Geodesy and Geodynamics 11 (2020) 18–30

Contents lists available at ScienceDirect

Geodesy and Geodynamics

journal homepage: http://www.keaipublishing.com/geog

Crustal thickness beneath Atlas region from gravity, topographic, sediment and seismic data

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ARTICLE INFO

Article history:
Received 19 May 2019
Accepted 8 August 2019
Available online 6 November 2019

Keywords:
Atlas
Gravity
Inversion
Moho
Seismic data

ABSTRACT

The Atlas region in northwest Africa is characterized by the Quaternary volcanism and elevated topography with past complex tectonic mitigation between the African and European plates. Geodynamics of this atypical region has left indubitably imprints in crustal architectonics, mainly regarding the crustal thickness as well as the crustal density structure. The knowledge of crustal thickness variations is of a significant interest, since it provides a crucial constraint to geodynamic and geophysical modelling of this region. In this study, we use gravity, topographic, bathymetric and sediment data together with results of seismic surveys to image the Moho topography beneath the Atlas region. The Bouguer gravity anomalies used for a gravimetric Moho recovery are obtained from the free-air gravity anomalies after subtracting the gravitational contributions of topography, bathymetry and sediments. The regional gravimetric Moho inversion constrained on seismic data is carried out by applying a regularized inversion technique based on Gauss-Newton's formulation of improved Bott's method, while adopting Earth's spherical approximation. The numerical result reveals relatively significant Moho depth variations in the Moroccan Atlas, with minima of approximately 24 km along continental margins of the Mediterranean Sea and maxima exceeding 51 km beneath the Rif Cordillera. The Moho depth beneath the West African Craton varies from 32 km in its southern margin to 45 km beneath the Middle Atlas. The Tell Atlas is characterized by the shallow Moho depth of approximately 22 km and further deepening to 42 km towards the northern edge of the Aures Mountains. Our findings indicate a limited tectonic shortening of the High Atlas with the crustal thickness mostly within 36–42 km. Topographic discrepancies between the Rif Cordillera and the Atlas Mountains suggest that the hypothesis of isostatic compensation cannot be fully established.

1. Introduction

The Atlas Mountains evolved through a long and complex geological history, which formed an intra-continental mountain belt that resulted from the convergence between the African and Eurasian plates. This process began in the Late Caenozoic and continues to present times [1–3]. As the result, the crustal structure of this region is composed of a variety of different geological units. The crustal variability is one of the most important factor that manifests a tectonic evolution of this region. Its nature and geodynamic settings have been the subject of numerous studies, especially over last few decades. Among published results, we

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Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.geog.2019.08.002

could mention seismic studies by Van den Bosch et al. [4], Makris et al. [5], Wigger et al. [6], Van Der Meijde et al. [7], Urchulutegui et al. [8], Bezada et al. [9], Spieker et al. [10], De Lis Mancilla and Diaz [11], Saki et al. [12], Diaz et al. [13], Jessell et al. [14], Ebinger et al. [15], or Civiero et al. [16]. Gravimetric studies of this region were conducted, for instance, by Mickus and Jallouli [17], or more recently by Jallouli et al. [18]. Despite having significant knowledge about the geology and formation of the Atlas region, a broader image of detailed crustal configuration of the whole region including the West African Craton is not yet available. This is particularly relevant to margins between the Atlas and the West African Craton due to a lack of seismic data there. Even the resolution of existing Moho and crustal structure models is still low in areas such as the Saharan Atlas, Tell and Aures Mountains, where the crustal structure and the Moho geometry are estimated only by extrapolating from sparsely located seismic data points. The Moho depth obtained from ground-based gravity data [17,18] for the Morocco Atlas was produced and published, but only for some areas, not the whole region. Thus, there is still a necessity to update a Moho model of the entire Atlas region using available seismic and gravity data and applying advanced regional inverse techniques. Due to a lack of ground-based gravity data, satellite gravity information is used to improve the understanding of crustal configuration, particularly in regions with a sparse or missing seismic data.

To address this issue, in this study we provide a broader image of the Moho topography beneath the Tell and Atlas orogenic belts including adjoining parts of the West African Craton. The estimation of the Moho depth is realized through the analysis of gravity data integrated with the results of major seismic experiments that are used as physical constraints. Gravity information is particularly important to interpolate the crustal structure in regions with a sparse seismic data coverage in Algeria, compared to a relatively detailed coverage of Morocco and Tunisia by seismic surveys. In this study, we compiled the detailed Moho model of the whole region that allowed us to interpret the crustal configuration more realistically in the context of geological structure and tectonism.

The study begins with a brief geological and tectonic classification in section 2, followed by an overview of existing studies of the Atlas region in section 3. Input data and methods used for a gravimetric forward modelling and a Moho inversion are reviewed in section 4. The results are presented in section 5 and discussed in section 6. Major findings are then summarized in section 7.

2. Geological setting of Atlas region

The Atlas Mountains extend over 2000 km from Morocco, through Algeria to Tunisia. The topography of these mountain ranges is modest in their east part, while gradually elevates towards west in the High and Middle Atlas. The Atlas system comprises the Rif Cordillera and the Tell Mountains, rigid blocks, High Plateaus of Algeria, the Atlas Mountains (the Anti, Middle, High, Saharan and Tunisian Atlas) and the Sahara Platform. The Rif Cordillera and the Tell Mountains form a part of an Alpine thrust system that extends from the Beltic Mountains (in south Spain) to Tunisia and the Atlantic margin (Fig. 1). The current geological configuration of this region is mainly the result of the Caenozoic and Mesozoic extensional and compressional tectonic events, related to the opening and subsequent closing of the Mediterranean Sea [17,19]. The region of the High Plateaus of Algeria is typically divided into the Saharan Atlas and the Tell Atlas, while geologically the whole region belongs to the Atlas domain. A tectonic style of the Algerian Atlas, consisting of broad synclinal basins and narrow anticlinal pinches, is similar to that of the Moroccan Atlas. The folds, with the N 45°E axial strike, are oblique to the general N 60°E trend of the Atlas. These folds are seldom symmetrical and, as in Morocco, the anticlines grade into stretch-thrusts at depth. The faults are well expressed throughout the domain. Asfirane and Galdeano [20] have characterized its south part by a succession of epicontinental deposits (the Mesozoic sandstone representing its sedimentary layer) and in the north part by thinner sediments (Triassic to Neogene). The northern fringe of the West African Craton is located between the northwest edge of the Saharan Desert and series of hills of the High Atlas in south Morocco mainly behind the Anti-Atlas Mountains [14]. The West African Craton represents the main geological unit of the study area, underlying various late rocks of the Neoproterozoic and Palaeozoic orogenic mobile belts. The Saharan Meta-Craton and the West African Craton are bounded by the Pan-African Trans-Saharan Belt, forming the Archaean core of north Africa, extending from the Hoggar in Algeria to the Gulf of Guinea [21]. The geological configuration of Algeria is essentially formed by the Pan-African Trans-Saharan Belt with predominantly linear north-south trend all over the West African Craton and a higher metamorphic grade. In the Atlas orogen, localized magmatism follows the strike of the Atlas Mountains from the Canary Islands hotspot towards the Alboran Sea. The Tunisian Atlas and the Saharan Atlas mountains are intracontinental orogenic belts formed within the stable Proterozoic-Palaeozoic Sahara Platform that belongs to the old African basement. These orogenic belts consist of the Mesozoic rift sediments that were deformed into a series of large step folds. In the Saharan Atlas (the Tell and Atlas zones), the Mesozoic rift sediments were inverted into a major mountain range by thrust faults and block uplift tectonics, whereas the Tunisian Atlas was formed by thin-skin tectonics [22,23]. The nearest Archaean granitic basement outcrop appears in east Algeria, which may be in concordance with the basement of north Tunisia.

3. Crustal studies of Atlas region

As evident from earlier seismic and gravimetric studies of the Atlas region (summarized in Table 1), most of authors focused on north and west parts of the region along the Atlantic Ocean and the Mediterranean Sea based on the analysis of seismic refraction, receiver functions and terrestrial gravity measurements. Mickus and Jallouli [17] and Jallouli and Mickus [25] detected a crustal thickness of 38–40 km under the Saharan Atlas and 34–36 km under the Tunisian Atlas. Using Woollard's [26] empirical formula, Arfaoui et al. [27] estimated the Moho depth in Tunisia. Their result revealed that the Moho depth there varies between 29 and 39 km, with maxima under the Tunisian Atlas, where the Moho deepens gradually westwards. This crustal thickening continues under the Saharan Atlas in Algeria. They also identified the localized Moho deepening in north Tunisia (29 km) and in the Sahel (31 km). Using deep seismic sounding surveys, Diaz et al. [13] detected a maximum crustal thickness beneath the Rif Cordillera with the Moho depth there exceeding 45 km. They also demonstrated that the Atlas Mountains, and in particular the High Atlas are characterized by crustal thickness variations roughly within 35–40 km. They detected a thin crust along continental margins (the Mediterranean domain and the Atlantic margins) with the Moho depth typically approximately 15 km and a gradual Moho deepening towards inland with maxima exceeding 50 km beneath the Rif Cordillera. This estimate is significantly larger than the result presented earlier by Urchulutegui et al. [8]. According to their result, using a simple approach based on the analysis of regional topographic and geoidal data, the Moho deepens only to approximately 34 km under the Rif Cordillera and to approximately 38 km beneath the Atlas Mountains. A similar estimate for the Rif Cordillera was given by Giese and Jacobshagen [28]. They reported a maximum crustal thickness of 40 km. Mancilla and Diaz [11], based on the P-

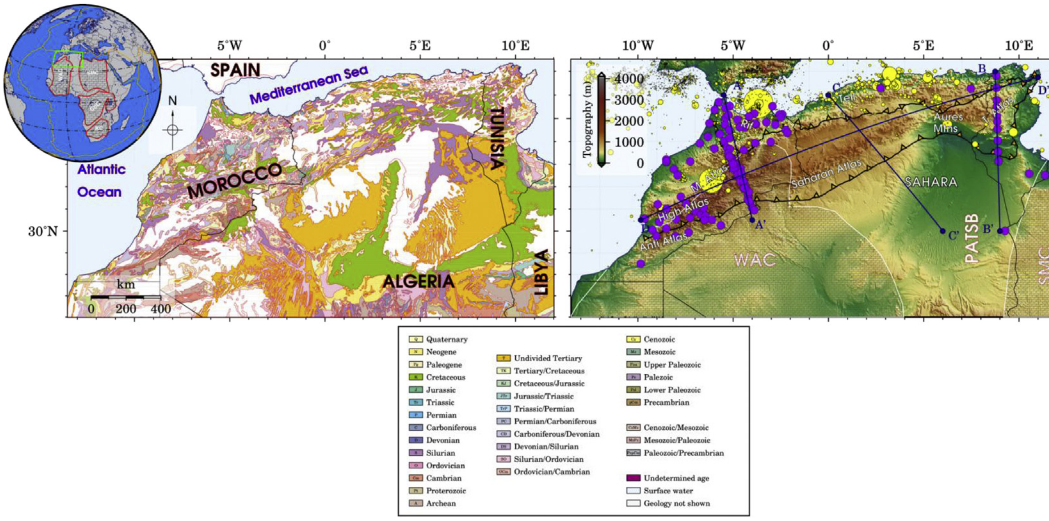

Fig. 1. Regional geological and tectonic configuration of the Atlas region including seismicity. AA′, BB′, CC′ and DD′ (Fig. 10) indicate four selected profiles. The inset shows the location of the Rif-Tell-Atlas orogenic region along the Eurasian-African plate boundary. The orange lines indicate plate boundaries according to Bird [24]. Notation used: West African Craton (WAC), Pan-African Trans-Saharan Belt (PATSB) and Sahara Meta-Craton (SMC).

Table 1
Moho depths of previous investigations for the Rif-Tell-Atlas orogenic system.

Area	References	Methods	Depth Estimates (km)
Rif	Gil et al. [30]	Deep Seismic Sounding (DSS)	29–42
	Mancilla et al. [31]	Receiver Functions (RF)	21.6–44.4
	Van der Meijde et al. [7]		
	Urchulutegui et al. [8]	Regional elevation and geoid data	34
Atlas	Ayarza et al. [29]	Deep Seismic Sounding (DSS)	33–41
	Wigger et al. [6]		
	Makris et al. [5]		
	Mancilla et al. [31]	Receiver Functions (RF)	23–44.7
	Sandvol et al. [32]		
	Spieker et al. [10]		
	Cooper and Miller [33]		
	Mickus and Jallouli [17]	Gravity	26–38
	Jallouli and Mickus [25]		
	Urchulutegui et al. [8]	Regional elevation and geoid data	38–40
	Arfaoui et al. [27]	Gravity	29–39
Meseta	Makris et al. [5]	Deep Seismic Sounding (DSS)	~35
	Mancilla et al. [31]	Receiver Functions (RF)	30.7–37.6
	Diaz [13]	P-receiver function (PRF)	30–35
North-western Morocco Margin	Contrucci et al. [34]	Deep Seismic Sounding (DSS)	34–35
South-western Morocco Margin	Makris et al. [5]		27–29
West African Craton	Sandvol et al. [32]	Receiver Functions (RF)	41–42.6
	Kosarian [35]		
	Di Leo et al. [36]		

receiver function analysis, detected significant variations in the Moho geometry in north Morocco that could be characterized by three distinctive regions. A thick crust beneath the Rif Cordillera. A thinned crust in northeast Morocco, and the region of 30–35 km thick crust in the transition to the Meseta domain. Further south, moderate crustal roots with the Moho roughly 40 km deep are clearly identified under the High Atlas. Ayarza et al. [29], using geological evidence and terrestrial gravity data, detected the under thrusting slab of the Saharan Atlas. They also identified a dense lower crust of local crustal roots with the Moho deepening to 38–41 km beneath the central High Atlas. These results have reinforced models of crustal under-compensation and a Moho involvement in the deformation that have implications for a deep structure of intracontinental mountain belts.

Beneath the Tell and Atlas orogenic belts including adjoining parts of the West African Craton most studies have used seismic data to resolve the crustal structure (e.g. [16]). The Atlas region is not an exception, with fewer gravity studies than continental-scale seismic studies. A limitation of seismically derived crustal thickness maps is an inherent uncertainty about crustal structures in areas with limited or low-quality data coverage. To our knowledge, continental-scale crustal thickness models of the Atlas region are generally constructed from seismic studies (e.g. [14–16]) with only a handful of models derived from gravity studies (e.g. [17,18,25]). In all instances, however, the limited availability of both seismic and ground-based gravity measurements has resulted in unconstrained crustal structure models in the Atlas. To partially these deficiencies, we estimated the Moho depth based on the gravity (from global model) inversion constrained on available seismic data.

4. Data acquisition

In this section, we briefly summarized input data and numerical procedures and then presented results of a gravimetric forward modelling.

4.1. Free-air gravity data

We used the EIGEN−6C4 global gravitational model [37] to generate the free-air gravity anomalies with a spectral resolution complete to the spherical harmonic degree of 2160. We note that EIGEN-6C4 is available via the International Centre for Global Earth Models website [38]. The free-air gravity anomalies computed on a 5' × 5' geographic grid of surface points are shown in Fig. 2. At the study area, these gravity anomalies vary mostly between −100 and 250 mGal. Positive values prevail over most of moderately elevated and mountainous regions. Over lowlands, the values are mostly negative. In the central High Atlas, the contours of the free-air gravity anomalies strike roughly N 55°E direction, reflecting the direction of most elevated regions. This observation obviously agrees with the expected high spatial correlation between the free-air gravity anomalies and the topography. However, this trend is slightly oblique to the general structural direction of the High Atlas, which is approximately in N 75°E direction. Maxima of the free-air gravity anomalies reaching approximately 250 mGal in west part of the central High Atlas correlate with the highest summits that exceed elevations of 4000 m. Over lowlands to north and south of the High Atlas, the free-air gravity anomalies decrease substantially, with most of values within ±50 mGal. Over the north part of continental margins from Morocco to Tunisia, except for the coastal area along the Rif Cordillera, the free-air gravity anomalies are typically positive, while mostly negative in south of the Aures Mountains (−100 mGal), the Sahara (−75 mGal), the central (−25 mGal) and east parts (−80 mGal) of the West African Craton. In the central part of the Pan-African Trans-Saharan Belt, the free-air gravity anomalies vary roughly from −60 to −90 mGal, while gradually decrease westwards along the West African Craton with negative values below −100 mGal.

4.2. Bouguer gravity data

We used the ETOPO1 [39] global (solid) topography data to compute the topographic and bathymetric gravity corrections with the same spectral resolution as used for the free-air gravity data. Both gravity corrections were computed simultaneously by applying the tesseroid method. For a detailed description of this method, we refer readers to the study by Uieda and Barbosa [40]. Since a lack of information about the topographic density distribution in most parts of northwest Africa, the topographic gravity correction was computed for a homogenous density distribution. In particular, we used the density value of 2670 kg m^{-3} that is typically adopted to represent the upper continental crustal density (cf. [41]). The bathymetric gravity correction was computed for the ocean density contrast of 1630 kg m^{-3}. It is worth mentioning that for a more accurate computation of the bathymetric gravity correction, the depth-dependent seawater density model developed by Gladkikh and Tenzer [42] could be used; see also Tenzer et al. [43–45]. We further used the sediment data from the CRUST1.0 global seismic crustal model [46] to compute the sediment gravity correction. In regions with a well-known geological stratigraphy, additional gravity corrections can also be applied to model and subtract the gravitational signature of deeper lithospheric structures (e.g. [47–50]).

The combined topographic-bathymetric gravity correction computed on a 5' × 5' geographic grid of surface points is shown in Fig. 3A. This combined gravity correction is spatially correlated with the topography. Within the study area, it varies roughly between ±300 mGal. Large positive values apply for the High, Middle, Saharan and Tunisian Atlas mountain ranges with localized maxima exceeding even 300 mGal over the Middle Atlas. Lowlands and shoreline regions of the Aures Mountains and the Moroccan coast are characterized by small negative values (to about −20 mGal). The sediment gravity correction is shown in Fig. 3B. Values of this gravity correction are everywhere negative with absolute maxima along the Pan-African Trans-Saharan Belt south of the Aures Mountains.

We applied the topographic-bathymetric gravity correction to the free-air gravity anomalies. The Bouguer gravity map is shown in Fig. 4A. Subsequently, we applied the sediment gravity correction to the Bouguer gravity anomalies. The sediment-corrected Bouguer

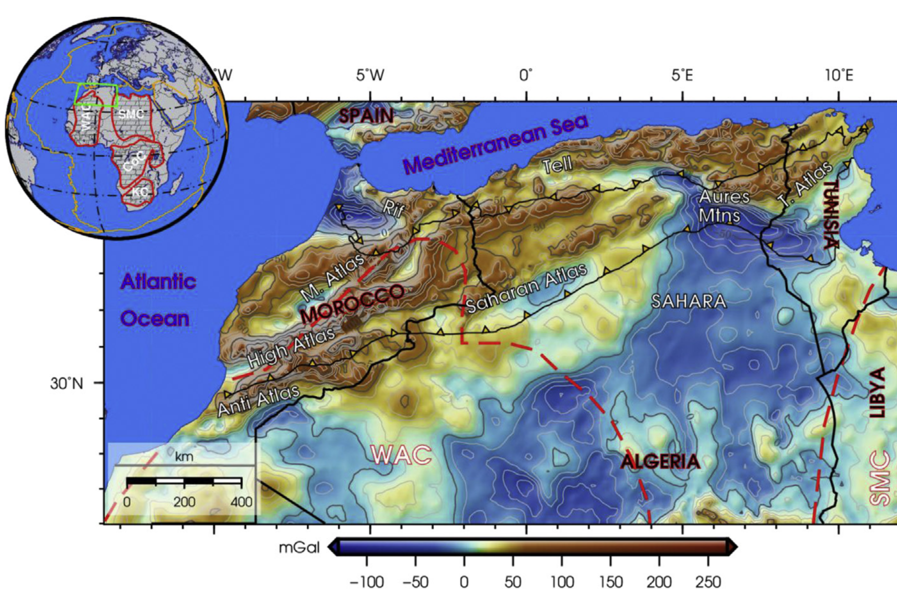

Fig. 2. Regional maps the free-air gravity anomalies computed on a 5' × 5′ grid of surface points.

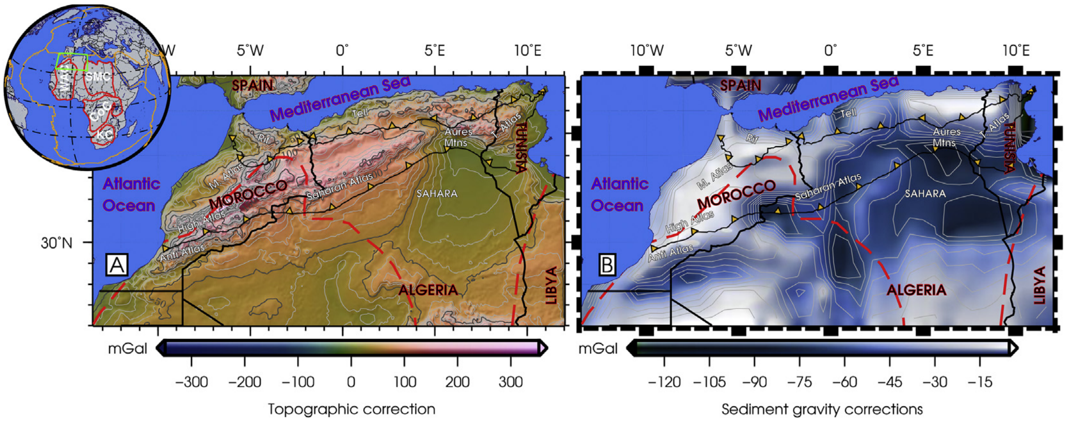

Fig. 3. Regional maps of: (**A**) the topographic-bathymetric and (**B**) sediment gravity corrections computed on a 5′ × 5′ grid of surface points.

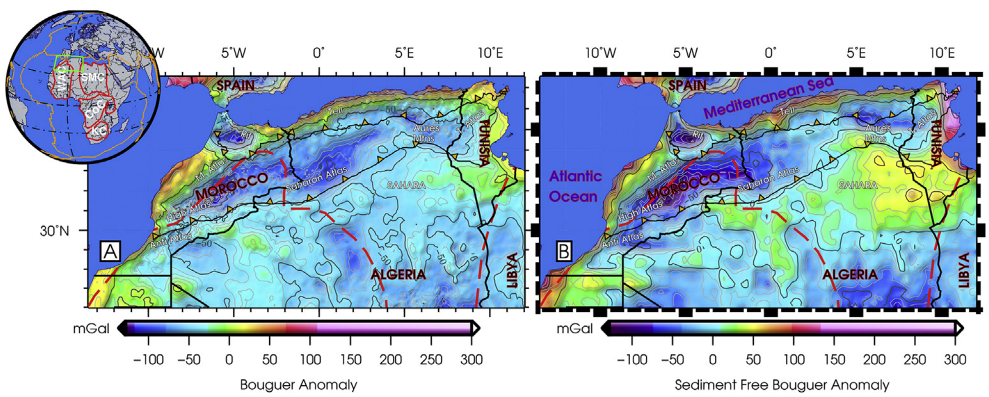

Fig. 4. Regional maps of the Bouguer gravity anomalies: (**A**) before and (**B**) after applying the sediment gravity correction computed on a 5′ × 5′ grid of surface points.

gravity anomalies are shown in Fig. 4B. From comparing Figs. 2 and 4A, we see that the application of the combined topographic-bathymetric gravity correction significantly modified the free-air gravity pattern. Some substantial changes are also recognized in the Bouguer gravity map after applying the sediment gravity correction, particularly along the east coast of Tunisia and over the Sahara Plateau. The application of the sediment gravity correction increased the long-wavelength negative Bouguer gravity anomalies in Morocco along the Central and Middle Atlas, where values of this correction varies approximately between −50 and −100 mGal. Other significant modification of the Bouguer gravity pattern by this correction is to the south of the Aures Mountains.

As seen in Fig. 4B, the sediment-corrected Bouguer gravity anomalies range from −120 to 250 mGal. Over the central High Atlas, these values are mostly negative between −40 and −120 mGal, with the largest negative values close to the southern border of central and west parts of the central High Atlas. Despite large negative values are mostly distributed over the elevated topography, these values do not coincide with the highest summits that are located further north. Similarly, in the high plains between the Middle and High Atlas mountain ranges, the highest topographic elevations do not coincide with minima of the sediment-corrected Bouguer gravity anomalies. Consequently, the expected spatial correlation between the Bouguer gravity anomalies and the topography is not clearly manifested in the High Atlas. Instead, we see misfits, suggesting a lack of local isostatic equilibrium at a crustal level. Moreover, the Bouguer gravity anomalies in the Atlas Mountains are not clearly pronounced with respect to bordering lowlands to the north and the south that are otherwise exhibited in the free-air gravity map, characterized by a significant contrast between gravity anomaly highs over the elevated topography and gravity anomaly lows over lowlands. The long-wavelength pattern of negative values of the sediment-corrected Bouguer gravity anomalies is along the Tunisian Atlas. In contrast, the long-wavelength pattern of positive values prevails over the Tell Atlas, the Sahel as well as the southeast coastal zones. Other region with large negative values (−100 mGal) is detected in the Algerian anticlinorium, characterized by significant structural high gradients (north-south axis) that are associated with a significant structural alignment. In agreement with findings by Jallouli and Mickus [25], we see that the sediment-corrected Bouguer gravity anomalies are largely spatially correlated with major geological units in Tunisia. Positive values over the Sahel are limited to the west by the high gradient defining the north-south axis. This axis is observed throughout the Sahel. Arfaoui et al. [27] argued that it is not simply a response of the Bouguer gravity anomalies to a change in density of the Mio-Plio-Quaternary outcrops dominating this region. Instead, this gravity pattern is more likely due to a rising of the basement towards the east and to a crustal thinning. Negative anomalies over the Tunisian Atlas Mountains coupled by positive anomalies along coastal regions and lowlands indicate that the long-wavelength Bouguer anomalies correlate inversely with major topographic features. This finding suggests that the Tunisian Atlas is isostatically compensated. In other worlds, the gravitational contribution of the elevated topography is compensated at depth by a mass deficit, reflecting a thick crust with a density that is relatively lower compared to an underlying uppermost mantle density. The effects of mass deficits at the base of the crust generally mask the gravity signal associated with shallower crustal sources. The Atlas Mountains

(−130 mGal) and the Rif Cordillera (−100 mGal) in north Morocco are characterized by similar Bouguer gravity minima, while much less elevated topography. The cause of this steady anomaly has been suggested by Fullea et al. [51] to be mainly due to the thickening (up to 6 km) of the Phanerozoic sediments present in this region. The overall anomaly observed along the West African Craton is negative mainly on its northern edge. The sediment-corrected Bouguer gravity anomalies along the West African Craton are largely negative within the range from −120 to 20 mGal. The overall gravity anomaly trend makes it possible to separate the West African Craton into two parts on either side of the latitude 31°N. Negative values are observed outside the range of latitude 31°N, well expressed under a slightly oblique to the East-North-East general orientation of the High Atlas belt delineating the northern part of the West African Craton. In its northern edge, we observe a lack of correlation between the Bouguer gravity anomalies and the topography, indicating the absence of isostatic equilibrium at a crustal level. On the other hand, positive anomalies observed below the latitude 31°N that extend over the Pan-African Trans-Saharan Belt express mainly the EW trending. The overall anomaly values there decrease towards west from the Tunisian coast to Sahara. The origin of this progressive decrease is, for the most part, associated with a thickening of the Phanerozoic sediments (up to 6 km thick at places), taking place over basement uplift [25], with the contribution from a crustal thickening in the neighbourhood of 32–36 km.

4.3. Seismic data

We used the Moho depth estimates regionally concentrated along the Rif-Tell-Atlas orogenic system from available deep seismic sounding [5,29,34] and receiver function [10,31,36] studies. Our total database includes 111 seismic points from these referred works. The seismic data distribution and the seismic Moho depth estimates are visualized in Fig. 5. We see a relatively dense seismic data distribution in Morocco and Tunisia, in contrast to their absence in most parts of Algeria. In these cases, the observations were assessed qualitatively based on the reliability or accuracy of the crustal thickness observations. For a brief review of passive source seismic studies in Africa, and especially in the study area, we refer readers to study by Fishwick and Bastow [52]. The seismic Moho depths are within the interval from 34 to 44 km, with a mean of 34 km.

4.4. Gravity inversion

We applied a regularized non-linear gravity inversion according to the technique presented by Uieda and Barbosa [40] to estimate the Moho depth from the sediment-corrected Bouguer gravity anomalies. This gravity inversion technique is based on applying the modified Bott's method [53] with the Tikhonov's regularization to stabilize the inverse solution in a two-step numerical scenario. Firstly, we determined the regularization parameter by using a predefined set of initial values of the Moho depth and density contrast. In the second step, we carried out a gravimetric inversion for different values of the Moho density contrast as well as the mean Moho depth. The final gravimetric solution was then selected based on the principle of minimizing the Mean Square Error (MSE) of the Moho depth differences between the gravimetric and seismic results. The detailed description of gravity inversion algorithms applied in this study can be found in Uieda and Barbosa [40].

5. Results

The Bouguer gravity data described in section 4 were used to estimate the Moho depth. The result of the gravimetric Moho inversion constrained by seismic data is presented and then compared with the available seismic results as well as existing gravimetric studies in this section.

5.1. Comparison with seismic Moho depth estimates

Results of the gravity inversion are controlled by two parameters, namely by the Moho reference depth and the Moho density contrast. We used previous seismic studies to validate gravimetric results by examining all possible combinations for the Moho reference depth values at the range from 20 to 40 km with a 0.5 km step, and for the Moho density contrast values between 200 and 500 kg m^{-3} with a 50 kg m^{-3} step. The best fit by means of minimizing the mean-square-error (MSE) of the Moho depth differences between the gravimetric and seismic solutions was attained for the values of 32.5 km and 500 kg m^{-3} of the mean Moho depth and the Moho density contrast respectively (see Fig. 6). The result of a regional Moho recovery is shown in Fig. 7 (for 3-D Moho image see the Fig. 7C). We also plotted (in Fig. 7B) the histogram of Moho depth differences between seismic and gravimetric estimates. At a regional scale, we see a good MSE fit between gravimetric and seismic results. Nevertheless, some large localized discrepancies also exist. In the Rif Cordillera in north Morocco, the comparison with seismic data is somewhat ambiguous with a strong heterogeneous crust, with the presence of large crustal roots beneath this mountain range and a thinned Moho to the east, close to the Algerian border. In the west part of the Atlas Mountains, we observe a crustal root beneath the High Atlas reaching 44 km. As

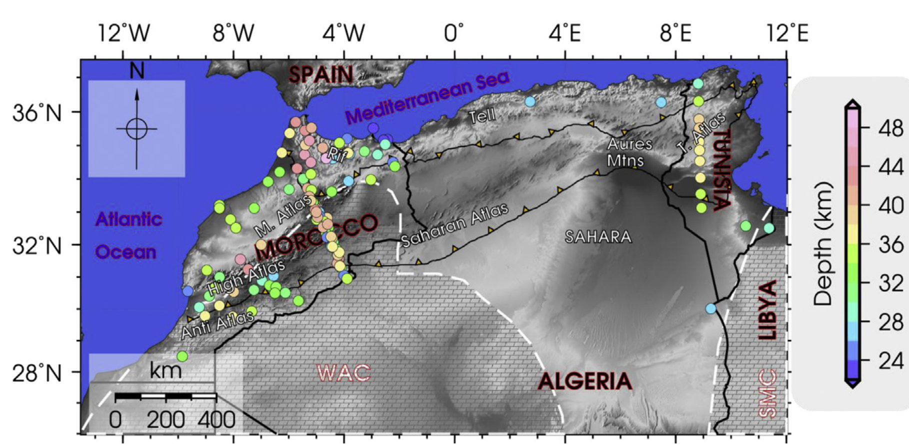

Fig. 5. Seismic Moho depth estimates from receiver functions analysis seismograph stations (circles), superimposed on a regional shaded topography.

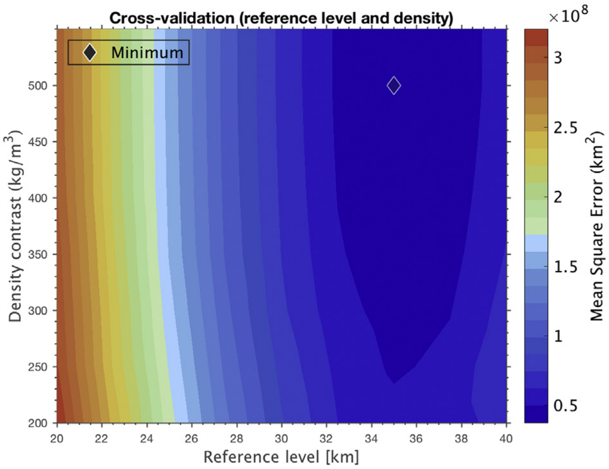

Fig. 6. Validation steps exploited to determine the Moho reference depth and the Moho density contrast. The colour scale represents the Mean Square Error. The best-fit model is marked by a grey rectangular (for the Moho density contrast of 500 kg m^{-3} and the Moho reference depth of 35 km).

seen in Fig. 7B, the Moho depth differences are roughly between −19 and 15 km with a bias of only 0.14 km and a STD of 3.5 km. These values indicate that the gravity-derived Moho is in a relatively good agreement with the Moho depth derived from receiver function analysis. Fig. 8 displays remarkable crustal thickness variations deduced in the study area by presenting the crustal thickness of the final 3D model and below different given depths. The Moho depth in the Rif-Tell-Atlas orogenic system varies between 16 and 53 km. The deepest Moho is observed beneath the Rif Cordillera, with values exceeding 40 km under the Aures Mountains and reaching maxima 53 km at some locations (Fig. 8A). The crustal roots beneath of the west basin of the Tunisian Atlas, the High and Middle Atlas are clearly exhibited, with the Moho depth there varying from 30 to about 40 km (Fig. 8B). As seen in Fig. 8B–C, the Moho depth shallows gradually eastwards to 25 km. A similar trend is also detected in north Tunisia (26 km) and the north part of the Pan-African Trans-Saharan Belt, particularly in the Sahel (28 km). The Moho topography beneath the Tunisian Atlas is marked by a flexure between the depression and uplift zones, exhibiting some major faults in east and south. The West African Craton, including the Atlas Mountains and in particular the Anti, High and Middle Atlas in its northern edge, have some topographic elevations exceeding 4100 m while its Moho depths varying mostly within 32–44 km. An opposite situation characterizes the Rif Cordillera, with low topographic elevations below 2000 m and the deep Moho exceeding even 50 km. A thinner crust ranging from 29–37 km is, on the other hand, depicted along the eastern margin of the West African Craton.

5.2. Comparison of regional Moho models

We compared our Moho model with three gravity-derived models, namely, the GEMMA [54], Tugume2013 model [55] and the Tedla2011 model [56]; see Fig. 9 and statistical summaries in Table 2. The Moho depth differences are plotted in Fig. 10, with their statistical summaries given in Table 3. We see that the TUGUME13

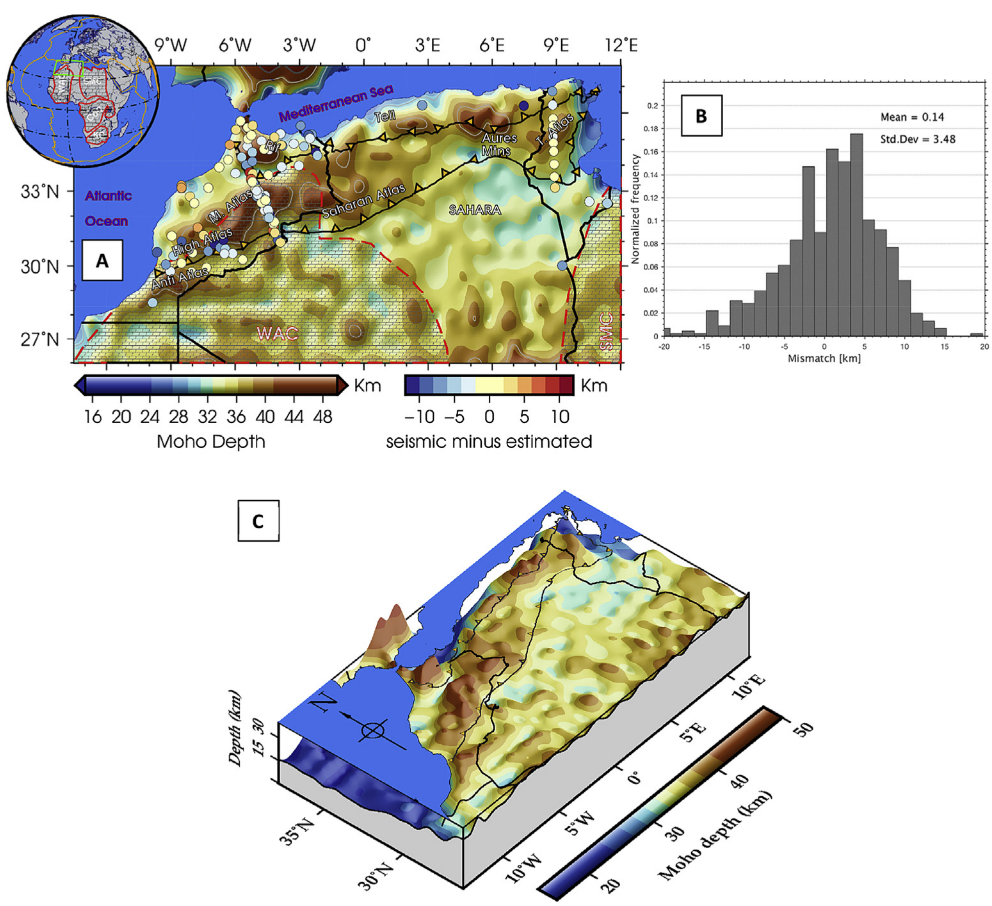

Fig. 7. Regional map of the Moho depth estimated based on a regularized non-linear inversion of the sediment-corrected Bouguer gravity data. The Moho depth differences between seismic and gravimetric solutions is shown at seismic sites. Figure also includes the histogram of these differences.

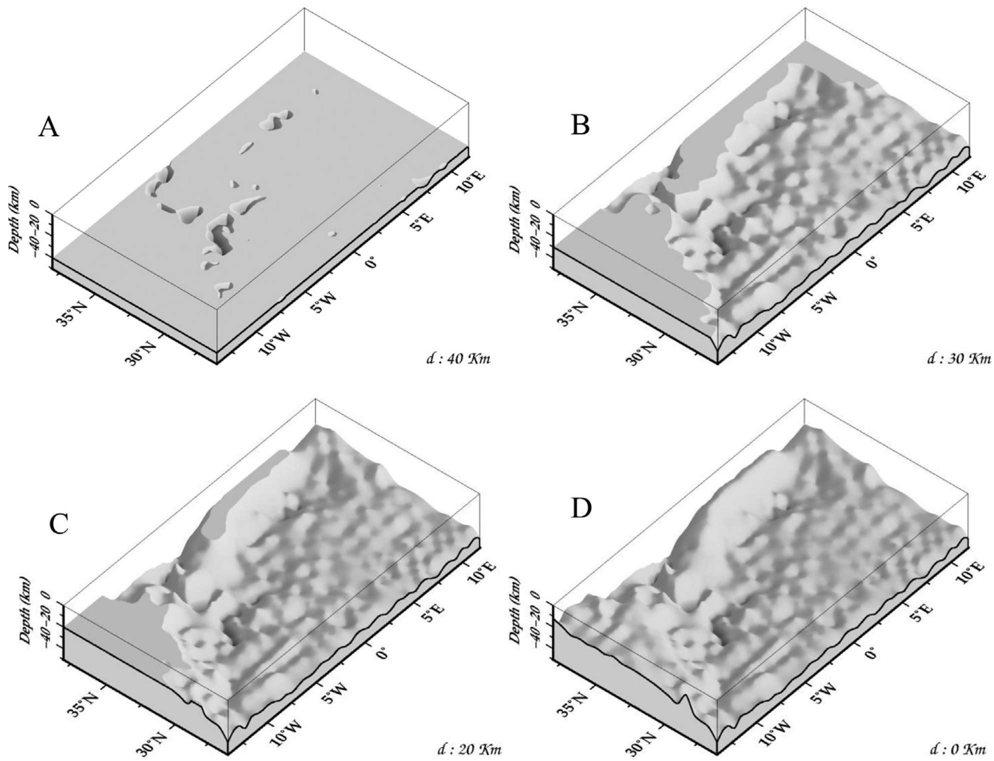

Fig. 8. 3D ensemble views of the crustal topography. Panels show the Moho geometry below depth of: (**A**) 40 (**B**) 30 (**C**) 20, and (**D**) 0 km.

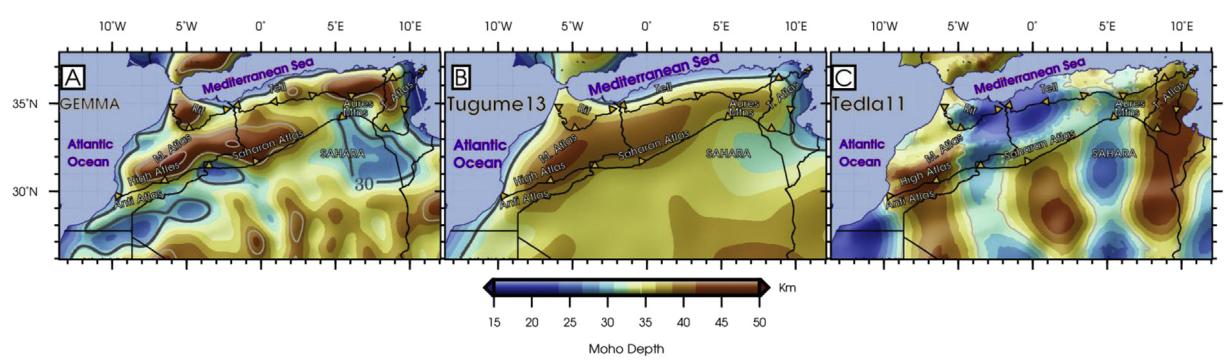

Fig. 9. The juxtaposition of existing crustal models for the Atlas region. The gravity-based models are GEMMA, Tugume13 and Tedla11.

Table 2
Statistics of the referenced crustal models.

Models	Min (Km)	Coverage	Methods	Max (Km)	Mean (Km)	STD (Km)
GEMMA [54]	4.80	Global	Combined gravity and seismic model	105.19	22.36	12.12
Tugume 2013 [55]	3.97	Continental	Gravity, Parker-Oldenburg iterative inversion	44.48	23.62	11.43
Tedla 2011 [56]	32.99	Continental	Gravity, 3-D Euler deconvolution	47.70	39.45	2.36

and GEMMA models are clustered and closer to our model than Tedla11.

6. Discussion of results

The results of gravimetric forward modelling (presented in section 4) and the result of gravimetric Moho recovery (shown in section 5) are discussed in the context of geological and tectonic setting of the study area.

6.1. Gravity maps

The sediment-corrected Bouguer gravity map presented in Fig. 4B exhibits clearly the gravitational signature of different geological units within north Morocco, Algeria and Tunisia. Values of the sediment-corrected Bouguer gravity anomalies range from −140 mGal in the High Atlas Mountains of Morocco to 200 mGal along the northeast coast of Algeria. The Bouguer gravity map (corrected for the sediment effect) is likely more realistic than the Bouguer gravity map presented by Mickus and Jallouli [17], Jallouli

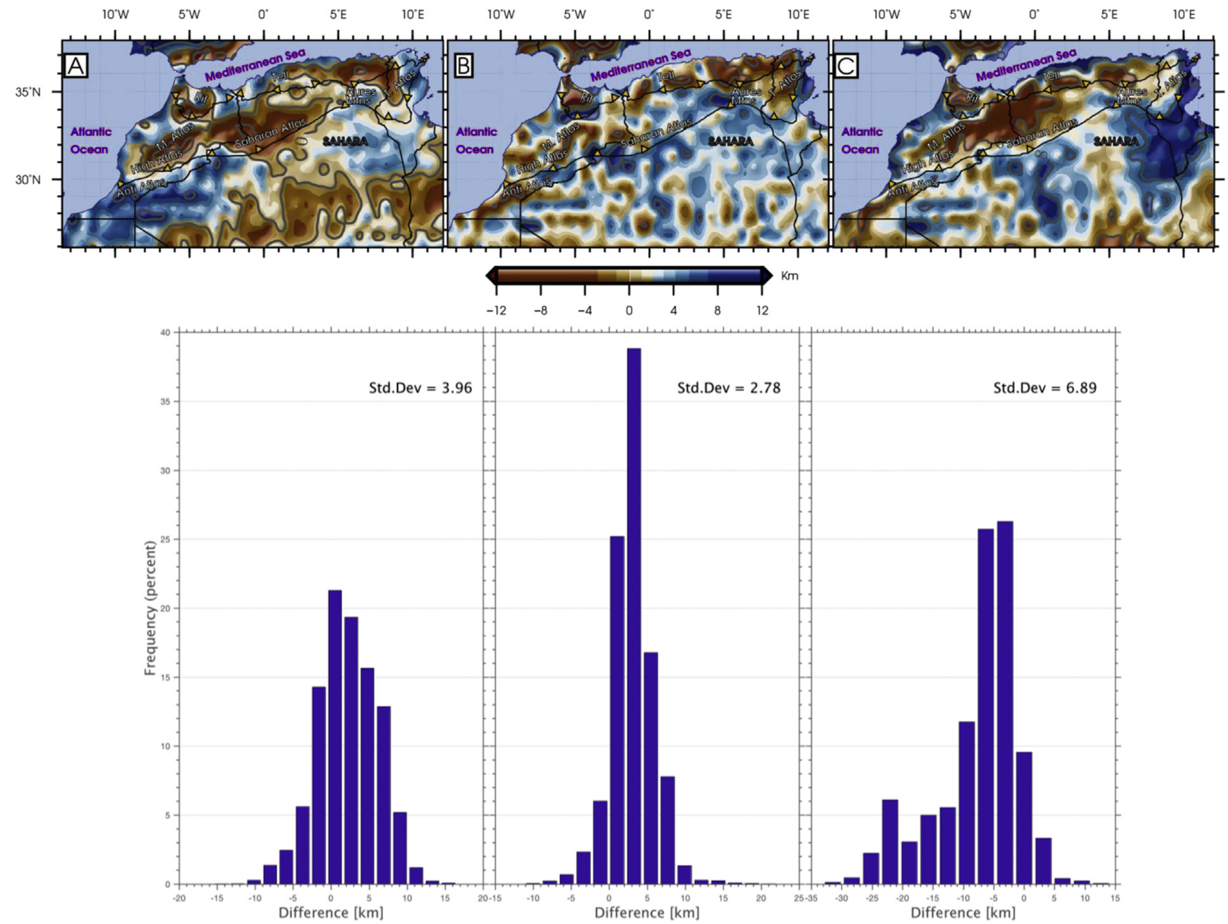

Fig. 10. Comparison between regional crustal thickness models and our model. The Moho depth differences with respect to: (**A**) GEMMA model by Reguzzoni et al. [54], (**B**) Tugume13 model by Tugume et al. [55], and (**C**) Tedla11 model by Tedla et al. [56].

Table 3
Statistics of differences between values of the new density model and the referenced crustal models.

Differences	Min (km)	Max (km)	Mean (km)	STD (km)
GEMMA [54]	−15.50	16.51	2.16	3.96
Tugume 2013 [55]	−11.15	22.09	3.06	2.78
Tedla 2011 [56]	−33.06	14.19	−7.57	6.89

et al. [18], or Arfaoui et al. [27]. Most of spatial features in our Bouguer gravity map reflects largely crustal thickness variations and a low density of sedimentary basins. Additional gravity variations are attributed to a density structure within the deep lithosphere. More specifically, sources of gravity anomalies within the Atlas Mountains involve crustal thickness variations as well as sedimentary rocks overlying the Precambrian and younger basement rocks and crustal thickness changes. Minima of the sediment-corrected Bouguer gravity anomalies are over the High Atlas at the intersection of the Tell Atlas with the Tunisian Atlas Mountains and the Rif Cordillera. These gravity anomaly lows are possibly attributed to the isostatic signature of a significant Moho deepening under these mountain ranges. The Saharan Atlas Mountains in Algeria are associated with broad-scale, southwest-trending minima in the sediment-corrected Bouguer gravity map. These minima extend beyond surface boundaries of the Saharan Atlas Mountains northwards over the High Plateau region and southwards over the South Atlas Front and the Sahara Platform. This large-scale gravity anomaly low may be explained by a crustal thickening caused by the loading of the Saharan Atlas onto the continental crust that is similar with the source of gravity anomaly over the High Atlas. Our estimate of the crustal thickness confirmed the existence of a thick crust (36–40 km) across the Saharan Atlas. A general idea about the isostatic compensation of the entire Tell and Atlas Mountains can be seen by comparing the sediment-corrected Bouguer gravity map (Fig. 4B), the free-air gravity map (Fig. 2) and the topographic relief (Fig. 1). Arfaoui et al. [27] noticed that the Tunisian Atlas is associated with the positive free-air gravity anomalies that, in general, mirror the topography. Their finding agrees with our result. Nonetheless, the Saharan Atlas comprises also regions with the negative free-air gravity anomalies and with the corresponding negative values of the sediment-corrected Bouguer gravity anomalies that indicate a possible overcompensation. The rest of the Saharan Atlas appears to be compensated, except near the boundary with the Tunisian Atlas. This may imply again an overcompensation, but such conclusion could be an oversimplification, as a thick low-density material may be the cause of these anomalies, as is the case for the Rif Cordillera.

6.2. Comparisons of Moho depth estimates

New continental-scale Moho estimates beneath Africa, based on gravity modelling, were presented by Tedla et al. [56] and Tugume et al. [55]. Both studies provide gravity-derived crustal thickness maps, calibrated against seismic Moho estimates. These results exhibit only minor variations in crustal thickness between terranes of the Archaean and Proterozoic age [57]. The crustal model of Tugume et al. [55] shows overall a thinner crust than the model presented by Tedla et al. [56], with differences exceeding 6 km in the part covered by our study area. A feature common to all three models mentioned above is a relatively thick crust (35–45 km) beneath the High and Middle Atlas. GEMMA is more prominent and reliable than models presented by Tedla et al. [56] and Tugume et al. [55]. The comparison of the Moho depth differences of these three models with our solution (see Fig. 10) shows that significant Moho differences are observed for all three models, although differences between our model and GEMMA and Tugume et al. [55] models are acceptable for most parts of the study area with ±4 km for the Moho. In the study area, the maximum Moho depths (42–48 km) correspond to the West African Craton and to the Rif Cordillera. The maximum Moho deepening in northwest Africa is detected in the Atlas Mountains (approximately 37 km) with local maxima under the High Atlas (45 km). Compared to the Moho depth estimates from active seismic experiments in Morocco [6,29,30], our model is in a good agreement with the crustal structure across the Atlas Mountains. In the northwest Moroccan platform, the Moho depth estimate of approximately 32.5 km is slightly lower than the Moho depth of approximately 35 km reported by Contrucci et al. [34]. Our estimate, also very closely agrees with the result published by Globig et al. [57]. Tadili et al. [58] found that the crustal thickness varies from 25 km along the Atlantic coast to 40 km in the central High Atlas, which argues for a possibly thinner crust less than 35 km along the Moroccan margin. According to our estimate, in the west parts of the High and Middle Atlas Mountains, the Moho depth varies within 34–42 km and closely spatially agrees with GEMMA, Tedla et al. [56] and Tugume et al. [55] models. Our model, however, disagrees with these models in the very southwest part of the High Atlas. According to our result, the Moho depth there exceeds 38 km in agreement with the finding of Makris et al. [5]. The comparison of our Moho model with the result for the Moroccan Meseta and the Rif Cordillera presented by Mancilla et al. [31] shows that both results agree within ±7 km in these regions. A generally better agreement between both results is found in the east part of the Rif Cordillera. According to our result, the minimum Moho depth there is roughly 35 km, while Mancilla et al. [31] estimated a thinner crust with the Moho depth of only 27 km.

6.3. Study profiles

We selected four representative profiles at the study area to compare and interpret the gravity anomaly (free-air and Bouguer) variations with respect to the topography and the Moho depth. The locations of these four profiles are indicated in Fig. 1. The gravity anomaly variations along the profiles are plotted in Fig. 11, with the statistical summaries given in Table 4.

The AA' section (Fig. 10A) trends NNW-SSE and crosses the Rif Cordillera and the High Atlas. This region is characterised by the deepest Moho, varying from 31 to 49 km, with the peak at the distance from 175 km and anti-correlation observed between the gravity anomaly trend and the Moho depth (section 80–300 km). In the Rif Cordillera region, values of the free-air and Bouguer gravity anomalies are in phase and negative with an isostatic imbalance characterised by the deepest Moho. Minima of the short-wavelength gravity spectrums reach almost −100 mGal, suggesting the presence of a very low-density structure at shallow levels. Both, the central High (35–36 km) and Middle (43–42.5 km) Atlas mountain ranges have more shallow sub-crustal depths than the Rif Cordillera (49 km) that spatially correlate with mountain hills along with the areas of the thinnest lithosphere. The northern edge of the West African Craton has a shallower Moho depth, varying from 42 km in the Middle Atlas to 34 km in the High Atlas, confirming the observation done by Jessell et al. [14].

The BB' section (Fig. 10B) crosses Tunisia, from the Tunisian Atlas to Sahara. The Tunisian Atlas is characterised by the positive free-air gravity anomalies (up to 62 mGal) and the negative Bouguer gravity anomalies (to −45 mGal). The free-air gravity anomalies reflect a thick crust (39 km) beneath this region. At the distance of 360 km, the Moho depth decreases to 32 km, corresponding to an extension of the West African Craton into the northern segment of the Pan-African Trans-Saharan Belt, or the West African Mobile Zone present in the Saharan region. The free-air gravity anomalies remain negative. The Bouguer gravity anomalies exhibit a long-wavelength trend.

The CC' section crosses Algeria from the Tell Atlas to Sahara. Within this profile, the free-air gravity anomalies and the Moho depth undulations vary in a similar mode with a thicker crust beneath the Tell Atlas. Along the first part of the section (to 265 km), the Bouguer gravity anomalies decrease to −22 mGal, then slightly increase from the Saharan Atlas to Sahara. The isostatic compensation between the Tell and Sahara Atlas is apparent based on comparing gravity anomalies with the Moho depth. The Saharan Atlas is isostatically compensated, with the exception close to the Tunisian Atlas. Across Saharan section of this profile, the free-air gravity anomalies are mostly negative with a large amplitude, while the Bouguer gravity anomalies are negative. The crustal thickening in the Tell Atlas (40 km) weakens towards Sahara (38 km) through the Saharan Atlas (36 km), highlighting the sediments contribution (Palaeozoic, Mesozoic, and Caenozoic) mainly occurring in the Pan-African Trans-Saharan Belt.

Along the DD' section, the Moho depth merely correlates with the free-air gravity anomalies between the High Atlas and the Saharan Atlas. However, the Bouguer gravity anomalies are characterised by a short wavelength with the minimum of −125 mGal in the Middle Atlas. In contrast, a non-isostatic compensation likely occurs in the Tunisian Atlas, due to the short-wavelength minima (−25 mGal) observed in the free-air anomaly signal. A lack of correlation between the free-air and Bouguer gravity anomalies and the crustal thickness along the High, Middle, Saharan Atlas and the coastal border of the Tunisian Atlas reflect mainly a combined effect of the Caenozoic, Mesozoic and Palaeozoic to recent tectonic sediments. Along the north edge of the West African Craton, located between the High and Middle Atlas, maxima of the free-air anomalies (150–205 mGal) and of the Moho depth (40–46 km) indicate the presence of a very low-density material at shallow levels along the northern margin of the West African Craton.

7. Summary and concluding remarks

We have complied a new regional model of the Moho depth of the Atlas region (i.e. the Rif-Tell-Atlas orogenic region) and adjoining part of the West African Craton using gravity, topographic, bathymetric and sediment models constrained by seismic data by applying a regularized inversion based on the Gauss-Newton's formulation of the improved Bott's method with the regularization and tesseroid techniques involved.

The Moho topography inferred by this method exhibits an all-inclusive remarkable consistency. Variations in the crustal thickness are heterogeneous in the east-west directions and closely related to the long-term Mesozoic to recent tectonic events of the Atlas orogenic formation. In the Western Atlas (comprising the Anti, High and Middle Atlas mountain ranges), the crustal thickness is roughly 35–44 km, while the Central Atlas Massif exhibits a rather non-uniform Moho depth of 36 km in the Saharan Atlas and 32 km in the Aures Mountains system. A sharp crustal thickness transitions are observed between the Rif Cordillera to the Middle

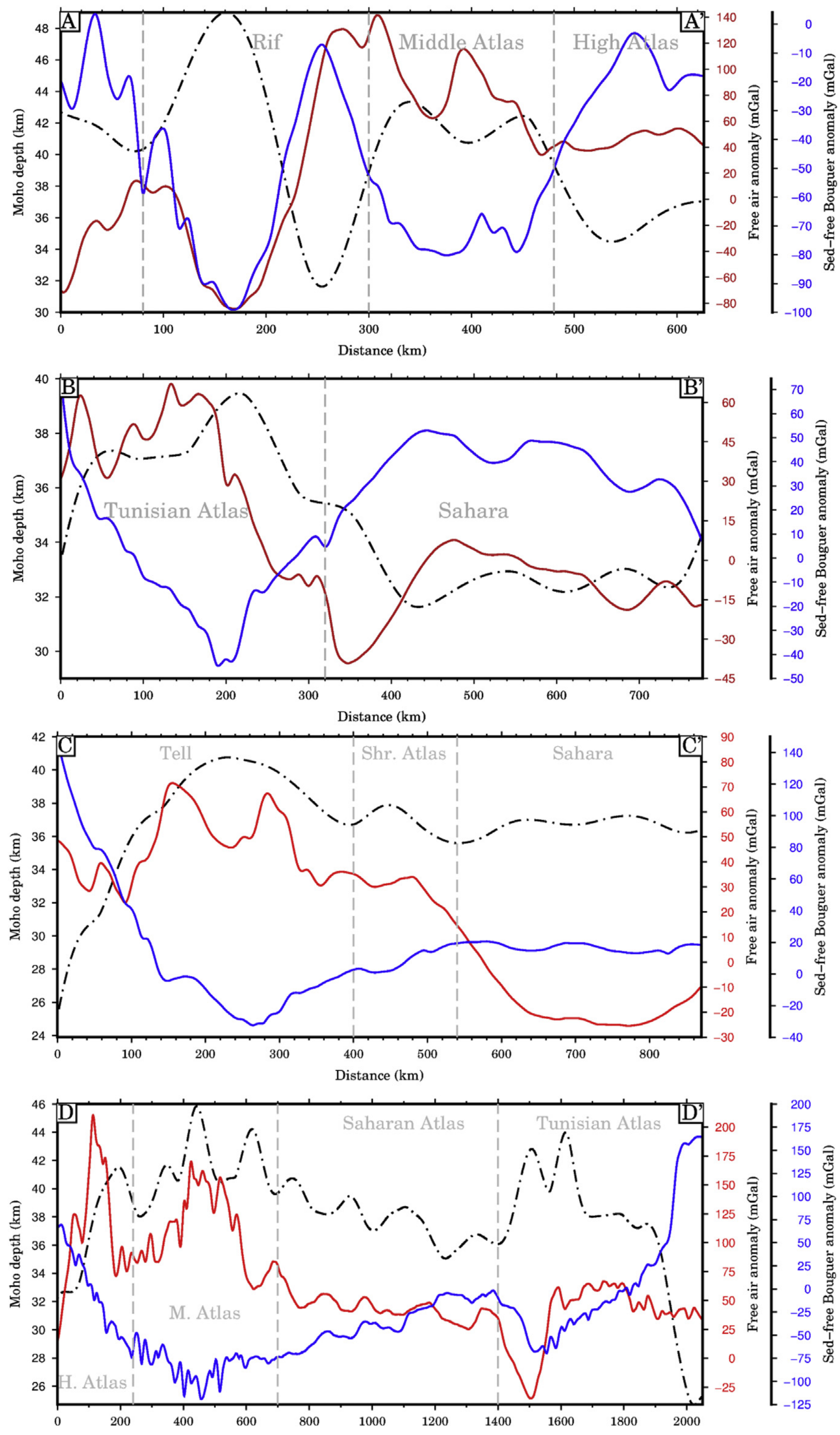

Fig. 11. Study profiles for comparing values of the free-air and Bouguer gravity anomalies with the Moho depth and the topography across the Rif-Tell-Atlas orogenic region (see locations in Fig. 1): AA′ profile along the Morocco Atlas system, BB′ profile along the Tunisia Atlas system, CC′ profile along the Atlas system, and DD′ profile through Morocco, Algeria, and Tunisia.

Table 4
Characteristics of the studied sections drawn on the Moho depth, the free-air and sediment-free Bouguer gravity maps.

Section	Distance (km)	Orientation	Borders
AA′	623	NNW - SSE	Rif – High Atlas
BB′	770	N–S	Tunisian Atlas - Sahara
CC′	865	NW–SE	Tell - Sahara
DD′	2050	WSW - ENE	High Atlas – Tunisian Atlas

Atlas and around the Tell Atlas, where the Moho deepens to 55 km. In the Tunisian Atlas region, the Moho depth varies between 28 and 42 km, with a westward gradual deepening and maxima (42 km) under the Aures Mountains.

Some inconsistencies identified between the Rif and Atlas Ranges cannot simply be explained under the assumption of isostatic compensation, while looking at the thickened crust of the Atlas Ranges with the Moho depth variations roughly within 36–42 km. The profile analysis revealed that the Atlas region is partially to fully compensated, with regions of possible overcompensation in the Saharan Atlas. The signature of the West African Craton in the Atlas is marked by a deep crustal geometry varying from 38 km in the Anti Atlas and from 40 to 44 km in the High and Middle Atlas. This crustal geometry of the West African Craton in the northern margin of the Atlas is supported by a high topography. The Pan-African Trans-Saharan Belt limited to the west by the West African Craton, to the east by the Sahara Meta-Craton and to the north by the Aures Mountains is mainly constituted by the Palaeozoic, Mesozoic and Caenozoic sedimentary. The presence of these sediments is cause of a shallow crust in Sahara, the south Tunisia and in the south flank of the Aures Mountains. In the Tell Atlas, an average Moho depth between 30 and 35 km is detected in Tunisia. Thus, the NW–SE trending observed along the Atlas hills is associated with the thickest crust in north Africa.

The Moho models from previous studies compiled using various methodologies in the Atlas region were used to check the reliability of our high-resolution crustal thickness estimate. The comparison of results revealed that our Moho model better agrees with seismic depth estimates than existing gravimetric Moho models (GEMMA, TUGUME13 and TEDLA11). This is particularly evident for the Rif Cordillera and the Atlas Mountains, where these models underestimate or even provide unrealistic Moho depth estimates.

Conflicts of interest

The authors declare that there is no conflicts of interest.

Acknowledgments

This research is conducted under the HK science project 1-ZE8F: Remote-sensing data for studding the Earth's and planetary inner structure. We are thankful to the Editor for quick editorial handling. Two anonymous reviewers are thanked for their constructive comments and suggestions that greatly improved the manuscript. The authors thank Dr. Mohamed Sobh for providing receiver functions depth data. Grid compilation and figures were generated using Generic Mapping Tools (GMT) [59]. Most figures use perceptually uniform color-maps from the Scientific Colour Maps collection to prevent visual distortion of the data [60].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geog.2019.08.002.

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