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Seismic wave attenuation in the lithosphere of the North Tanzanian divergence zone (*East African rift system*)

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Abstract

The seismic effective quality factor (Q_C) and its frequently dependences or the frequency parameter (n) and attenuation coefficient (δ) for the Earth's crust and upper mantle of the North Tanzanian divergence zone (East African rift system) were estimated from an analysis of the earthquake coda waves recorded in the SEISMO-TANZ'07 French-Tanzanian seismic experiment. The Q_C values increase and the n and δ values decrease with increasing frequency and length of the lapse time window. This behavior of the attenuation parameters may be evidence that the degree of heterogeneity of the lithosphere decreases with depth. Comparison of the depth variations in the attenuation coefficient δ and the frequency parameter n with the velocity structure of the region shows that there is a distinct change in the behavior of seismic wave attenuation at velocity discontinuities. The obtained attenuation parameters were compared with the same parameters obtained in our previous studies for other continental rift systems—the Baikal rift system (Eurasia) and the Basin and Range Province (North America).

Keywords: seismic quality factor; attenuation; coda; North Tanzanian divergence; East African rift system

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Introduction

The scattering and absorption of seismic waves are fundamental properties of the lithosphere which depend on a combination of many parameters such as the mechanical fragmentation of the medium, the degree of tectonic activity, fluid content, heat flow, etc. The decrease in the amplitude (or energy) of seismic waves propagating in the earth due to geometrical spreading, scattering by heterogeneities, heat dissipation, etc. is called attenuation (Aki and Chouet, 1975). The attenuation of seismic energy in the earth is described using the dimensionless parameter—the seismic quality factor Q and its frequency dependences or the frequency parameter (n) and the attenuation coefficient (δ). In practice, knowledge of seismic wave attenuation parameters is necessary for seismic and microseismic zoning, calculating synthetic seismograms, studying macroseismic manifestations of strong earthquakes, etc. A number of methods for determining the quality factor of a medium based on active seismic experiments (sounding using explosions, vibration sources, etc.) and passive seismic experiments (processing of earthquake records, microseisms) have been developed, in which the seismic quality factor can be estimated from the direct waves (P and S waves) and from coda waves. Both approaches have advantages and disadvantages, but the latter is preferred in most cases.

This paper presents estimates of seismic wave attenuation from the coda of short-period shear (S) waves in the lithosphere of the North Tanzanian divergence zone. For the southern part of the East African Rift System (which includes the North-Tanzanian divergence zone), the quality factor was previously estimated in the KRSP85, 90, and 94 seismological experiments in 1985, 1990 and 1994, where the effective quality factor ($Q^C L_g$) was evaluated by analysis of Love surface wave coda (Mitchell, 1995; Romanowicz and Mitchell,

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2007) and estimates were obtained for two attenuation components—intrinsic attenuation and scattering attenuation (Jemberie and Nyblade, 2009). The use of different approaches for different regions in estimating the attenuation precludes valid comparisons. Therefore, the objective of the present study is to obtain information on the seismic wave attenuation parameters in the lithosphere and upper mantle of the North Tanzanian divergence zone from *S*-wave coda using the single backscattering model for subsequent comparison with the same parameters of other rift systems of the world.

Study area

The East African rift system (EARS) is the largest continental rift of the Earth. It is confined to the borders of the Arabian, Nubian, and Somali lithospheric plates and extends about 6000 kilometers from northern Ethiopia to central Mozambique (Fig. 1). The oldest Ethiopian rift formed in the Afar region. Further to the south is a series of rifts surrounding the Tanzanian craton in the west (western branch) and in the east (eastern branch). The Tanzanian rift is located at the southern end of the eastern branch of the EARS. At a latitude of ~2.5°, the single axis of the rift branches into several deformation zones with different strikes to form the North Tanzanian divergence zone (Fig. 1) (Dawson, 1992).

Unlike the western branch, the eastern branch of the EARS is characterized by active modern volcanism (Fig. 2) (Mulwa, 2011). In the study region (4.25°–2.5° S and 34.5°–37.5° E, Fig. 1) three areas can be identified: (1) the Magadi–Natron rift system in the north, which is a roughly NS-trending narrow basin with a width of 50 to 70 km, to which numerous centers of volcanic activity are adjacent (Fig. 2, inset (Mulwa, 2011)); (2), the EW-trending Ngorongoro–Kilimanjaro volcanic belt with dimensions of 200×50 km in the central part; and (3) the North Tanzanian divergence zone formed by the Eyasi, Manyara, and Pangani fault systems in the southern part (Fig. 1) (Le Gall et al., 2008). The volcanism activity sharply decreases to the south of the volcanic belt.

Both tectonic and volcanic earthquakes contribute to the high seismic activity in the region (Mulwa et al., 2014) (Fig. 2). The crust beneath rift basins is slightly thinned and reaches 35 km in the south of Kenya (Magadi–Natron basin) (Birt et al., 1997) and 37 km in the north of Tanzania (Last et al., 1997), and the lithosphere under the North Tanzanian divergence zone is thermally modified (Huerta et al., 2009; Ritsema et al., 1998; Weeraratne et al., 2003). Seismic tomography data (two-plane wave tomography) do not confirm the presence of an anomalous mantle layer beneath the crust of the Tanzanian craton (O'Donnell et al., 2013), in contrast to the northern part of the EARS (Puzyrev, 1981). The crust in the North Tanzanian divergence zone is characterized by low surface heat flow (Nyblade et al., 1990).

Data

The attenuation parameters were evaluated using data obtained in the SEISMO-TANZ'07 joint Franco-Tanzanian seismic experiment (Albaric et al., 2009). The experiment took place from June 01 to November 20, 2007 in North Tanzania, where a network of 35 three-component seismic stations operated at the southern end of the eastern branch of the EARS (Table 1, Fig. 3). The sampling rate was 125 Hz at all stations, except at the MOSH station located near the Kilimanjaro volcano (here the sampling frequency was 62.5 Hz, due to the high noise level).

The seismic wave attenuation parameters were evaluated from the foreshocks and aftershocks of the Gelai earthquake (July 17, 2007, $M_W = 5.9$) which occurred in the volcanic area of the Natron basin in the period from early June to late July, 2007 (Fig. 3). A total of 50 earthquakes with magnitudes $M_C = 2.9$–4.7 were used, with the epicentral distance varying from 47 to 205 km. The depths of earthquake hypocenters are estimated at 3.3–16.7 km, with most of the events confined to depths of 5 to 10 km (Albaric et al., 2009).

Methods and data processing

The calculation of Q_C and the interpretation of the results were carried out according to the single-backscattering model (Aki and Chouet, 1975). This model treats a coda wave as a superposition of body waves reflected from heterogeneities randomly distributed in the Earth's crust. The decrease in the coda amplitude with time is due to the energy attenuation and geometrical spreading and does not depend on the characteristics of the earthquake source, distance, and details of wave path to the seismic station (Aki, 1969).

For a seismogram filtered at central frequency *f*, the coda amplitude A_C at time *t* from the origin time is related to the quality factor by the following formula (Aki and Chouet, 1975):

$$A_C(f, t) = S(f) \cdot t^{-\gamma} \cdot \exp\left[\frac{-\pi f t}{Q_C(f)}\right]. \tag{1}$$

Here *S(f)* is the time function of the source and γ is a geometrical spreading characteristic; γ is 1.0, 0.5, and 0.75 for body, surface, and diffuse waves, respectively, according to (Sato and Fehler, 1998). For the events considered, *S*-wave coda are analyzed, so that the parameter γ is 1. Taking the logarithm of (1), we obtain.

$$\ln\left(A_C(f, t) \cdot t^{\gamma}\right) = \ln\left(S(f)\right) - \frac{-\pi f t}{Q_C(f)}. \tag{2}$$

The slope of the curve of $\ln(A_C(f, t) \cdot t^{\gamma})$ versus time *t* determines the value of Q_C for the considered frequency *f*. According to Rautian and Khalturin (1978), the above relations are valid for times greater than twice the *S*-wave travel time (Fig. 4), i.e., the source process can be neglected for these times.