ANNALS OF GEOPHYSICS, 67, 1, GD103, 2024; doi: 10.4401/ag-9002
OPEN ACCESS

Crustal Attenuation Tomographic Image of Northern Morocco: Indication of High Tectonic Activities

Abdelkarim Najim[1], Mohamed El Hilali[*,1], Youssef Timoulali[1], Lahcen El Moudnib[1]

[(1)] Scientific Institute, Mohammed V University in Rabat, Morocco

Article history: received. July 25, 2023; accepted January 9, 2024

Abstract

Northern Morocco is known by its complex tectonic activity and has been the subject of various geophysical and geodynamic studies aimed to understand the physical properties and composition of the Earth's crust and upper mantle. The waveforms of earthquakes recorded by the Topo – Iberia – Picasso seismic networks from 2008 to 2012 are analyzed to determine the decay properties of the coda wave and map the attenuation and absorption properties of the crust in this region. The coda quality factor Q_c was estimated in five non-overlapping frequency windows, ranging from 1.5 to 24 Hz, using recordings of local earthquakes. The measurements of Q_c were then used to create maps of the absorption quality factor (Qi) using a linearized approximation. These maps were compared with the tectonic settings of the region to gain further insight into the crustal properties. Lateral and vertical variations of the coda quality factor (Q_c) were investigated by creating a three-dimensional tomographic image of the region. The results showed strong lateral variations of absorption in the northern part of Morocco, indicating high tectonic activity. Areas with high tectonic activity and high absorption were characterized by low values of Q_c, while areas with low tectonic activity and low absorption had high values of Q_c. The areas with thick cover sedimentary materials and shallow geothermal activity showed low-frequency absorption. When compared to previous studies in northern Morocco, the study provides new information about the three-dimensional attenuation model of the Earth's crust.

Keywords: Seismic attenuation; Coda waves; Earthquake; Tectonic activity; Northern Morocco

1. Introduction

The North of Morocco is considered as a complex tectonic region due to its geological and geodynamic complexity with several geological structures. The Betic-Rif Cordillera which the north Morocco is one part, is located in the area of interaction of several tectonic plates including the African, Eurasian, and Iberian plates [Civiero et al., 2020; Diaz et al., 2021]. Their collision and movement over millions of years has led to the formation of various geological features and earthquakes. The geophysical studies and geodynamic modeling focused on the lithosphere and uppermost Mantle, shown that the physical properties and composition of the crust and upper mantle beneath the

Betic-Rif Cordillera vary significantly across the region [Pasquale et al., 1996; Custodio et al., 2019; Gea et al., 2023]. The crust and upper mantle in the region are composed of different types of rocks, which have different densities, magnetic properties, and seismic wave velocities. The study of the physical properties and composition of the crust and upper mantle in northern Morocco provides important information about the region's tectonic evolution and the mechanisms that drive plate tectonics and earthquakes.

Such studies have been conducted to investigate the local crustal structure and better understand the geological and tectonic processes that have shaped the region [Gil et al., 2014; Mancilla and Diaz, 2015; Timoulali et al., 2014a, 2022]. These studies use various geophysical techniques, such as seismic reflection and refraction, seismic/electrical tomography, magnetic surveys, and stations measurements to map the subsurface structure as well as the basins geometry [for Deep Seismic Sounding in the Alboran Sea 1974, 1978; Gurrria and Mezcua, 2000; Timoulali et al., 2014; 2022; El Fellah et al., 2019; EL Hilali et al., 2021; 2023; Taj et al., 2024]. The crust thickness beneath the Betic Cordillera in Southern Spain is estimated to be around 35-38 km. This thickness is derived from a deep seismic sounding in the Alboran Sea [Banda and Ansorge, 1980]. The crust in the Betic Cordillera is thicker than the average crust thickness, which is around 25-30 km, due to the collision of the African and Eurasian tectonic plates. The crust thins progressively towards the Est of Iberian Massif (near 30 km). The crustal thickness beneath the Alboran Sea is estimated to be around 10- to 20-km. The crust is thin in the Alboran sea compared to the thicker crust in surrounding areas, such as the Betic Cordillera in Southern Spain and the Rif Mountains in North Morocco (25 to 35 km) [Gil et al., 2014]. The gravimetric studies have confirmed the presence of anomalous crustal thickness in the Betic-Rif Cordillera and confirmed that the crust in the Betic-Rif Cordillera is thicker than the average crust thickness. The maximum thickness beneath the peak of gravity anomaly is about 40 km [Baratin et al., 2016].

The crustal seismicity in the Rif and Betic regions is scattered and not confined to a specific area. The distribution of earthquakes reflects the complex tectonic history of the region, including the collision and movement of the African, Eurasian, and Iberian plates, as well as the presence of several fault systems [Jiménez-Munt et al., 2019; Civiero et al., 2020]. The intermediate-depth earthquakes are generally concentrated along an N-S trending line at 4.5°W also in the central part of the Alboran Sea. This line represents a zone of active deformation and tectonic stress, which is related to the collision of the Iberian and African plates. The concentration of intermediate-depth earthquakes along this line reflects the presence of a tectonic stress in the mantle. Seismic studies have used measurements of P and S wave velocities to determine the physical properties of the crust and mantle beneath the Rif and Betic regions. The speed at which these waves travel through the subsurface rocks can provide information about the rock properties, including density, elasticity, and temperature [Calvert et al., 2000]. These studies have identified an anomalous mantle below the Betic-Rif Cordillera and Alboran Sea, which is characterized by unusual seismic velocity and temperature structures compared to surrounding regions.

Seismic attenuation refers to the reduction of seismic wave energy as it propagates through the Earth's crust. It is a complex process that is influenced by several factors, including the frequency and wavelength of the seismic wave, the density and elasticity of the crustal materials, and the presence of cracks and other inhomogeneities in the crust. The measurement of seismic attenuation can provide important information about the structure and composition of the Earth's crust. By analyzing the decay of the coda wave energy over time, the amount of energy lost, or attenuated, by the subsurface materials can be estimated. The attenuation of seismic waves is quantified through the measured of quality factor Q, which denotes the fractional energy loss per cycle of the wave. One approach to estimate coda-Q (Q_c) involves analyzing the decay rate of coda waves, which is scattered by randomly distributed heterogeneities within the medium [Sivaram and Gupta, 2022; Demirci and Bekler, 2023]. Q_c serves as a parameter that summarize the comprehensive attenuation characteristics of the Earth's crust, encompassing both intrinsic or inelastic absorption and scattering attenuation resulting from random heterogeneities in the medium [Zhou et al., 2021; Karakostas et al., 2021].

However, the mains challenges, which are faced in northern Morocco, include complex lithospheric aspect, frequency-dependent attenuation, filtering data and its need for comprehensive seismic data. These challenges are commonly encountered in crustal attenuation studies in various regions with complex geological features and heterogeneous crustal properties. Despite this, local earthquakes events recorded by 45 broad-band seismic stations from the Topo-Iberia, Picasso broad-band seismic network located in northern Morocco are used to address these difficulties. The fundamental goals of this study are:

1) Analyzing the decay properties of the coda wave and the absorption properties of crust. By analyzing the decay properties of the coda wave and the absorption properties of the crust, valuable information about the physical

properties of the subsurface rocks can be provided and used to improve our understanding of the Earth's subsurface structure and behavior, as well as to assess the potential seismic risk in the region.

2) Creating a detailed map of spatial variations of seismic attenuation properties in North of Morocco. The mapping of spatial variations of seismic attenuation properties allow to identify areas of the subsurface with unusual seismic properties, such as high or low seismic energy absorption, which can indicate the presence of geological structures, such as faults or mineral deposits, or anomalies in the subsurface temperature or fluid conditions. The spatial variations of seismic attenuation properties can affect the seismic wave propagation and the amount of energy that is absorbed or dissipated by the subsurface rocks. This can result in significant differences in the seismic hazard between different areas, even within the same region [Pasyanos, 2015].

The quality factor (Q) can be estimated using the coda wave method. In this method, the late-time part of the seismic waveform, known as the "coda," is analyzed to determine the rate of energy decay. The Q value is then calculated based on the decay rate, frequency of the wave, and the damping coefficient [e.g. Aki and Chouet, 1975; Sato, 1977]. The parameter Q_c represents the total attenuation, or energy loss, of seismic waves as they propagate through the Earth. A high Q_c value indicates low attenuation, meaning that the seismic waves maintain a significant portion of their energy as they propagate through the Earth, while a low Q_c value indicates high attenuation and significant energy loss. The values of Q_c vary with frequency. In general, Q_c decreases with increasing frequency because the higher frequency waves are more affected by the subsurface heterogeneities, such as variations in density and other physical properties, which cause them to scatter and lose energy. These heterogeneities cause the seismic wave to spread out and lose energy, leading to a reduction in wave amplitude. Also, referred to as scattering attenuation, is an important component of the overall seismic wave attenuation in the Earth [Lee, 1999].

Several studies have been conducted using the coda waves of local earthquakes to determine the rate of energy decay and the seismic attenuation. This energy decay rate is then used to estimate the total seismic wave attenuation in the Earth, represented by the parameter Q [Aki and Chouet, 1975; Gupta et al., 1996; Sato et al., 2012; Boulanouar et al., 2018; Arab et al., 2020]. Consequently, the lapse-time dependence of Q_c is attributed to the combined effects of multiple scattering and depth. Multiple scattering occurs when the seismic wave encounters multiple subsurface heterogeneities, causing it to scatter and lose energy. As the seismic wave travels deeper into the Earth, it encounters more heterogeneities and experiences more scattering, leading to a decrease in Q_c with time [Masahiro, 1992].

Absorption and scattering processes affect ground motion and they can have a significant impact on seismic hazard estimates; absorption refers to a reduction in the amplitude of ground motion. Scattering or the deflection of seismic waves by heterogeneities in the subsurface can cause changes in wave direction and increase ground motion.

2. Geological setting

The Rif Mountains, located in the North Morocco, have been interpreted as a result of collisional orogeny between the African and Eurasian tectonic plates. The Rif chain forms the southern branch of the Betic-Rif arcuate orocline, curved mountain range that extends across southern Spain and northern Morocco (Fig. 1). The structural framework of Morocco is characterized by a transition from the African tectonic domain in the southern part of the country to the Alpine folded structures in the Atlas and Rif domains [Durand-Delga, 1960; Michard, 1976].

The African domain is characterized by large, stable cratonic blocks with relatively low levels of deformation and tectonic activity, while the Atlas and Rif domains are characterized by complex, folded mountain ranges that have formed as a result of intense tectonic activity. The convergence between Africa and Eurasia began in the Cretaceous period. During this time, the initial direction of convergence is northeasterly to southwesterly direction. However, during the Late Miocene time the direction of convergence shifted a northwest to southeast direction [Dewey et al., 1989].

The Rif Basin was formed as a result of extensional tectonics in northern Morocco during the Late Oligocene to Early Miocene time period [Durand-Delga, 1960; Lonergan and White, 1997; Chalouan et al., 2008a]. This tectonic activity caused the crust to stretch and thin, creating a large sediment-filled basin [Jolivet and Faccenna, 2000]. The exhumation process caused the rocks to be exposed at the Earth's surface, leading to the formation of topographic features such as mountains and valleys [Platt et al., 1998; Zeck, 1999]. The Rif orogenic systems have three principal tectonic zones: (1) the internal zones; (2) the flysch nappes; and (3) the external zones [Gomez et al., 2000]. The

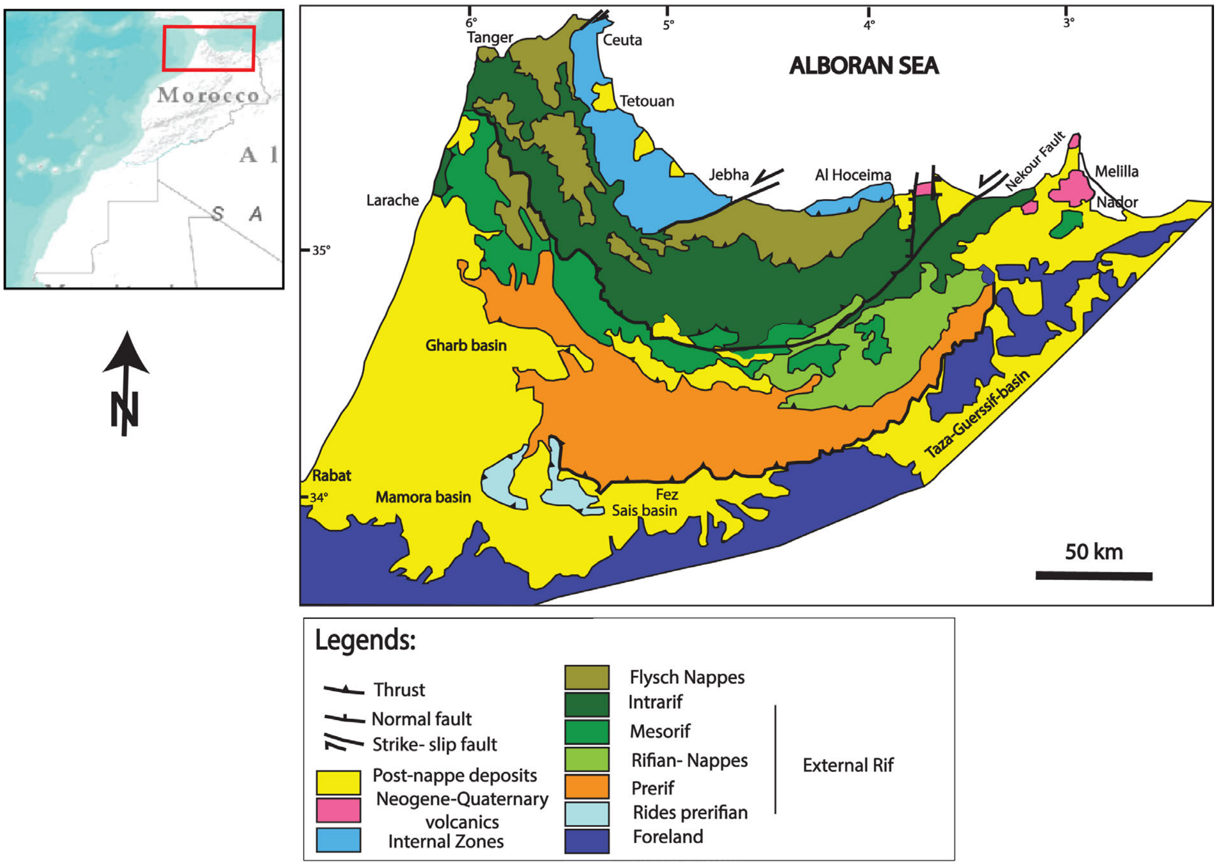

Figure 1. Geological map of Rif region [Suter 1980, modified].

internal zones are located in the central part of the Rif orogenic system and consist of metamorphic and plutonic rocks. These rocks have been formed as a result of high-pressure, low-temperature metamorphism [Jolivet et al., 2003; Chalouan et al., 2001, 2008b]. The flysch nappes are a sequence of sedimentary rocks that have been thrust over the internal zones as a result of tectonic activity. The external zones are located along the margins of the Rif orogenic system and consist of sedimentary and volcanic rocks.

The detection of heterogeneous upper crust, with resistive (metamorphic rocks) and conductive bodies composed of peridotites by A NW-SE oriented magneto-telluric profile across the Rif [Anahnah et al., 2011], provides important information about the subsurface geology of the region. These structures are located in the uppermost 10 km of internal Zone. A highly conductive body is also detected in the External Zones and foreland basin. The combination of resistive and conductive bodies in the upper crust of the Rif suggests a complex geological history, with different rock types having been brought to the surface through tectonic processes such as uplift and exhumation.

The crustal seismicity is scattered in the West Alboran especially under the Rif and the Betic is associated with the Alpine collisional tectonic event (Fig. 2). The earthquakes in this region are a result of the collision and convergence of the African and Eurasian tectonic plates, which is causing the uplift and formation of the Alpine mountain range [Van Hinsbergen et al., 2009]. The scattered distribution of earthquakes in the West Alboran region is likely due to the complex interplay of geological and geophysical factors, including faulting, rock strength, and fluid migration. The geophysical data, including gravity, elevation, heat flow and seismic data can provide information about the Moho discontinuity in the Rif region of Morocco [Mancilla and Diaz, 2015; Timoulali et al., 2022]. The results suggest that the Moho is deepest, at a maximum depth of 36 km, under the Rif Mountains, and gradually decreases in depth to a minimum of 30 km toward the coast [Fullea et al., 2007; Torné et al., 2000; De Lis Mancilla and Diaz, 2015; Timoulali et al., 2022].

Moreover, the analysis of seismic data suggest that the Rif Mountains have a relatively thick crust, while the shallower Moho near the coast may reflect different geological processes and a different crustal structure Timoulali et al., 2022].

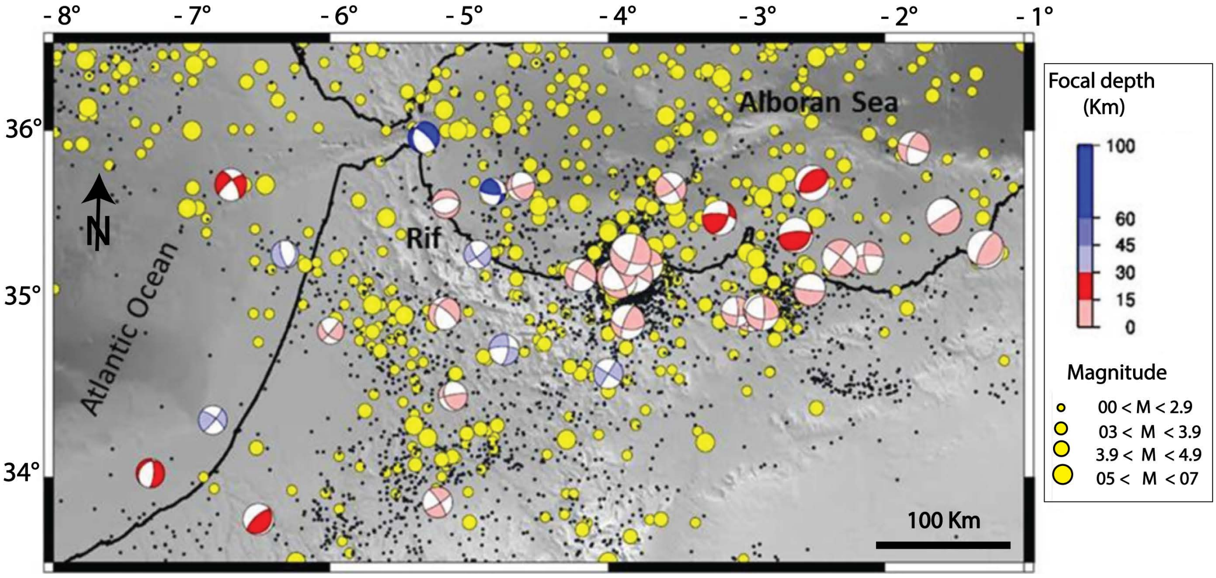

Figure 2. Seismic activity and tectonic processes for the period 1988-2018.

3. Data and method

The data was collected from 45 broadband seismic stations located in North Morocco, as part of the Topo-Iberia and Picasso seismic network (Fig. 3). The study is using local earthquake events recorded with epicentral distances smaller than 200 km, the focal depth of the earthquakes ranges from 1 to 30 km, and the local magnitude varies between 3.5 and 5. Only seismograms with a signal-to-noise ratio greater than 4.0 are used in the analysis. These criteria helps to ensure that the seismic data being used is of high quality and free of significant background noise,

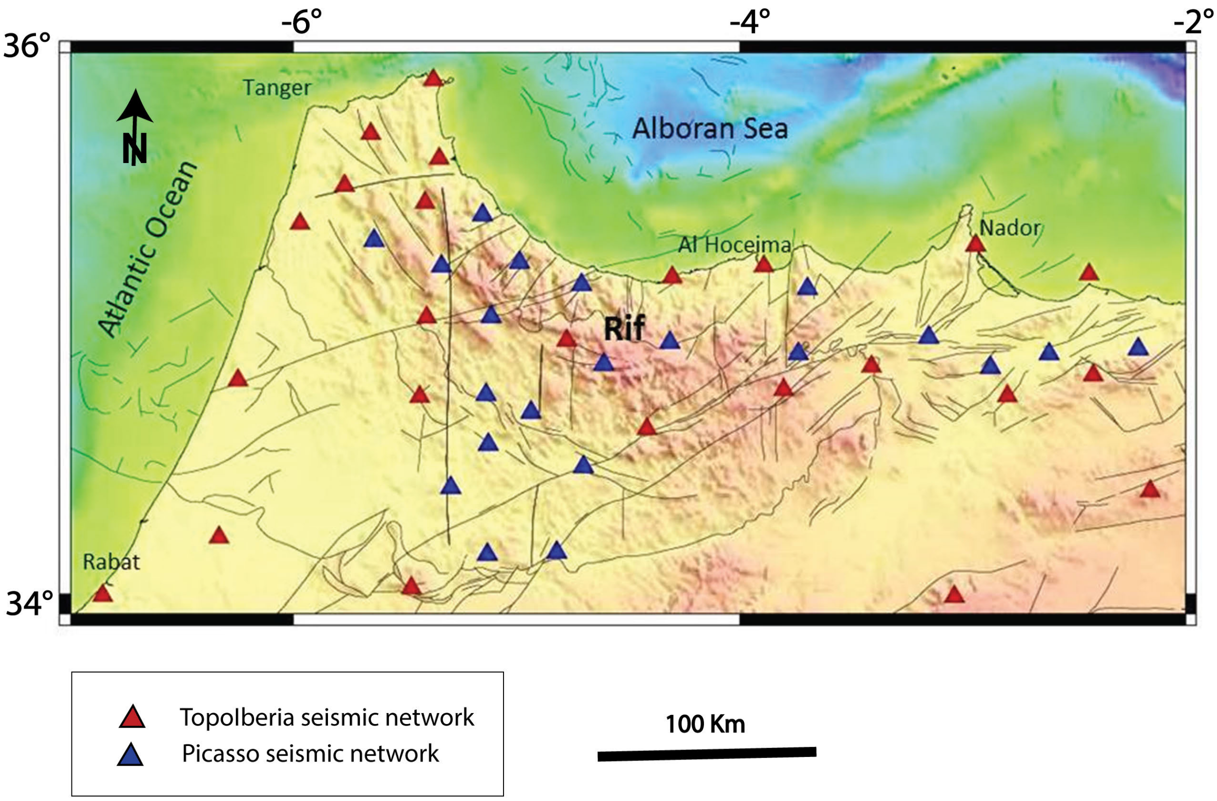

Figure 3. Location of seismic stations analyzed in the Rif domain.

which can interfere with the accurate measurement of seismic wave attenuation. By focusing on earthquakes within a limited distance and with a specific range of magnitudes and focal depths, the study can help to provide a more accurate and reliable estimate of seismic wave attenuation in the region. The seismic events used in this work are shown in Fig. 4.

Crustal seismic attenuation is commonly quantified by the quality factor Q or its reciprocal Q^{-1}. The quality factor is a measure of the amount of energy absorbed or dissipated by the subsurface materials during seismic wave propagation through the Earth's interior [Aki, 1980]. In the previous study, a linear dependence of Q on frequency between 1 and 25 Hz is a commonly observed phenomenon. It means that the quality factor Q varies linearly with frequency within this frequency range. This linear relationship is expressed as:

$$\boldsymbol{Q_c = Q_0 f^n} \tag{1}$$

Where Q_0 is a frequency-independent constant, f is the frequency, and n is a frequency exponent that characterizes the frequency dependence of Q [Singh and Herrmann, 1983]. The frequency exponent n is typically between 0.5 and 1.0, with values close to 1 indicating a stronger frequency dependence (Q_0 is the value of Q_c at 1 Hz). Gupta et al., [1999] show that dependence is stronger in areas with enhanced tectonic activity due to the presence of more complex geological structures such as faults and fractures that can impact the velocity and attenuation of seismic waves.

The classical formula of Aki and Chouet [1975] is used to estimate the quality factor (Q_c) from seismic data. Q_c is a seismic quality factor that represents the energy dissipation rate of the subsurface materials.

$$\boldsymbol{E(t,f)\ \alpha\ \frac{exp^{-\frac{2\pi f t}{Q_c(f)}}}{t^{\alpha}}} \tag{2}$$

Where t is the lapse time after the origin time of the earthquake, α is a fixed exponent depending on the interpretation model of coda wave propagation and Q_c is the coda quality factor characterizing the coda attenuation.

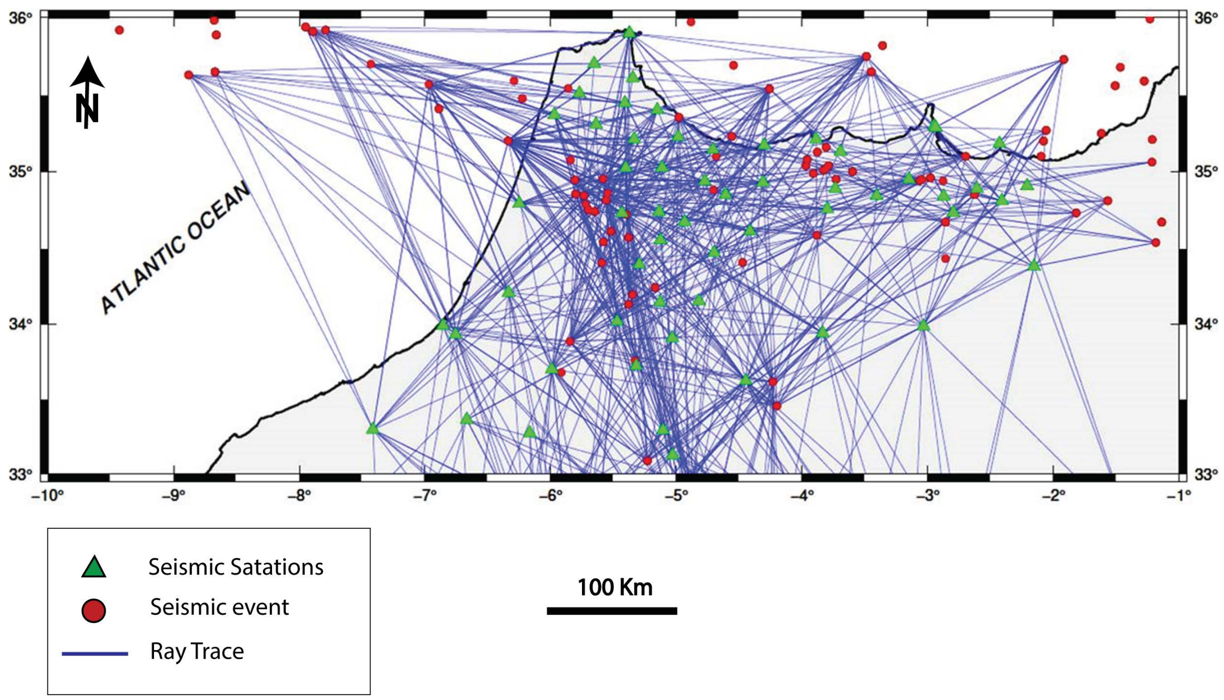

Figure 4. Map of the northern Morocco showing the locations and path of seismic events that occurred from 2008 to 2012.

Q_c is a measure of seismic wave quality that varies with time-lapse and coda window parameters. It is influenced by coda onset time (tw), coda duration (Lw), and epicentral distance range (R) [Calvet and Margerin, 2013]. The variation of Q_c is denoted by the change in epicentral distance. To reduce measurement biases, a standard set of parameters including a coda onset time of 70 s, coda duration of 50 s, and an epicentral distance range of 0-200 km are commonly used. The data is filtered into five frequency bands (1-2, 2-4, 4-8, 8-16, 16-32 Hz) for analysis. The resulting value of Q_c is accepted when the correlation coefficient of the linear regression is greater than 0.7 and the signal to noise (SN) ratio over the entire duration Lw of the coda window is greater than 4.

4. Result and discussion

To visualize the degree of energy dissipation (or absorption) of seismic waves as they travel through subsurface materials an absorption map is created. The map is typically created by measuring the amplitude of the waves at different depths and plotting the results. The coda quality factor (Q_c) and the spatially-dependent quality factor (Qi) are related as the equation shows [Mayor et al., 2016].

$$\boldsymbol{Qc^{-1}(r,s) \approx \frac{\int ray\, Q_i^{-1}(s)ds}{\int ray\ ds}} \tag{3}$$

Qi is the average of Q_c over all ray paths. The spatial variability of Qi can be used to estimate the coda quality factor by taking into account the combined effects of all subsurface materials along the wave path. Q_c is strongest on the direct ray path connecting the source (s) to the station (r).

In fact, the values of Q_c obtained using a single scattering model are dependent on the tectonic activity of a region. In general, for tectonically active regions, such as areas with active faulting and high seismic activity, the values of Q_0 are typically less than 200, while the values of n (the frequency exponent) are high, greater than 1. This means that Q_c decreases rapidly with frequency in tectonically active regions. On the other hand, for stable areas, such as regions with low seismic activity and little to no faulting, the values of Q_0 are typically greater than 200, while the values of n are low, less than 1. This means that Q_c decreases more slowly with frequency in stable areas. Tectonically active regions tend to have more complex subsurface structures and greater heterogeneity, leading to increased scattering and energy loss for seismic waves. On the other hand, stable areas tend to have simpler subsurface structures and less heterogeneity, leading to lower seismic wave attenuation [Sato et al., 2012].

Therefore, the spatial dependence of Qi/Qm for each frequency band (1-2 Hz, 2-4 Hz, 4-8 Hz, and 6-16 Hz) is shown in figure 5, where Qm represents the spatial average of Qi over the study region. The attenuation levels in the Rif domain vary with frequency and depth, showing distinct patterns in different zones. The highest values and weak absorption signatures were found in the western and eastern parts external Rif domain at a lower central frequency of 1.5 Hz. On the other hand, the lowest values and high-absorption signatures were identified in the central Rif domain and in the Nador region (eastern Rif domain). This means that, the strong absorption (low Qi/Qm values) observed in this region is typically associated with the presence of major Cenozoic units and extensional basins filled with dominantly Maghrebian paleomargin deposits [Belayouni et al., 2012].

Moreover, by increasing frequency bands (12-15 Hz), the moderate and low values of attenuation become dominant. This significant that, the low-frequency coda is mainly dominated by surface waves and it is highly sensitive to the shallow part of the crust. As the frequency increases, the transport of energy by body waves becomes more effective, leading to enhanced sensitivity of the coda to deeper crustal structures. This hypothesis was formulated by Aki and Chouet in 1975, based on the observed frequency dependence of the coda quality factor.

The analysis of frequency-dependent attenuation structure in the north of Morocco is used to study the structure and composition of the Earth's interior as different frequencies. The map of the average quality factor (Figs. 5 and 6) reveals apparent variations in the absorption structures of the Earth's subsurface. The strong absorption (low Qi/Qm values) observed on the map is generally associated with the presence of major Cenozoic units and extensional basins filled with dominantly Maghrebian paleomargin deposits which cover the entire region and identified on Fig. 1. These deposits are thought to play a major role in the high level of attenuation of seismic waves, as the properties of these materials affect the energy dissipation of the waves. Shallow geothermal fields are widespread in the North Morocco and probably contribute to the overall attenuation in this region. The high-frequency coda

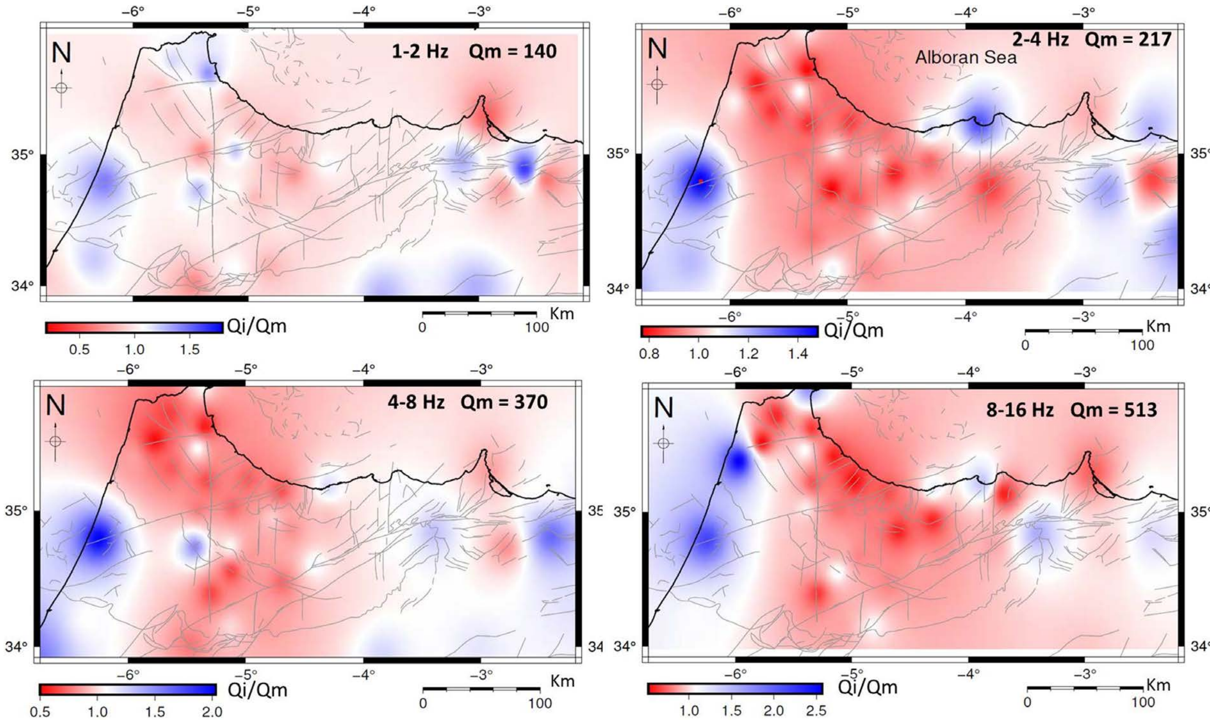

Figure 5. Map of attenuation levels in the Rif domain in frequency 1.5, 3, 6, 9 Hz.

waves, which probe deeper crustal structures mostly composed of crystalline rocks, are consistent with the weak absorption observed in these regions. Also, the highest average values and weak absorption signatures were found in the external Rif domain in the western and eastern parts (Fig. 6).

Seismicity occurs in high Qi regions but is relatively abundant in the surrounding low Qi regions in the western part of the Rif domain and in Al Hoceima and eastern part of the Rif domain (Fig. 7). In northern Morocco, seismic activity in zones with sedimentary cover is related to the crystalline rocks underlying the low Qi Cenozoic

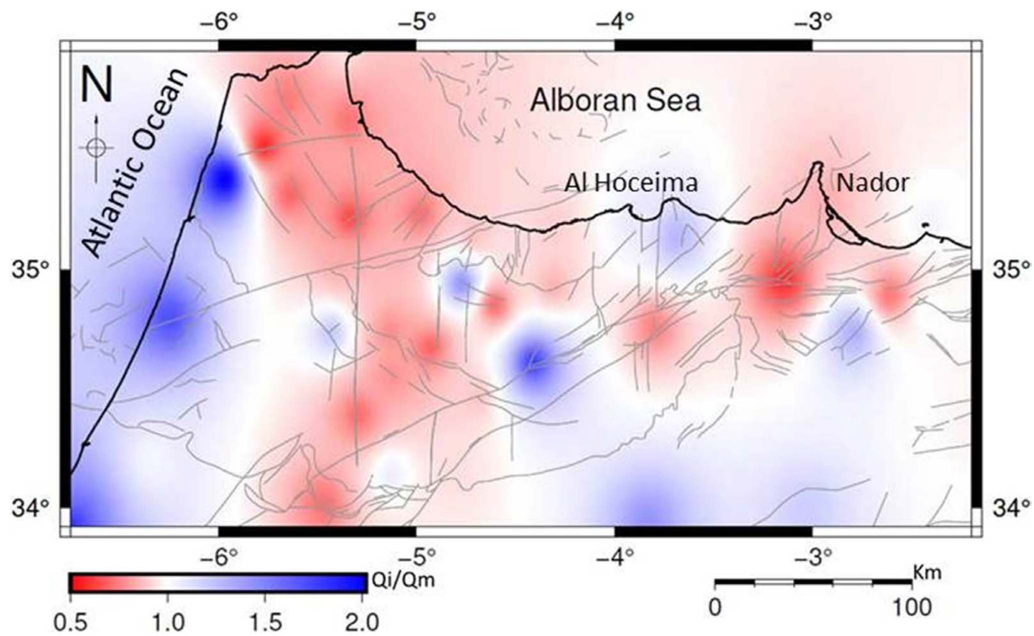

Figure 6. The distribution of the average Qi/Qm values provides insights into the variation of attenuation levels in the region.

sedimentary cover in the western Rif Domain zone. This observation supports the idea that a significant proportion of major earthquakes tend to occur in high Qi zones and/or surrounding low Qi zones, which is consistent with the interpretation of frequency-dependent attenuation. In addition, the seismicity is typically absent from high Qi regions and its relatively abundant in the surrounding low Qi regions. This pattern is particularly evident in the western part of the Rif domain and in Al Hoceima and the eastern part of the Rif domain (Yellow points denote earthquakes of magnitude ≥ 3.0 located by CNRST catalogue), as showing in figure 7.

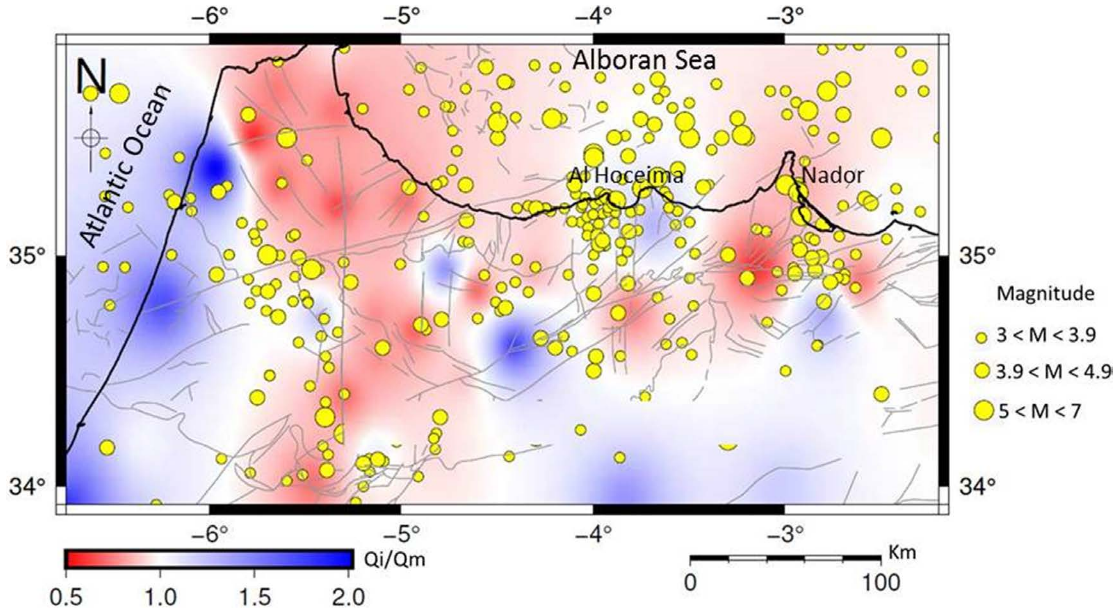

Figure 7. Map of the distribution of average Qi/Qm values and seismicity provides information on the relationship between attenuation levels and seismic activity in the Rif domain.

Hence, several studies have been conducted on crustal attenuation tomography in northern Morocco. The studies have utilized different models and techniques to investigate the attenuation of seismic waves and map the variations in attenuation across the region. First, Boulanouar et al., [2016], used the Single Backscattering model proposed by Aki and Chouet in 1975, to compute Coda values. and their lateral variations through a tomographic inversion by employed the Xie and Mitchell [1990] model. The investigation specifically concentrated on seismic attenuation tomography in northern Morocco, uncovering a correlation between seismic attenuation and the geological structure units within the research area. This correlation emphasizes the pronounced attenuation characteristics of the region.

Second study by Palomeras et al. [2017], that developed a model to analyze the attenuation structure of Iberia and northern Morocco. Their approach involved utilizing a waveform-matching method with P-wave data from teleseismic events. Their results indicate that the attenuation structure in the region aligns with the existence of a substantial lithosphere beneath the Rif Mountains.

Yet, Arab et al. [2020], demonstrated that the estimated quality factor (Q_c) values exhibit significant frequency dependence within the 1.5-24 Hz range. This variation is associated with pronounced attenuation levels in that particular frequency band. The latest study in the Rif belt authored by Boulanouar et al. [2023], suggested that the attenuation of the coda waves decreases with increasing lapse time window, indicating that the upper part of the lithosphere is more heterogeneous compared to the lower layers. Indeed, by comparing our findings, we suggest that the crustal attenuation tomography image in northern Morocco, particularly in the Rif region, is influenced by the complexity of the crustal structure as well as by the geology context and indicating a high tectonic activity, leading to distinct attenuation characteristics not observed in other areas, which are revealed by the above studies.

The mentioned studies, focus on aspects such as crustal thickness variations, lithospheric geometry, seismic and coda wave attenuation. Limitations may include a lack of detailed understanding of the specific geological and tectonic factors influencing crustal attenuation, as well as the need for more extensive data and advanced modeling techniques to accurately characterize attenuation properties in northern Morocco. Further research and data collection may be necessary to address these limitations and enhance the understanding of crustal attenuation in the region.

5. Conclusion

The analysis of coda waves in the frequency band 1-32 Hz allowed for the creation of absorption maps for North Morocco. The inversion technique of coda waves was used to estimate seismic attenuation beneath the region, revealing significant contrasts in the Rif Domain. The highest levels of attenuation were found in the Cenozoic sedimentary basin in the western and eastern part of the Rif Domain, while lower levels were detected in the Al Hoceima zone and in the western and external zones of the Rif Domain. Seismicity is relatively abundant in high Qi zone and in the surrounding low Q zones in the western part of the Rif domain and in the eastern part of the Rif Domain. The seismicity located in low Qi zones is related to the crystalline rocks underlying the low Qi Cenozoic sedimentary cover.

Nevertheless, our research needs to be completed by the geophysical studies and geodynamic models for more understanding of coda waves attenuation in northern Morocco, which is essential for accurate seismic risk assessment and hazard mitigation in the region.

Acknowledgements. This study was supported by Scientific Institute of Rabat, Morocco. The data used are provide from Topo- Iberia, Picasso, and Scientific institute networks. Some of the figures were prepared using the public domain GMT software [Wessel and Smith, 1998].

References

Aki, K. (1980). Scattering and attenuation of shear waves in the lithosphere. J. Geophys. Res. Solid Earth 85, 6496-6504. https://doi.org/10.1029/JB085iB11p06496.

Aki, K. and B. Chouet (1975). Origin of coda waves: source, attenuation, and scattering effects, J. Geophys. Res., 80, 3322-3342, https://doi.org/10.1029/JB080i023p03322.

Anahnah, F., J. Galindo-Zaldivar, A. Chalouan, J. Pous, P. Ruano, A. Pedrera A. Ruiz-Constán, M. Ahmamou, M. Benmakhlouf and P. Ibarra (2011). Crustal resistivity structure of the southwestern transect of the Rif Cordillera (Morocco), Geochem. Geophys. Geosys., 12, https://doi.org/10.1029/2011GC003783.

Arab, O., R. Azguet, I. Ouchen, Y. El Fellah, M. Harnafi, J. Sebbani and A. Villaseñor (2020). Attenuation of seismic coda waves in the Rif area, northern Morocco. J. African Earth Sci. 165, 103815. https://doi.org/10.1016/j.jafrearsci.2020.103815.

Banda E. and J. Ansorge (1980). Crustal structure under the central and eastern part of the Betic Cordillera. Geophys. J. Int., 63, 515-532, https://doi.org/10.1111/j.1365-246X.1980.tb02635.x.

Baratin, L-M., S. Mazzotti, J. Chéry, P. Vernant, A. Tahayt and T. Mourabit (2016). Incipient mantle delamination, active tectonics and crustal thickening in Northern Morocco: Insights from gravity data and numerical modeling, Earth Planet. Sci., Lett. 454, 113-120.

Belayouni, H., F. Guerrera, M.M. Martin and F. Serrano (2012). Stratigraphic update of the Cenozoic Sub-Numidian formations of the Tunisian Tell (North Africa): Tectonic/sedimentary evolution and correlations along the Maghrebian Chain, J. African Earth Sci., 64, 48-64.

Boulanouar, A., A. Dobrynina, A. Rahmouni, A. Samaouali, M. Harnafi and J. Sebbani (2023). Two-dimensional variations of the coda Q in Northern Morocco and their interpretation, J. Seismol., 27, 805-820. https://doi.org/10.1007/s10950-022-10103-x.

Boulanouar, A, L. El Moudnib, S.R. Ford, M. Harnafi, A. Villasenor, J. Gallart Muset, A. Rahmouni, M. Boukalouch and J. Sebbani (2016). Coda wave attenuation tomography in Northern Morocco, J. Mater. Environ. Sci, 7, 2880- 2885.

Boulanouar, A., L. El Moudnib, S. Padhy, M. Harnafi, A. Villaseñor, J. Gallart, A. Pazos, A. Rahmouni, M. Boukalouch and J. Sebbani (2018). Estimation of coda wave attenuation in Northern Morocco, Pure Appl. Geophys, 175, 883-897.

Calvert, A, E. Sandvol, D. Seber, M. Barazangi, S. Roecker, T. Mourabit, F. Vidal, G. Alguacil and N. Jabour (2000). Geodynamic evolution of the lithosphere and upper mantle beneath the Alboran region of the western Mediterranean: Constraints from travel time tomography, J. Geophys. Res. Solid Earth, 105, 10871-10898.

Calvet, M. and L. Margerin (2013). Lapse-time dependence of coda Q: Anisotropic multiple-scattering models and application to the Pyrenees, Bull. Seismol. Soc. Am., 103, 1993-2010, https://doi.org/10.1785/0120120239.

Chalouan, A., A. Michard, H. Feinberg, R. Montigny and O. Saddiqi (2001). The Rif mountain building (Morocco); a new tectonic scenario, Bull. la Société géologique Fr., 172: 603-616, https://doi.org/10.2113/172.5.603.

Chalouan, A., A. Michard, K. Kadiri El, F. Negro, D.F. Lamotte de, J.I. Soto and O. Saddiqi (2008a). The rif belt. Cont. Evol. Geol. Morocco Struct. Stratigr. tectonics Africa-Atlantic-Mediterranean triple junction, 203-302, https://doi.org/10.1007/978-3-540-77076-3_5.

Custodio, S., C. Civiero, J. Duarte, V.B. Mendes and C. Faccenna (2019). Dynamics of the Gibraltar Arc System: A Complex Interaction Between Plate Convergence, Slab Pull and Mantle Flow, In: AGU Fall Meeting Abstracts., p T23B-03.

Demirci, A. and T. Bekler (2023). Azimuthal Path Variations of Regional Body Wave Attenuation via Coda-Source Normalized Method: An Example from Eastern Marmara (NW Turkey), J. Earthq. Eng., 27, 451-463.

Dewey, J.F., M.L. Helman, S.D. Knott, E. Turco and D.H.W. Hutton (1989). Kinematics of the western Mediterranean. Geol. Soc. London, Spec. Publ. 45, 265-283.

Diaz, J., M. Torné M, J. Vergés, I. Jimenez-Munt, J. Martin, R. Carbonell, M. Schimmel, A. Geyer, M. Ruiz and D. Garcia-Castellanos (2021). Four decades of geophysical research on Iberia and adjacent margins, Earth-Science Rev. 222, 103841.

Durand-Delga, M. (1960). Données actuelles sur la structure du Rif. En vente à la Société géologique de France.

El Fellah, Y., G. Bouskri, M. Harnafi, A.E.A.K Abd El, Y. Timoulali, I. Ouchen and R. Azguet (2019). Tracking regional heterogeneities through seismic ambient noise constrains: What Rayleigh wave tomography can tell about deep structures in northern Morocco, J. Afr. Earth Sci., 160, 103615.

Fullea, J., M. Fernandez, H. Zeyen and J. Vergés (2007). A rapid method to map the crustal and lithospheric thickness using elevation, geoid anomaly and thermal analysis. Application to the Gibraltar Arc System, Atlas Mountains and adjacent zones, Tectonophysics, 430, 97-117, https://doi.org/10.1016/j.tecto.2006.11.003.

Gea, P.J., A.M. Negredo and F. Mancilla de Lis (2023). The Gibraltar slab dynamics and its influence on past and present-day Alboran domain deformation: Insights from thermo-mechanical numerical modelling, Front. Earth Sci., 11, 995041.

Gil, A., J. Gallart, J. Diaz, R. Carbonell, M. Torne, A. Levander and M. Harnafi (2014). Crustal structure beneath the R if C ordillera, N orth M orocco, from the RIFSIS wide-angle reflection seismic experiment, Geochem. Geophys. Geosyst., 15, 4712-4733.

Gomez, F., M. Barazangi and A. Demnati (2000). Structure and evolution of the Neogene Guercif Basin at the junction of the Middle Atlas Mountains and the Rif Thrust Belt, Morocco. Am. Assoc. Pet. Geol. Bull., 84, 1340-1364.

Gupta, S.C., A. Kumar, V.N. Singh and S. Basu (1996). Lapse-time dependence of Q_c in the Garhwal Himalaya, Bull. Indian Soc. Earthq. Technol., 33, 147-159.

Gupta, S.C., S.S.Teotia, S.S. Rai and N. Gautam (1999). Coda Q estimates in the Koyna region, India, Q Earth Glob. Reg. Lab. Stud., 713-731

Gurria, E. and J. Mezcua (2000). Seismic tomography of the crust and lithospheric mantle in the Betic Cordillera and Alboran Sea, Tectonophysics 329, 99-119.

El Hilali, M., A. Bounabi, Y. Timoulali, J.E.S. El Messari and M. Ahniche (2023). Seismic site-effects assessment in a fluvial sedimentary environment: case of Oued Martil floodplain, Northern Morocco, Nat. Hazards, 1-23, https://doi.org/10.1007/s11069-023-06032-8

El Hilali, M., Y. Timoulali, T. Benyounes, M. Ahniche, R. El Bardai and S. Yattara (2021). Earthquake-induced liquefaction in the coastal zone, Case of Martil city, Morocco. In: E3S Web of Conferences, https://doi.org/10.1051/e3sconf/202129801002.

Jiménez-Munt, I., M. Torne, M. Fernàndez, J. Vergés, A. Kumar, A. Carballo and D. Garcia-Castellanos (2019). Deep seated density anomalies across the Iberia-Africa plate boundary and its topographic response, J. Geophys. Res. Solid Earth 124, 13310-13332.

Jolivet, L. and C. Faccenna (2000). Mediterranean extension and the Africa-Eurasia collision. Tectonics 19: 1095-1106, https://doi.org/10.1029/2000TC900018.

Jolivet, L., C. Faccenna, B. Goffé, E. Burov and P. Agard (2003). Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens, Am. J. Sci. 303, 353-409.

Karakostas, F., N. Schmerr, R. Maguire, Q. Huang, D. Kim, V. Lekic, L. Margerin, C. Nunn, S. Menina and T. Kawamura (2021). Scattering attenuation of the Martian interior through coda-wave analysis, Bull. Seismol. Soc. Am., 111, 3035-3054.

Lee, W.S. and K. Lee (1999). Q estimates using the coda waves in the Kyeongsang Basin, J. Earthq. Eng. Soc. Korea 3, 67-73.

De Lis Mancilla, F. and J. Diaz (2015). High resolution Moho topography map beneath Iberia and Northern Morocco from receiver function analysis, Tectonophysics 663, 203-211.

Lonergan, L. and N. White (1997). Origin of the Betic-Rif mountain belt, Tectonics 16, 504-522.

Masahiro, K. (1992). Dependence of Coda Q on Frequency and Lapse Time in the Western Nagano Region, Central Japan. J. Phys. Earth, 40, 421-445.

Mayor, J., M. Calvet, L. Margerin, O. Vanderhaeghe and P. Traversa (2016). Crustal structure of the Alps as seen by attenuation tomography, Earth Planet. Sci. Lett., 439, 71-80.

Michard, A. (1976). Eléments de géologie marocaine. Notes et Mémoire. Serv. Carte géol. Maroc, 252, 408.

Palomeras, I., A. Villaseñor, S. Thurner, A. Levander, J. Gallart and M. Harnafi (2017). Lithospheric structure of Iberia and Morocco using finite-frequency Rayleigh wave tomography from earthquakes and seismic ambient noise, Geochem. Geophys. Geosyst., 18, 1824-1840.

Pasquale, V., M. Verdoya and P. Chiozzi (1996). Some geophysical constraints to dynamic processes in the Southwestern Mediterranean, Ann. Geophys., 39, 6.

Pasyanos, M. (2015). Validation of attenuation models for ground motion applications in central and eastern North America, Earthq. Spectra, 31, 2281-2300.

Platt, J.P., J-I. Soto, M. Whitehouse, A.J. Hurford and S.P. Kelley (1998). Thermal evolution, rate of exhumation, and tectonic significance of metamorphic rocks from the floor of the Alboran extensional basin, western Mediterranean., Tectonics, 17, 671-689.

Sato, H. (1977). Energy propagation including scattering effects sengle isotropic scattering approximation, J. Phys. Earth, 25, 27-41, https://doi.org/10.4294/jpe1952.25.27.

Sato, H., M.C. Fehler and T. Maeda (2012). Seismic wave propagation and scattering in the heterogeneous Earth, Springer Science & Business Media.

Singh, S. and R.B. Herrmann (1983). Regionalization of crustal coda Q in the continental United States, J. Geophys. Res. Solid Earth 88, 527-538. https://doi.org/10.1029/JB088iB01p00527.

Sivaram, K and S. Gupta S. (2022). Frequency-dependent attenuation characteristics of coda and body waves in the Kumaun Himalaya: implications for regional geology and seismic hazards, Pure Appl. Geophys. 179, 949-972.

Taj B., M. Mastere, B. Benzougagh, M. El Hilali, S. Sassioui and B. El Fellah (2024). Geotechnical Prospects and Electrical Tomography to Study Slope Instability in the Rif Alboran Sea Shoreline on the Mediterranean By-Road (Northern Morocco), Ecol. Eng. Environ. Technol, 25.

The Working Group For Deep Seismic Sounding in the Alboran Sea 1974 WG. (1978). Crustal seismic profiles in the Alboran Sea—Preliminary results. Pure Appl. Geophys. 116, 167-180.

Timoulali, Y., H. Djellit, Y. Hahou, N. Jabour and R. Merrouch (2014a). New evidence of delamination in the Western Alboran Sea: Geodynamic evolution of the Alboran domain and its margins, J. Geodyn. 77, 206-216.

Timoulali, Y., Y. Hahou, N. Jabour, R. Merrouch and A. El Kharrim (2014b). Main features of the deep structure by local earthquake tomography and active tectonics: case of Rif Mountain (morocco) and Betic Cordillera (Spain), J. Seismol. 18, 221-234.

Timoulali, Y., M. El Hilali, A. Hosny, L. El Moudnib, M. Bouiflane, M. Chourak and S. Badrane (2022). Joint inversion of receiver functions and surface wave dispersion velocities to investigate the crustal structure of north of Morocco: case of Rif domain, Mediterr. Geosci. Rev., 1-18, https://doi.org/10.1007/s42990-022-00084-x.

Torné, M., M. Fernandez, M.C. Comas and J.J. Soto (2000). Lithospheric structure beneath the Alboran Basin: results from 3D gravity modeling and tectonic relevance, J. Geophys. Res. Solid Earth 105, 3209-3228.

Van Hinsbergen, D.J.J., M.A. Edwards, and R. Govers (2009). Geodynamics of collision and collapse at the Africa—Arabia—Eurasia subduction zone—an introduction, Geol. Soc. London, Spec. Publ. 311, 1-7. https://doi.org/10.1144/SP311.1.

Wessel, P. and W.H.F. Smith (1998). New, improved version of Generic Mapping Tools released, Eos, Trans. Am. Geophys. Union 79, 579. https://doi.org/10.1029/98EO00426.

Xie, J. and B.J. Mitchell (1990). A back-projection method for imaging large-scale lateral variations of Lg coda Q with application to continental Africa, Geophys. J. Int. 100, 161-181.

Zeck, H.P. (1999). Alpine plate kinematics in the western Mediterranean: a westward-directed subduction regime followed by slab roll-back and slab detachment, Geol. Soc. London, Spec. Publ. 156, 109-120. https://doi.org/10.1144/GSL.SP.1999.156.01.07.

Zhou, H, X. Jia, L.-Y. Fu and A. Tourin. (2021). Monte Carlo Simulations of Ultrasound Scattering and Absorption in Finite-Size Heterogeneous Materials, Phys. Rev. Appl. 16, 34009.

***CORRESPONDING AUTHOR:** **Mohamed EL HILALI**,
Scientific Institute, Mohammed V University in Rabat, Morocco
e-mail: elhilalimohamed96@gmail.com