Spatial Heterogeneity of Tectonic Features in the Area between the Qatar-Kazerun and the Minab Faults, the Southeast of the Zagros Fold-and-Thrust Belt, Iran

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Abstract
Tectonic activity in the southeast of the Zagros of Iran varies in intensity. Investigators have evaluated the tectonics using the geological and geophysical features of the region for several decades. We have analyzed many of the data geostatistically to map the two-dimensional spatial distributions of seismicity, topography and structure. We distinguished two contrasting tectonic domains: the less tectonic activities in the north-northeast than south-southwest. The transition between the two domains is gradual and not clearly defined. It seems that the buried and blind thrust faults lie between them. We conclude that the tectonic features mapped by geostatistical modelling in the region characterize the two-dimensional tectonic pattern. However this study has not solved all the tectonic ambiguities of the region. But it shows in map form that the region between the Qatar-Kazerun and the Minab faults consists of spatially heterogeneous tectonic features, which in turn account for the varied tectonic behavior.

Keywords
Spatial heterogeneity; Tectonics; Seismicity; Geostatistical modeling; Zagros fold-and-thrust belt

Introduction
Among the current active convergent zones, the Zagros continental collision zone is one of the youngest and most seismically active zones on Earth. It experienced several tectonic episodes of collisions during Late Mesozoic and Miocene times [1]. The deformation in the Zagros began in the Late Cretaceous, but has been most extensive since the Miocene [2]. The earthquakes that happen nowadays in the region show that the seismic activity still continues [3]. This deformation is dominated by subsurface blind thrusting, surface strike-slip faulting, asymmetric folding and surface thrusting ramping up from detachments [1].

The main feature of the Zagros Fold-and-Thrust Belt is a linear, asymmetrical folded belt, which forms a 200-300 km wide with the series of mountain ranges extending for about 1800 km from eastern Turkey to the Strait of Hormoz [4]. In detail the geological and geophysical features such as seismicity, topography and structures of the entire belt have a complex spatial distribution, although it is possible in some areas to distinguish homogenous zones [5,6]. For several decades, the study of the spatial distribution of geological and geophysical features of the Zagros Fold-and-Thrust Belt has been the subject of several investigations. Such distinct spatial patterns are identified for it [3,6-15]. Despite the achievements made it is necessary and useful to use quantitative methods based on numerical criteria, to provide objective results and to increase the objectivity of the research. There are, however, few references available in the literature [6,13,16,17].

We recognize the achievements of the early investigators, but we wish to put our study on a quantitative footing as well as a qualitative. We have analyzed the geological and geophysical data geostatistically so as to map the tectonic character of the whole area between the Qatar-Kazerun and the Minab faults. The area between the Qata-Kazerun and the Minab faults, in the southeastern part of the Zagros, is significant for its tectonic and seismicity setting and presence oil and gas reservoirs. We hope that by modeling be able to understand it better than we have done in the past.

Geostatistics allows modeling the spatial variations based on the correlations between measurements at various distances. In fact, geostatistics is used to describe and utilize correlation among spatially distributed data in the form of variograms and to build models that can be adapted to practical situations. Once a suitable model has been found, it can be used with data to estimate that variable at locations where no measurements have been made. Geostatistical estimation, or kriging, is a prediction of the value of a spatially distributed variable from the values elsewhere using the interdependence expressed in the model variogram.

The general aim of this research is to determine whether the distribution of the considerable tectonic features obtained from geostatistical modeling in the region characterizes quantitatively the tectonic pattern in two dimensions. More specifically it aims (i) to discuss the spatial distributions, and if possible to map them, and (ii) to relate the distributions observed to the tectonic of the area.

Regional Tectonic Setting
The Zagros basin is defined by a 7-14 km thick succession of cover sediments deposited along the north-northeast edge of the Arabian plate, since the end of Precombrian [14,18]. This sequence is distinct from the rocks of Central Iran, and is separated from them by a structure called the Zagros Thrust System that marks the northeast boundary of the Zagros [15,19] (Figure 1). The sediments are decoupled from the underlying basement at the level of the Hormuz salt and by higher, younger evaporate horizons. Geological evidence indicates that the Zagros experienced various tectonic episodes that affected parts of the belt [7]. The building processes started during the Upper Cretaceous and were associated with the obduction of the Neyriz ophiolite along the line suture parallel to the Zagros Thrust System and subduction of the Thethyan oceanic crust. Throughout the Mesozoic, a thick layer of sediments was deposited on the stretched
and thinned, subsiding Arabian continental margin [1]. A second period of compressional tectonics started during the Plio-Quaternary and created the uplifting and folding of the sedimentary section now observed in the Zagros [1]. However, most of the width of the Zagros is occupied by what is known as the “Simple Folded Belt” which contains the thick Paleozoic-Mesozoic-Tertiary shelf deposits that were warped into the elongate, open folds in the Miocene onwards [20] (Figure 1). Exposed folds in the Zagros match the orientations of the underlying blind thrust faults [1], which are in consist with the regional seismicity pattern [21-23].

Morphology

The Zagros Fold-and-Thrust Belt, located between the Persian Gulf to the southwest and the Zagros Thrust System to the northeast. The Zagros range can be divided into two zones that are distinct in their topography, geomorphology, exposed stratigraphy and seismicity. The 100 km wide north-eastern zone, called the High Zagros, averages 1.5-2 km in elevation (with numerous peaks over 4000 m) and exposes stratigraphic levels in the Mesozoic and Palaeozoic. The 100-300 km wide south-western zone, called the Simply Folded Belt, rises from sea level in the SW to 1.5 km in the NE and exposes Palaeozoic strata only rarely (except for the Hormuz salt plugs) [1,7,23,24] (Figure 1).

The present morphology of the Zagros active Fold-and-Thrust Belt is the result of its structural evolution and depositional history: a platform phase during the Palaeozoic; rifting in the Permian Triassic; passive continental margin (with sea floor spreading to the northeast) in the Jurassic-Early Cretaceous; subduction to the northeast and passive continental margin (with sea floor spreading to the northeast) platform phase during the Paleozoic; rifting in the Permian Triassic; and thinned, subsiding Arabian continental margin [1]. A second period of compressional tectonics started during the Plio-Quaternary and created the uplifting and folding of the sedimentary section now observed in the Zagros [1]. However, most of the width of the Zagros is occupied by what is known as the “Simple Folded Belt” which contains the thick Paleozoic-Mesozoic-Tertiary shelf deposits that were warped into the elongate, open folds in the Miocene onwards [20] (Figure 1). Exposed folds in the Zagros match the orientations of the underlying blind thrust faults [1], which are in consist with the regional seismicity pattern [21-23].

Structures

Basement thrust faults: In the Zagros Fold-and-Thrust Belt of Iran it is firmly established thick-skinned structures. Evidence for this comes essentially from the relatively intense midcrustal seismic activity recorded in the Zagros. Focal mechanisms determined for the seismic events show that the majority of basement faults are of reverse type [26]. This is supported by the fact that the basement faults are also associated with major vertical steps in the general topography and a vertical shift of the syncline base level in the hanging wall of basement faults. Based on these two criteria, seismicity and topography, Berberian (1995) [1] proposed a map of the main active basement faults in the Zagros Fold-and-Thrust Belt. Other maps have been proposed based upon analysis of satellite imagery [27-29]. However, because the basement faults in Zagros rarely reach the surface, their overall geometry and lateral extent, and in many cases their precise location, remain a matter of debate.

Basement faults are thought to have played a role in the development of the Arabian palao-margin since the Late Precambrian and the deposition of the Hormuz Formation [26]. These faults are masked by the Phanerozoic folded sedimentary cover, but have a distinct effect at the surface morphotectonics and topography, and major displacement at depth. Despite evaporate layers at the Lower Cambrian Hormuz and the Miocene Gachsaran horizons (the lower and the upper detachments), a tentative correlation can now be made between the surface structures, topography, macroseismic pattern and the major basement active faults in the Zagros [1]. Seismic slip along the basement (blind) faults has produced coseismic uplift and folding of Quaternary deposits and surfaces in the belt. The nodal planes of the fault plane solutions of the Zagros earthquakes are parallel to the regional anticline axes at the surface and deep seated (blind) longitudinal thrust faults (except for the transverse strike-slip active faults) with linear Hormuz Salt intrusions along them. This pattern presumambly proposes that the asymmetric longitudinal anticlines of the Zagros are cored by longitudinal active basement (blind) thrust faults, and that part of their growth with Quaternary deformation can be explained by repeated motion on these basement faults during hidden earthquakes. The asymmetry of the Zagros anticlines (with steeper or inverted southwestern flanks), with the dip of the deep seated boundary faults, favor interpreting active basement (blind) reverse faults in the Zagros having a dip to the northeast and north. The anticline mountains and hills in the Zagros are therefore propagating into the synclinal depressions and valleys toward the south and southwest [1,7,30].

Thrust faults: Faults in the Zagros Fold-and-Thrust Belt are largely northeast-dipping, southwest-verging thrusts. They are mostly young and low-angle in near the Zagros range front, but older and high-angle (most probably due to back-rotation resulting from displacement of rocks on the lower thrusts) in the hinterland. Near the northeastern boundary of the belt, where elevation is generally ~2 to 3 km, large overlapping thrust nappes composed of various cover strata and also ophiolite slivers. Major thrusts generally developed
progressively in-sequence from northeast to southwest, as growth strata and progressive unconformities indicate [31] (Figure 2).

**Strike-slip faults:** They are assigned to three groups, attributed to three major geotectonic events, which have affected the Afro-Arabian plate [31]. The first group includes the generally N-S trending lineaments which are thought to originate from the Pan-African orogeny (~670-570 Ma) [31]. Examples of these structures in the Zagros Fold-and-Thrust Belt are the Kazerun and Mangarak fault systems. In addition, several north-south trending gentle folds (or broad “arches”) are attributed to the Pan-African structural grain superimposed by the Zagros folds near the Zagros deformational front to produce local broad domes by structural interference. The second group comprises the northwest-southeast trending lineaments attributed to the latest Neoproterozoic-earliest Cambrian Najd strike-slip tectonism (~550-540 Ma) [31]. Within the Arabian shield, these faults transect and displace the Pan-African structures. To the northeast, in the Zagros orogen, the Main Recent Fault (MRF) and other the northwest-southeast trending blind faults delineated by magnetic anomalies may be reactivated faults of this category. The third group consists of structures developed during the opening of the Neo-Tethys ocean in Permian and Triassic times. These structures form major the northeast-southwest trending transfer/transform faults, such as the Oman Line [31].

Among the basement structures, the Kazerun-Mangarak fault system and the Oman Line, which form the northwestern and southeastern boundaries of the Fars salient, may be considered as transverse zones, forming relatively narrow bands rather than discrete lines. In these transverse zones, Zagros structures are either terminated or delected (Figure 2) [31].

**Salt domes:** The Fars province of southern Iran is an area of spectacular salt diapirism. The diapir field is bounded by the Oman line to the east, the Kazerun fault to the west, and the Zagros Thrust System to the north (Figure 2). They occur in great number also in the form of small islands in the Persian Gulf, south of the boundary of the Zagros Folded Belt. More than 200 salt plugs now are known in the Persian Gulf region. Apart from those in the Zagros imbricate belt, salt domes are confined largely to eastern Fars Province and the Kazerun district. No Hormuz salt plugs are known east of the north-south trending Oman line or northeast of the Zagros Thrust System [18,32,33]. The presence of numerous salt domes, mainly of the Hormuz Formation, indicates tectonic activity of the Zagros Fold-and-Thrust Belt.

Although the plugs generally are associated with anticlines, they are not known in synclines. Of those bursting through anticlines, many have pierced the structure at the plunging end or on the flanks. The earliest Hormuz plugs reached the surface in the Late Cretaceous, as evidenced by the presence of derived Hormuz material in the sediments peripheral to the salt areal coverage [18,32,33].

Ala (1974) and Kent (1979) [32,33] have revealed that the earliest evidence of doming related to the Triassic in some areas. The first period of salt activity was a pre-Zagros phase, going as far back as the Triassic in some areas. Although the plugs initiated in this phase are not necessarily associated with the later anticline culminations, they probably played a prominent role in determining the loci of fold formation during the late Tertiary Zagros orogeny. It is reasonable to expect a fold to rise preferentially over an already domed area, or at an emergent salt plug. The second period of salt activity was a late Tertiary syn- to postorogenic phase, as the direct consequence of decollement folding over an evaporate substrate.

**Seismicity:** Earthquakes occur throughout the 200-300 km width of the Zagros Mountains, with an abrupt cut-off in the northeast, along the Zagros Thrust System. However, except in the northeast of the belt, most of the larger (m ≥ 5.0) earthquakes in the Zagros occur along its southwest front, between the coast of the Persian Gulf and the 1500 m topographic contour [34,35]. Except for smaller earthquakes, the highest elevations of the Zagros, which reach 3000-4000 m, are relatively aseismic [36]. Medium to large magnitude earthquakes frequently occur in the Zagros region but rarely exceed magnitude m ≈ 7.0 Richter [35] (Figure 3).

Also earthquakes show the major lateral variation in the spatial distribution of events relative to the Zagros Thrust System that approximately coincides with the Kazerun Line region. The Kazerun Line is basement structure that appears to have significantly affected the sedimentation pattern during the Mesozoic and Cenozoic times and appears to slightly offset surface geologic structures in a right-lateral strike-slip sense. In a way, the Kazerun Line separates the seismicity of the Zagros into northwestern and southeastern regions [22,35].

In the northwestern Zagros the seismicity is abruptly terminated at the Zagros Thrust System. In contrast, seismicity in the southeastern Zagros (the Fars region) is distributed within a curvilinear band whose trend is quite separated from the Zagros Thrust System. The northeastern boundary of Zagros seismicity closely coincides with the Kazerun Line region. The Kazerun Line is basement structure that appears to have significantly affected the sedimentation pattern during the Mesozoic and Cenozoic times and appears to slightly offset surface geologic structures in a right-lateral strike-slip sense. In a way, the Kazerun Line separates the seismicity of the Zagros into northwestern and southeastern regions [22,35].

Figure 2: Geological map of the area between the Qatar-Kazerun and the Minab faults.
Figure 3: The spatial distribution of epicenters of earthquakes in the study area with mb 4.0 and greater. (Events reported by PDE (2000) and ISC (2000) Bulletins and Ambraseys and Melville (1982) during the period 1900–2010). Area higher than 1250 m is dotted.

Figure 4: The base map of the study area shows the sampling grid points.

The majority of earthquakes in the Zagros are located between 8-15 km depth. No earthquakes are reliably located a depth greater than 30 km. The seismicity, therefore, is likely to be located in the upper part of the crystalline basement below the 11 km thick sedimentary layer. The concentration of events at 8-15 km could be related to a decollement between the sedimentary layer and the crystalline crust. Furthermore, there is general increase of the topography, from ~500 m in the southwest to ~1500 m in the northeast along the same section. Therefore, the deepening of seismicity is likely related to a deepening of the interface between the sedimentary cover and the crystalline basement which is of the same order as the northeastward deepening of the Moho beneath the Zagros [22,38].

Methodology

Exploratory data analysis

On the basis our present purposes we first determined the boundaries of the area of study between the Qatar-Kazerun and the Minab faults in the southeastern part of the Zagros Fold-and-Thrust Belt. We identified three features, namely the Kazerun fault zone, the Zagros Thrust System and the Minab fault. Then we divided the study area into cells (geographic window) of 0.5°x0.5° on a regular grid. We overlapped the windows in steps of 0.25° along the directions of east, south and southeast of the grid to provide finer resolution and smoother continuity. This technique increases the number of grid cells. We closed the geographic window with a moving step of 0.25° so that we had sufficient data to represent the variables for each and every grid cell [39,40]. Each grid cell was represented by its central point. This gave 230 points, the positions of which are shown in Figure 4. We obtained values of variables in each cell. Parameters that were used as possible measures of earthquake activity are: a count of earthquakes with the magnitude (mb) 4.0 and greater per unit area (NE4A); the maximum magnitude of earthquakes (MME); the average focal depth of earthquakes (AFDE); the b-value in the
Gutenberg-Richter’s formula (BVAL), which is a measure of the crustal level. The data on the earthquakes were taken from PDE (2000) and ISC (2000) and Ambraseys and Melville (1982) [41-43]. Measures of the topographic relief were used as possible index of the stress level in the upper position on the earth in each cell, being the difference between the highest and lowest level. Finally, a count was made of faults per unit area (NFA) and the fault length density (FLD), which are measures of the heterogeneity of crust. Our choice of the above parameters depends on tectonic intuition and experience. It seems that these parameters characterize the intensity of the tectonic activities.

Table 1 summarizes the statistics of the data. Some of the variables are positively skewed. We therefore transformed them by SPSS to stabilize their variances for subsequent analysis and in doing so obtained distributions that were fairly close to normal. NE4A, NFA and FLD transformed into square roots; and BVAL transformed into logarithm. Other variables have the normal distribution (Table 1, Figure 3).

Spatial correlation analysis

We assumed that the variables are continuous in space and their values are spatially correlated at area scale. Spatial correlation can also vary with direction, and therefore is accommodated in the variogram. The variogram analysis characterizes the spatial correlation structure of the data [39,44,45]. The mapping variables by kriging is done to obtain models for the variograms on the assumption that the observed values of the variables are the outcomes of underlying random processes. The variogram of such a process is

\[
\gamma(h) = \frac{1}{2} E \left[ (Z(x) - Z(x+h))^2 \right] \quad \text{for all } h.
\]

In this equation, \(Z(x)\) and \(Z(x+h)\) are the random variables at places \(x\) and \(x+h\) separated in space by the vector \(h\). We estimated \(\gamma(h)\) by the usual method of moments:

\[
\hat{\gamma}(h) = \frac{1}{2m(h)} \sum_{j=1}^{m} (Z(x_j) - Z(x_j + h))^2,
\]

in which \(Z(x_j)\) and \(Z(x_j + h)\) are the observed values of \(Z\) at \(x_j\) and \(x_j + h\) separated by the lag vector \(h\) for which there are \(m(h)\) paired comparisons. We could not detect any significant differences in obtained variograms in the different directions, and so we treated the variation as isotropic and the lag as a separation in distance only, setting \(h = |h|\) and incrementing \(h\) in steps of 25 km with bins 25 km wide. The plotted points in Figure 6 show the resulting experimental variograms.

We fitted theoretical models to the sequences of experimental values. The spherical model seemed to fit best, and it is shown as the curve in each graph. Its formula is

\[
\gamma(h) = \begin{cases} 
  c_0 + c \frac{3h}{2a} \left( \frac{h}{a} \right)^2 & 0 < h < a \\
  c_0 & h \geq a \\
  0 & h = 0 
\end{cases}
\]

Here \(c_0\) is the ‘nugget’ variance, the intercept of the function on the coordinate, \(c\) is the variance of the spatially correlated component of the variation, and \(a\) is the range, the maximum distance within which there is spatial correlation. Their values are listed in Table 2.

Spatial estimation

Kriged estimations are weighted combinations of the observed values. The weights are determined for each interpolated location by minimization of the error variances. All methods of kriging are elaborations on a basic generalized regression algorithm and the corresponding estimator. In this study, having fitted the function we used the values of the parameters to estimate by kriging values of the variables at 25 km intervals. We used the now standard ordinary punctual kriging [44-46] for its definition and details-within a moving window of maximum diameter 300 km. The dense fields of estimates were then converted to isarithmic (‘contour’) maps, which are displayed in Figure 7. In these maps, the darker are the tones the
Figure 5: Histograms of the variables with normal distribution curves superimposed on them.
Figure 6: Omnidirectional variograms plotted as points with the fitted spherical models shown as the continuous lines. The fitting parameters are listed in Table 2.
Figures 7c, 7d, and 7f show the crust is very heterogeneous there.  
Further south-southwest, NE4A and MME present larger values of 0.1 km$^2$ and 4.5 Richter, respectively. Based on the study made by Berberian (1995) [1] the anticlines are cored by active blind faults in this part of the region. Also, Ni and Barazangi (1986) and Hatzfeld et al. (2010) [22,35] purposed the intensity of seismicity and the occurrence of large earthquakes in this part along with the lake of the mapped faults and the simplicity of folding that show the sedimentary sections act as a plastic layer and is decoupled from the underlying basement along the Hormuz salt beds. The large NE4A and MME values with, the anticlines are cored by active blind faults and the occurrence of large earthquakes in this part of the region is well correlated.

The Figure 7c corresponds to the distribution of AFDE. The south-southwestern part of the region defined by AFDE values 37-52 km; toward a domain with the large average focal depth. As observed in this figure, the large AFDE values with the seismic activities of the region are correlated. Such that the large AFDE values, and the large NE4A and MME values accord with a zone about 150-200 km wide in the south-southwestern part. They show no tendency to increase toward the Zagros Thrust System [21,23,35]. The only deviation from this regional trend can be seen at northwest, where an increase of focal depth is associated with the action of the Kazerun fault zone.

In Figure 7d for BVAL, we see that the northeastern and southeastern parts of the region are dominated by large values of b (more than 0.2 on the logarithmic scale), while in the southwestern and central parts the values of b are generally small (less than 0.01 on the logarithmic scale). A strong correlation exists between the regions with the large values of b and those that experience numerous small earthquakes (Figure 7b) and have dense fracturing (Figure 1). This seems to be because the rocks are weak and the crust is very heterogeneous there [47].

TOR widely is distributed (Figure 7e). To east-southeast and northwest-west, the TOR shows values of near 2700 m and individualizes zones characterized by the large topographic relief. Elsewhere the values are small (450-1210 m). The parts with the large TOR values coincide with the area where an increase topographic relief associated with the action of the strike-slip faults (e.g. Kazerun fault zone and Kar Bas fault) and thrust faults (e.g. High Zagros thrust, Mountain front fault and Qir-Surmeh fault) (Figure 3).

Finally, NFA and FLD show similar distributions (Figure 7f and Figure 7g). In the north-northeastern part of the study area a more fractured domain with a trend nearly northwest-southeast defined by the large NFA and FLD values (more than 0.085 km$^2$ and 0.25 km$^2$, respectively). To south-southwest, NFA and FLD present the small values (less than 0.055 km$^2$ and 0.19 km$^2$, respectively). The distribution of the NFA and FLD is well correlated with the distribution of the faults and seismic activities in the region (Figure 3). Such that Ni and Barazangi (1986) and Hatzfeld et al. (2010) [35,22] suggested the lake of the mapped faults and the intensity of seismicity in the south-southwest is the result of the action the Hormuz salt beds.

### Uncertainties in the estimation

The maps show the variables to vary smoothly. To some extent this is because kriging is smooth, especially when the nugget variance is a substantial proportion of the sill, $c_2 + c$ in Equation (3). To identify places where the kriged estimates departed markedly from the data we did a cross-validation. This involved our removing in turn the data points one at a time, estimating by kriging the values at those locations from the values in their neighbourhoods and then comparing the estimates with the observed values. Generally, the estimates closely matched the observed values—the method would not be of value otherwise. The maps of the residuals in Figure 8 show where these large residuals lie.

### Discussion and Conclusions

The present study indicates the situation of the tectonic activities distributed over the area between the Qatar-Kazerun and the Minab faults. We divided the region into two tectonic domains based on the distribution of the tectonic features. As follows:

Domain 1 the north-northeastern part as the less active domain with

Domain 2 the south-southwestern part as the more active domain with

It seems though a threshold value that separates both tectonic domains is not clearly observed.

Towards the northeast of the region, comparatively low seismic activities with large b-values seem to be related to the thrust faults such as the Zagros Thrust System and the High Zagros Fault. Such low to moderate seismicity, with large b-values, can be accounted for by a high degree of heterogeneity and low rheological strength in the crust, allowing brittle failure at lower levels of stress. Possibly a high density of rock fractures, following strong tectonization related to the reactivations of pre-Cenozoic normal faults inherited from the previously extended Arabian plate margin as thrust faults [1,30], resulted in a zone of weaker crust near Zagros Thrust System. The substantial seismicity and large b-values in the

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### Table 2: Parameters of spherical models fitted to the experimental variograms of the variables. See text and Equation (3) for definitions of the symbols.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$c_2$</th>
<th>c</th>
<th>a/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE4A (sqrt)</td>
<td>0.00012</td>
<td>0.00300</td>
<td>21.4</td>
</tr>
<tr>
<td>MME</td>
<td>0.03</td>
<td>0.49</td>
<td>22.3</td>
</tr>
<tr>
<td>AFDE</td>
<td>14.8</td>
<td>25.9</td>
<td>12.1</td>
</tr>
<tr>
<td>BVAL (log)</td>
<td>0.012</td>
<td>0.023</td>
<td>18.3</td>
</tr>
<tr>
<td>TOR</td>
<td>8460</td>
<td>82794</td>
<td>12.9</td>
</tr>
<tr>
<td>NFA (sqrt)</td>
<td>0.00017</td>
<td>0.00059</td>
<td>19.8</td>
</tr>
<tr>
<td>FLD ( sqrt)</td>
<td>0.00104</td>
<td>0.00700</td>
<td>23.7</td>
</tr>
</tbody>
</table>

1 (NE4A) a count of earthquakes with the magnitude (m) 4.0 and greater per unit area. (MME) the maximum magnitude of earthquakes. (AFDE) the average focal depth of earthquakes. (BVAL) the b-value in the Gutenberg-Richter’s formula, (TOR) the topographic relief, (NFA) the count of faults per unit area and (FLD) the fault length density.

2 sqrt means transformed to square root, and log means transformed to common logarithm.
southeast are possibly the result of tectonic adjustments between the Zagros Fold-and-Thrust Belt and the Makran prism. Towards southwest, the high level of seismicity and low $b$-values is possibly the result of the buried and blind thrust faults. They are blind thrust faults with important structural, topographic, geomorphic and seismotectonic characteristics. They are as evidenced by deformation of the asymmetric anticlines in the hanging wall of the blind thrusts, are segmented and discontinuous, and are separated by gaps in faulting that have presumably controlled the extent of rupture and the magnitude of earthquakes. These seismologically active thrusts are displaced right-laterally by deep-seated active transverse faults of Kazerun, Sarvestan and Sabz Pushan [1]. In these parts might be why we encounter the Hormuz salt and higher evaporate horizons there: most of the anticlines in there are pierced by salt diapirs or have salt diapirs on the surface. This geometry suggests that anticlines are penetrated by active blind faults, which have facilitated the migration of salt into the cores of anticlines [1]. We might therefore consider their locations as potentially seismic zones where future earthquakes are likely.

On the southwest boundary of the area, particularly towards the coast of Persian Gulf, the weak seismicity and small $b$-values suggest that there is or has been a great deal of the activity potential there.
We interpret this as resulting from the migration of the Zagros deformation front southwestward and the increase the potential for the tectonic conditions in that direction [11,48,49].

Comparison of the Bouguer gravity anomaly with that of $b$ is interesting. Previous workers [22,37,38,47,50-52] delineated a uniformly thickened crustal root for the area between the Qatar-Kazerun and the Minab faults, based on the gravity surveys and the velocity structure of the crust. They recorded the small Bouguer gravity anomaly along the coast of the Persian Gulf and large values along the Zagros Thrust System which indicate the existence of its considerable thickening of the crust there where the crust is thickest below the Zagros Thrust System with values ranging between 50000 and 55000 m [50].

We believe that the intermediate to large values of $b$ apparent on the map where there are also the small to moderate values of the Bouguer gravity anomaly [22,37,38,47,50-52] mean that the crustal root is thick there, where energy has been intermittently dissipated through earthquakes. These interpretations confirm the migration of the Zagros deformation front southwestward [11,48,49].

Also, this contention is consistent with the observation made in
this study from variation in focal depth. Reliable fault plane solutions and focal depths of the earthquakes in the Zagros show that most earthquakes occur on high-angle thrust faults (40°-50°) at centroid depths of 8-12 km in the uppermost part of the metamorphic basement beneath the Hormuz salt and the top sedimentary cover on large number of faults distributed across the belt that are concealed by the folded shallow sedimentary cover [30,34,35].

However, studies of the focal depth of the Zagros earthquakes show that all of the larger Zagros earthquakes are located at depths less than 20 km [21-23,35,36]. There is no reliable evidence for an increase in depth northeastward or for any seismicity in the mantle beneath the Central Zagros [4]. The concentration of events at this depth could be related to a decollement between the sedimentary layer and the crystalline crust. Furthermore, there is general increase of the topography, from ~ 500 m in the southwest to ~ 1500 m in the northeast along the same section. Therefore, the deepening of seismicity is likely related to a deepening of the interface between the sedimentary cover and the crystalline basement which is of the same order as the northeastward deepening of the Moho beneath the Zagros.

Both theoretical and observed data have indicated that the stresses induced by topography are appreciable and may cause seismicity to concentrate in the regions of large topographic anomalies. This is in agreement with the results of Jackson and McKenzie (1984) and Zamani and Hashemi (2000) [34,16], which show a remarkable similarity between the seismicity and the topographic setting. Our measures of the topographic relief indicate that the locations of large topographic relief, where strong earthquakes have not occurred in historic times, should be considered as potentially hazards zones, where future strong earthquakes may take place [16].

The variation in the tectonic activity in the area between the Qatar-Kazerun and the Minab faults may be due to the propagation of the Zagros fold-and-thrust belt towards the southwest. Such that the crustal thickness [50,51], topography, intensity of deformation [7,20], fold amplitude, reverse fault displacement, relative shearing along the Hormuz decollement and age of the folded and faulted sedimentary rocks decrease from the Zagros Thrust System in the north and northeast toward the Zagros foredeep in the south and southwest [1].

A simple model of deformation of the area between the Qatar-Kazerun and the Minab faults is proposed by Sarkarinejad et al. (2013) [47] explains the variation in the tectonic activity. The convergence between Arabia and Central Iran has resulted in mountains with a deformation front that migrated southward and drove the foreland basin in front of it. GPS measurements by Hessami (2002) [11] show that the Zagros fold-and-thrust belt is being shortened at a lower rate (9-11 mm/year). Navapour et al., (2007) [53] indicate that the first NE compressive direction in the High Zagros Belt can be attributed to the onset of deformation in the early Miocene. The main folding and thrusting deformation of the High Zagros Belt is characterized by the NNE belt perpendicular compressive direction in the Miocene. To the south, throughout the Zagros fold-and-thrust belt of the study area, folding deformation is mainly achieved under the last N-S compressive direction in the late Miocene-Recent times. The existence of salt in the region suggests that the Central Iran may be viewed as a rigid backstop to the fold-and-thrust belt. On the other hand, the lack of the salt in the western of the Kazerun fault system and the lateral boundary of salt at the Oman line may have acted as frictional lateral boundaries. It allow for the sequential propagation of the fold-and-thrust belt as suggested by foreland basin studies [11]. The frictional lateral boundary in the Oman line (the north of the Strait Hormuz) is resulted in the frontal part of the fold-and-thrust belt swings through 70° from NW-SE in the north west to E-W in the southeast, where the three faults join, namely Zagros Thrust System, High Zagros Fault and Mountain Front Fault. Their activities caused the concentration of deformation as rapid uplift erosion and the accumulation at a hanging sedimentary load in this region. The frictional lateral boundary in the Kazerun fault system acted as transfer fault separating the southwestward movement of the Mountain Front Fault in the eastern and western of the Kazerun fault system. The Mountain Front Fault coincides approximately with the 1500 m topographic contour map and major zone of seismicity along the belt as presented by Jackson and McKenzie (1984) and Ni and Barazangi (1986) [34,35].

The plate motion model proposed here (Figure 9) predicts on oblique component to the convergence between Arabia and Eurasia in the Zagros fold-and-thrust belt. Present day plate motions based upon GPS and earthquake seismicity analyses indicate a north to north-northeast motion of the Arabian plate at ~25-30 mm per year with respect to the Eurasian plate [54,55]. They show N ~5° E motion at 25 mm per year for the Arabian plate towards southwestern Iran. This is approximately 50° oblique to the dominate NW-SE strike of the Zagros fold-and-thrust belt. Apparently this oblique convergence in the study area partitioned into pure thrusting along the area NW-SE trending basement faults and pure strike-slip motion along the NW-SE and NE-SW trending basement faults. The change in the strike of the strike-slip faults may indicate a probable rotation of these faults about vertical axes. In fact the fault bounded basement blocks did indeed rotate about vertical axes and may well have moved south westward [55].

The studies of earthquake focal mechanism in the region [1,21-23,28] show the nodal planes are parallel to the regional anticlinal axes at surface and deep seated (blind) thrust faults with linear Hormuz salt intrusions along them. This pattern presumably suggests that asymmetric anticlines of the Zagros are cored by active basement (blind) thrust faults, and that part of their growth with Quaternary deformation can explained by repeated motion on these basement faulting during hidden earthquakes. The asymmetry of Zagros anticlines, with the dip of the deep seated boundary faults, favor interpreting active basement (blind) reverse faults in the region having a dip to the northeast and north. The antclinal mountains and hills in the region are therefore propagating into the synclinal depressions and valleys toward the south and southward. Most of these anticlines are pierced by salt domes. This geometry may indicate that the anticlines are cored by active faults, which facilitated the salt migration into cores of anticlines [1,7,30].

On the other hand, Bahroudi (2003) [56] purposed in following the deformation the thickness of Hormuz salt layer has increased from NE to SW. Also, there is an inverse relationship between the thickness of the viscous Hormuz salt and the number faults formed in the overlying layers. As the thickness of the viscous Hormuz salt decrease the number of faults formed in the overlying layers increase and vice versa. The lake of the mapped faults and the intensity of seismicity in the south-southwest are confirm the action the Hormuz salt layer [35]. In the south-southwest the blind thrust faults are masked by the Phanerozoic folded sedimentary cover. Seismic slip along these faults has produced coseismic uplift and folding of Quaternary deposits and surfaces in the region. The nodal planes of the fault plane solutions of
the Zagros earthquakes are parallel to the regional anticline axes at the surface and blind thrust faults with linear Hormuz Salt intrusions along them.

Geomorphologic observations suggest that the folds located at the shore of the Persian Gulf are the most active structures of the Zagros. This is consistent with the GPS measurements showing that most of the present-day shortening in Fars is also accommodated at the shore. This present-day activity located at the edge of the Zagros fold belt, along the Persian Gulf shore, is consistent with the southwestward propagation of the front of the Simply Folded Belt from the Eocene (and therefore earlier than the onset of collision) to the present time [28,48,49].

The seismicity associated with shortening and reverse mechanisms is mostly located in the Zagros Fold Belt. Therefore neither the Zagros Thrust System nor the High Zagros Fault is active or both are lubricated and slip aseismically. This seems true both for the study area, where the seismic inactivity of these two faults is consistent with the absence of surface motion from GPS measurements across them. More precisely, the seismicity associated with reverse mechanisms is restricted to topography less than 1000 m, as pointed out by Talebian and Jackson (2004) [21]. This could be due to the gradient in topography [21] but Hatzfeld et al., (2010) [22] suspect it is related to the propagation of the deformation front to the SW, as evidenced from structural studies [57], geomorphology and GPS. The two could be linked, however, if it considers a critical-wedge model for the evolution of the Zagros Fold-and-Thrust Belt [58]. This propagation of deformation, and therefore of the construction of topography, explains why seismicity is bounded by the Persian Gulf shore, even though this shoreline has no tectonic significance and the water depth in the Persian Gulf is less than 70 m [22].

In the study area, seismicity is spread throughout the area between 1000 m elevation and the shore (which might be related to the Mountain front fault and the Zagros foredeep fault, respectively). The gradient in topography is also smoother in region than in the northwest of the Zagros. GPS shortening is restricted to the shore and unrelated to the high elevation. Thus, both the seismicity and the gradient in topography (which record basement deformation) are correlated with the pattern of cumulative (on a million years scale) deformation. On the other hand, GPS shortening and geomorphology (which record shallow deformation) are concentrated at the range front of the deformation [22].

Molinaro et al., (2005) and Sherkati et al., (2005, 2006) [24,59,60] have defended a general scenario in which the present thick-skinned style is recent (post-Pliocene) following a previous thin-skinned style during the Miocene. In contrast, Bahroudi and Talbot (2003) and Mouthereau et al., (2006) [58,61] have proposed a more classical view, in which the main basement faults have been accommodating reverse movement since the beginning of the collision, particularly along the Main Frontal Flexure, which is considered to be the range front of the belt.

Finally, we conclude that the main tectonic features revealed and mapped by geostatistical modelling in the region characterize the two-dimensional tectonic pattern. Although this study has not solved all the complications and ambiguities in tectonic of the region. But it shows in map form that the region between the Qatar-Kazerun and
the Minab faults consists of spatially heterogeneous tectonic features, which in turn account for the varied tectonic behavior.

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