Earth and Planetary Science Letters 282 (2009) 285–293

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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

Measurement and implications of frequency dependence of attenuation

Ved Lekić [a,*], Jan Matas [b], Mark Panning [c], Barbara Romanowicz [a]

[a] Berkeley Seismological Laboratory, 225 McCone Hall, University of California, Berkeley, USA
[b] Laboratoire de Sciences de la Terre, CNRS-UMR 5570, Université de Lyon, Ecole normale supérieure de Lyon, 46, allée d'Italie, 69007 Lyon, France
[c] Department of Geological Sciences, 241 Williamson Hall, University of Florida, Gainesville, USA

ARTICLE INFO

Article history:
Received 22 September 2008
Received in revised form 5 February 2009
Accepted 13 March 2009
Available online 23 April 2009

Editor: R.D. van der Hilst

Keywords:
seismic attenuation
absorption band models
normal modes

ABSTRACT

Constraining the frequency dependence of intrinsic seismic attenuation in the Earth is crucial for: 1. correcting for velocity dispersion due to attenuation; 2. constructing attenuation and velocity models of the interior using datasets with different frequency contents; and, 3. interpreting lateral variations of velocity and attenuation in terms of temperature and composition. Frequency dependence of attenuation q can be represented by a power law $q \propto q_0 \omega^{-\alpha}$. Despite its importance, efforts at determining α from surface wave and free oscillation data have been thwarted by the strong tradeoffs between the depth- and frequency dependence of attenuation. We develop and validate a new method that eliminates this tradeoff, allowing a direct estimation of effective frequency dependence of attenuation without having to construct a new depth-dependent model of attenuation. Using normal mode and surface wave attenuation measurements between 80 and 3000 s, we find that α varies with frequency within the absorption band. It is 0.3 at periods shorter than 200 s, it decreases to 0.1 between 300 and 800 s, and becomes negative at periods longer than 1000 s.

1. Introduction

As they propagate through the Earth, seismic waves experience attenuation and dispersion resulting from microscopic dissipative processes operating at a variety of relaxation times. These dissipative effects can be summarized by the macroscopic quantity $q = -\Delta E/2\pi E_{\max}$, where ΔE is the internal energy lost by a seismic wave in one cycle. This quantity can be related to the often-used quality factor Q through $q \equiv (1/Q)$. The Earth acts as an absorption band (e.g. Anderson, 1976) and attenuation depends on the frequency of oscillation. Within the absorption band, attenuation is relatively high and does not strongly depend on frequency. Outside the band, attenuation rapidly decreases with frequency. Since the relaxation times of the dissipative processes giving rise to the absorption band might strongly depend on pressure and temperature, the frequency bounds of the band can change with depth (e.g. Anderson and Minster, 1979; Minster and Anderson, 1981; Anderson and Given, 1982). Within the absorption band, the frequency dependence of q can be described using a power law, $q \propto \omega^{-\alpha}$, with a model-dependent α, usually thought to be smaller than 0.5 (e.g. Anderson and Minster, 1979).

In the past few years, three new models of 3-D variations in upper mantle attenuation have been developed (Selby and Woodhouse, 2002; Gung and Romanowicz, 2004; Dalton and Ekström, 2006), offering the promise of clarifying the origin (thermal versus chemical) of lateral heterogeneities. Yet, knowing the value of α within the absorption band is required for interpreting lateral variations in attenuation in terms of temperature. It is also one of the governing parameters for interpreting observed lateral variations in seismic velocities. Matas and Bukowinski (2007) proposed a self-consistent attenuation model based on solid state physics and showed that anelasticity can substantially enhance seismic anomalies due to high temperature (by ~30%), thus confirming earlier observations of Romanowicz (1994). It is important to note that interpreting attenuation in terms of temperature and predicting its effects on seismic anomalies is only reasonable if the contribution of scattering is small compared to that due to intrinsic anelastic processes.

A non-zero α implies that seismic waves of different frequencies are differently attenuated, and accordingly modifies the velocity dispersion relation. This has three important consequences: 1) because oscillations at different frequencies can have very different depth sensitivities to elastic and anelastic properties of the Earth, the value of α affects the construction and interpretation of such profiles. In particular, the lower mantle q is mostly constrained by low-frequency modes and is thus not directly comparable to q obtained from high-frequency modes, which sample the upper mantle. A single radial attenuation profile is only relevant if $\alpha = 0$; 2) because the frequency content of different attenuation measurements can differ, combining these datasets requires accounting for the effect of α. For instance, if $\alpha = 0.3$, then q varies by a factor of two in a dataset including periods between 50 s and 5 s; 3) because geophysical datasets used to constrain Earth structure have very different dominant frequencies, using them together requires applying a

* Corresponding author.
E-mail address: lekic@seismo.berkeley.edu (V. Lekić).

0012-821X/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2009.03.030

dispersion correction whose functional form is different for a non-zero α than it is under the assumption of frequency-independent attenuation (Minster and Anderson, 1981).

Efforts at determining α of the mantle have followed three approaches: theoretical studies, laboratory experiments and seismological observations. Theoretical investigations have focused on explaining the origin of the absorption band and incorporating models of likely relaxation mechanisms developed using solid state physics. Liu et al., (1976) and Kanamori and Anderson (1977) modeled the absorption band for a standard linear solid as a superposition of relaxation mechanisms, whose combined effects resulted in a frequency-independent q within the absorption band. Minster and Anderson (1981) applied insights from solid state physics to suggest that, for dissipation dominated by dislocation creep, $\alpha>0$ within the absorption band. Building on this work, Anderson and Given (1982) developed an absorption band model of the Earth in which the effects of pressure and temperature on the underlying relaxation mechanisms caused the frequency bounds of the band to change with depth.

Despite observational and experimental advances, no clear consensus concerning the value of mantle α has emerged over the past 25 years. Nevertheless, theoretical predictions of $\alpha>0$ have been systematically confirmed in various laboratory studies. In their review paper, Karato and Spetzler (1990) argued that its value lies between 0.2 and 0.4. A more recent review by Romanowicz and Mitchell (2007) identifies a number of studies that collectively constrain α to the 0.1–0.4 range. On the laboratory front, Jackson et al., (2005) obtained α of 0.28 ± 0.01 for a fine-grained olivine sample at a pressure of 300 MPa and temperature of 1200 °C. Relating laboratory measurements to α in the real mantle, however, is not straightforward, due to uncertainties in extrapolating laboratory measurements to actual mantle materials under high-pressure and high-temperature conditions prevailing in the mantle.

On the other hand, seismological efforts at constraining globally-averaged α within the absorption band have benefited from numerous measurements of surface wave or normal mode attenuation. Yet, although attenuation measurements of nearly 250 individual modes are currently available from the website of the Reference Earth Model project (http://mahi.ucsd.edu/Gabi/rem.html, see Fig. 1), the determination of α has been confounded by the fact that oscillations at different frequencies can have very different depth sensitivities to elastic and anelastic properties of the Earth. As a result of this tradeoff between frequency and depth effects, radial variations of attenuation can obscure the α signal. The only studies attempting to obtain α within the absorption band have found α ranging from 0.1 to 0.3 while emphasizing the lack of resolution on the inferred values (Anderson and Minster, 1979; Anderson and Given, 1982; Smith and Dahlen, 1981). More recent studies (e.g. Shito et al., 2004; Cheng and Kennett, 2002; Flanagan and Wiens, 1998) have relied upon analysis of body waves to argue for values of α in the 0.1–0.4 range. However, these studies were restricted to frequencies higher than 40 mHz and were of regional character, leaving unanswered the question of the average mantle α.

A further complication in determining the frequency dependence of attenuation from seismic data arises from the discrepancy between attenuation measurements of spheroidal modes carried out using a propagating (surface) wave and those using a standing wave (normal mode) approach. As can be seen in Fig. 1, surface wave studies indicate attenuation values that are higher by about 15–20% than normal mode measurements of the same frequency. This discrepancy is not present in the toroidal modes. The origin of the discrepancy has not yet been determined. Durek and Ekström (1997) argued that noise can bias normal mode measurements toward lower attenuation values by up to 5–10%, Masters and Laske (1997) pointed to difficulties in choosing an appropriate time window for long-period surface waves as a reason for favoring normal mode measurements. A more recent study by Roult and Clévédé (2000) based on a detailed analysis of measurement techniques and associated errors argues that the normal mode measurements are the more reliable. Yet, their analysis is far from being complete (Romanowicz and Mitchell, 2007), and the question of which set of measurements is more representative of the Earth's attenuation remains open. The compilation of attenuation measurements used in this study (Masters, personal communication) relies on careful windowing and a multi-taper approach in order to achieve a smooth transition from the normal mode values at lower frequencies to surface wave values at higher frequencies (see Fig. 1).

In light of the data uncertainties and the strong tradeoff between the depth- and frequency dependence of attenuation, seismic studies routinely focus on modeling the depth dependence of attenuation

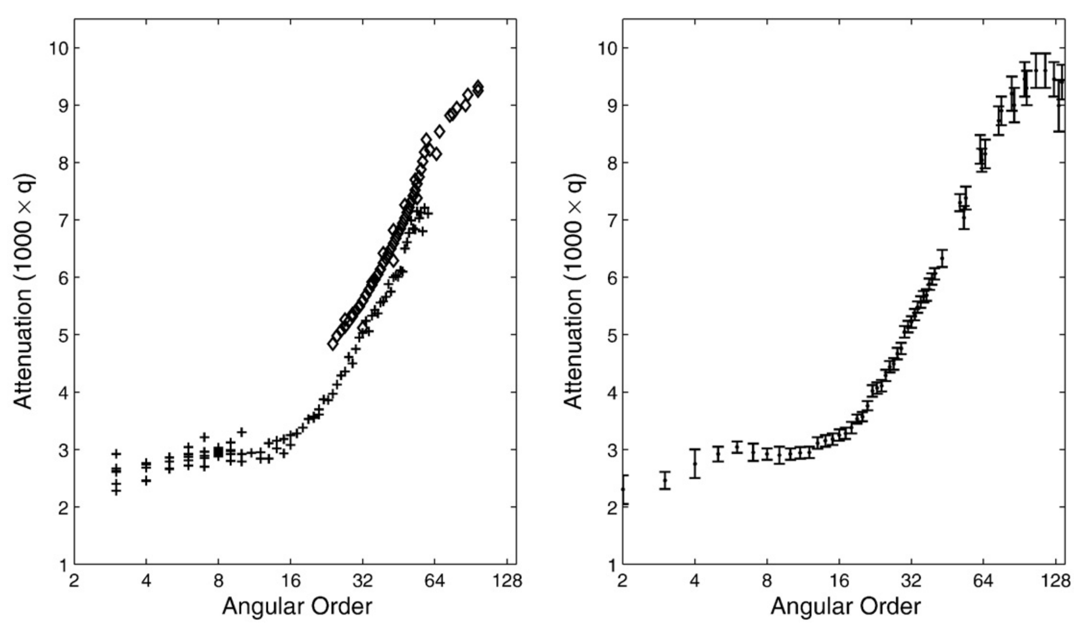

Fig. 1. Left: Attenuation measurements for the spheroidal fundamental mode branch (compilation from http://mahi.ucsd.edu/Gabi/rem.html). Measurements based on normal mode analysis (plusses) show attenuation values 15–20% smaller than corresponding surface wave-based measurements (circles). Right: The data compilation used in this study (Masters, *personal communication*) transitions smoothly from values more consistent with normal mode analyses at low frequencies to values consistent with surface wave analyses at higher frequencies.