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A new tectonic map of the Iranian plateau based on aeromagnetic identification of magmatic arcs and ophiolite belts

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Highlights:

- The Radially averaged power spectrum method is applied to calculate average magnetic susceptibility in Iran.
- The shows known occurrences of Magmatic-Ophiolite Arcs (MOA) correlate with high average susceptibility areas.
- We interpret two parallel, hitherto unknown, MOAs in eastern Iran developed in a steeply dipping (>60º dip) subduction zone.
- Neo-Tethys subduction shallow angle (<20º) in NW and steep (>60º) in SE of Urmia-Dokhtar Magmatic Arc indicates slab tearing.
- We define a new outline of the economically important Tabas sedimentary basin.

Abstract

The Iranian plateau is one of the most complex geodynamic settings within the Alpine-Himalayan belt. The Paleo-Tethys and Neo-Tethys ocean subduction is responsible for the formation of several magmatic arcs and sedimentary basins within the plateau. These zones mostly are separated by thrust faults related to paleo-suture zones, which are highlighted by ophiolites. Sediment cover and overprint of a different magmatic phase from late Triassic to the Quaternary impede identification of some magmatic arcs and ophiolite belts.

We track the known magmatic arcs, such as the Urmia-Dokhtar Magmatic Arc (UDMA), and unknown, sediment covered magmatic arcs by aeromagnetic data. We present a new map of average susceptibility calculated by the radially averaged power spectrum method. High average susceptibility values indicate the presence of a number of lineaments that correlate with known occurrences of Magmatic-Ophiolite Arcs (MOA), and low average susceptibility coincides with known sedimentary basins like Zagros, Makran, Kopeh-Dagh, and Tabas. In analogy to Zagros, low average susceptibility values indicate sedimentary basins to the south of the Darouneh fault and in the northern part of the Lut, Tabas and Yazd blocks. We interpret the Tabas basin as a pull-apart or back-arc basin. We identify hitherto unknown parallel MOAs in eastern Iran and the SE part of UDMA which both indicate steeply dipping (>60º dip) paleo-subduction zones. In contrast, we interpret shallow subduction (<20º dip) of Neo-Tethys in the NW part of UDMA as well as in the Sabzevar-Kavir MOA.

Keywords: Aeromagnetic data, susceptibility, Tectonics, Iranian plateau, magmatic arcs, ophiolites, sedimentary basins.

1. **Introduction**

The Iranian Plateau is a complex puzzle of continental and oceanic fragments that were amalgamated during the closure of the Paleo-Tethys and Neo-Tethys oceans. The structure of the plateau reflects the geological-tectonic evolution, including subduction, collision, and magmatism in the Alpine–Himalayan orogenic belt (Stampfli and Borel, 2002) (**Figure 1**). The opening and continuous subduction along the northern margin of the Paleo-Tethys ocean from Paleozoic to late Triassic, and later along the northern margin of the Neo-Tethys ocean from Mesozoic to Cenozoic time, emplaced several ophiolite belts and long magmatic arcs, and also created intracontinental basins (Berberian and King, 1981; Richards, 2015; Stampfli and Borel, 2002; Verdel et al., 2011). Ophiolites are normally emplaced along major faults and are generally interpreted as marks of sutures. The vast plateau area includes remote parts, which are sparsely studied and mostly covered by young and thick sedimentary sequences. Almost no information on basement age is available in these regions with the exception of some Precambrian age continental fragments trapped within the Iranian Plateau.

Interpretation of aeromagnetic data provides an efficient and fast geophysical tool for geological mapping of vast areas as the Iranian plateau. The highest magnetic susceptibility values are usually observed in igneous rocks and ophiolites in contrast to the low values in most sedimentary rocks (Clark and Emerson, 1991; Hunt et al., 1995; Teknik et al., 2019) (**Figure 2**). The radially averaged power spectrum (RAPS) method (e.g. Bouligand et al., 2009; Maus and Dimri, 1995) is widely used for estimating the Curie depth. Here we extend its application to calculation of the vertically averaged crustal magnetic susceptibility from aeromagnetic data. Application of this method provides a solution which is insensitive to the latitude dependence of magnetic data (Maus and Dimri, 1995a), and therefore provides a tool for estimation of the horizontal variation of susceptibility and for identification of high susceptibility rocks in magmatic and suture zones. This routine is easy to implement and fast in comparison to traditional inversion methods, which are based on further assumptions and require a priory information for calculation of the vertical variation of susceptibility (e.g. Li and Oldenburg, 1993).

In this work, we use the RAPS method to calculate the average crustal susceptibility in the Iranian plateau. The results indicate qualitative correlation between strong susceptibility anomalies and the distribution of magmatic arcs and ophiolite belts. Low susceptibility values coincide with major sedimentary basins where the geology is known. On this basis, we extend our analysis to mapping similar features in the remote and sediment-covered parts of the Iranian Plateau. Our analysis identifies unknown magmatic ophiolite arcs (MOA) and boundaries of sedimentary basins, and thereby we revise parts of the tectono-magmatic evolution of the Iranian Plateau.

2. **Geologic setting**

The geodynamic evolution of the Iranian Plateau has been controlled by the opening and closure of the Neo-Tethys and Paleo-Tethys oceans in the south and north of the Iranian plateau, respectively (Stampfli and Borel, 2002). During Permian extension of the Neo-Tethys Ocean, various continental blocks (Cimmerian blocks) were rifted off from the NE margin of Gondwana while the Paleo-Tethys Ocean subducted beneath Laurasia (Richards, 2015; Stampfli and Borel, 2002). These blocks, including central Iranian blocks collided with Laurasia during the closure of the Paleo-Tethys ocean and the subsequent Cimmerian orogeny. After the eventual collision of the Central Iranian blocks with Laurasia, the subduction shifted SW-ward, and Neo-Tethys subducted beneath the Central Iranian blocks in the Triassic (Stampfli and Borel, 2002). The subduction of the Tethys oceans and consequent collision formed a series of magmatic arcs and back-arc basins (the largest may be the south Caspian basin and parts of the Black Sea). Eventually, the Neo-Tethys Ocean and smaller back arc basins were closed by the collision of the Arabian plate with central Iranian blocks in the early Miocene. Trapped remnants of the Tethys Oceans are mapped as ophiolites within the collisional belt (Berberian and King, 1981; Boulin, 1991; Nowroozi, 1971; Stocklin, 1968; Verdel et al., 2011)

Three major structural units of the Iranian plateau are categorized by reconstruction of the Paleo-Tethys and Neo-Tethys oceans (Berberian and King, 1981): (1) The Zagros - Makran orogenic system, which formed during subduction of Neo-Thetys and subsequent collision; (2) The Central Iranian micro plate which formed by amalgamation of Cimmerian blocks to Eurasia; and (3) The NE Turan part of the Iranian Plateau, which formed in relation to the subduction of Paleo-Thetys and subsequent collision (**Figure 1**).

The NW-SE to E-W trending Zagros-Makran orogenic belt is located in the western and southern parts of the Iranian plateau. The Talesh-Alborz-Kopeh-Dagh belt in the northern part of the Iranian plateau trends along the southern edge of Eurasia and the south Caspian basin. The Central Iranian micro plates and magmatic arcs are located between these two major orogenic belts. Zagros, Makran, Kopeh-Dagh, eastern Alborz and some central Iranian blocks, e.g. Tabas, include major sedimentary basins, which host hydrocarbon reservoirs. The Sanandaj-Sirjan metamorphic Zone (SSZ), and the parallel Urmia-Dokhtar Magmatic Arc (UDMA), extend from the NW to the SE of the plateau. The Sabzevar-Kavir magmatic ophiolite belt and the eastern magmatic zone are located at the boundaries of the Central Iranian micro plates and in the eastern Sistan suture Zone (**Figure 1 and 3a**).

Urumieh-Dokhtar Magmatic Arc (UDMA) evolution: The Urumieh-Dokhtar Magmatic Arc formed by subduction of the Neo-Tethys Ocean beneath Central Iran (e.g. Berberian and King, 1981; Verdel et al., 2011). Different phase of magmatic activity may have overlapped in the Iranian plateau. The magmatic activity related to the Neo-Tethys subduction started from Jurassic (155 MA), in the SSZ Mesozoic arc. After a magmatic activity gap in the early Cretaceous, magmatic activity started along the UDMA from Late Cretaceous (100MA), but the maximum magmatic activity of the UDMA elongated an igneous “flare-up” event during the Eocene-

Oligocene (55–25 Ma) (**Figure 3b)**. The UDMA magmatism ceased in the Late Miocene. Then, the post-collisional volcanism started ca. 11 Ma in the Lesser Caucasus, NW Iran and eastern Anatolia regions **(Figure 3b**) (Chiu and et. al., 2013).

Zagros and Makran orogenic belt: The NW-SE trending Zagros orogenic system can be divided into three parallel structural domains (a) Zagros Fold and thrust belt (ZFTB); (b) The Mesozoic metamorphic and magmatic Sanandaj–Sirjan Zone separated from ZFTB by the Main Recent Fault (MRF) and Main Zagros Thrust (MZT), and (c) the Tertiary Urumieh–Dokhtar Magmatic Arc (Berberian, 1995; Sepehr and Cosgrove, 2004) (**Figure 1**). Its SE continuation identifies the location where the last remnant of the Neo-Tethys Ocean is currently subducting along the Makran trench south of Iran and Pakistan. North of this belt, the Cenozoic Jazmurian basin is interpreted as a back-arc basin of the Makran subduction system (Burg, 2018; Glennie et al., 1990; McCall and Kidd, 1982).

Central Iran microplates: The region includes three major crustal blocks (from east to west): the Lut, Tabas, and Yazd blocks (**Figure 1**). Geological origin and age of this continental part are poorly known but the blocks are considered Cimmerian (Richards, 2015; Stampfli and Borel, 2002). The presence of ophiolite belts across central Iran suggests that several small back-arc basins formed during the subduction of the Neo-Tethys Ocean. These inner plateau oceans (such as Sabzevar and Sistan oceans) were destroyed mainly after the collision between the Arabian plate and central Iranian plates in the Neogene (Şengör, 1990a; Şengör 1990b). The Sabzevar-Kavir magmatic ophiolite arc (MOA), which includes an ophiolitic mélange, is considered one of the back-arc basins (Richards, 2015).

Eastern Iran: The Sistan zone - Lut region includes ophiolites, Tertiary magmatic rocks, and major, late Tertiary strike-slip faults. No comprehensive tectonic – geological mapping has been carried out since the mapping by Stocklin (1968). Key questions concern the location of the eastern boundary of the Central Iranian block and the nature of obducted ophiolites and their relationship to the Sabzevar-Kavir zone. Back-arc rifting may have opened several small oceanic basins and subsequent closure caused magmatism in the eastern Iran (Alaminia et al., 2013; Arjmandzadeh et al., 2011; Richards, 2015).

Talesh-Alborz and Kopeh-Dagh: The arch-curved, 3-5 km high Alborz Mountains south of the Palaeo-Tethys suture zone includes about 5 km of Phanerozoic rocks (Ballato et al., 2011; Teknik and Ghods, 2017). The Kopeh-Dagh Mountains mark the north-eastern edge of the Arabia–Eurasia collision zone in Iran and include a 10 km deep sedimentary basin with folded Mesozoic-Tertiary sedimentary rocks (Berberian and Berberian, 1981).

South Caspian Basin includes a 20–25 km thick sedimentary sequence on top of a 10 km thick crystalline crust (Jackson et al., 2002) . Its origin is disputed. Models include a Paleo-Tethys oceanic remnant (Dewey et al., 1973), a trapped remnant of an early Mesozoic back-arc oceanic crust (Berberian, 1983), and a Cretaceous to Paleogene strike slip-related pull-apart basin (Şengör, 1990). Our recent gravity modelling indicates that the South Caspian Basin may be of continental rather than oceanic origin (Teknik et al., 2019).

3. Data and Method

We apply the radially averaged power spectrum (RAPS) method to calculate the average crustal magnetic susceptibility. This approach assumes fractal induced crustal magnetization and parallel or antiparallel remanent magnetization to the present geomagnetic field (Maus et al., 1997). The susceptibility is estimated inside a horizontal window and we assume that the values represent the vertically averaged susceptibility from the surface to the Curie depth point (CDP) inside the window. The spatial resolution is limited by the averaging window (80 x 80 km) with 90% overlap between windows.

The magnetic data originates from the aeromagnetic survey of Iran, which was conducted by Aeroservice (Houston, Texas) in 1974-1977 for the Iranian Geological Survey with an average line spacing of 7.5 km and perpendicular lines every 40 km. The survey includes more than 250,000 km profiles with ca. 4.4 million data points. The direction of flight lines varies and depends on the topographical and geological features trend. We use the composite aeromagnetic 1 × 1 km grid calculated from the original raw data by Saleh, (2006) by using bidirectional interpolation scheme (**Figure 4**).

4. Results

Sedimentary basins: Sedimentary rocks usually are weakly magnetized and we mainly attribute low average susceptibility to the presence of sedimentary basins. Our results confirm the location of major basins, such as in the Zagros, Kopeh-Dagh and Makran accretionary prisms with their extremely low average susceptibility. Similar to these basins, we suggest considerable sediment cover without any magmatic activity in the Tabas basin and central part of the Yazd block. The low susceptibility values of the Yazd block suggest the presence of a possible sedimentary basin parallel to the Zagros trend. Despite the presence of igneous rock outcrops in the northern part of the Lut block, the low susceptibility anomaly suggests the presence of a sedimentary basin in this region, similar to the Tabas and Yazd blocks. Our results show an unexpected NNW-SSE extension of the Yazd-Tabas basins into central Iran with extremely low average crustal susceptibility which is almost 250 km long in the NNW-SSE direction and around 150 km wide. (**Figure 1 and 8**).

The western Alborz low susceptibility anomaly suggest a large sediment volume or limited magmatic activity and/or ophiolite emplacement in comparison to the eastern Alborz. Further, high average susceptibility indicates that the Sabzevar magmatic ophiolite belt may extend SW-ward below the Great Kavir sedimentary basin (**Figure 1, 6 and 7**). The Great Kavir basin, despite the low relief, shows relatively high average susceptibility and sporadic anomalies.

The high susceptibility anomaly in the Jazmurian depression, in the SE corner of the SSZ, suggests the presence of igneous and/or oceanic crustal rocks beneath the sedimentary cover, whereas the low susceptibility anomaly in the NW of SSZ (NE front of Kermanshah ophiolites) suggests the presence of a local basin.

Ophiolite belts: In this study, we observe direct correlation between ophiolite outcrops and high average susceptibility anomalies in the Iranian plateau (**Figure 3 and 6**). In the Zagros suture zone, the high susceptibility anomalies of the Neyriz ophiolite continues to the NE below the sedimentary cover, suggesting that the ophiolite extends under the sedimentary cover. Lower intensity of the susceptibility anomaly suggests that the volume of the Kermanshah ophiolites is smaller than for the Neyriz ophiolites.

The Makran ophiolite is characterized by very high susceptibility with a sharp northward increase in amplitude at the edge of the ophiolite outcrops. The anomaly extends further north as a high-amplitude broad zone despite lack of outcrops at surface of ophiolite or igneous rocks. This observation suggests a northward extension of the Makran ophiolites and/or Cretaceous age igneous rocks beneath the sedimentary cover (**Figure 3 and 6**). The Cretaceous igneous rocks, located in the south and north of Jazmurian depression (**Figure 3)**, are emplaced during a age rifting event that was active during Jurassic-early Cretaceous (Burg, 2018). .

In Eastern Iran, the Sistan zone ophiolites have high susceptibility in two arch-shaped anomalies. We name the arch-shaped anomalies the Southern Sistan Magmatic Arc (SSMA) and the Northern Sistan Magmatic Arc (NSMA) magmatic anomalies (**Figure 11**). The SSMA matches with ophiolite outcrops in the south but bends toward the west into a zone where possible ophiolite are covered by sedimentary rocks, and the shape of the NSMA anomaly has the same trend as the SSMA.

Based on the susceptibility map we interpret the Sabzevar zone and Great Kavir Basin with their thick sedimentary cover as one tectonic block between Afghanistan and central Iran, which is southward limited by the Darouneh strike-slip fault. In the western part of Sabzevar-Great Kavir zone the high susceptibility anomalies, mostly, coincide with ophiolites, while, toward to the west igneous rocks are dominant at the surface.

Magmatic zones: Geological mapping identifies four major magmatic areas in the Iranian Plateau (Figure 3): 1- The Tertiary Urumieh–Dokhtar Magmatic Arc (UDMA). 2- The Mesozoic Sanandaj-Sirjan magmatic arc. 3-Sabzevar – Kavir magmatic ophiolite belt and 4- Lut volcanic-plutonic belt of central eastern Iran (**Figure 3**).

Our results show a strong correlation between high average susceptibility and the location of surface outcrops of all these magmatic zones (**Figure 6**), in particular along the Urumieh–Dokhtar Magmatic Arc. This observation motivates us to identify new magmatic belts from the average suceptibility. Toward the SW of the Urmia-Dokhtar magmatic arc, the average susceptibility value in the Sanandaj-Sirjan zone is higher than in the Zagros Belt, which indicates tectonic differences between Zagros and SSZ. Sporadic high susceptibility anomalies indicate a sporadic distribution of the Mesozoic age magmatic outcrops and ophiolites in the Sanandaj-Sirjan zone.

Our results show a remarkable correlation between igneous rock outcrops and high susceptibility anomalies in the magmatic-ophiolite belt of the Sabzevar-Great Kavir. The high susceptibility anomaly in the middle of Lut block does not match any outcrop of igneous rocks, probably, due to sediment cover, but suggest the presence of large magmatic/ophiolite bodies.

The Yazd block is separated from the Tabas block by a linear susceptibility anomaly, where the parts with sporadic high susceptibility correspond to outcrops of Precambrian age rocks (**Figure 3 and 6**). These Precambrian outcrops represent an intense, approximately east-west striking Eocene crustal extension that formed a ~400-km-long NE-SW belt of metamorphic core complexes, which now are localized along the boundary between the Yazd and Tabas tectonic blocks (Verdel et al., 2007) as highlighted by the large average susceptibility values.

5. Discussion:

A first-order observation confirms that mapped mafic igneous and ophiolite rocks correspond to areas with strong positive average susceptibility, and that the major sedimentary basins correspond to areas with the lowest values of average susceptibility (Figure 5). The strong correlation between susceptibility anomalies and surface magmatic - ophiolite outcrops motivate us to extend our interpretation to other regions with anomalous susceptibility and less constrained tectonics. We have earlier demonstrated that variation in magnetic susceptibility, along a NE-SW striking profile in NW Iran, may identify sutures and terranes (Teknik et al., 2019). Furthermore, the susceptibility contrast between the crystalline basement and sediment cover has been used for mapping magnetic basement in the Iranian plateau (Teknik and Ghods, 2017). Similar to our study, Munt et al. (2012) attributed the residual gravity anomaly to the upper crustal structures such as deep basins, igneous and ophiolite complexes. The basins with salt deposits are characterized by negative values (∼−20 mGal) and positive anomalies are related to the shallow basement depths and igneous-ophiolite rocks(∼20 mGal). In addition to the sparsity of the terrestrial gravity data of Iran, the order of susceptibility contrast between igneous- ophiolite (generally; crystalline) rocks and sedimentary rocks are much higher than density contrast. Therefore, we find that the magnetic data can better show these contrasts. The residual gravity anomaly map by Munt et al. (2012) partially confirms correlation between distribution of igneous and ophiolite, but our results highlights the efficiency of our method.

5.1 Sedimentary Basins

The low average susceptibility anomaly in the best known basins of the study area (e.g. Zagros, Makran, Kopeh-Dagh, and Tabas) is caused by the presence of a thick, non-magnetized sedimentary cover. This implies that these basins have not been subject to mafic magmatic activity and ophiolite emplacement, at least in the upper sequences. We observe sporadic susceptibility anomalies in the eastern part of the Alborz and Jazmurian depression and Great Kavir sedimentary basin which indicates the presence of volcanic and magmatic rocks at depth in the sedimentary cover.

Despite hydrocarbon exploration in the major Zagros, Makran and Kopeh-Dagh basins, thickness and surface extent of basins in the Iranian plateau are still uncertain. The intra-plateau Tabas block has been subject to geological studies (e.g. Konon et al., 2016) which show that it is fault bounded. No igneous intrusions have been mapped within the Tabas block, probably due to thick sedimentary cover. By analogy to the Zagros-Makran system, we interpret low, homogeneous susceptibility values by the presence of a large, deep sedimentary basin without magmatic rocks. We propose that the Tabas basin extends northwestward into the Yazd block (Figure 8) and that its northern and southern boundaries do not coincide with the suggested boundaries of the Tabas block (**Figure 8**) (Berberian and King, 1981; Talbot and Alavi, 1996). Large scale dextral transtension along the bounding faults may have created the Tabas basin as proposed by Konon et al., (2016), e.g. during counterclockwise rotation of the tectonic Lut, Tabas, and Yazd blocks (Şengör, 1990b). Another explanation may be related to westward subduction of ancient Sistan oceanic crust under the Lut block (Verdel et al., 2007).

The core complex zone between the Yazd and Tabas blocks (Verdel et al., 2007), includes Precambrian crystalline units that contrast the Mesozoic and younger rocks in the two blocks. The high susceptibility along this zone suggests that the sedimentary cover is thin, possibly due to early Miocene erosional exhumation (Şengör, 1990b; Verdel et al., 2007).

The Zagros suture is characterised by a sharp susceptibility contrast, which we attribute to compositional variation in the near surface rocks, noting that the susceptibility usually is higher in metamorphic than sedimentary rocks (**Figure 2**). The NW and SE parts of SSZ have relatively low average susceptibility with sporadic high susceptibility spots that indicate a dispersed distribution of ophiolites, e.g. at the Kermanshah and Neyriz ophiolites zones (**Figure 6 and Figure 7**). Our results suggest that these ophiolites connect under the sedimentary cover along the strike of the SSZ. Low susceptibility in the central part of the

SSZ, in agreement with surface geological observations, indicates the absence of magmatic and ophiolite complexes.

In the SE end of the SSZ, the high susceptibility anomaly suggests that the Makran ophiolites may extend beneath the sediment cover of the Jazmurian depression (**Figure 11**). The Juzmurian depression may be a remnant of a back-arc basin below the present-day Jazmurian basin (e.g. Burg 2018) or a fore-arc basin of the Urumieh-Dokhtar Magmatic arc (e.g. Alavi, 1994; Alavi, 2007). Cretaceous magmatic rocks are located at the northern and southern border of the Jazmurian depression (Figure 3) around an extensional area (Burg 2018). We speculate that the northward extent of the Makran high susceptibility may indicate the presence of Cretaceous magmatic rocks beneath the Jazmurian sediments.

5.2 Magmatic arcs and their relation to paleo-subduction properties

Subduction zones are sites where tectonic processes destroy oceanic lithosphere and form new magmatic material that may be the building blocks of new continental crust (Tatsumi 2005). Magmatic arcs usually exhibit some characteristics of their associated subduction system. Two global studies demonstrate that the volcanic arc width (Tatsumi and Eggins, 1997) and the depth to the top of the zones of intermediate-depth seismicity beneath arc volcanoes (England et al., 2004)show negative linear correlation with the subduction angle. We use the results by Tatsumi and Eggins (1997) to estimate the paleo-dip of subduction systems related to the MOAs in Iran from the distance between the trench and magmatic arcs (Figure 9).

Urmia Dokhtar Magmatic Arc (UDMA): The magnetic susceptibility results indicate that the UDMA may be divided into the 600 km long and up/to 200 km wide Azarbayjan-Alborz

Magmatic Arc (AAMA) north of 34° N, and the 1300 km long and 50 to 60 km wide Arak-Jazmurian magmatic arc (AJMA) (Figure 8). The width of the magmatic arcs indicates very shallow subduction with a dip of <20 º for AAMA, whereas the AJMA was characterized by steep subduction at an angle of 50 º to 70 º dip (Figure 9 and Figure 10). Shallow subduction requires a buoyant slab. The absence of magmatic activity in the Alborz to the east of the Damavand volcano suggests shallow subduction.

The Central Iran magmatic activity: Eastern Iran includes a series of volcanic–plutonic ophiolite complexes which extend ca. 1000 km southward from the Sabzevar-Kavir MOA into the Lut block. The Sabzevar-Kavir MOA includes arch-shaped anomalies typical of island arcs. Their width of 100 km in the east and 200 km in the west suggests that the subduction angle had an east to west decrease from 50º to less than 20º (Figure 9). Our data indicate that this igneous complex extends westward into the Great Kavir basin.

In Eastern Iran, despite the occurrence of massive magmatic and ophiolitic belts, there are no clear magnetic arc-shaped patterns reported in the geology maps and studies. We observe two clear parallel arc-shaped, high-susceptibility belts below the sedimentary cover in eastern Iran which have never been identified before (**Figure 11**). We propose that these anomalies represent two hitherto unknown magmatic arcs, which we name Southern Sistan Magmatic Arc (SSMA) and Northern Sistan Magmatic Arc (NSMA). We suggest that these two arcs are part of a Mesosoic magmatic arc at the Sistan suture zones, which are bended and segmented due to anti clockwise rotation of the Lut block (Mattei et al., 2012) in response to the convergence between the Arabian plate and the rigid Eurasian plate. Another interpretation may suggest that two independent magmatic arcs formed by lateral displacement of the subduction system, possibly after accretion of a micro-continent which today is located between the two magmatic arcs.

The length of each arc is ca 400-450 km and the width is ca 40 km to 60 km similar to the AJMA, corresponding to a dip angle of ca. 60º (**Figure 9** and **11**). The existence of two parallel magmatic arcs is unusual and we are unaware of any tectonic analogues, although deformation of the Paleozoic subduction complexes in Asia created a series of repeated magmatic complexes similar to the Altaides (Şengör et al., 2014). However, by slab retreat the same subduction system could have sourced the two parallel zones, which then would represent two paired zones of volcanoes as proposed by Tatsumi (2005). In this case, the joint system would be ca. 200 km wide, corresponding to a subduction dip angle of <20º.

Regions with poor correlation of susceptibility and MOA: Two areas with known presence of igneous and ophiolite rocks are characterized by low average susceptibility, mainly NW of the SSZ and north of the Lut block beneath Darouneh falut (**Figure 1,4 and 6**).We speculate that the low susceptibility values may be caused by alteration of the original rocks or by effects from remnant magnetization in the opposite direction of the induced magnetization. An inherent assumption of the RAPS method is that remnant and induced magnetization must be parallel and in the same direction. This observation indicates uncertainty in our results here and a different origin and deformation history of these magmatic arcs from other arcs of the Iranian Plateau.

A discontinuous Mesozoic magmatic arc is indicated by scattered Jurassic to Cretaceous intrusive rocks from the Sanandaj Sirjan zone to Makran and further to the easternmost part of Lut (**Figure 3**) (Berberian and Berberian, 1981; Sengor 1990b). There is no significant correlation with Mesozoic magmatic outcrops. It has been proposed that the high susceptibility value for Paleogene arcs in central and northern Iran, relative to the Mesozoic arc, reflects different source of magmatism as discussed by Verdel et al. (2011). This interpretation proposes that the two parallel easternmost anomalies may derived from ophiolites, in analogy to the Kermashah and Neyriz ophiolite in the SSZ (Figure 8).

6. **Conclusion**

We have applied the RASP method to calculate and map the average magnetic susceptibility in Iran. The results demonstrate that known occurrences of Magmatic-Ophiolite Arcs (MOA) correlate with high average susceptibility areas, although the calculated susceptibility is low at two MOAs. We conclude that magnetic susceptibility is a useful parameter for identification of MOAs in areas with sparse geological information, be it due to a remote location or thick sedimentary cover.

We discover two parallel, hitherto unknown MOAs in eastern Iran which developed in a steeply dipping (>60º dip) subduction zone, although we cannot completely rule out that they represent paired lines of volcanoes in a system with shallow subduction. Our results indicate shallow subduction (<20º dip) of the Neo-Tethys ocean in the NW (AMAA) and SE parts of the Alborz as well as in the Sabzevar-Kavir MOA. In contrast, the major, central part (AJMA) of the Alborz and the newly discovered eastern MOAs formed in steeply dipping (>60º dip) subduction systems. Based on the magnetic susceptibility results we identify new boundaries of the economically valuable Tabas sedimentary basin.

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Figures

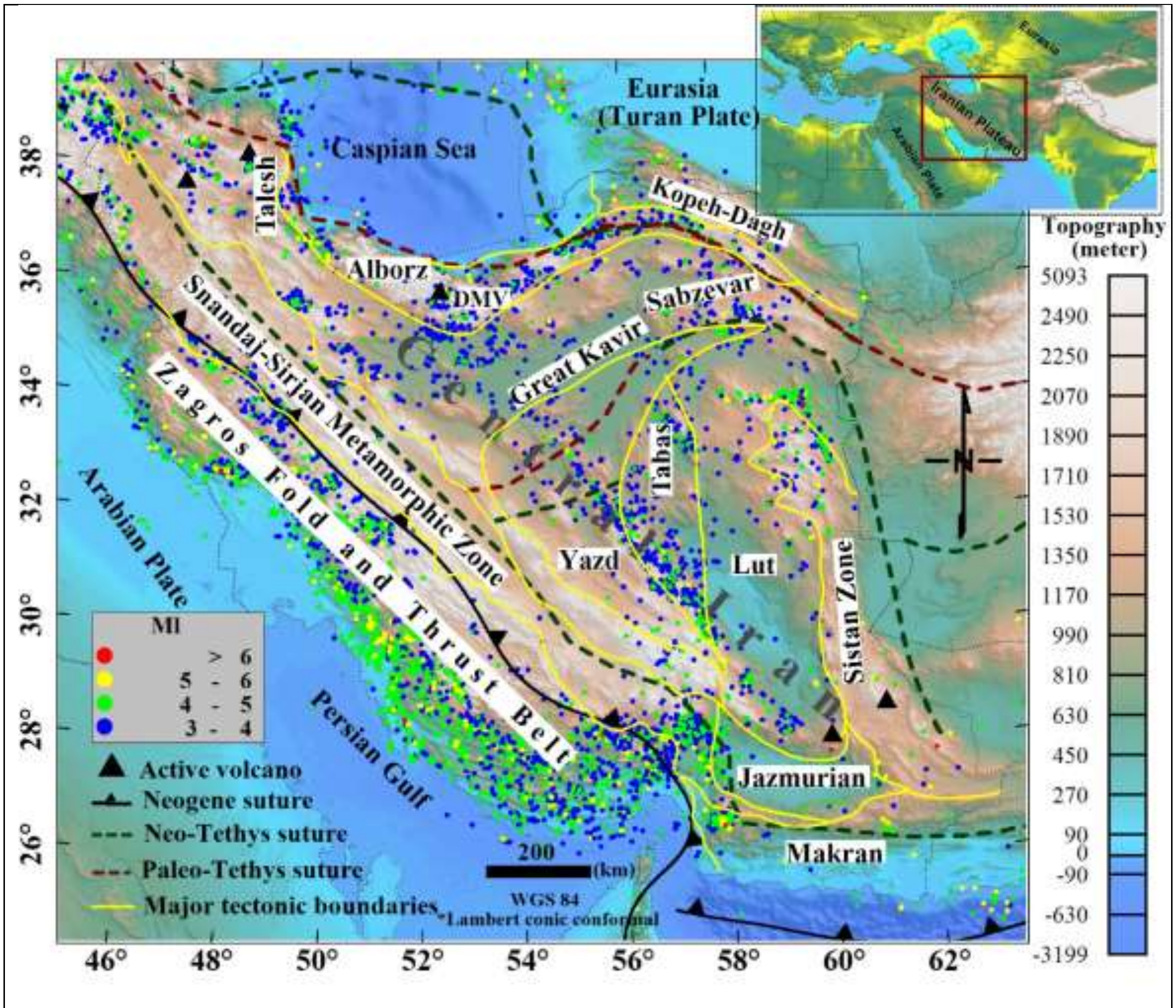

Figure 1: Topography of the Iranian plateau based on the ETOPO 1 global elevation model (Amante and Eakins, 2009) with main tectonic structures superimposed. Thick lines represent major suture zones associated with the Paleo-Tethys (Permian to Jurassic) and Neo-Tethys oceans (Cretaceous–Cenozoic) subduction and collision closures (after Richards and Şengör, 2017) and yellow bold lines outline other main tectonic features (after Nogole-Sadat and Almasian, 1993). Colored dots mark earthquake epicenters and magnitudes (MI in the figure) from Engdahl et al. (2006) for the period of 1964-1998, supplemented by recently collected data by Institute of Geophysics of Tehran University (IGUT) from the Iranian Seismological Center website (irsc.ut.ac.ir/bulletin.php last download March 2017). The IRSC catalogue is searched for magnitude larger than 3.0 and azimuthal gap smaller than 120. The tectonically active part of the Iranian Plateau is defined by broad bands of seismicity concentrated in belts around small, relatively stable blocks.

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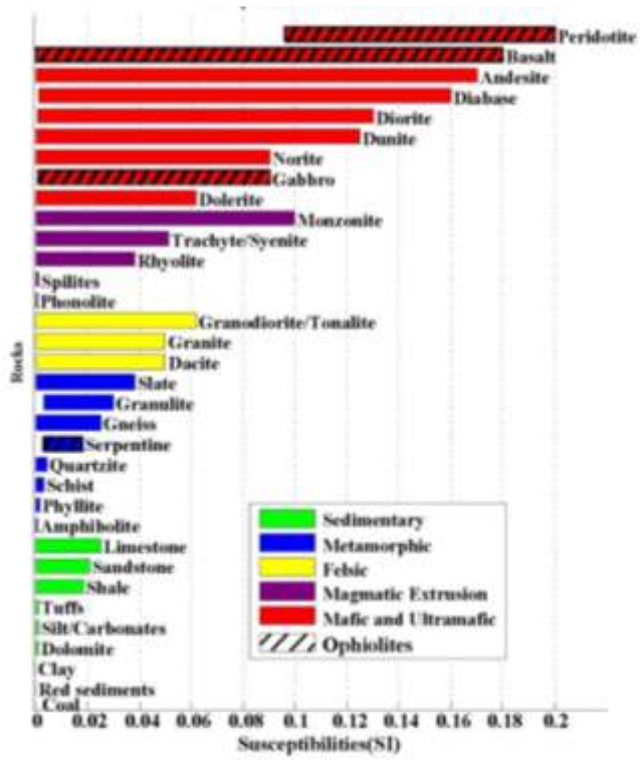
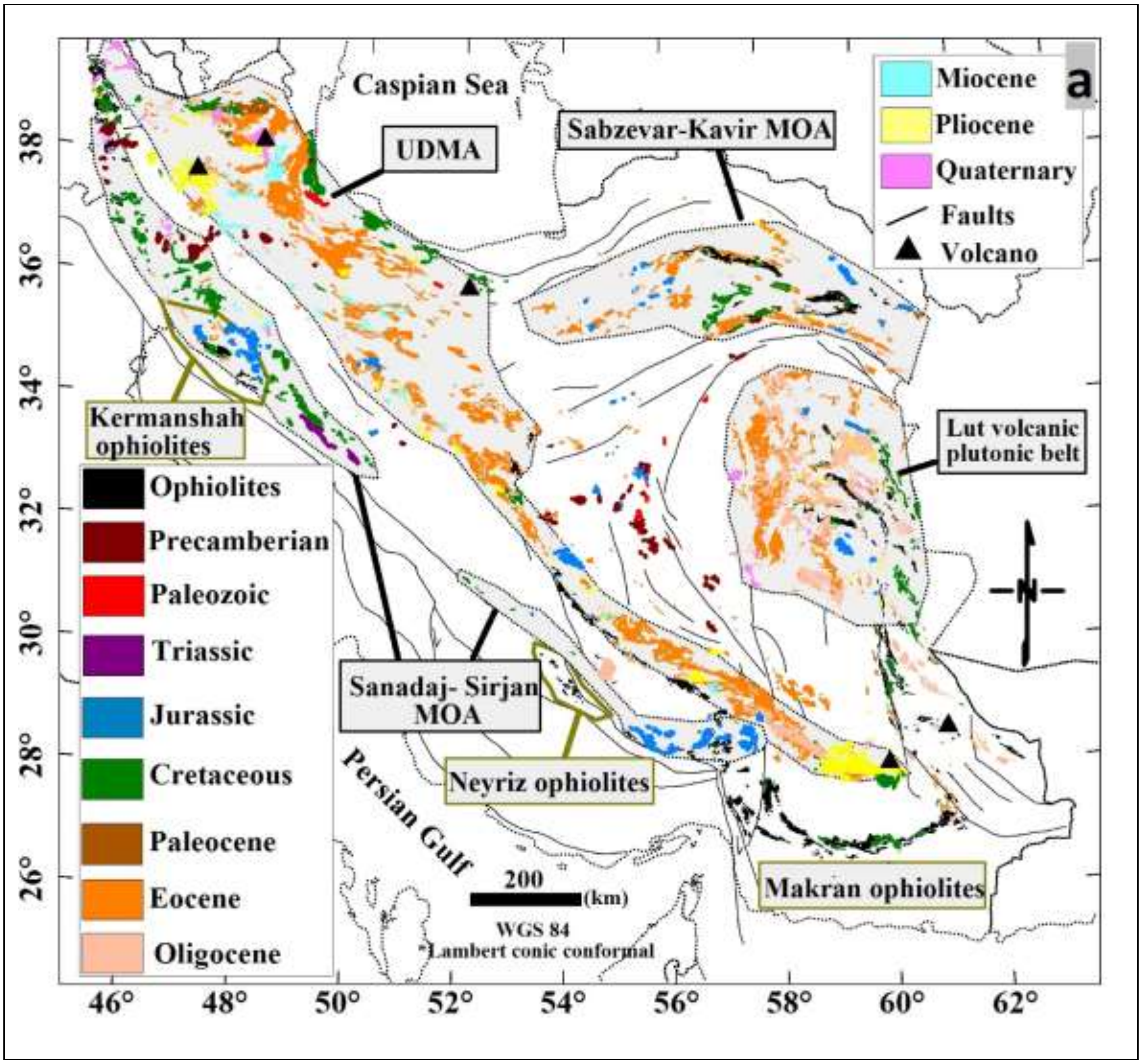


Figure 2: Range of magnetic susceptibility variation for different rock types (based on Clark and Emerson, 1991; Hunt and et al, 1995). Mafic and ultramafic rocks have the highest susceptibilities, sedimentary rocks have the lowest susceptibilities


a
Caspian Sea
UDMA
Sabzevar-Kavir MOA
Miocene
Pliocene
Quaternary
Faults
Volcano
Kermanshah ophiolites
Lut volcanic plutonic belt
Ophiolites
Precamberian
Paleozoic
Triassic
Jurassic
Cretaceous
Paleocene
Eocene
Oligocene
Sanadaj- Sirjan MOA
Neyriz ophiolites
Persian Gulf
Makran ophiolites
200 (km)
WGS 84
*Lambert conic conformal
N
38°
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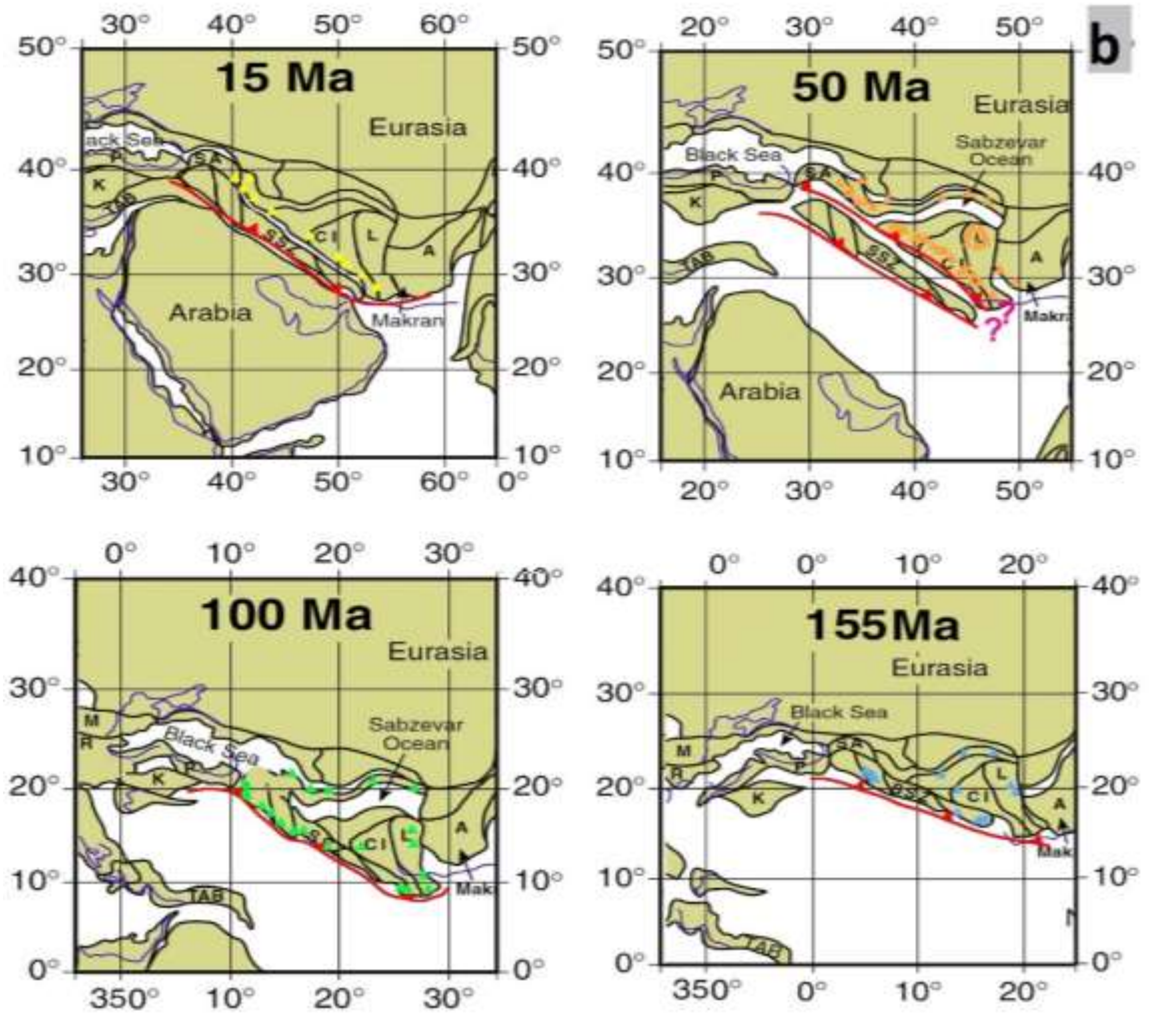

Figure 3: a) Location and age of mapped magmatic rocks and four major magmatic zones in Iran based on 1:100 000 scale maps from the Geological Survey of Iran.

b) Paleogeographic reconstructions of the central Neo-Tethys realm (after Richards 2015). Blue lines represent present-day coastlines, for reference. The red line indicates the subduction places The triangles indicates the distribution of magmatism inferred from magmatic map (**Figure 3a)** and colours of the triangles indicates age according the magmatic map (**Figure 3a).**

Abbreviations: UDMA – Urumieh-Dokhtar Magmatic Arc; MOA – Magmatic Ophiolite Arc; A – Afghan block; CI – Central Iranian block; K – Kirşehir block; L – Lut block; P – Pontides; SA – South Armenian block; SSZ – Sanandaj Sirjan Zone; TAB – Tauride Anatolide block.

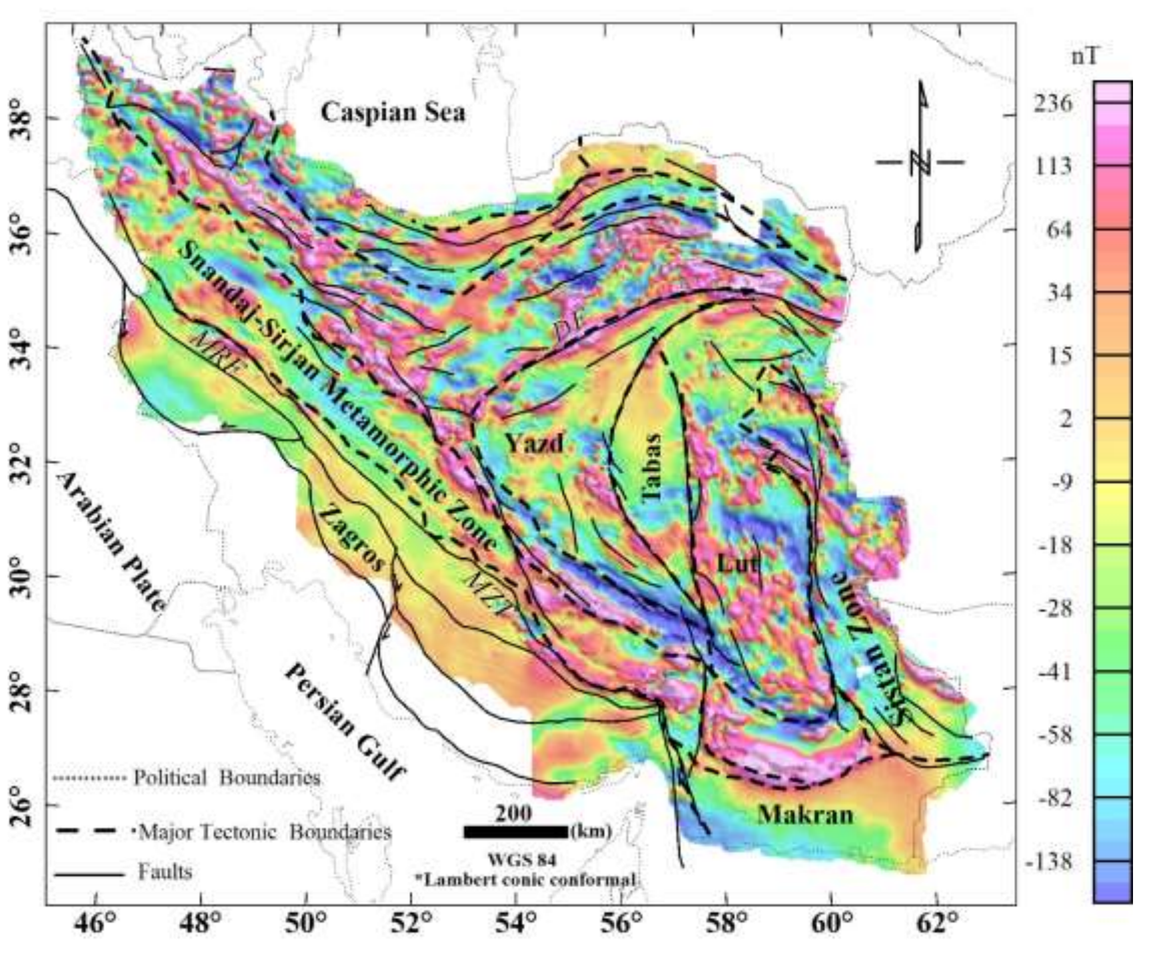

Figure 4: Aeromagnetic map of Iran (after Saleh, 2006). The black solid lines show the surface traces of active faults (after Hessami et al., 2003). Abbreviations: DF-Darouneh Fault; MZT - Main Zagros Thrust; MRF-Main Recent Fault.

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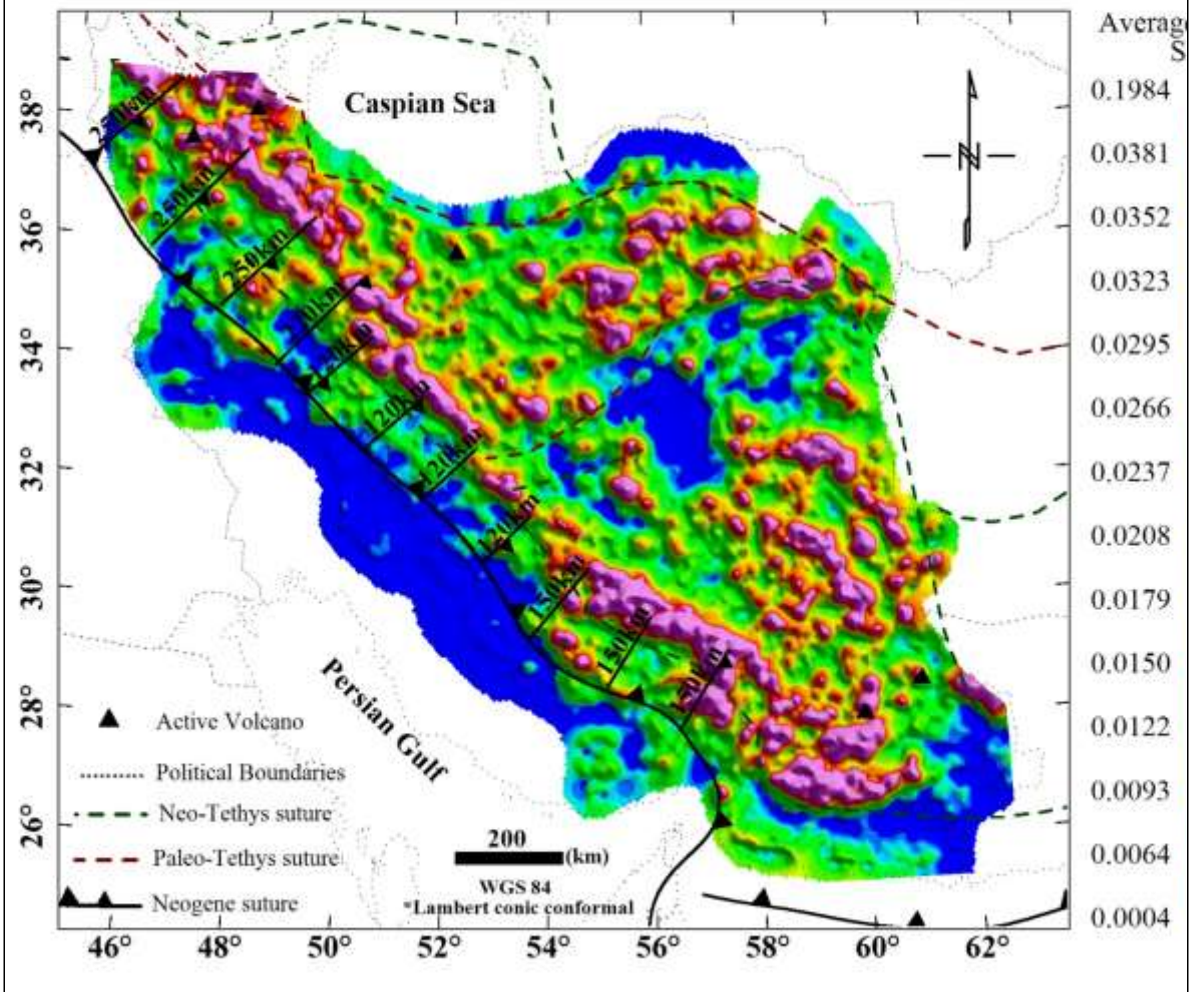

Figure 5: Calculated average crustal susceptibility of Iran overlain by (thick dashed lines) suture zones (after Richards and Şengör, 2017). Resolution is limited by the 80 × 80 km horizontal averaging and the vertical averaging from the surface to the Curie Depth Point (CDP). Present-day arc-trench distances along Urmia Dokhtar Magmatic Arc are marked at selected locations.

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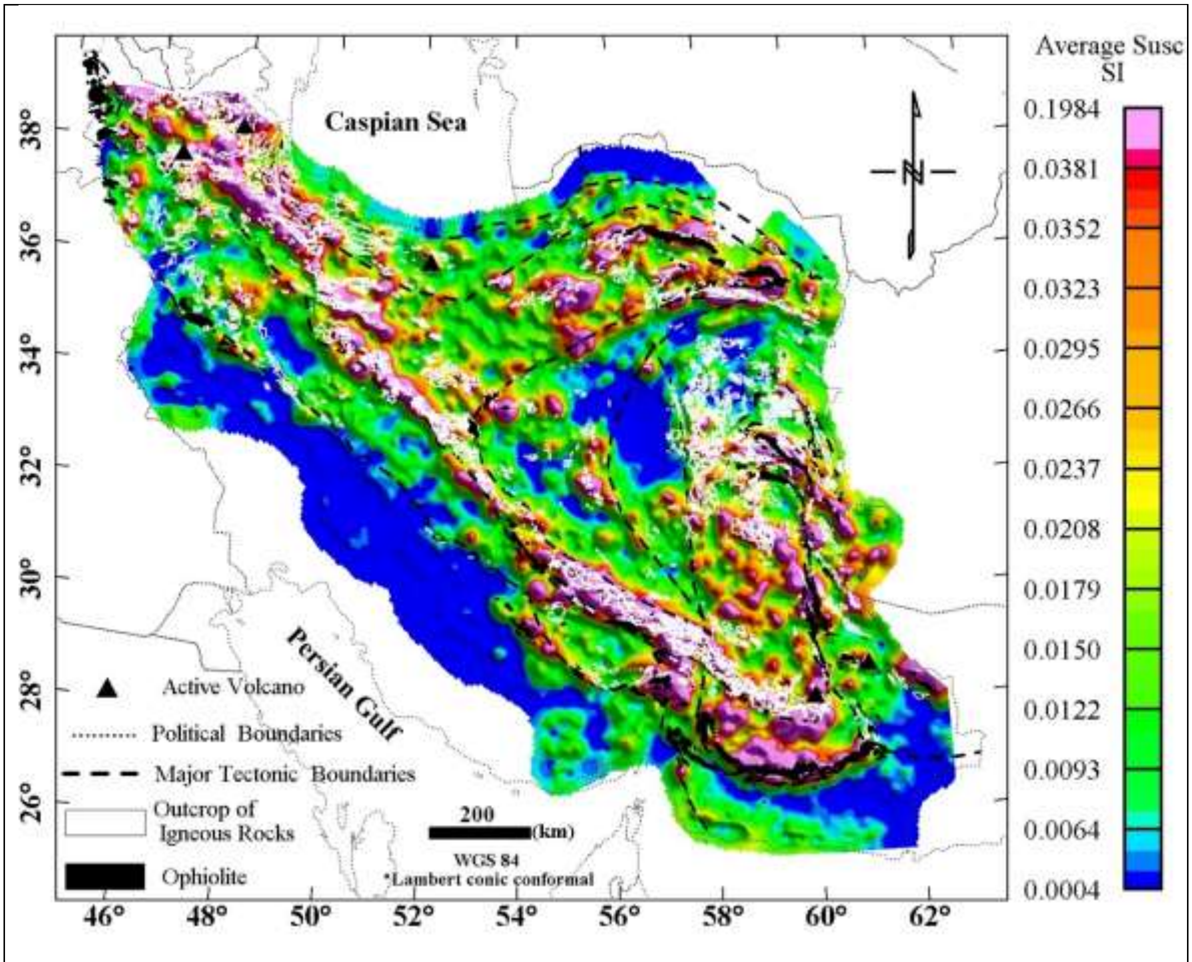

Figure 6: Average susceptibility map overlain by locations of surface outcrops of igneous rocks and ophiolites (thin white and black lines, respectively). Black dashed lines are borders of geological units (after Nogole-Sadat and Almasian, 1993).

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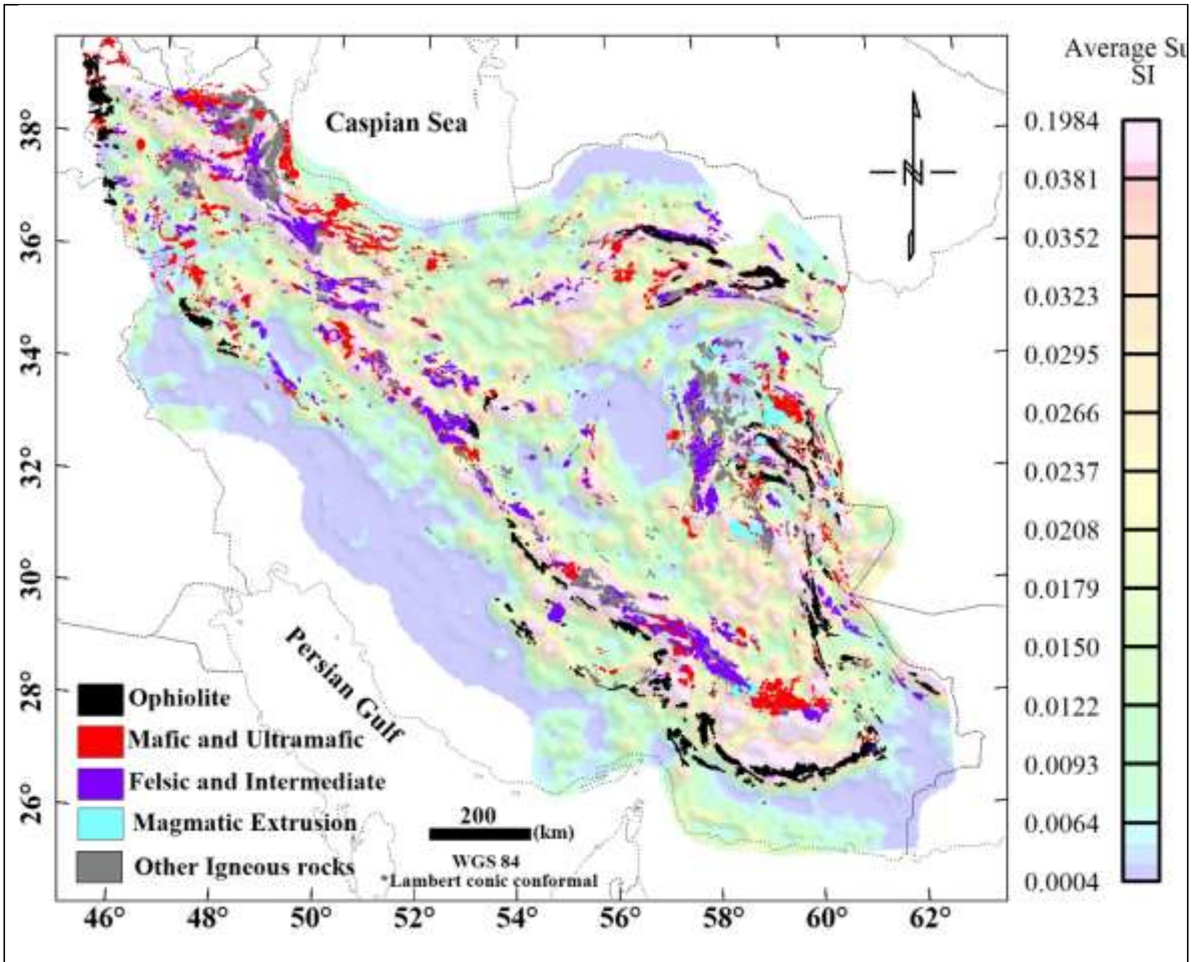

Figure 7: Average susceptibility map super-imposed by a classification of igneous rocks based on division in figure 2 and major trends in average susceptibility values.

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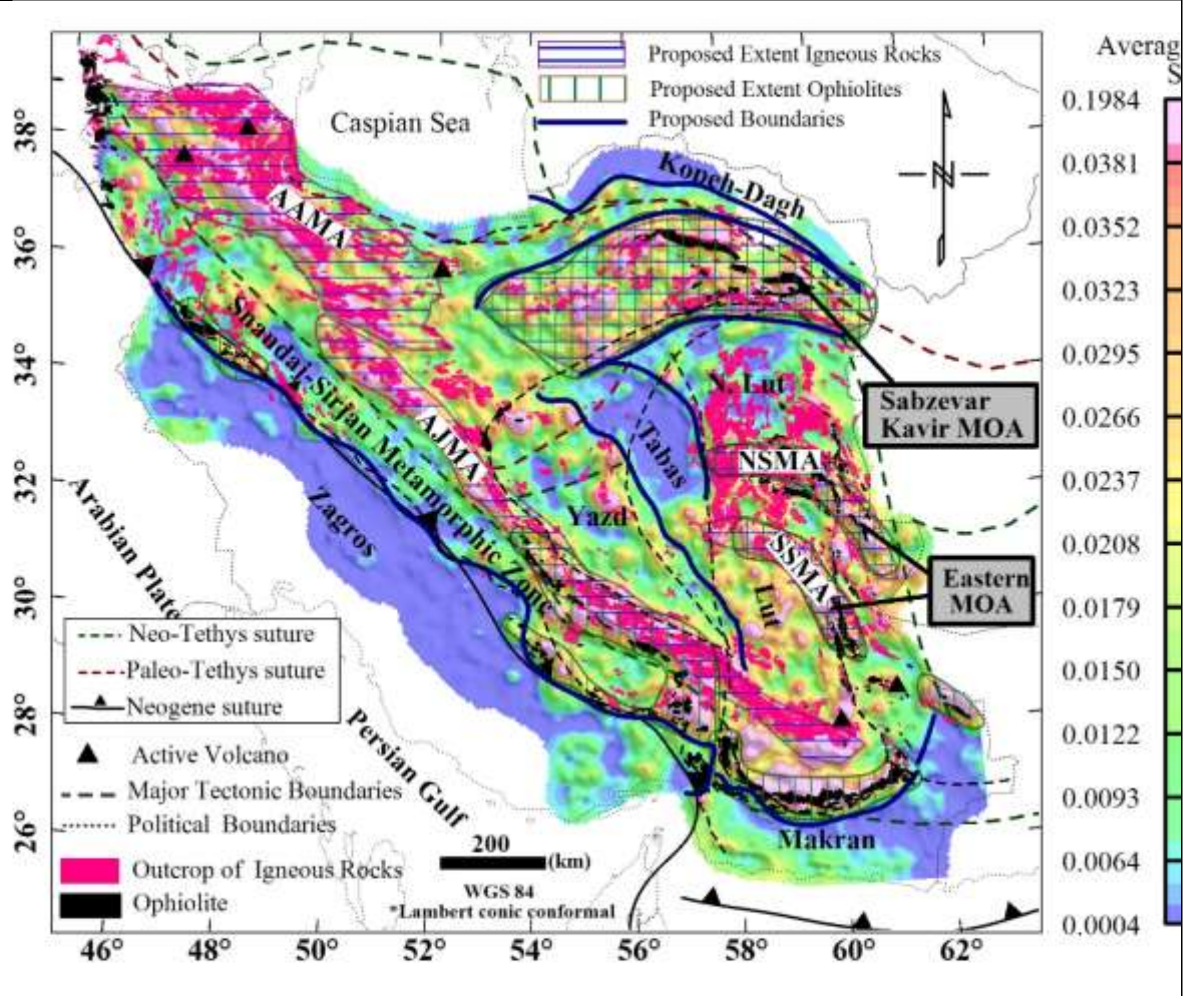

igure 8: New tectonic interpretation based on average susceptibility and correlation with distribution of outcropped ophiolite and igneous rocks. Results shows that the Urmia Dokhtar Magmatic Arc (UDMA)can be divided into a wide and curved Azarbayjan-Alborz Magmatic Arc (AAMA) in the NW and a narrow and straight Arak-Jazmurian Magmatic Arc (AJMA) from central Iran to SE of Iran. We recognize the Tabas basin as a tectonic province with new properties and we revise the boundaries between Tabas and Yazd blocks. We also interpreted two new parallel arch shapes in eastern Iran including Southern Sistan Magmatic Arc (SSMA) and Northern Sistan Magmatic Arc (NSMA)

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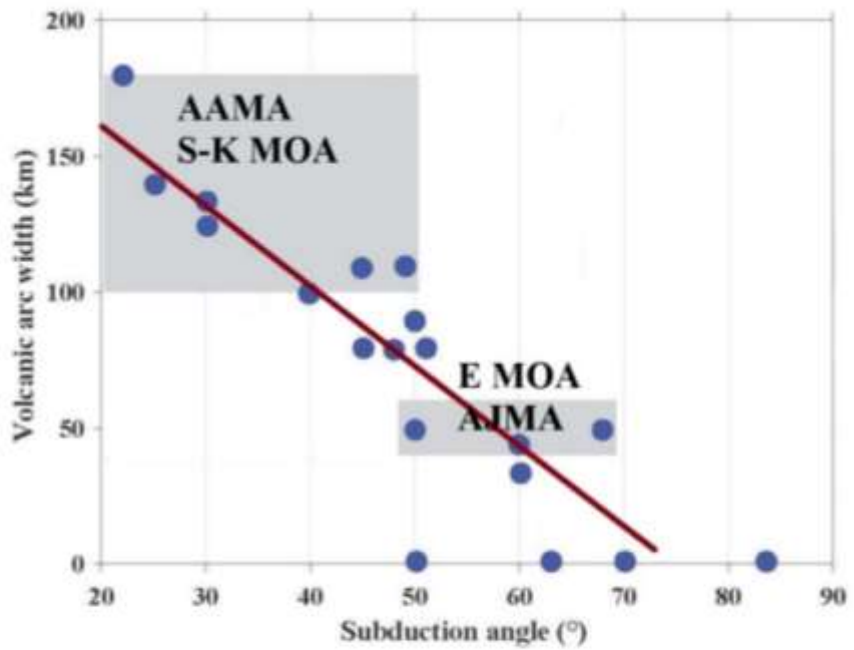

Figure 9: Tectonic characteristics of subduction zone magmatism demonstrating a negative correlation between subduction angle and volcanic arc width (blue circles; Tatsumi and Eggins, 1997). The width of the grey rectangles corresponds to the range of width of the inferred magmatic belts (100-180 km for AAMA and S-K MOA; and 40-60 km for E MOA and AJMA), and the length of the rectangles indicate the range of estimated subduction angle. The red line indicates the best fit line and the crossing points with grey rectangles indicate the mean value volcanic arc width and subduction angle for each arc. Abbreviations: AAMA: Azarbayjan-Alborz Magmatic Arc; S-K MOA: Sabzevar-Kavir magmatic-ophiolite arc; E MOA: Eastern magmatic-ophiolite arc; and AJMA: Arak-Jazmurian magmatic arc.

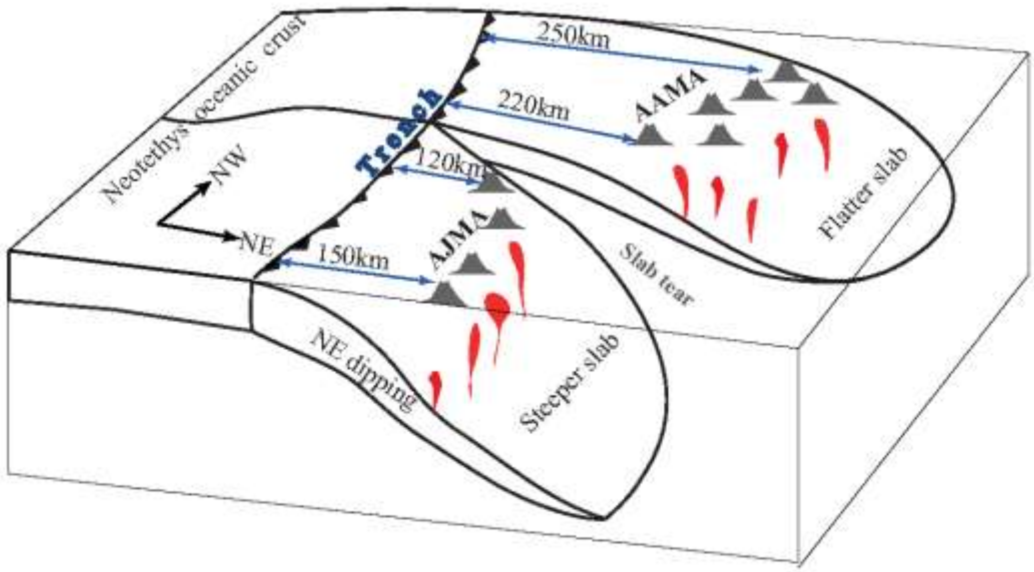

Figure 10: Schematic model of the Neo-Thetys ocean paleo-subduction beneath the Iranian plateau based on this study. The model explains the shift in the arc-trench distance with changing angle of subduction according to **Figure 9**.

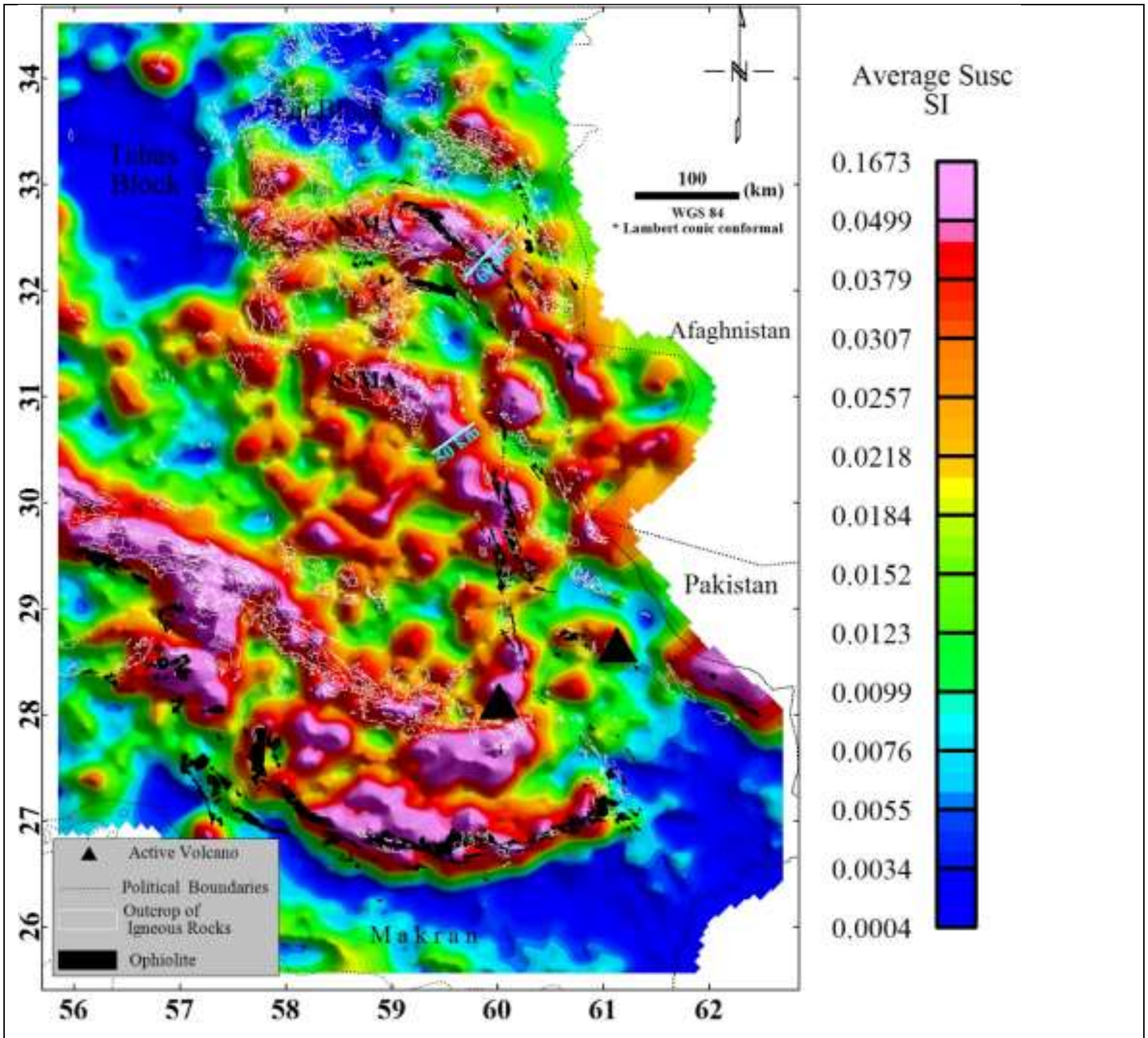

Figure 11: Average susceptibility map of eastern Iran shows anomalies of two parallel Eastern MOA including Southern Sistan Magmatic Arc (SSMA) and Northern Sistan Magmatic Arc (NSMA).