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HIGH-RESOLUTION SEISMIC VELOCITY AND ATTENUATION MODELS OF THE CAUCASUS-CASPIAN REGION

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ABSTRACT

The Caucasus-Caspian region is part of the Alpine-Himalayan collision belt and is an area of complex structure accompanied by large variations in seismic wave velocities. Using data from 29 new broadband seismic stations in the region as well as data from a temporary (1999-2001) deployment in eastern Turkey, a unified velocity structure is developed using teleseismic receiver functions and surface waves. . Crustal thickness in the Kura Basin and at the edge of the Caspian is less well constrained due to pronounced multiples associated with thick sedimentary layers but the preferred results suggest a Moho depth of 38 to 48 km and lower crustal velocities (Vs=3.1 km/s). Joint inversion of surface wave dispersion curves generated from ambient noise with receiver functions show that crustal thickness varies from 34 to 52 km in the region. The thickest crust is in Lesser Caucasus and the thinnest is in the Arabian Plate. Thin crust is also observed near the Caspian. The lithospheric mantle in the Greater Caucasus and the Kura depression is faster than the Anatolian Plateau and Lesser Caucasus. This possibly indicates the presence of cold lithosphere. The lower crust is slowest in the northeastern part of the Anatolian Plateau where Holocene volcanoes are located. The fundamental mode Rayleigh wave phase velocities is determined at periods between 20 and 145 seconds. We observe a relatively high velocity zone located in the upper mantle under the Kura basin and the western part of Caspian Sea that is continuous to the Moho. Also our images show very low velocities beneath the eastern Anatolian plateau implying the existence of a partially molten asthenospheric material underlying a very thin lithosphere. Using a two-station method, efficient Lg propagation is observed throughout much of the Arabian plate. Moderate Lg Q is observed in the Lesser Caucasus and Kura Basin while low Lg Q is observed in the East Anatolian plateau. Pg shows highly variable propagation throughout the region.

OBJECTIVES

The objectives of the research is to develop 3D seismic velocity structure and regional phase attenuation for the Caucasus-Caspian region, which is roughly defined as lying between 40 and 55 E longitude and between 37 and 44 N latitude (Figure 1). Specifically, the purpose of this work was to:

- Create upper mantle/crustal velocity models using data from new stations in the region.
- Construct detailed maps of regional phase attenuation.
- Compare and validate results and models using the various algorithms as well as independent datasets

The work consisted of four main tasks: data collection, regional phase analysis, crustal and upper mantle velocity determination, and model validation.

RESEARCH ACCOMPLISHED

Data collection. Waveform data was collected from 33 stations (Figure 1) in the region as part of collaborative effort with the individual seismic surveys. The primary focus was collecting continuous data from 2006-2008, although waveform data from other years was collected as available. All data has been provided to the Knowledge Base at LLNL.

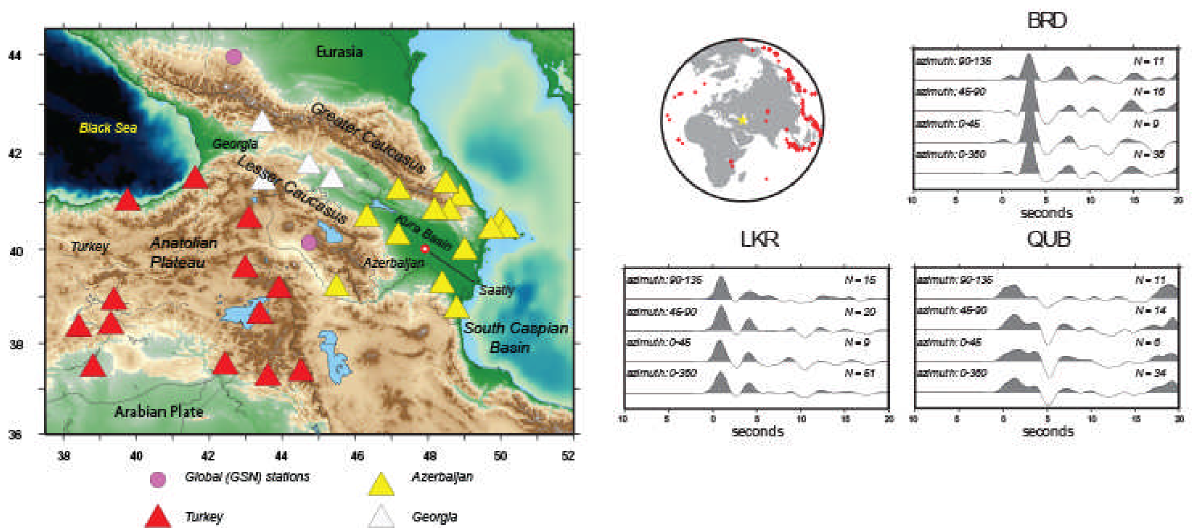

Figure 1. (left) Area of study showing broadband stations. Broad-band stations include STS-2, ESP3T, ESP3ESD and CMG40T type instruments.(right) Example receiver functions stacked by back-azimuth for selected Azerbaijan stations. Global map shows recorded events (red dots) and location of stations (yellow star). Small red circle shows position of Saatly 8 km deep well used for model validation.

Surface wave group velocity and receiver function joint inversion. To develop a comprehensive model of crustal and upper mantle velocities, joint inversion of receiver functions and surface waves was applied. Crustal receiver functions are sensitive to velocity discontinuities while surface wave dispersion is controlled by average S-wave velocity structure (e.g. Julia et al., 2000). Therefore, combining the two methods yields a robust estimate of crustal and upper mantle velocities. Receiver functions using events at distances between 30 and 90 degrees were calculated for all stations using iterative deconvolution at Gaussian width of 1.0, 1.5 and 2.5. Each receiver function (Figure 2) was examined for coherency of signals with excessive amplitudes on the tangential component or grossly different from the stacked average for each station was discarded. Coverage was best for back-azimuths to the east and sparse to the west. Initially, the receiver functions were modeled independently to investigate quality. In general, the stations near the Caspian show poor quality receiver functions with indications of considerable crustal scattering and reverberations due to the thick sediments. These were difficult to model. Some indications of 3D structure were observed for station in the Greater Caucasus as the receiver functions showed clear variations with back azimuth.

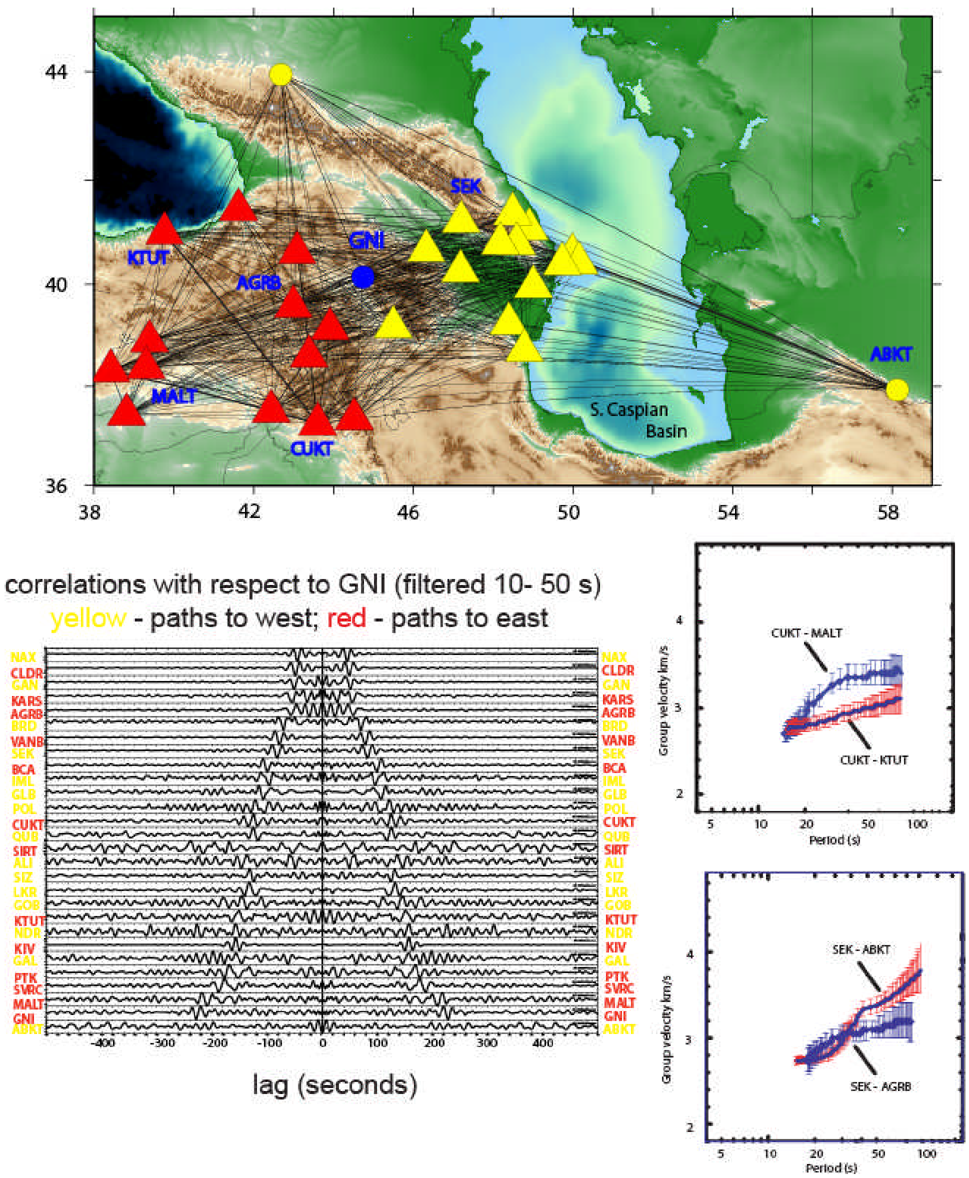

Figure 2. (top) Ray paths used in ambient noise surface wave correlation. (bottom, left) Correlations of stations with respect to station GNI. Stations marked in red show ray paths from west and stations in yellow are east of GNI. (bottom, right) Dispersion curves for stations pairs located in the Anatolia plateau and across the South Caspian.

Surface wave group velocity dispersion measurements were made using both event-based and ambient noise correlation methods. Love and Rayleigh wave group velocity dispersion curves were estimated for over 1500 waveforms at periods of 7-100 sec. Ambient noise correlation was applied to all possible station pairs (~400) to obtain Rayleigh wave group velocities. All dispersion curves were picked manually and then included in the global/regional tomographic inversion of *Pasyanos et al*. (2005). We then extracted the dispersion curves from the tomography maps of surface waves and combined them with stacked receiver functions.

Horizontal depth slices of 11, 35 and 87 km are shown in Figures 2 as well as an estimated Moho thickness map. The thick sediments of Kura Basin are evident in upper crust with low velocities averaging Vs=2.8 km/s. The eastern part of the Greater Caucasus shows similar low velocities in the upper crust. The slowest lower crustal velocities are observed in the northeastern Anatolian plateau and Lesser Caucasus region where considerable Neogene/Quaternary, Holocene volcanic activity has occurred (Figure 2B, 35 km depth). Faster lower crustal

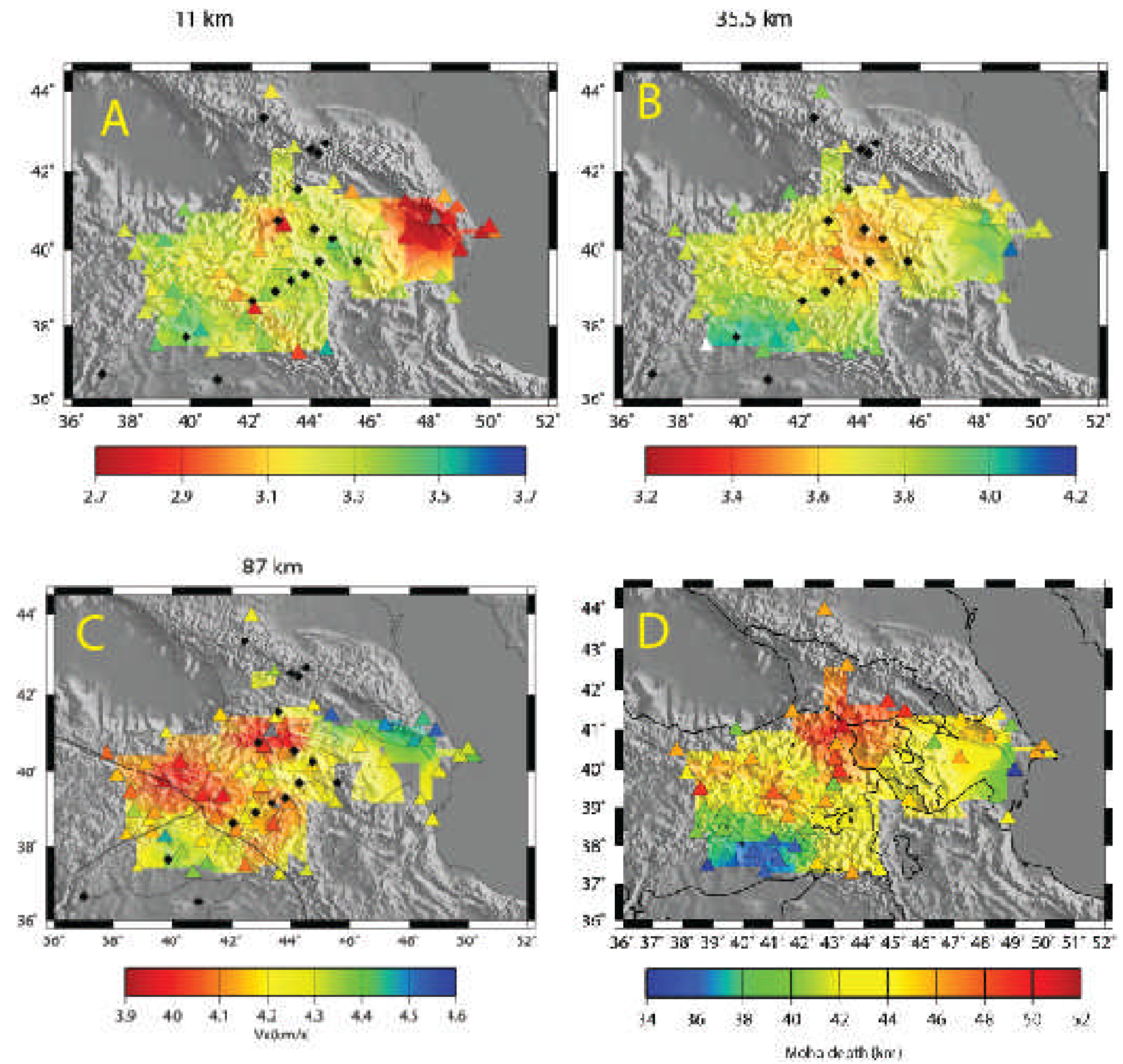

Figure 3. A, B) Crustal S velocities estimated from joint inversion at depths of 11 (left) and 35.5 km (right). C) Upper mantle S velocities at a depth of 87 km. D) Moho depth inferred from velocity profiles based from joint inversion. Black diamonds are Holocene volcanoes.

velocities occur at the edge of the Caspian and in the Arabian plate. The upper mantle appears distinctly slow under the Anatolian plateau and to the southeast. Indications of faster upper mantle velocities occur under the Greater Caucasus. It was noted that inversion for Love and Rayleigh waves provided differing results, possible due to anisotropy.

Surface wave phase velocity inversion. To investigate variations in upper mantle velocities, surface wave phase velocities measured from earthquake were also inverted, as earthquake produce high signal to noise ratios especially at longer wavelengths than is possible with ambient noise measurements. Data from an earlier temporary deployment of 29 stations was used as well as the newer data. Teleseismic earthquakes with a magnitude greater than 5.8 were selected and the waveforms were evaluated for high signal to noise at the longer periods (50 and 125 seconds). Unfortunately, many of the Azerbaijan stations showed high noise levels at the longer periods even on the vertical component, possibly due to barometric variations. This restricted the data set to 20 events. The data for each event were filtered to create 13 frequency bands with corresponding centered periods ranging from 20 to 145 seconds and dispersion curves were estimated from these results. Initially, the Rayleigh wave phase dispersion was inverted to estimate 1D velocities. The results were topographically inverted for 2D structure on a 50 km grid using two methods: *Forsyth et al*. (1998) and *Yang and Forsyth* (2006). The two methods are similar but the *Tang and Forsyth* technique attempts to compensate for scattering caused by local heterogeneities and therefore should improve spatial resolution. The results at shorter wavelengths were more robust than for the longer wavelengths especially for the area covered by the Azeri stations, possibly due to excessive noise at longer wavelengths. Higher upper mantle velocities were observed under Anatolia and lower velocities under the Caucasus/Caspian.

Regional phase analysis. The purpose of the regional phase analysis was to map attenuation of *Pg* and *Lg* throughout Anatolia and the Caucasus (Figure 4). The mapping was performed by first measuring attenuation between stations and then inverting to solve for the average Q in discrete spatial cells. The direct two-station method was used (e.g. *Zor et al*., 2007; *Xie et al*., 2004) to estimate attenuation. This method relies on spectral ratios between pairs of station aligned with the ray paths from each event. Phases were identified manually to avoid problems caused by variations in crustal velocities. Spectra for each phase were estimated after windowing. Station pairs for each event were selected using a criteria based on inter-station distance and alignment with event (±15°). The spectral ratio between two stations was calculated for appropriate station pairs after correction for distance (*Xie et al*., 2004) and geometrical spreading. Q and η (frequency dependence) were then estimated from the spectral ratios using linear regression. This Q and η represents the attenuation along a line between the two stations. These attenuation measurements were added to an existing Middle East dataset which was inverted to create a regional map (Figure 3 and 4). The dataset includes approximately 3000 station pairs. Separate inversions were conducted for both *Lg* and *Pg*. Checkerboard tests were performed to evaluate resolution and both ART and LSQR algorithms were tested to evaluate the effect of possible numerical artifacts. Results were similar for both algorithms. Raypath coverage is good in eastern Anatolia but is sparser towards the Caucasus and Caspian.

The 1 Hz *Lg* results show a broad zone of high attenuation (low Q) extending roughly east-west north of the Arabian plate from Anatolia to the Caspian. Considerable spatial variation exists which likely reflects the complicated tectonics. *Lg* appears to propagate well in the Arabian plate but is dramatically attenuated in the Lesser Caucasus. This may be due to the volcanism and the possibility of partial melt in the crust. The Kura basin and the extreme eastern Caucasus show moderate to low attenuation, which may reflect the influence of the Eurasia plate. It is clear from these results that the Kura basin is underlain by continental crust and is distinct from the South Caspian. The variations in *Lg* attenuation appear to result from a combination of both crustal heterogeneity and changes in crustal thickness. While Moho depth increases by 5 to 10 km at the northern edge of the Arabian Plate the variation in depth from Anatolia to the Lesser Caucasus is fairly small and yet relatively low *Lg* Q is observed. Volcanic regions are often observed to possess low Lg Q possibly due to high attenuation of shear waves by partial melt in the crust. *Pg*

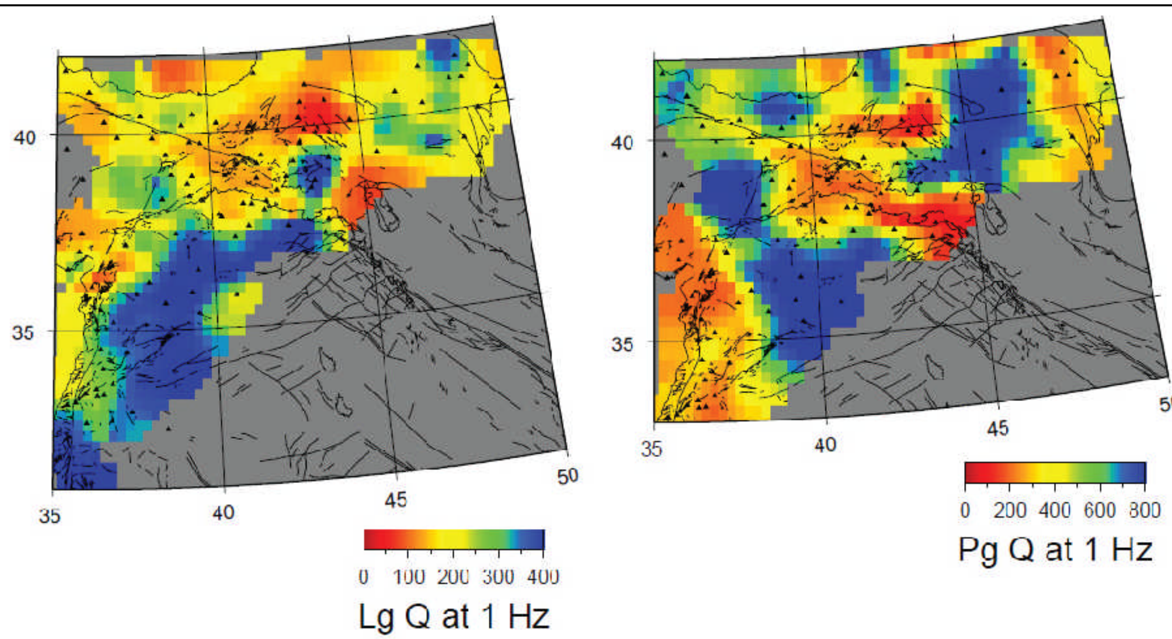

Figure 4. Attenuation maps for *Lg* (left) and *Pg* (right).

reveals a distinctly different pattern. The transition between the Arabian plate and Anatolian plateau is defined by an abrupt change in *Pg* Q east of about 38 E longitude but a clear zone of high Q exists in the Lesser Caucasus. The zone of low Q along the Caspian and Kura basin may be caused by the abrupt thickening in sediments and dipping Moho, which decreases the efficiency of the crustal *P* waveguide.

Model validation. The model was tested in several ways: comparison with alternate datasets such as reflection seismic and gravity, earthquake hypocenters comparison, and with waveform modeling. Seismic reflection data shows clearly the deep sedimentary layers in the South Caspian and coastline. Gravity data also suggests deep basement, which closely matches the low velocities for the area observed by the joint inversion. The Moho depths inferred by refraction data are also similar. 2D modeling of gravity data through the center of the Kura depression shows a clear gravity high that runs roughly north-south and parallel to the Caspian coast and delineates the Kura from the South Caspian. The existence of this raised basement is confirmed by the Saatly well, which penetrated to a depth of 9 km through a succession of sediment and then volcanoclastic layers. To first order, alternate datasets are consistent with our results, both for crustal and mantle velocities and with phase propagation.

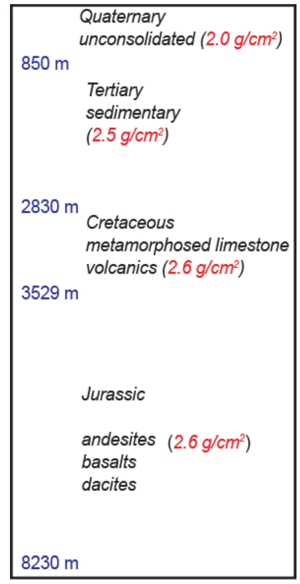

Figure 5. Lithologic profile from the Saatly deep well with densities.

A second set of tests was conducted with earthquake locations and limited waveform modeling. This effort was focused in the Azerbaijan region. The 3D model was averaged to produce an average 1d model. Hypocenter locations were calculated using this model and with global (IASP91) model. Waveforms for events with known focal mechanisms were also calculated using this model.

CONCLUSIONS AND RECOMMENDATIONS

An improved crustal and upper mantle velocity and attenuation model has been developed for the Caucasus/Caspian region and Anatolian plateau. The Caspian and Kura basin show pronounced low velocities in the upper crust but slightly elevated lower crustal velocities. Crustal thickness varies from about 50 km in the Lesser Caucasus to 35 km in the Arabian plate. Upper mantle is slow under the Anatolian plateau and slightly fast under the Greater Caucasus.

Striking variations in regional phase propagation and velocities are mapped. Lg is highly attenuated not only in the South Caspian and Black Sea basins but also in the Anatolian plateau, possibly due to a combination of crustal properties under the volcanic areas and varying crustal thickness. A narrow band of moderate *Lg* attenuation exists in the Kura basin and along the Caspian.

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