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Research paper

ARTc: Anisotropic reflectivity and transmissivity calculator

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ABSTRACT

While seismic anisotropy is known to exist within the Earth's crust and even deeper, isotropic or even highly symmetric elastic anisotropic assumptions for seismic imaging is an over-simplification which may create artifacts in the image, target mis-positioning and hence flawed interpretation. In this paper, we have developed the ARTc algorithm to solve reflectivity, transmissivity as well as velocity and particle polarization in the most general case of elastic anisotropy. This algorithm is able to provide reflectivity solution from the boundary between two anisotropic slabs with arbitrary symmetry and orientation up to triclinic.

To achieve this, the algorithm solves full elastic wave equation to find polarization, slowness and amplitude of all six wave-modes generated from the incident plane-wave and welded interface. In the first step to calculate the reflectivity, the algorithm solves properties of the incident wave such as particle polarization and slowness. After calculation of the direction of generated waves, the algorithm solves their respective slowness and particle polarization. With this information, the algorithm then solves a system of equations incorporating the imposed boundary conditions to arrive at the scattered wave amplitudes, and thus reflectivity and transmissivity.

Reflectivity results as well as slowness and polarization are then tested in complex computational anisotropic models to ensure their accuracy and reliability. ARTc is coded in MATLAB® and bundled with an interactive GUI and bash script to run on single or multi-processor computers.

1. Introduction

The evidence that the Earth's crust, mantle, and even inner core are anisotropic to seismic waves has grown significantly in the last half-century, Belonoshko et al. (2008) and Bao et al. (2016). For instance, Di Leo et al. (2014) studied the feasibility study of the correlation between mantle flow direction and its respective shear wave splitting around subduction zones. Despite this, seismic observations are still largely interpreted by assuming that the media in which the waves are passing through are isotropic or highly symmetric. Incorporating elastic anisotropy into seismic data analysis will have two significant advantages. First, elastic anisotropy exists once the structural symmetry at any scale is broken; and generally less symmetry implies higher degrees of anisotropy. The character and degree of anisotropy are apparent in traditionally varying wave speeds and anomalous polarization. Consequently such observations can tell us about i) mineralogical textures (e.g., Gassmann, 1964; Kaarsberg, 1959; Wenk and Houtte, 2004; Mainprice and Nicolas, 1989); ii) layering (Helbig, 1994; Backus, 1962; Rokhlin, 1986), and iii) fracturing and stress regimes of the region (Sayers et al., 2015; Crampin, 1985; Stewart et al., 2013) or iv) combination of them (e.g., Far et al., 2013; Schijns et al., 2012).

Second, the transit times and travel paths of seismic rays moving through anisotropic layers can differ significantly from those through isotropic structures, Ben-Menahem and Sena (1990) and Behura and Tsvankin (2006) and Behura and Tsvankin (2009). Ignoring this deviation in the patterns of reflection and refraction introduces error in seismic imaging; considering it in the processing scheme results in improvements in the veracity of seismic imaging. There is no need to emphasize the potential use of this code in addition to the applications in exploration seismology including but not limited to the computation of the synthetic receiver function in global and local seismology, to its use as a key component of a ray tracer for general anisotropic layered media and the construction of the synthetic seismic data as implemented by Kendall and Thomson (1989), and Guest et al. (1993).

1.1. Background of elastic anisotropy

There are many sources, that are linked to elastic anisotropy, which can be categorized as mineralogical or structural. Fig. 1a,b shows how the preferred orientation of minerals in the rock, as well as very finely deposited layers of rocks which are very common in the Earth, reflects elastic anisotropy in seismic data. Satellite picture

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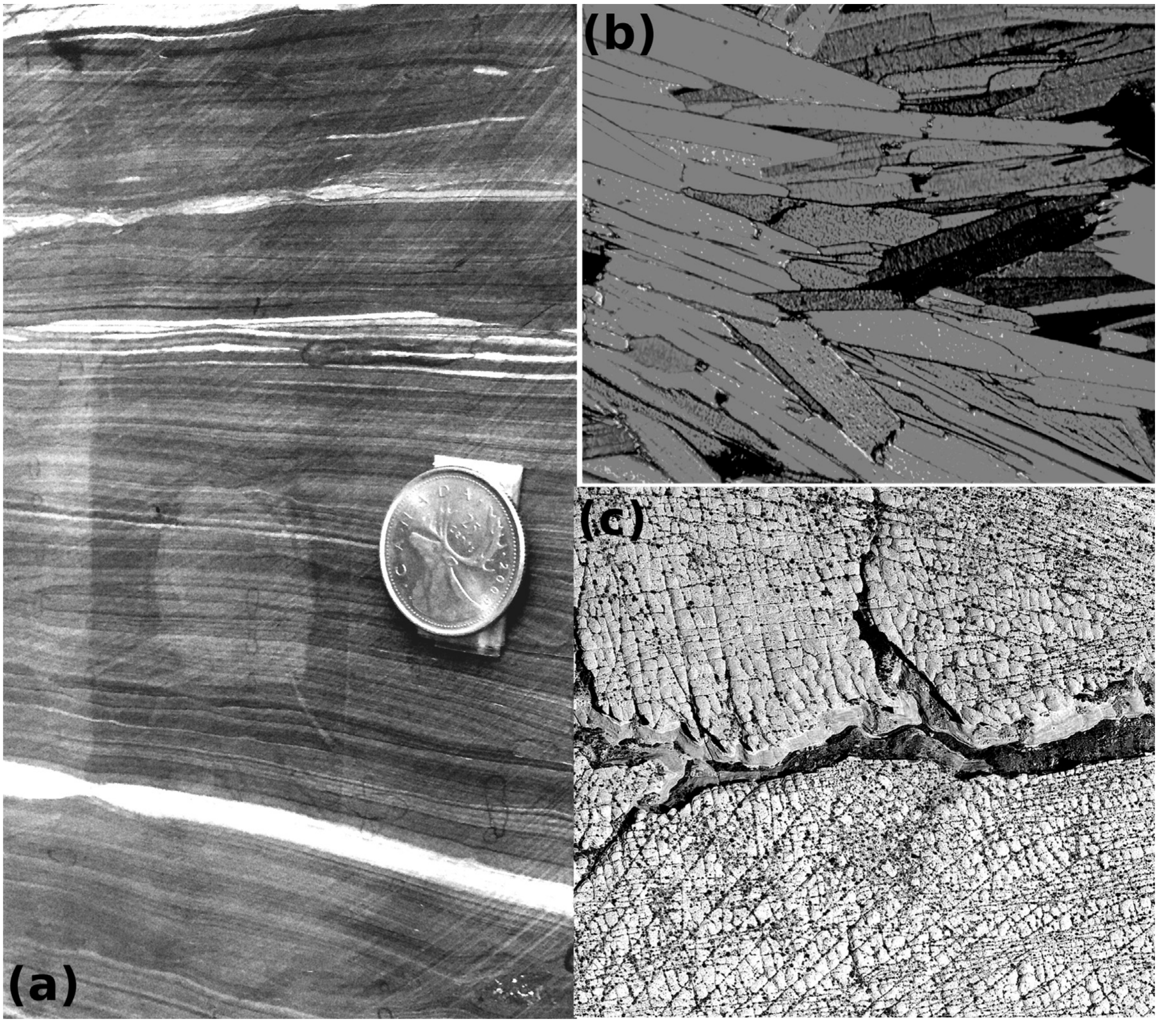

Fig. 1. Structural deformation or crystallographic orientation of minerals are two main sources of elastic anisotropy in the hard rock environment. (a) and (b) depict two media with microscopic scale preferred orientation of minerals and deposition of the minerals, respectively; which would create elastic anisotropy. c) Displays two sets of large-scale fractures on the surface with different orientation on North from South of the Freshwater Spring River in Utah. In the North part fractures are almost orthogonal which could create orthorhombic anisotropy, however in the Southern part of the river non-orthogonal fractures may represent monoclinic or triclinic elastic anisotropy, after Far et al. (2013).

from Utah, United State, which shows two sets of fractures occurs in large-scale also could represent two different elastic anisotropic media in the very close proximity, after Far et al. (2013).

Despite the fact that the importance of anisotropy is widely recognized, there are rather few tools to properly deal with it in seismology; and usually, we rely on numerous simplifying assumptions and approximations that have made including anisotropy more palatable such as the weak anisotropy formulations introduced by Thomsen (1986) for transversely isotropic (TI) and later for orthorhombic materials by Ruger (1997,1998) and Tsvankin (1997) as well as many others. Such approaches have promoted the more general acceptance of seismic anisotropy, but they usually cannot provide suitable answers for more realistic geological structures that may be less symmetric. This is becoming increasingly vital in the techniques, which use the variations in seismic properties with respect to the direction of propagation to understand how the stress regime, fracture orientation, spacing, or deposition alignments are around the point of interest deep underground, Helbig and Thomsen (2006).

Our primary objective in this paper is to provide to the community a program that provides the general solution for the reflection and transmission from all wave-modes and welded interface bonding two homogeneous anisotropic slabs with arbitrary symmetry and orientation. In other words, the paper includes a program that can calculate the plane-wave reflection coefficients from an interface between arbitrarily oriented anisotropic media. A number of requisite subsidiary programs that determine directional dependent wave speed and polarization are also included.

Elastic wave propagation in anisotropic media has been studied extensively over the last century as it is of fundamental concern to condensed matter physicists and of practical consequence to geophysicists and material engineers. A number of textbooks exist that cover the mathematics in details (e.g. Auld, 1973; Helbig, 1994; Musgrave, 1970).

The paper begins with a review of studies of reflectivity, continues through the essential mathematical background, provides a description of the programs provided, and ends with some examples of the application of the program to cases of increasing complexity.

1.2. Early modeling of seismic anisotropy

In any given propagation direction through an anisotropic material, there will be three distinct and orthogonal wave-modes: one quasi-longitudinal mode (qP) and two quasi-transverse modes (qS1 and qS2) with respective polarization nearly parallel or perpendicular to the propagation direction, respectively. One further point to