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Review Article

Inferring upper-mantle flow from seismic anisotropy: An experimental perspective

Philip Skemer [a,*], Lars N. Hansen [b]

[a] *Washington University in St Louis, USA*
[b] *Oxford University, UK*

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ABSTRACT

Patterns of mantle flow are most directly inferred from observations of seismic anisotropy, which is mainly caused by the crystallographic preferred orientation (CPO) of olivine, the most abundant mineral in the upper mantle. CPO is generated by high temperature ductile deformation, which often yields predictable relationships between the elastic or seismic properties of a material and the kinematics of flow. Over the last 15 years there has been a wealth of new data describing the how olivine CPO forms and evolves as a function of deformation conditions and strain magnitude. In this review, we explore the relationships between deformation, the evolution of CPO, and the development of seismic anisotropy, from the perspective of experimental rock mechanics. We first review the experimental basis for the study of olivine CPO evolution from the formative studies in the early nineteen sixties through recent advances. We then review some emerging complications to the study of CPO evolution, such as the long-lived transient CPOs that arise from changes in deformation kinematics, mechanisms, and conditions. Finally we discuss the origins of seismic anisotropy and the challenges of interpreting seismic anisotropy in terms of mantle flow.

Contents

1. Introduction

The flow of rocks in Earth's interior is a manifestation of mantle convection and one of the basic elements of Earth's secular evolution. In principle, knowledge of mantle flow patterns provides fundamental

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[*] Corresponding author at: Rudolph Hall Rm 110, Washington University in Saint Louis, 1 Brookings Drive, Saint Louis, MO 63130, USA. Tel.: +1 314 935 3584.
E-mail address: pskemer@wustl.edu (P. Skemer).

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constraints to the thermal and chemical history of the planet and the physical processes that are the foundation of plate tectonics. The study of mantle flow has benefited from the integrated effort of scientists from disciplines spanning the earth sciences. In this review, we will provide an overview of the interpretation of mantle flow from seismological observations while highlighting the perspective provided by experimental rock deformation.

By the mid-20th century, a growing body a literature demonstrated that olivine-rich rocks often exhibit a crystallographic texture. This texture was recognized by the systematic relationship between olivine's crystallographic axes and the macroscopic foliation of the rock (Andreatta, 1934; Turner, 1942), a feature now widely described as crystallographic preferred orientation (CPO) or lattice-preferred orientation (LPO).[1] In many cases olivine grains are oriented so that the [010] crystallographic axes are clustered normal to the schistosity or compositional banding, while the [100] and [001] axes are distributed in a girdle within the foliation plane, producing a texture that is axially symmetric (Brothers, 1959). Although both igneous and metamorphic origins of these microstructures were proposed, by the 1960s it was generally concluded that most CPO was generated by plastic deformation and recrystallization under sub-solidus conditions (Christensen and Crosson, 1968; Turner and Weiss, 1963).

Around the same time, laboratory measurements began documenting the orientation dependence of seismic wave velocities in olivine (Birch, 1960, 1961; Verma, 1960). In experiments on olivine single crystals, compressional waves were shown to travel fastest parallel to [100] and slowest parallel to [010], reflecting anisotropy in excess of 24% (Verma, 1960). In polycrystalline samples of dunite and olivine-rich harzburgite similar trends were observed, with the slowest velocities recorded in orientations parallel to concentrations of [010] axes. Although the magnitude of compressional wave anisotropy is smaller in polycrystalline materials, ranging from 3–10% (Birch, 1961), the potential significance of olivine CPO as a source of anisotropy in the mantle was clear.

A major conceptual advancement, linking mantle flow, olivine CPO, and seismic anisotropy was first proposed by Hess (1964). In this seminal work, Hess discussed results by Raitt (1963) and Shor and Pollard (1964), which described azimuthal variation of horizontally propagating seismic wave velocities near the Mendicino and Molokai fracture zones in the Pacific Basin. The fastest directions of wave propagation were those parallel to the strike of the fracture zones, which was also interpreted to be the direction of mantle flow. Citing the petrofabrics described by Turner (1942) and the experimental results of Verma (1960), Hess suggested that the seismic anisotropy could be attributed to the tectonically driven shear deformation of olivine. This fundamental idea established the basis for 50 years of study on the flow patterns in Earth's mantle.

Over the last several decades two basic approaches, illustrated schematically in Fig. 1, have been used to advance the study of mantle flow. The first approach, which we will call the inverse approach, uses as its starting point seismological observations. Seismic anisotropy at the plate scale (e.g. Ekstrom and Dziewonski, 1998; Nishimura and Forsyth, 1989; Tanimoto and Anderson, 1985; Wolfe and Solomon, 1998; Yuan and Romanowicz, 2010) is related to micro-scale or continuum descriptions of CPOs, which may be derived from rock physics experiments (Bystricky et al., 2000; Jung and Karato, 2001; Nicolas et al., 1973; Zhang and Karato, 1995) geological observations (Ben Ismail and Mainprice, 1998; Christensen and Lundquist, 1982; Mercier and Nicolas, 1975; Nicolas and Christensen, 1987; Nicolas et al., 1971), or microphysical modeling (Chastel et al., 1993; Kaminski and Ribe, 2001; Ribe and Yu, 1991; Tommasi et al., 2000; Wenk and Tomé, 1999; Wenk et al., 1991). The relationship between the inferred CPO and the kinematics of rock deformation is used to constrain patterns of mantle flow in the tectonic setting of interest (Carter et al., 1972; Karato et al., 2008; Long and Silver, 2009; Mainprice and Silver, 1993; Nicolas and Christensen, 1987).

The second approach, which we will call the forward approach, uses as its starting point a numerical model for mantle flow (Becker et al., 2003, 2006, 2008; Blackman and Kendall, 2002; Castelnau et al., 2009; Conrad and Behn, 2010; Faccenda and Capitanio, 2012; Kneller et al., 2005; Tanimoto and Anderson, 1984; Tommasi, 1998). The flow model is coupled to a conceptual or numerical model for CPO evolution, parameterized through comparison with geological observations or laboratory experiments (Castelnau et al., 2008; Kaminski et al., 2004; Tommasi et al., 2000; Wenk and Tomé, 1999). The CPO generated in this manner is used to forward model mantle anisotropy using data on mineral elasticity (Baker and Carter, 1972). Comparison between the forward model and seismological observations is used to test the validity of this approach (Becker et al., 2006, 2014; Conder and Wiens, 2007; Conrad et al., 2007; Ito et al., 2015).

In both the inverse and forward approaches there are several layers of assumptions that must be made. Among the most critical are the relationships between flow and the evolution of CPO. CPO is not a simple property of materials, and varies in strength, symmetry, and orientation as a function of composition; strain magnitude, path, and geometry; stress; temperature; pressure; and deformation mechanism (e.g. Karato et al., 2008; Mainprice, 2015). Moreover, CPO may evolve slowly with progressive strain and may not be in equilibrium with the instantaneous strain field, particularly under continents and near plate boundaries (Becker et al., 2003, 2014; Boneh et al., 2015; Castelnau et al., 2009; Conrad et al., 2007; Kaminski and Ribe, 2002; Skemer et al., 2012). For these reasons the relationships among mantle flow, CPO, and seismic anisotropy are non-trivial and geodynamic interpretations must be evaluated critically.

There have been several recent reviews related to these topics. The reader is directed to Mainprice (2015) for a review of the underlying mineral physics of mantle seismic anisotropy, to Karato et al. (2008) for a discussion of the relationships between olivine fabrics and mantle geodynamics, and Long and Silver (2009) and Long and Becker (2010) for reviews of the state of understanding of mantle anisotropy. In this paper, we will focus mainly on the experimental perspective, reviewing the experimental basis for the generation of olivine CPO, with particular emphasis placed on the importance of the evolution of CPO as a function of deformation conditions. In Section 2 we review experimental studies of CPO evolution from the early nineteen sixties to the present. In Section 3 we discuss some details of CPO evolution, in particular the transient CPOs that arise from changes in deformation kinematics, mechanisms, and conditions. In Section 4 we review the origins of seismic anisotropy and discuss the specific challenges of interpreting seismic anisotropy in terms of mantle flow.

2. Experimental studies of olivine CPO

2.1. Experimental studies (1963–2000)

With the emergence of plate tectonic theory came renewed interest in the constitution and rheology of the mantle (Carter et al., 1972). Rock deformation experiments sought to understand both the rheology of plausible upper-mantle compositions and the microstructures produced by deformation. Microstructure, including CPO, is a key to relating processes observed in the lab to processes in nature. Comparison of microstructures formed in these two different environments helps to validate the extrapolation of laboratory flow laws to geologic time scales, providing a framework for interpreting seismic anisotropy.

Some of the first high-pressure and temperature deformation experiments on olivine were performed by Raleigh (1963). Detailed microstructural observation, including analysis of slip bands, deformation

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[1] In geophysical literature CPO and LPO are used synonymously, although there is some regional preference in their application. As the term "lattice" is more ambiguous than "crystallographic," we have a slight preference for CPO and will use this term throughout the present review.