GPS-MEASURED SLIP RATES VS. SEISMIC MOMENT RELEASED BY PAST SEISMICITY ALONG ALBORZ MOUNTAIN RANGE IN IRAN

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ABSTRACT:

The area under study in this paper covers the northern boundary of Central Iranian Block which coincides with the Alborz Mountains. This belt has been responsible for several known catastrophic earthquakes in the past. The Manjil Earthquake of June 20, 1990 with over 50,000 human casualties and more than $7biliion of economic damage is an example of such events in Alborz. The occurrence of moderate to large earthquakes in the Alborz indicates that significant portion of the shortening between Iran and Eurasia takes place in the Alborz. In this study, the records of historical earthquakes along Alborz are used to calculate and plot the geographical distribution of seismic moment released in time. A two dimensional distribution function is proposed and used here to spread the seismic moment along causative tectonic features. Using accumulated seismic moment, the average slip rates across seismogenic faults are estimated for 32 sub-zones along the Alborz Mountains and western Kopet Dag. The estimated horizontal slip rate of 4-5 mm/year is in good agreement with the geodetic vectors recently estimated from a regional GPS survey in this region. The study also reveals geographical variation of slip rate along some 900 km length of this zone which may suggest appearance of seismic gaps or areas with aseismic nature. The completeness of the historical earthquake catalogue and its reliability with regard to the estimates of earthquake magnitudes, locations and rupturing systems are among many plausible factors controlling the credibility of such results. Therefore, any conclusions derived from these results remain as reliable as the data used for the analyses.

KEYWORDS: Seismic moment rate, Alborz, Iran, GPS slip rate

1 INTRODUCTION

There are several large rigid blocks within the Alpine belt which are surrounded by marginal seismically active belts. Large areas such as central Turkey, north-western Iran (Azerbaijan), Central Iran and the southern Caspian, have showed low seismicity compared to those of the narrow marginal belts surrounding them (*e.g.* Jackson & McKenzie 1988). The belts surrounding these blocks are not single faults, but contain distributed deformation over a width of up to 400 km (Jackson & McKenzie 1984). The Iranian mountain ranges have long been known as part of the Alpine-Himalayan system of western Asia. They form the folded belts between the Arabian plate in the south and southwest, and the Turan plate in the northeast. Based on geodetic data, convergence between the Arabian and the Eurasian plates is estimated at around 21mm/year at a longitude of 52 E (*e.g.* McClusky *et al.* 2003; Vernant *et al*. 2004a). This convergence results in a continuous thickening and shortening of the continental crust along many mountain-borders in north-eastern and south-western Iran.

The area under study in this research covers the northern boundary of Central Iranian Block. This zone consists of Alborz Mountains as well as part of the Kopet Dag region. This study attempts to compare the average slip rates released by historical and recent earthquakes with the motion rates inferred from recent GPS survey in the Alborz belt. This paper summarizes the study and conclusions recently conducted by Zolfaghari (2008).

2 SEISMOTECTONIC SETTING OF THE STUDY AREA

The active belt of seismicity in northern Iran coincides with the Alborz Mountains. The occurrence of moderate to large earthquakes in the Alborz implies the significance of current tectonic deformation taking place on this mountain belt. This belt has been responsible for many catastrophic earthquakes in the past (Ambraseys & Melville 1982; Berberian & Yeats 2001). The Manjil earthquake of 20 June 1990, which is the most disastrous Iranian earthquake in the twentieth century, occurred in this belt. Both thrust and strike-slip faulting have been reported in this belt (Jackson & McKenzie 1984; Ritz *et al*. 2006; Guest *et al*. 2006). Priestley *et al*. (1994) believe that the oblique deformation in the north-western part of the Alborz Mountains is partitioned into pure strike-slip faulting, as it was seen during the Manjil earthquake of 20 June 1990, and pure thrusting, as it was in the earthquake of 22 July 1983. The Alborz belt is bordered by the Central Iranian Block in the south and the South Caspian Basin in the north (Figure 1). Further to the east, this belt joins the active belt of Kopet Dag in north-eastern Iran.

The Central Iranian Block is being compressed between two plates of greater rigidity, Arabia and Eurasia, while it is laterally trapped between the Arabian plate in the west and the Indian plate in the east. The Central Iranian Block is characterised by coherent plate motion with internal deformation of less than 2 mm/year (Vernant *et al*. 2004a). The low level residual velocities for five GPS stations across this plate (Vernant *et al*. 2004a) together with low seismicity suggest the rigid description of the Central Iranian Block. This block is bordered by the Zagros Folded belt in the south-west, the Alborz Mountains in the north, the Kopet Dag Mountains in the north-east and several strike-slip faults in the east (Figure 1). Several earthquakes are associated with surface faulting in this region. Central Iranian Block is characterised by discontinuous seismic activity with shallow large magnitude earthquakes, apparently with long recurrence periods.

The South Caspian Basin is an aseismic block in the Alpine belt which is surrounded by several zones of high seismic activity (Figure 1). Recent GPS survey indicates roughly northward motion of South Caspian Basin at 6.5±2 mm/year relative to Eurasia (Vernant *et al*. 2004b). This block is surrounded by the Talesh and Alborz Mountains to the west and south respectively, and joins the west Turkmenian lowlands at its eastern boundary (Figure 1). The Talesh and Alborz Mountains are overthrusting the “oceanic-like crust” of the South Caspian Basin (*e.g.* Berberian 1983). The extending south-east trace of the Caucasus Mountains towards the Kopet Dag Mountains, forms a separation line between the deeper water, approximately 1,000 m, and shallower water approximately 200m, of the central Caspian Sea and the South Caspian Basin (Priestley *et al*. 1994).

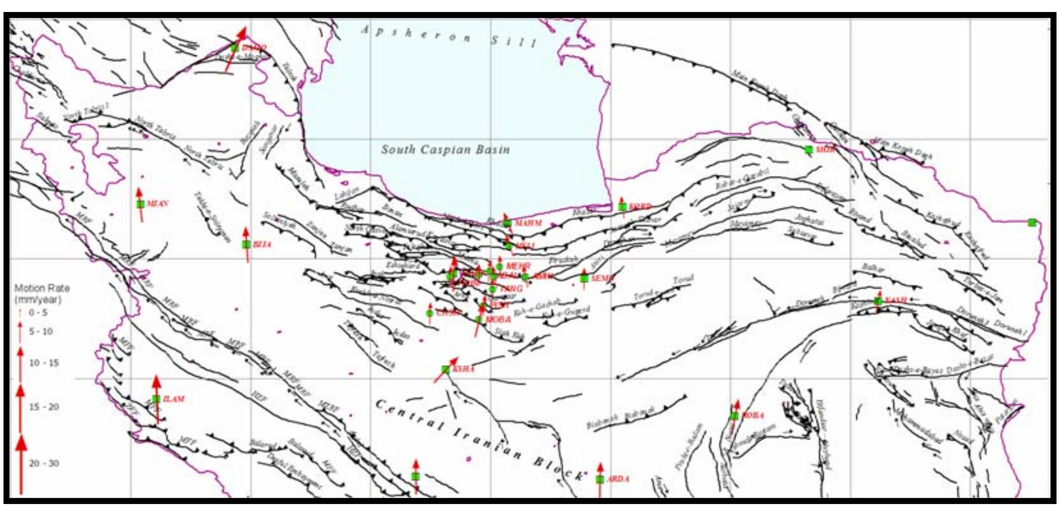


Figure 1 GPS horizontal velocity field in northern Iran. The square and circles represent the stations referred by (Vernant *et al.* (2004a) and (Vernant *et al.* (2004b) respectively

In the Kopet Dag, the crustal shortening has taken place in a belt of up to 200-300 km wide as a result of compressional motion of the Central Iranian Block against the stable plates of Turkemenistan and Afghanistan (Figure 1). Many north-eastern trending faults with left-lateral motion have been observed in the western Kopet Dag, none of which cross the Kopet Dag Main Fault Zone but continue towards the south-west into Iran and eastern Alborz (Jackson & McKenzie 1984). According to Priestley *et al.* (1994), existence of both strike-slip and thrust faulting in this region is perhaps an indication of partitioning of oblique slip similar to that of the north-west part of the Alborz Mountains. A trend of intermediate seismicity extends into the Caspian Sea and joins the seismicity in the Caucasus (Figure 1). This seismic zone (Apsheron Sill) has been interpreted as a northward subduction of the South Caspian Basin under Eurasia (Jackson *et al*. 2002).

3 EARTHQUAKE CATALOGUE

The seismicity database available for Iran, like many other regions in the world, can be divided into three periods. The first part is the historical data up to the beginning of the twentieth century, which is based on only macroseismic information. The second period extends from 1900 through 1963, during which the development of seismographic instruments in quantity and quality, results in a variety of seismicity data. The third period is the modern instrumental period which extends after 1964 and contains the most complete and homogenous data. Historical earthquakes used in this study consist of mainly the pre-1900 earthquake catalogue prepared by Ambraseys & Melville (1982). This catalogue refers to earthquakes as old as 400 BC and contains references to 256 pre-1900 historical earthquakes. The completeness and uniformity of this catalogue, both temporally and spatially, are probably poor, particularly for smaller events. Nevertheless, considering large earthquakes, which are the most important events in this study, they are likely to be more complete than the record considered as a whole. For post-1900 events, epicentral locations calculated by Ambraseys & Melville (1996) prior to 1980, and ISC and Harvard estimates after 1980 have been used. Figure 2 shows geographical distribution of major historical and recent earthquakes compiled for the study area.

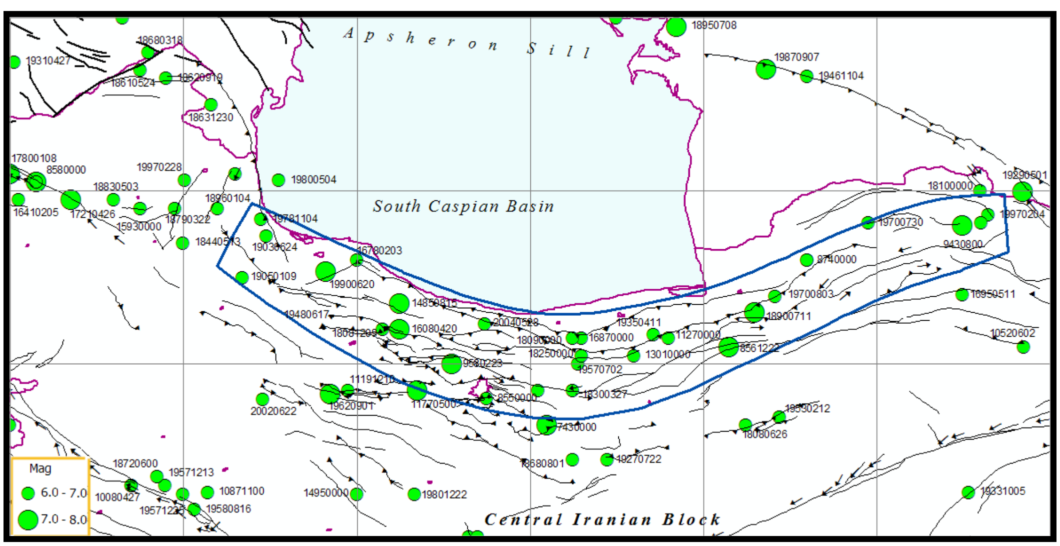


Figure 2 Geographical distribution of the compiled earthquake catalogue for the Alborz-Kopet Dag belt

4 METHODOLOGY

In this study, records of past earthquakes in the Alborz region are used to determine the distribution of seismic moment released by historical earthquakes in time and space. To allow the seismic moment released by each historical earthquake to get distributed along its tectonic feature, a smoothing process is proposed and used here.

The smoothing process is based on a 2D spatial distribution function, which allows seismic moment to spread along the causative fault ruptures. Detailed information describing fault rupture is not always available for all historical earthquakes. Therefore, assignment of exact fault rupture to each historical earthquake may not be always possible. In this study an attempt has been made to generalize the faulting information in the study area and to allow all historical earthquakes to take faulting characteristics from a synthetic fault map. In this study, raster geographic data layers presenting special features in the form of cell-based data models are used in order to implement rupture geometry into the smoothing process. Following in this section brief explanation is provided for this process, however, more detailed discussion on the methodology and assumptions used for such smoothing process are presented by Zolfaghari (2008).

In order to construct seismic moment maps, the seismic moment generated by each of the earthquakes in the catalogue is calculated first. Magnitude conversion relationships are used in order to estimate seismic moment released by earlier events. The estimated seismic moment generated by each earthquake is distributed spatially using a 2D distribution function. This distribution model assumes the seismic moment to spread uniformly along the rupture length but normally across the rupture zone. In order to use such smoothing model it is essential to assign a fault rupture to each historical earthquake. Depending on the level and quality of information representing rupture plane and its geometry, a simple or detailed geometric model may be used to model a rupture plane. The approach used in this paper is based on the generalization of a variety of available seismotectonic information and preparation of a synthetic line segment map. Each line in this map represents a specific fault or fault zone. Each historical earthquake in the catalogue is assigned a faulting azimuth based on its location relative to the raster data layer representing faulting. A rupture length is also assigned to each earthquake based on an empirical correlation between magnitude and rupture length. The smoothing process is an attempt to spread seismic moment along causative tectonic features and also to take into account the uncertainties associated with the locations of past earthquakes.

The smoothed seismic moment calculated for all historical earthquakes, once accumulated, reveals the accumulation pattern of moment in space and time. Figure 3a for example shows the cumulative regional seismic moment released during the last 106 years. The visualization of seismic moment in this format presents the seismic history and how different portions of tectonic features were engaged in different periods. These kinds of map can represent the development pattern of seismic strain released in time and space. As the accumulation time period extends for these maps, more continues pattern of seismic moment builds up, depicting the overall tectonic features responsible for seismic activity in the region. It is possible to use such maps to study the seismic vs. aseismic strain or to predict the segments most likely to produce the next large earthquakes or to investigate the concept of seismic gap, if a complete catalogue of large historical events is available. Those parts not ruptured recently relative to neighbouring segments, are either regions of aseismic nature or otherwise have accumulated considerable stress, and therefore are the most likely sites for the next large earthquakes. There are of course uncertainties associated with the data and assumptions used to construct these maps. Completeness of the historical earthquake catalogue, magnitude sizes, earthquake locations and proposed faulting orientations are among the most important sources of such uncertainties.

5 RESULTS

In order to map long term seismic strain along tectonic features a seismic zone representing the study area is delimited to cover the active region of the Alborz Mountain and western Kopet Dag (Figure 2). This zone extends some 900 km, separating the Central Iranian Block from the South Caspian Basin (Figure 4). The zone well coincides with the mapped active faults, topographic features characterising Alborz Mountains and the seismic activity shown by proposed seismic moment maps. The zone is further subdivided into 32 segments, each segment representing some 27 km length of rupture in this area (Figure 4). The seismic moment shown on maps presented in Figures 3 is then aggregated using the 32 polygons. Each segment of this belt is then characterised with the total seismic moment accumulated at various periods.

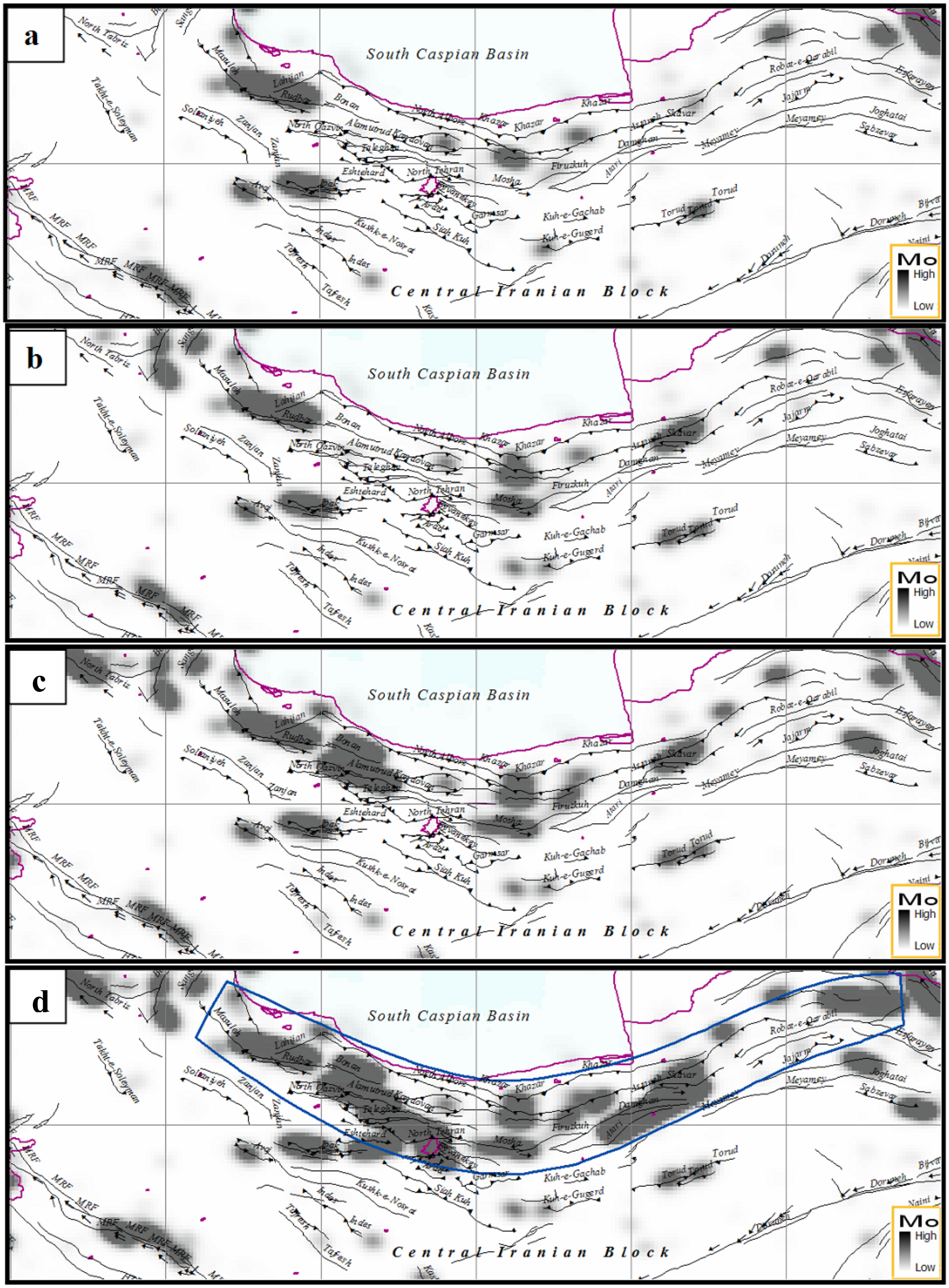


Figure 3 Geographical distribution of aggregated seismic moment released in time; a) 1900-2006, b) 1800-2006, c) 1200-2006, d) 800-2006

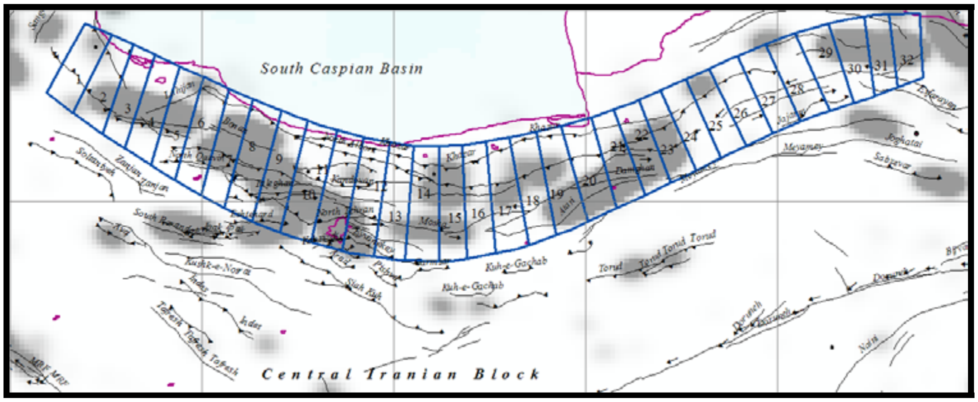


Figure 4 The active region of the Alborz and Kopet Dag belt

In order to estimate the average seismic strain rate across each segment, it is essential to determine the rupture area involved at each segment. Focal depths estimated from waveform modelling propose seismogenic layers of around 15 km thickness in Iran (Jackson & McKenzie 1988; Jackson *et al*. 2002). Such estimate for the Zagros and Alborz belts has been further confirmed by microseismic studies (Hatzfeld *et al*. 2003) and focal mechanism studies from teleseismic waves (Talebian & Jackson 2004). Therefore, for this study a locking depth of 15km is used for all historical earthquakes in the Alborz. Taking into account the high dip angles (generally higher than 75 degree) the rupture widths for fault segments in this region are of around 15 to 18 km. It is not well known how much of the deformation on this zone is taking place seismically. Based on comparison between geodetic and seismic deformation, Masson *et al.* (2005) reconfirmed the more or less aseismic deformation in southern part of Iran versus to the seismic deformation in northern part of Iran. Jackson & McKenzie (1988) proposed seismic deformation of 50 to 100 percent in the Alborz, Kopet Dag and eastern Iran. In this study it is assumed that the recorded seismicity accounts for only 80% of slip along the Alborz and Kopet Dag belts. This reduction is to compensate the incompleteness of the earthquake catalogue as well as the aseismic slip occurring on these zones. The value of shear modulus is also considered to be μ=3.0 x1011 dyn/cm2. Average slip rate for each segment is therefore, estimated using aggregated seismic moment, rupture plane geometry and aseismic rate.

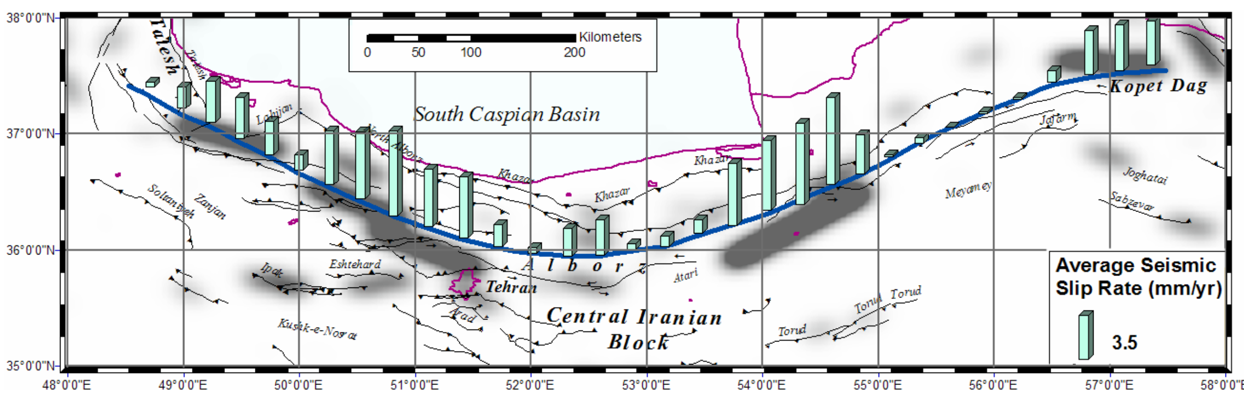
6 DISCUSSION AND CONCLUSIONS

In this study the seismic moment released by reported historical and instrumental earthquakes along active belts of Alborz and Kopet Dag is compared against the geodetic slip vectors measured in recent GPS surveys. Recent GPS survey in Iran showed that the Central Iranian Block moves with a rate of almost 14mm/yr to the north with respect to Eurasia (Vernant *et al.* 2004b). The same study also dismissed any eastward motion of the Central Iranian Block, suggesting that the Lut and Helmand Blocks prevent eastward motion of the Central Iranian Block. Such observations imply that the deformation of the Alborz and Kopet Dag mountains must be explained through the south-north shortening currently taking place between the Central Iranian Block and the stable Eurasian Plate. The Alborz mountain belt accommodates part of this differential motion between the Central Iranian Block and the South Caspian Basin. The GPS measurements at MAHM station in the Central Iranian Block (Figure 1) and MOBA Station in the South Caspian Basin reveal an average northward differential convergence of 5 ± 2 mm/year in the Alborz (Vernant *et al.* 2004b). This rate also appears compatible with 6 mm/year strain estimated from shortening taken place during the Pliocene-Quaternary period which is thought to be 30km over 5 My (Allen *et al.* 2003).

The seismotectonic of Alborz range is largely controlled by major thrust faults, from north to south these are: the North Alborz, Mekarud, Kandovan, Mosha and North Tehran faults. Current seismicity in the Central Alborz is also believed to indicate a left-lateral transpression regime, accompanied by strain partitioning (Jackson *et al*. 2002; Ashtari *et al*. 2005). Therefore, in addition to the south-north motion component in the

Alborz, there are slight E-W shear motions accommodated by some of the E-W trending faults in this region. Among them, the Mosha fault is the most prominent left-lateral strike-slip fault in the Central Alborz. The Mosha Fault is a major structural element in south central Alborz Range controlling the sedimentary deposition and partitioning the deformation along the range from east to west. The Firouzkouh fault and the Taleghan fault are the extension of the Mosha fault mechanism to the east and west respectively. These three faults are more or less connected and belong to a range-parallel shear zone inside the central Alborz (Ritz *et al.* 2006).

Using earthquake data for the twentieth century, Masson *et al.* (2005) showed that the eastern Alborz and western Kopet Dag experiences very little seismic deformation while the strain deduced from GPS measurement is large. However, their findings showed close agreement between seismic and geodetic style and direction of deformation in the Alborz. The distributed seismic moment from instrumental and historical earthquakes presented in this work reveal similar conclusion for part of eastern Alborz and western Kopet Dag. The earthquake catalogue used in this study extends far beyond the data used by Masson *et al.* (2005) and covers several other historical earthquakes, in particular the of Qumes earthquake (22 December 856, Mw7.6) and the Taleghan earthquake (23 February 958, Mw7.5) (Ambraseys & Melville 1982). The inclusion of these events in the analyses result in a more continues and stable pattern of seismic moment along this belt (Figure 3d). The slip rates averaged over the entire 1200 years of historical seismicity show more robust picture of long-term seismic strain in this region. Figure 5 shows an average slip rate of 4 mm/year along most part of the Alborz Mountains which despite many sources of uncertainties involved, stays in good agreement with the geodetic GPS measurements on this belt (Vernant *et al*. 2004b).



Figures 5 Average seismic slip rates over 1200 years of historical seismicity in the Alborz Mountains

The low seismic strain released by some 200 km length of this belt in the Central Alborz, between longitude 52^{o} and 53^{o}30' is mostly dominated by the activity on the Mosha and Firuzkuh faults. This part shows seismic strain of generally lower than 3 mm/year which is mostly reflecting the 1830 earthquake on Mosha fault (Figure 5). Vernant *et al*. (2004b) suggests that most of the range-parallel velocity component in the Central Alborz is accommodated by the Mosha fault and all other faults in this region can be considered pure thrust faults. Therefore, one could argue that no or little seismic slip is associated with the thrust faults in this region. Based on such observations, it is tempting to propose that portions of this belt are either experiencing higher proportion of aseismic deformation than those assumed in this research (*i.e.* higher than 20%) or otherwise they are expecting overdue earthquakes. As stated earlier, the completeness of the historical earthquake catalogue and its reliability with regard to earthquake magnitudes, locations and rupturing systems are among many plausible factors controlling the credibility of such conclusions. Besides the uncertainties associated with the geodetic GPS measurements and their independencies from transient motion due to seismic cycle need to be taken into account. Therefore, any conclusions derived form these results remain as reliable as the data and assumptions used for the analyses.

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