Spatial Heterogeneity of Stress and Attenuation Aata Revealing the Complex Seismotectonic Nature of the Central Alborz

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Abstract:

The Alborz is one of the most seismically active seismotectonic provinces in Iran. Furthermore, the existence of Tehran in this range intensifies the seismic hazard in it. In this study, a new method is introduced for stress mapping. The SHmax values in the Alborz region extracted from earthquake focal mechanism data are mapped by using this new approach. The attenuation of coda waves, Q_c, is also estimated in this region, using a single back-scattering model of S-coda envelopes. The results show substantial variation in SHmax directions, which reflects the complicated tectonic nature of the region. The average Q_c values estimated and their frequency-dependent relationships also correlate well with a highly heterogeneous and highly tectonically active region. From the stress studies point of view, in the central Alborz, more small-area and localized anomalies in maximum horizontal stress direction are observed, emphasizing the heterogeneity of the stress field. Q_c results also show that the attenuation is higher in the central region of Alborz compared to other areas. Thus, both approaches confirm the high seismotectonic complexity in the central Alborz which necessitates more studies in this region for seismic hazard and risk mitigation purposes.

Keywords: Attenuation, Coda wave, Earthquake, Focal mechanism, Heterogeneity, Stress.

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1 Introduction

Iran has suffered many devastating earthquakes, with many casualties and enormous damages. Meanwhile, advances in civil, mining, and petroleum engineering over the past century have led to the development of stress measurement technologies. Attenuation quantifies the behavior of the seismic energy propagation in the lithosphere and can be utilized for seismic hazard mitigation.In geosciences, it is essential to learn about the stress field to understand folded structures' development and the motion on faults that cause earthquakes. Seismic waves have produced an enormous amount of information about the Earth's interior. The real Earth is not perfectly elastic, and propagating waves attenuate with time due to various energy-loss mechanisms. Observations of coda waves have shown that there are heterogeneities which have random sizes and contrasts of physical properties, scattered randomly throughout the Earth's lithosphere. Number of factors cause the attenuation of seismic waves, including geometrical spreading, scattering and intrinsic absorption due to heterogeneities in the medium (Aki et al , 1975). These heterogeneities are mainly due to tectonic processes such as folding, faulting, large-scale crustal movements associated with plate tectonics, the irregular subsurface geometry of faults and results in velocity perturbations caused by changes in rock type and cracks (Sato and Fehler , 1998; Mahood , 2014).

In the following sections, we will review the Alborz zone's tectonic setting to emphasize the stress studies' importance in this Seismo-structurally complicated zone. Then we will go through the seismicity and earthquakes in the region and extract stress information from single focal mechanism data. Simultaneously, the attenuation study is performed in the region. Finally, the results are interpreted according to the geology of the area and new findings of this research are discussed.

2 Tectonic Setting of the Study Area

During the convergence between the Arabian plate and Eurasia, the relative north-northeast movement of the Arabian plate relative to Eurasia from west to east changes from 18 to 25 mm per year, and the pole of this rotation is in North Africa (Vernant et al , 2004; Masson , 2005; Raeesi , 2016). Knowing about stress variations in the Alborz zone, northwest Iran, is necessary to study the deformation resulting from the oblique collision between the Eurasian and the Arabian plates and gain insight into the complicated tectonics of this very important region (Fig. 1). The formation of the Alborz Mountains happened during the collision of Central Iran with Eurasia in the Late Triassic and the collision of Arabia with Eurasia (Berberian and King , 1981; Alavi , 1996; Zanchi et al , 2006). The Alborz basement is covered by Mesozoic and Cenozoic sediments while Including Paleozoic deposits. The volcanic activity took place during the Cenozoic, from Late Cretaceous to the quaternary (Alavi , 1996). Two motions with different velocities control tectonic activity in this range, the 5 mm/year northward convergence of central Iran toward Eurasia causing compression from 7 Ma and the 4 mm/year left-lateral shear north-westward motion of the South Caspian Basin resulting in a left-lateral transpressive tectonic environment in the Alborz (Ritz , 2006; Vernant et al , 2004). Since middle Pleistocene transtensional motion is dominating the region because of acceleration of SCB motion toward North West (Ritz , 2006; Masson at al , 2006), some studies indicate a transpressive tectonic environment in the borders of the Alborz range, while transtension is evidenced within the field (Ritz , 2006). The seismicity rate of the area is high both from historical and instrumental earthquakes catalogs (e.g., Engdahl et al. 1998). The focal mechanism solutions of the earthquakes from the GCMT (Ekström et al , 2012), teleseismic waveform modeling (Jackson et al , 2002), and local seismic networks (Tatar et al , 2007, 2012) indicate a left-lateral strike-slip motion and thrust faulting in the Alborz mountains. The study area contains many active faults, mainly parallel to the Alborz belt, form V shape like pattern with WNWESE, and NEWSW strikes in western and eastern parts of the Central Alborz. North Alborz and Khazar's south-dipping thrust faults are the main active thrust structures bounding the belt to the North. North Tehran, Garmsar, and Parchin north-dipping thrust faults limit the range to the South. The Taleghan, Mosha, and Firouzkouh faults localize the left-lateral strike-slip motion within the mountain range. (Berberian , 1983; Ritz , 2006; Berberian and Yeats , 2001).

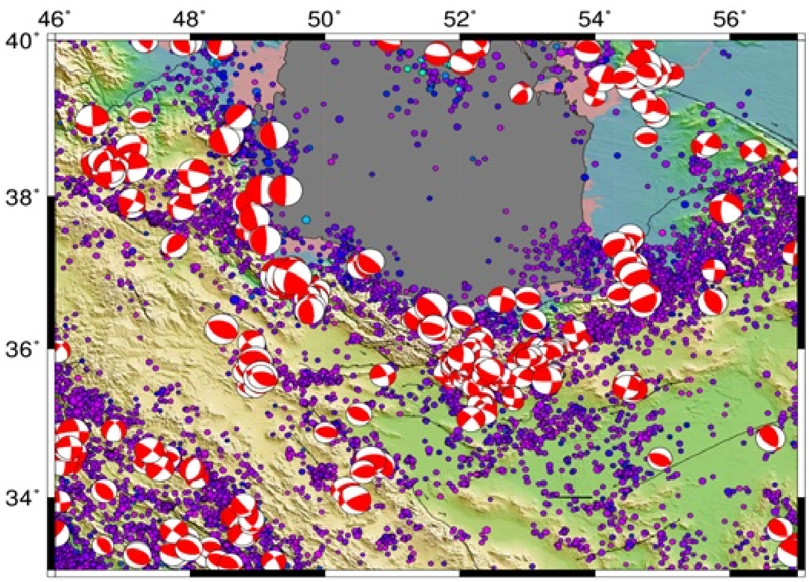

Figure 1: Map of the study area, including the focal mechanisms used in this study taken from various references described in the text in addition to active faults overlaid on topography. The small colored circles show the seismicity from 1960 to 2020 from IRSC concerning the events' depth.

3 SHmax Estimation

The color circle method is implemented for stress data available in the study area. The color pallet values are assigned to each cell, and interpolation is used, and Fig. 2 is obtained by applying the technique. In other words, for the stress or SHmax directions obtained by processing the single earthquake focal mechanism data, we use the proposed color circle. This figure contains some unseen anomalies in the stress directions and provides the first real color scaled stress map in the study area. There exist some anomalies in SHmax directions in several places that need careful examination to declare its relevance to the geology and tectonics of the study area, which is beyond the scope of this study. In Fig 2, the cyan bars show the Maximum Horizontal Stress directions from single focal mechanisms, with the small white circles showing the earthquakes' location.

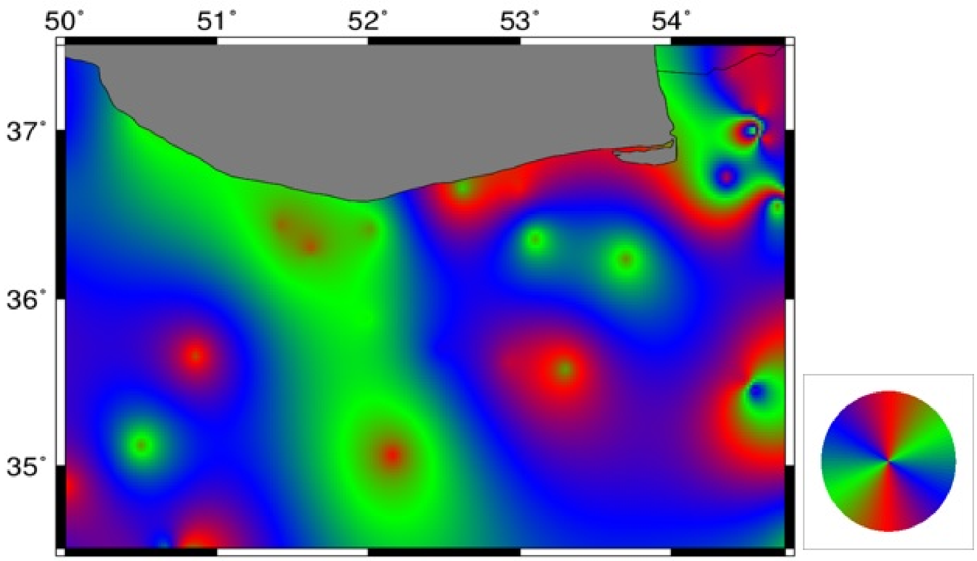

Figure 2: Stress direction mapping with the proposed circular color scale below.

4 Coda-Q Estimation

The single backscattering model, proposed by Aki et al (1975), is often used for describing the behavior of the coda waves from local earthquakes. According to this model the coda waves are interpreted as backscattered body waves generated by randomly distributed heterogeneities in the earths crust and upper mantle. The coda amplitudes, $A(f,t)$, in a seismogram can be expressed for a central frequency (f) over a narrow band width signal, as a function of the lapse time (t), measured from the origin time of the seismic event, as

$$A(f,t) = S(f)t^{-\alpha} \exp\left(-\frac{\pi f t}{Q_c(f)}\right) \tag{4.1}$$

where, $S(f)$ is the source function at frequency f. It has been observed that the coda spectrum of small earthquakes at local distances is independent of earthquake size, epicentral distance and the path between station and epicenter but it depends on lapse time from the origin time of the earthquake (Aki et al , 1975). This suggests that the coda part of the seismogram is due to an average scattering effect of the medium in the region near the source and station (Kumar et al , 2005). α is the geometrical spreading factor and it is considered as 1 for body waves, and Q_c represents the quality factor of coda waves. Equation (1) can be written as

$$\ln[A(f,t)t] = c - bt \tag{4.2}$$

where, b and c are equal to $-\pi f/Q_c$ and $\ln[S(f)]$, respectively. Because the source factor can be treated as a constant for a single frequency, according to equation (2) the slope of the straight line fitting the measured $\ln[A(f,t)t]$ versus t yields to a Q_c value for a specific frequency. Equation (2) holds, empirically, for $t > 2t_S$, where t_S is the S-wave travel time. Q_c manifests a dependence on frequency that follows the law

$$Q_c(f) = Q_0 f^n \tag{4.3}$$

where, Q_O is the value of Q_c at 1 Hz and n is a numerical constant (Singh and Herrmann, 1983). Figure (2) shows Lateral Q_O changes in the study region. Lines with the same value represent the areas with the highest path of seismic waves. The greater the number of wave paths, the higher the accuracy of the calculations. Lateral Q_O changes show much N-S direction heterogeneity in the region. Attenuation also depends on the depth and lateral heterogeneity.

Attenuation variations in the earth are usually greater than the velocity variations. Del Pezzo (2008) mentioned that differences in the attenuation patterns of high and low frequencies can be explained in terms of scale length of heterogeneities; therefore, a high value of n can be related to the heterogeneity of media. Our results also indicate the Alborz region is a tectonically active heterogeneous media. A low value of Q_o ($Q_0 < 200$) is associated with the tectonically and seismically active regions, whereas a high value of Q_o ($Q_0 > 600$) is characteristic of seismically inactive and stable regions. The average Q_c values, estimated for central and eastern Alborz and their frequency-dependent relationships show that the medium is tectonically active and highly heterogeneous. The

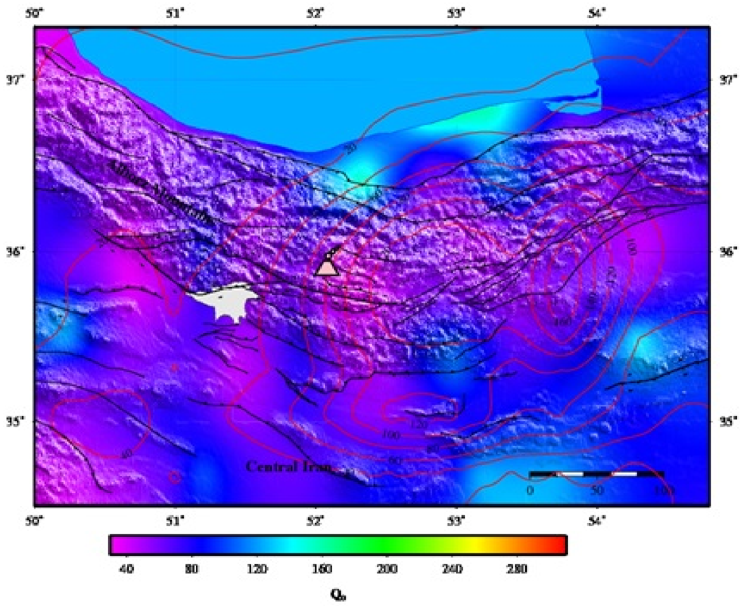

Figure 3: Lateral Q_O changes in the study area.

single scattering model has been used to estimate Q_c in different regions such as: Yunnan China ($Q_c = 49f^{0.95}$, Li et al (2004), Zagros Iran ($Q_c = 99f^{0.84}$, Rahimi and Hamzehloo (2008), NW Himalayan region (Q_c = 158 f 1.05, Kumar et al (2005)), Eastern-Iran ($Q_c = 108f^{0.96}$, Mahood (2014)). The larger values of Q_O of more than 600 have been observed for inactive or stable regions such as Central USA ($Q_c = 1000f^{0.2}$, Singh and Herrmann, (1983). The average Q_c values, estimated for the Alborz, and their frequency dependent relationships shows that the medium is highly heterogeneous and highly tectonically active.

5 Conclusion

In the present study, the compressional stress directions from single earthquake focal mechanisms are mapped. The original and unseen anomalies in stress directions in the Alborz region are observed for the first time. The final stress map correlated well with the structural geology of the study area. The comparison between compressional stress directions and Lateral Q_O changes shows N-S direction heterogeneity in the region. The low Q_O value may be related to the relatively highly dissipative layer beneath the lithosphere at a shallow lithosphereasthenosphere boundary. This might be also the reason underneath the observed stress direction anomaly.

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