ACTIVE DEFORMATION ACROSS THE ZAGROS COLLISIONAL BELT AS DEDUCED FROM GEODETIC AND SEISMOLOGICAL OBSERVATIONS: PRELIMINARY RESULTS

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Introduction. The current tectonic setting of the Bitlis-Zagros Fold and Thrust Belt (BZFTB) is related to the complex convergent process between the Arabian and Eurasian plates which has been continuous since Late Cretaceous times after the closure of the Neo-Tethys Ocean, with a late episode of accentuated shortening during the Pliocene-Quaternary (e.g. Dewey et al., 1973; Numan, 1997; Abdulnaby et al., 2013). BZFTB is ca. 1200 km long and trends NW-SE between eastern Turkey, where it connects to the Anatolian mountain belt, and the Strait of Hormuz, where it connects to the Makran subduction zone (Fig. 1). It shows two main trends: the Bitlis EW trend, between the Arabian Plate and the Anatolian tectonic block, and the Zagros NW-SE trend, between the Arabian Plate and the Iranian tectonic block (Fig. 1).
Here we focused on the Zagros mountains which, longitudinally, is divided into two main geological domains: the North Zagros (hereinafter NZ) to the west and the Central Zagros (hereinafter CZ) to the east, separated by the NS-trending strike-slip Kazerun Fault System that cross-cuts the entire belt. NZ is considered as an high-taper wedge (ca. $2^\circ$) above a high-friction contact between the Phanerozoic cover and its Precambrian basement, whereas to the east, beneath CZ, the taper is lower (<$1^\circ$) and pierced by diapirs of the infra-Cambrian Hormuz salt layer that lubricate the sole of the wedge (see Hessami et al., 2006 and references therein).

Taking into account a large geodetic and seismological dataset, we investigated the pattern of the present-day crustal tectonic stress and strain-rate fields characterizing the Zagros. In particular, we compiled a database of fault plane solutions (FPSs) by merging data from public catalogues and literature. Subsequently, we divided the mapped area into $1^\circ \times 1^\circ$ squares and applied a stress inversion analysis to estimate the directions of maximum horizontal compressional stress in each square. In addition, we analyzed new GPS data coming from recent continuously operating stations, which were rigorously integrated with published velocities in order to provide a more complete picture of the crustal deformation along the Zagros. As a final step, we compared the horizontal directions of compressive stress (from seismological and geological observations) with those of the minimum contractional geodetic strain-rate.

Fig. 1 – Regional plate tectonic setting of the study region and surrounding areas. Abbreviations are as follows: BS, Black Sea; CS, Caspian Sea; NAF; North Anatolian fault; ESF, East Anatolian fault; HTJ, Hatay triple junction; MS, Mediterranean Sea; DSFS, Dead Sea fault system; MSZ, Makran subduction zone. Red box is showing the study area.
Seismic data. Historical seismicity catalogues, probably incomplete due to political and social conditions in the area, reveal 5 events with M >7 before 1960 (Ambraseys and Jackson, 1998; Mirzaei et al., 1997). Seismicity is anyway spread over the width of the Zagros (Fig. 2a), but it is characterized by moderate magnitude, generally less than 5. Instrumental catalogues are devoid of earthquakes with M ≥ 7 but only 6 events with M_b ≥ 6.

Instrumental crustal seismicity (since 1960; M ≥ 2.5) registered on the investigated area is mainly distributed along the Zagros collisional belt, and defines elongated NW-SE-trending lineaments parallel to the fold axes (Fig. 2a). Seismicity decreases considerably toward the NW Arabia-Eurasia boundary line. In this gap, seismicity appears quite spread and earthquakes are little clustered. In the southern Iran and along Iran-Iraq southern boundary, seismic events show homogeneous behaviour in terms of magnitude and depth, which is generally confined in the first 35 km but most frequent between 10 and 25 km.

In order to study the pattern of seismic deformation and obtain a detailed map of stress orientations later, we have compiled a database of 387 fault plane solutions (with M ≥ 3) merging data from public catalogues and literature. We collected focal mechanisms from existing online and literature catalogues. In particular, we use the following on-line and free available moment tensor catalogues: Global Centroid Moment Tensor catalogue (Dziewonski et al., 1981; Ekström et al., 2012; GCMT; http://www.globalcmt.org); European-Mediterranean Regional Centroid Moment Tensor catalogue (Pondrelli et al., 2002, 2004, 2007, 2011; RCMT; http://www.bo.ingv.it/RCMT/searchRCMT.html) and U.S. Geological Survey catalogue (USGS; http://earthquake.usgs.gov/earthquakes/eqarchives/sopar/).

To extend back in time the dataset and enlarge the magnitude range, we use published first-motion FPSs collected in the “Earthquake Mechanisms of the Mediterranean Area” database (EMMA; Vannucci and Gasperini, 2003, 2004; Imprescia, 2010; Vannucci et al., 2010 and references therein) which contains in the last version (3.1) more than 12000 first-motion polarity FPSs of earthquakes from the Mediterranean area since 1905 and published until 2007. The final dataset count ca. 300 FPSs.

Focal mechanisms depict dominant reverse faulting and their nodal planes strike generally in a NW-SE direction which gradually changes toward EW approaching the south-east Persian Gulf (Fig. 2b). Nodal planes are parallel to regional structures and strikes behaviour follows folding directions of BZFTB, in accord with previous studies (e.g. Hatzfeld et al., 2010). A significant fraction of reverse focal mechanisms are associated with hypocentral depth < 20 km, probably due to seismicity in the basement and not in the sedimentary succession (Berberian, 1995), and high dip angle, maybe related to reactivation of Mesozoic normal faulting (Jackson, 1980) inherited from the opening of the Tethys Ocean. The shortening is also accommodated by frequent strike-slip faulting processes, rupturing along the major tectonic structures.

In addition, we present a preliminary inversion of the state of stress in the investigated area by taking into account our dataset of earthquake focal mechanisms. For the stress inversion method, we adopted the Spatial And Temporal Stress Inversion (SATSI) program (Hardebeck and Michael, 2006) available from the USGS webpage. The SATSI method is a damped grid-search inversion for stress tensor orientation. The damping helps to decrease the artificial noise or isolated data singularities associated with stress field orientation inversion (Hardebeck and Michael, 2006). We divided the mapped area into 1°×1° squares, requiring a minimum of 10 earthquakes in each square to be included into the inversion procedure. The smoothed results, reported in Fig. 2c, well evidence a regional trend of the maximum horizontal compressional stress (Sh_MAX) which systematically changes from a NNE-SSW attitude, along NZ and the western sector of CZ, to a NS attitude on the eastern sector of CZ, maintaining always an orthogonal orientation with respect to the collisional mountain belt.

GPS data. Data acquired by continuous GPS sites installed across the Zagros collisional belt and freely available on-line archives (i.e. SOPAC, UNAVCO, NGS) were processed by using the GAMIT/GLOBK software (Herring et al., 2010) following the strategy reported
Fig. 2 – a) Instrumental crustal seismicity (M ≥ 2.5) occurring in the investigated area since 1960 (http://www.isc.ac.uk). b) Lower hemisphere, equal area projection for the 387 FPSs compiled for this study; FPSs are coloured according to rake: red indicates pure thrust faulting, blue is pure normal faulting, and yellow is strike-slip faulting. c) $\text{Sh}_{\text{MAX}}$ pattern as obtained by preliminary inversion of the FPS dataset.
in Palano et al. (2012). To improve the overall configuration of the network and to tie the regional observations to an external global reference frame, data coming from 10 continuously operating IGS (International GNSS Service) stations were introduced in the processing. By using the GLOBK module, the regional observations are then combined, on a daily basis, with global solutions of the Scripps Orbital and Permanent Array Center (SOPAC) at University of California, San Diego (Bock et al., 1997) and aligned to the ITRF2008 reference frame through a seven-parameter Helmert transformation (3 translations, 3 rotations and a scale factor). We then combined the corrected daily position estimates and their full covariance matrices to estimate a long-term average site velocity in the ITRF2008 reference frame.

Our GPS network shares some stations with the ones processed by Walpersdorf et al. (2006), Masson et al. (2007), Tavakoli et al. (2008), Djamour et al. (2011) allowing a rigorous integration by applying a Helmert transformation of the five estimated velocity fields. To adequately show the crustal deformation pattern over the investigated area, we rotate the final ITRF2008 GPS velocity solution into an Arabian fixed reference frame (Fig. 3a; Palano et al., 2013). In addition, we compute the 2D strain-rate tensor over the studied area. In particular, as a first step, by taking into account the observed horizontal velocity field and associated

![Fig. 3 – a) GPS velocities and 95% confidence ellipses in a fixed Arabian plate (see Palano et al., 2013 for more details). b) geodetic strain-rate field: arrows represent the greatest extensional (red) and contractional (blue) horizontal strain-rates.](image-url)
covariance information, we derived a continuous velocity gradient tensor on a regular 1° x 1° grid (whose nodes do not coincide with any of the GPS stations) using a “spline in tension” technique (Wessel and Bercovici, 1998). The tension is controlled by a factor T, where T=0 leads to a minimum curvature (natural bicubic spline), while T=1 leads to a maximum curvature, allowing for maxima and minima only at observation points; in our computations we set T=0.4. As a final step, we computed the average 2D strain-rate tensor as derivative of the velocities at the nodes of each grid cell. The estimated strain-rates are shown in Fig. 3b.

As shown in Fig. 3a, available GPS data do not cover with the same density the investigated area. In particular, while the southern part (i.e. Central Zagros; CZ) shows a regular station density across the collisional belt, the northern part (i.e. North Zagros; NZ) is sampled by few data, mainly concentrated along its NE and SW borders. Beside this limitation, the geodetic velocity field clearly depicts two main features. NZ is affected by a prevailing right-lateral shear mainly concentrated along the Main Zagros Reverse Fault (MZRF): stations located NE of MZRF move toward SW with rates of ~12 mm/yr while stations located across the collision belt move toward SE with rates of ~3 mm/yr. Southward, the velocity field depicts a spectacular rotation passing from a South-directed motion (rates of ~10-13 mm/yr) NE of MZRF to a SWward motion across CZ (rates of ~1-3 mm/yr). The 2D strain-rate map highlights better these main features (Fig. 3b). In particular, the maximum contractional horizontal strain-rate shows a fan-shaped feature across CZ maintaining always an orthogonal orientation with respect to the curvature of the collisional mountain belt; across this area a shortening up to ~50 nanostrain/yr can be recognized. Along NZ, the 2D strain-rate shows a complex pattern, probably due to the poor station density; on this area a general shortening up to ~25 nanostrain/yr is inferred.

**Conclusive remarks.** Based on the data presented here and discussed in the previous section, we may draw the following conclusions:

- A large amount of instrumental seismicity of the Zagros collisional belt ruptures a narrow belt located westward of MZRF. Seismicity appears mainly confined into the 10 and 25 km depth interval.
- Focal mechanism solutions show prevailing high-angle reverse faulting features with NW-SE strikes, parallel to the folding and well depicting the contractional nature of the mountain belt. Preliminary results about the state of stress of the area infer a Sh^MAX pattern showing trends always orthogonal with respect to the collisional mountain belt.
- GPS data indicate that NZ is affected by a prevailing right-lateral shear mainly concentrated along the Main Zagros Reverse Fault (MZRF), while across CZ the velocity field depicts a spectacular rotation coupled with a decrease of the velocity values. These patterns are well recognized on the 2D strain-rate field.
- A simple visual comparison of seismological stress and geodetic strain-rate directions shows that crust in the investigated area is contracting in the direction of maximum compression evidencing that, at this scale of observation, the release of elastic stress is at par with the tectonic loading of the crust.

**References**


