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14. ABSTRACT The crust of southern Eurasia is characterized by low Q values (200-450) for 1-Hz *Lg* coda everywhere from Spain to China. The north-south extent of that low-Q zone varies from being relatively narrow in western Europe to being very broad from the Middle East to China. Those variations in both magnitude and width first became apparent with the development of continent-wide tomographic maps of *Lg* coda Q. The most recent mappings of *Lg* coda Q values at 1 Hz (Q_o), completed over the past year, show that the four regions of lowest Q_o values occur in regions marked by high levels of seismicity. Q_o in stable regions of Eurasia varies between about 450 and 900 with the highest values occurring in the Indian shield, the East European Craton, the Siberian Craton and the Khazakh Platform. The maps reveal relatively, and unexpectedly, low values of Q_o in the Siberian Trap region of Siberia. Variations in the mapped values of the frequency dependence of *Lg* coda Q at 1 Hz (η) show no systematic relationships to variations of Q_o in either southern or northern Eurasia.

Plots of point-spreading functions—measures of how well features can be resolved—reveal that features with dimensions as small as 800 to 1000 km can be resolved. The standard error for Q_o throughout a large portion of Eurasia is 50 or smaller and between 50 and 100 in most other regions. An exception to these small errors occurs in a region that extends southwestward from Lake Baykal where they are as large as 200. The Baykal values probably reflect complexities in the deep crust of that region. Standard errors for the frequency dependence of Q also show anomalously high values to the southwest of Lake Baykal.

Using values of Q_o and η obtained for *Lg* coda and assuming that η is the same for all frequencies, we have estimated Rayleigh-wave attenuation coefficient (γ_R) values for all of Eurasia at periods of 5, 10, 20 and 50 s. In our studies of Rayleigh-wave attenuation and its regional variation for various periods across Eurasia, we have assumed that the values of Q_o and η obtained from *Lg* coda can be used to infer values of shear-wave Q (Q_μ) and its frequency dependence (ζ). In that process we assume Q_o to be equivalent to an average value for shear-wave Q in each 3° x 3° cell of Eurasia and that the frequency dependence of shear-wave Q can be obtained using an empirically-derived multiplicative factor. We have tested this assumption for several crustal shear-wave Q models, one for the Arabian Peninsula, one for the Turkish/Iranian Plateaus and seven for China where both shear-wave Q models and *Lg* coda Q information are available. We find that the relations $Q_\mu = Q_o^C$ at all depths and $\zeta = 0.8\eta$ for the depth range 0-40 km and $\zeta = 0.5\eta$ for depths greater than 40 km provide realistic estimates for γ_R in the period range 5 – 70 s. We find that 5-s Rayleigh waves vary between 0.5×10^{-3} and 5.0×10^{-3} km^{-1}, 10-s waves vary between 0.2 and 2.2×10^{-3} km^{-1}, 20-s waves vary between 0.1 and 1.1×10^{-3} km^{-1} and 50-s waves vary between 0.06 and 0.3×10^{-3} km^{-1}. Sediments play a large role in attenuating 5-s and 10-s Rayleigh waves in some regions but have a much smaller effect for 20-s and especially 50-s waves.

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CONTINENT-WIDE MAPS OF 5-50 S RAYLEIGH-WAVE ATTENUATION FOR EURASIA INFERRED FROM MAPS OF 1-HZ LG CODA Q AND ITS FREQUENCY DEPENDENCE

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Sponsored by Air Force Research Laboratory

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ABSTRACT

The crust of southern Eurasia is characterized by low Q values (200-450) for 1-Hz *Lg* coda everywhere from Spain to China. The north-south extent of that low-Q zone varies from being relatively narrow in western Europe to being very broad from the Middle East to China. Those variations in both magnitude and width first became apparent with the development of continent-wide tomographic maps of *Lg* coda Q. The most recent mappings of *Lg* coda Q values at 1 Hz (Q_o), completed over the past year, show that the four regions of lowest Q_o values occur in regions marked by high levels of seismicity. Q_o in stable regions of Eurasia varies between about 450 and 900 with the highest values occurring in the Indian shield, the East European Craton, the Siberian Craton and the Khazakh Platform. The maps reveal relatively, and unexpectedly, low values of Q_o in the Siberian Trap region of Siberia. Variations in the mapped values of the frequency dependence of *Lg* coda Q at 1 Hz (η) show no systematic relationships to variations of Q_o in either southern or northern Eurasia.

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Using values of Q_o and η obtained for *Lg* coda and assuming that η is the same for all frequencies, we have estimated Rayleigh-wave attenuation coefficient (γ_R) values for all of Eurasia at periods of 5, 10, 20 and 50 s. In our studies of Rayleigh-wave attenuation and its regional variation for various periods across Eurasia, we have assumed that the values of Q_o and η obtained from *Lg* coda can be used to infer values of shear-wave Q (Q_μ) and its frequency dependence (ζ). In that process we assume Q_o to be equivalent to an average value for shear-wave Q in each 3° x 3° cell of Eurasia and that the frequency dependence of shear-wave Q can be obtained using an empirically-derived multiplicative factor. We have tested this assumption for several crustal shear-wave Q models, one for the Arabian Peninsula, one for the Turkish/Iranian Plateaus and seven for China where both shear-wave Q models and *Lg* coda Q information are available. We find that the relations $Q_\mu = Q_o{}^C$ at all depths and $\zeta = 0.8\eta$ for the depth range 0-40 km and $\zeta = 0.5\eta$ for depths greater than 40 km provide realistic estimates for γ_R in the period range 5 – 70 s. We find that 5-s Rayleigh waves vary between 0.5 x 10^{-3} and 5.0 x 10^{-3} km^{-1}, 10-s waves vary between 0.2 and 2.2 x 10^{-3} km^{-1}, 20-s waves vary between 0.1 and 1.1 x 10^{-3} km^{-1} and 50-s waves vary between 0.06 and 0.3 x 10^{-3} km^{-1}. Sediments play a large role in attenuating 5-s and 10-s Rayleigh waves in some regions but have a much smaller effect for 20-s and especially 50-s waves.

OBJECTIVES

Seismic Q is an important parameter that affects how rapidly various seismic waves attenuate with distance as they travel through the Earth. Its value can vary both spatially and with frequency. The overall purpose of our research is to better understand details of those variations throughout southern Asia and how they might affect our ability to detect waves generated by small seismic events, to estimate magnitudes and yields of those events, and to determine if they are explosions or earthquakes. To improve understanding in those areas we have focused on two specific objectives. Our first objective has been to expand and improve previously published maps of regional variations of *Lg* coda Q across Eurasia with emphasis on regions where path coverage was too sparse to obtain reliable and high-resolution results. Our second objective has been to use those new maps of *Lg* coda Q and its frequency dependence at 1 Hz (Q_o and η, respectively) to develop maps of Rayleigh-wave attenuation coefficients for various periods (5–50 s) throughout southern Asia.

RESEARCH ACCOMPLISHED

Lg Coda Q Variation

We presented new maps of Q_o and η, values of *Lg* coda Q and its frequency dependence at 1 Hz, for all of Eurasia in our paper for last year's Seismic Research Review meeting (Cong and Mitchell, 2005). Both last year's study and this one use the method developed by Xie and Mitchell (1990) to obtain tomographic maps of Q_o and η. Details about our methodology can be obtained from that paper. In this paper we again present maps of Q_o and η . This repetition of the process will allow comparison of our new maps of Rayleigh-wave attenuation variation for Eurasia with the Q_o. Also, our Q_o and η maps have been slightly revised because of a bug discovered in a new code that we used to determine *Lg* coda Q from individual records.

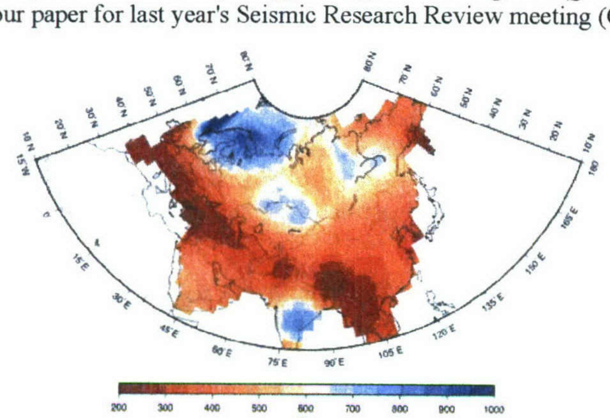

Figure 1. *Lg* coda *Q* at 1 Hz (Q_o) for

Figures 1 and 2 present continent-wide maps of Q_o and η for virtually all of Eurasia. They were constructed using 1383 determinations of those quantities from individual seismic records for paths confined to the Eurasian continent, compared with 440 determinations used by Mitchell et al., 1997 in an earlier study. Data coverage was best in regions where seismicity rates are highest; i.e., in the southern and eastern portions of the continent. The coverage was, however, more than adequate throughout the entire continent.

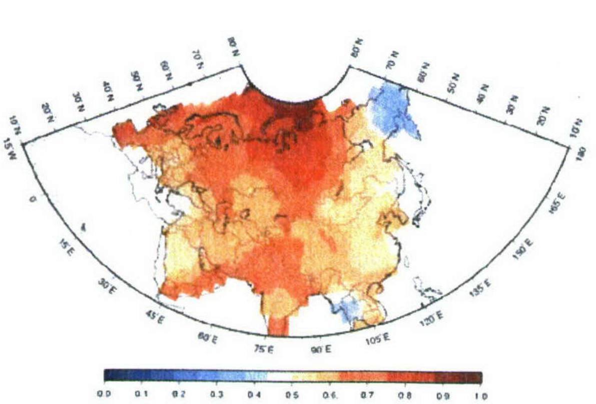

Figure 2. Frequency dependence of *Lg* coda *Q* at 1 Hz (η) for Eurasia.

Figure 1 indicates that, with the exception of the Indian platform, Q_o is generally higher in northern than in southern Eurasia. But even in northern Eurasia unexpectedly low values occur. The most conspicuous of these is in central Siberia where low Q_o values coincide with the most recent mapping of the Siberian Traps (Reichow et al., 2002). The lowest values for Q_o lie in the four regions where seismicity rates are highest. These are the Kamchatka Peninsula in northeastern Asia, the southeastern portion of the Tibetan Plateau, the Hindu Kush region slightly north of India, and western Turkey. The low Q_o in the southeastern Tibetan Plateau extends further to southeast and covers a broad region of enhanced seismicity. The Arabian Peninsula, even though it is a stable platform over its entire area and contains a shield in the western part of the peninsula, is marked by Q_o values that are lower than most other stable platforms.

The map of η variation in Figure 2 shows no clear relationship to Q_o variation. Low η correlates with low Q_o in Kamchatka in northeastern Siberia, high η correlates with low Q_o in Spain and the variation of the large low-η region in the north-central part of the map appears to be independent of Q_o variation in that region. This differs from some other continents we have studied, such as Africa and South America, where high Q_o values are associated with low η values and low Q_o values with low η values.

Cong and Mitchell (2005) computed point-spreading functions and measures of resolution, at six positions in Eurasia. They showed that our ability to resolve features in the crust was about the same everywhere in the continent and indicated that we could resolve features with dimensions between about 800 km and 1000 km. That paper also showed that the standard error in Q_o determinations was less than 50 in most places and between 50 and 100 in most of the other regions of Eurasia. A region to the southwest of Lake Baikal exhibited a standard error greater than 200. Since data coverage in that region was good, we interpret the high standard error to be due to a severe lateral variation in crustal properties in that region. Those determinations appear in Figure 3. Standard errors for the frequency dependence of Lg coda Q at 1 Hz (not shown) are less than 0.1 in most places and between 0.1 and 0.2 in most of the rest of Eurasia. Like Q_o, it is higher to the southwest of Lake Baikal.

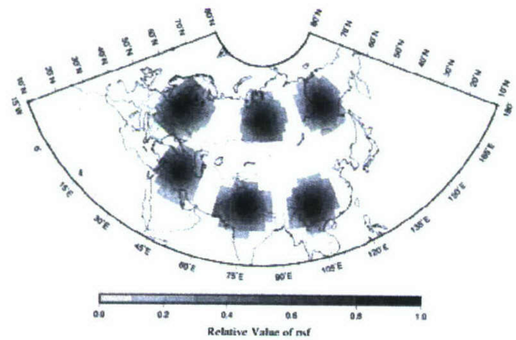

Figure 3. Point spreading function (psf) plots for six selected cells.

Continent-Wide Estimates of Rayleigh-Wave Attenuation Coefficients (γ_R) for Eurasia

Cong and Mitchell (2005) presented estimates of Rayleigh-wave attenuation coefficients for southern Asia for periods of 10, 20, and 50 s. In this paper we extend those determinations to include all of Eurasia and also add determinations for all of Eurasia at a period of 5 s. In those determinations, we use equations developed by Anderson et al. (1965) to estimate Rayleigh-wave attenuation coefficients from Lg coda Q. Lg coda Q can be expressed by the equation

$$Q^c_{Lg} = Q_o f^{\eta} \qquad (1)$$

where Q_o is Lg coda Q at 1 Hz and η is the frequency dependence of Q at 1 Hz. At least two studies (Herrmann and Kijko, 1983; Campillo et al., 1985) have found that Q_o in the above equation is a good approximation of the average value of shear-wave Q (Q_μ) in the crust. An expression for shear-wave is

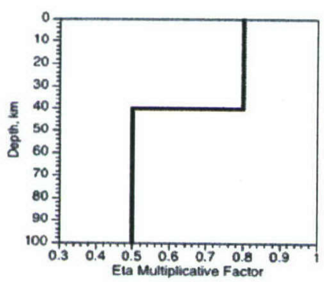

Figure 4. Factor by which Q_o must be multiplied to obtain a good empirical fit

$$Q_\mu = Q_o f^{\zeta} \qquad (2)$$

where ζ is the frequency dependence for Q_μ. We take Q_μ in this expression to approximate Q_o. We had initially thought we could let ζ approximate η but found that we could not duplicate measured values of Rayleigh-wave attenuation by doing that. We then, by trial and error, empirically obtained a depth-dependent factor that, when multiplied by η, provided a good fit between γ_R predicted by Lg coda Q and observed γ_R curves. That factor is 0.8 for the upper 40 km in the Earth and 0.5 at greater depths.

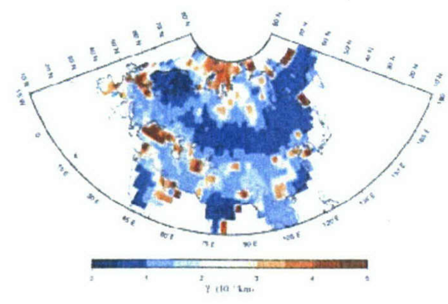

Figure 5. γ_R at a period of 5 s.

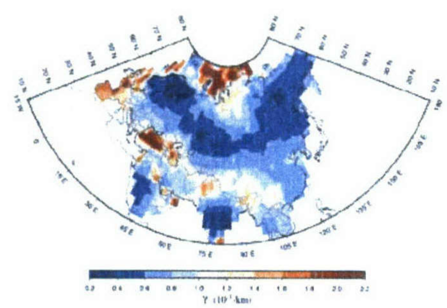

Figure 6. γ_R at a period of 10s.

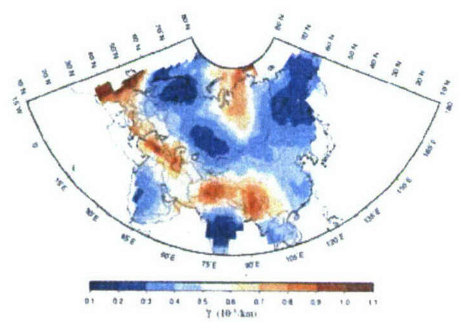

Figure 7. γ_R at a period of 20 s.

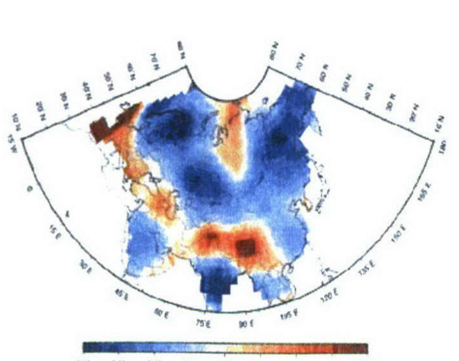

Figure 8. γ_R at a period of 50 s.

Equation 3 shows the equation of Anderson et al. (1965) as modified by Mitchell and Xie (1993) to take into consideration depth-variable frequency dependence of Q.

$$\gamma_R = \frac{\pi}{C_R^2 T} \sum_{l=1}^{N} \left[\left(\beta_l \frac{\partial C_R}{\partial \beta_l} \right)_{\omega\rho\alpha} + \frac{1}{2} \left(\alpha_l \frac{\partial C_R}{\partial \alpha_l} \right)_{\omega\rho\beta} \right] Q_{\mu l}^{-1} \tag{3}$$

In this expression, C_R refers to Rayleigh-wave phase velocity, T to period, β_l to shear-wave velocity in layer l, α_l to compressional-wave velocity in layer l and $Q_{\mu l}$ to shear-wave Q in layer l. The subscripts to the right of the partial derivatives refer to quantities held constant during the differentiation. ρ in those subscripts refers to density. The Rayleigh-wave phase velocities and the partial derivatives in equation 3 were computed for every 3° x 3° cell in our Q_o map using many shear-wave velocity models for Eurasia provided by M. Ritzwoller and A. Levshin.

We have tested the utility of our conversion for several crustal shear-wave Q models, one for the Arabian Peninsula, one for the Turkish/Iranian Plateaus, and seven for China where both shear-wave Q models and *Lg* coda Q information are available. As indicated above we find that the relations $Q_\mu = Q_o^{\,C}$ at all depths and $\zeta = 0.8\eta$ for the depth range 0-40 km and $\zeta = 0.5\eta$ for depths greater than 40 km provide realistic estimates for γ_R in the period range 5–70 s. We find that 5-s Rayleigh waves vary between 1.5 x 10^{-3} and 5.0 x 10^{-3} km^{-1}, 10-s waves vary between 0.2 and 2.2 x 10^{-3} km^{-1}, 20-s waves vary between 0.1 and 1.1 x 10^{-3} km^{-1},and 50-s waves vary between 0.06 and 0.3 x 10^{-3} km^{-1}. Sediments play a large role in attenuating 5-s and 10-s Rayleigh waves but are less important for 20-s and, especially, 50-s waves.

At both 5-and 10-s periods there are several regions where attenuation is quite high. Some of these, such as the Barents north of the continent and the Black Sea region are obviously associated with thick accumulations of sediments. There are also several smaller regions with high attenuation rates. We checked the velocity models for several of these regions and found that all of them were also marked by thick accumulations of low-velocity sediments. As periods increase, the smaller regions with high attenuation disappear and the Q variations are broader with fewer small-scale features. This is due to the smaller sensitivity of the longer wavelength waves to detail and to the fact that those waves are less sensitive to near-surface features.

At 50-s periods, the Rayleigh-wave attenuation coefficient map resembles the 1-Hz Lg coda Q map. This is probably because the *Lg* coda samples the entire crust and is not, like 5- and 10-s Rayleigh waves, dominated by the upper crust.

Similar to the Q_o map for Lg coda, the 50-s Rayleigh-wave attenuation map shows regions of low-attenuation (or high Q) in the three stable regions of northern Eurasia, as well as the Indian platform. It also shows low attenuation for most of the Arabian Peninsula and southeastern-most Asia in contrast to the relatively high attenuation (or low Q) exhibited by the Q_o map. This occurs because the frequency dependence parameters (η) in Figure 2 are relatively low in both of those regions.

CONCLUSIONS AND RECOMMENDATIONS

New maps of *Lg* coda Q at 1 Hz (Q_o and η) have been used, along with regionalized seismic velocity models, to develop continent-wide maps of Rayleigh-wave attenuation coefficients at periods of 5, 10, 20, and 50 s. The Lg coda Q maps were found to resolve features between about 800 km and 1000 km in dimension and to have relatively low standard deviations everywhere but a region southwest of Lake Baikal. The Rayleigh-wave attenuation coefficient maps were determined, based upon published work, assuming that Q_o in each $3^\circ \times 3^\circ$ cell of Eurasia represents an average value for the shear-wave Q (Q_μ) there and that the frequency dependence of Q_μ can be obtained from an empirically determined depth-dependent multiplicative factor. That factor is 0.8 at depths between 0 and 40 km and 0.5 at greater depths. It was tested for paths in China, the Arabian Peninsula, and the Iran/Turkey Plateaus and was found to be satisfactory in all cases but those where the Q_o or η may not be well determined. We find that 5-s Rayleigh waves vary across Eurasia from 0.5×10^{-3} and 5.0×10^{-3} km^{-1}, 10-s waves vary from about 0.2 tp 2.2×10^{-3} km^{-1}, 20-s waves vary from about 0.1 to 1.1×10^{-3} km^{-1},and 50-s waves vary from about 0.06 to 0.3×10^{-3} km^{-1}. Sediments play a large role in attenuating 5-s and 10-s Rayleigh waves in some regions but have a much smaller effect for 20-s and especially 50-s waves.

The validity of our empirical relation for obtaining shear-wave Q frequency dependence used in computing Rayleigh-wave attenuation coefficients is, so far, based only upon Rayleigh-wave attenuation information in tectonically active regions. For that reason, we recommend obtaining Rayleigh-wave attenuation measurements for regions in northern Eurasia that are relatively stable. Also, our determinations assume that the ratio of compressional-wave Q to shear-wave Q is equal to 2 in crystalline rock beneath sediments. Recent work suggests that that ratio is closer to 1, at least in tectonically active regions. We recommend conducting combined determinations of compressional-wave Q and shear-wave Q in a variety of tectonic regimes to obtain values for that ratio in the crust.

ACKNOWLEDGMENTS

We thank Jack Xie for making his code for tomographic mapping of Q_o and η available to us. The maps in this paper were prepared using GMT version 3.0 developed by Paul Wessel and H. F. Smith.

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