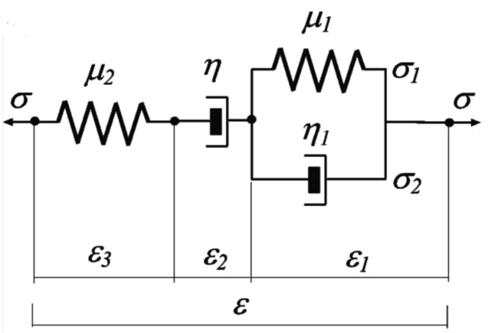

Fig. 1. Mechanical representation of the Burgers viscoelastic model for shear deformations (e.g., Carcione, 2014). σ, ϵ, μ and η represent stress, strain, shear modulus and viscosity, respectively, where η_1 describes seismic relaxation while η is related to plastic flow and processes such as dislocation creep.

The constitutive equation, including both the shear viscoelastic and ductile behavior, can be described with the Burgers model as reported in Carcione and Poletto (2013) and Carcione et al. (2014). The Burgers model is a series connection of a dashpot and a Zener model (Fig. 1) and its complex shear modulus can be written as

$$\mu_B = \frac{\mu_0(1 + i\omega\tau_\epsilon)}{1 + i\omega\tau_\sigma - \frac{i\mu_0}{\omega\eta}(1 + i\omega\tau_\epsilon)}. \qquad (1)$$

The quantities τ_σ and τ_ϵ are seismic relaxation times, μ_0 is the relaxed shear modulus (see below) and η is the flow viscosity describing the ductile behavior, $i = \sqrt{-1}$ and $\omega = 2\pi f$ is the angular frequency. The relaxation times can be expressed as

$$\tau_\epsilon = \frac{\tau_0}{Q_0}\left(\sqrt{{Q_0}^2 + 1} + 1\right), \quad \tau_\sigma = \tau_\epsilon - \frac{2\tau_0}{Q_0}, \qquad (2)$$

where τ_0 is a relaxation time such that $\omega_0 = 1/\tau_0$ is the center frequency of the relaxation peak and Q_0 is the minimum quality factor.

The limit $\eta \to \infty$ in Eq. (1) recovers the Zener kernel to describe the behavior of the brittle material, while $\tau_\sigma \to 0$ and $\tau_\epsilon \to 0$ yield the Maxwell model used by Dragoni and Pondrelli (1991): $\mu_B = \mu_0(1 - i\mu_0/\omega\eta)^{-1}$ (e.g., Carcione, 2014). For $\eta \to 0$, $\mu_B \to 0$ and the medium becomes a fluid. Moreover, if $\omega \to \infty$, $\mu_B \to \mu_0\tau_\epsilon/\tau_\sigma$, where μ_0 is the relaxed ($\omega = 0$) shear modulus of the Zener element ($\eta = \infty$).

The viscosity η can be expressed by the Arrhenius equation (e.g., Carcione et al., 2006; Montesi, 2007). It is related to the steady-state creep rate $\dot\epsilon$ by

$$\eta = \frac{\sigma_o}{2\dot\epsilon}, \quad \dot\epsilon = A_\infty \sigma_o^n \exp(-E/R_G T) \qquad (3)$$

where σ_o is the octahedral stress (e.g., Gangi, 1981, 1983; Carcione et al., 2006; Carcione and Poletto, 2013), A_∞ and n are constants, E is the activation energy, $R_G = 8.3144$ J/mol/°K is the gas constant and T is the absolute temperature. The octahedral stress is

$$\sigma_o = \frac{1}{3}\sqrt{(\sigma_v - \sigma_h)^2 + (\sigma_v - \sigma_H)^2 + (\sigma_h - \sigma_H)^2}, \qquad (4)$$

where the σ's are the stress components in the principal system, corresponding to the vertical (v) lithostatic stress, and the maximum (H) and minimum (h) horizontal tectonic stresses.

The temperature is a function of depth through the geothermal gradient G. A linear approximation is $T - T_0 = z\,G$, where z is the depth and T_0 is the temperature at the surface ($z = 0$).

2.2. The modified Gassmann model

Gassmann's equations are used to calculate changes in seismic velocity and elastic quantities due to different fluid saturations. In this