Fault-plane solutions and stress orientation in the greater region of Northern and Central Dinarides

ABSTRACT: We present a newly compiled database of fault-plane solutions (FPS) for 242 earthquakes which occurred in the Northern and Central Dinarides and the surrounding regions (mostly Croatia and Bosnia-Herzegovina), computed from the 14512 first motion polarity data as manually read from available regional seismograms (8634 onset amplitudes) and bulletin reports (5878 polarities, mostly for the pre-digital era). This is a continuation of the effort that started in 1995 with the first published collection of FPS in Croatia (Herak et al. 1995). The program used minimizes the misfit between the theoretical radiation pattern amplitudes and the ones assigned to each reading by the analyst. It also allows the use of amplitude ratios of direct P and S-waves in inversion. Such an approach enabled definition of confidence limits (and quality assignment) that are based on the shape of the misfit function.

The solutions indicate compressive regime throughout the region. Reverse and thrust dip-slip faulting is predominant in the Central External Dinarides (Dalmatia south of Zadar and the Montenegrin coast), in the central Adriatic, and in NW Croatia. Mostly strike-slip solutions were obtained in the transition zone from the External to Internal Dinarides in southwestern and central Bosnia-Herzegovina, and in the border region between Croatia and Slovenia NW from Rijeka. Mixed styles of faulting are seen primarily in the Banja Luka area in NW Bosnia-Herzegovina, and in the vicinity of Novi Vinodolski (to the North of Mt. Velebit). The P-axes for the best solutions strike on average SW–NE, i.e. perpendicularly to the trend of the Dinarides in their southern part, and turn counter-clockwise further to the NW. In northwestern and northern Croatia the stress is on average oriented SSW–NNE to S–N. We also present spatially smoothed angular histograms of the P-axes direction, considering all individual solutions within the 75% confidence limits. These new fault mechanism solutions considerably enlarge rather sparse existing dataset documenting the style of faulting and the stress regime in the region.

Marijan Herak, Davorka Herak and Iva Dasović

University of Zagreb, Faculty of Science,
Department of Geophysics
Horvatovac 95, 10000 Zagreb, Croatia
herak@irb.hr, dherak@gfz.hr, dasovici@gfz.hr

METHOD

The best fitting double-couple parameters were sought by exhaustive grid-search for the triplet (φ_o – strike, δ_o – dip, λ_o – rake) that minimizes the misfit function D defined for N observations as:

$$D(\varphi,\delta,\lambda) = \frac{\sum_{i=1}^{N} w_i\,[r_i(\varphi,\delta,\lambda) - p_i]^2}{\sum_{i=1}^{N} w_i}\;\frac{1}{g(\varphi,\delta,\lambda)}$$

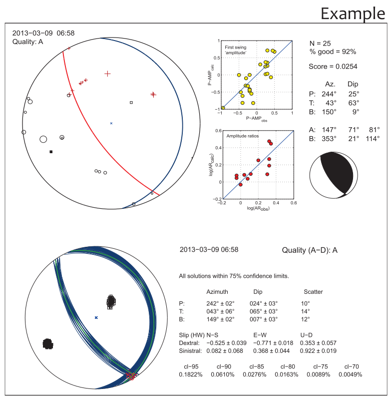
- r – theoretical radiation pattern,
- p – observed normalized amplitude of the P-wave first onset
- w – corresponding weight (depend on clarity of onset, proximity to the nodal plane, and whether it comes from bulletin or is read from the seismogram)
- g – the percentage of correct polarities for the choice (φ,δ,λ) (ranging from 0.5 to 1.0).

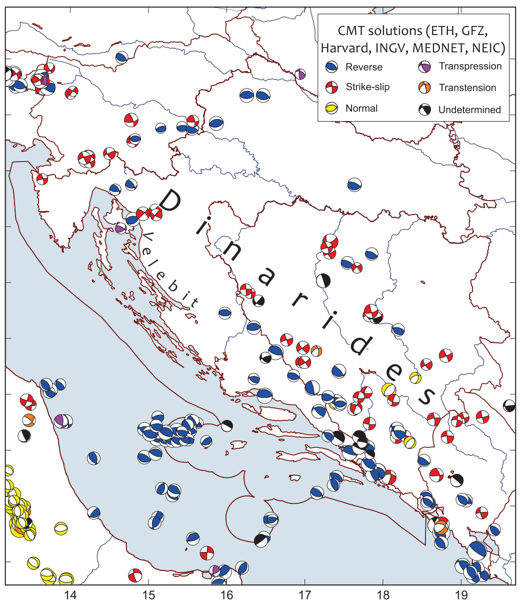
The observable p may be simply ±1 (polarity), but it may also be discretized into any number of classes between 0.0 and ±1.0 indicating the amplitude of the first swing. For instance, 0.1, 0.3, 0.5, 0.7, 0.9, may signify first amplitudes that are qualitatively described as "very small" (probably close to the nodal plane), "small", "average", "large", and "very large" (probably close to the center of the quadrant), respectively.
Once D has been determined for all combinations of (φ,δ,λ), it is possible to use the F-function cumulative distribution with (N–3, N–3) DOF to extract a set of solutions that are within the desired confidence limits, and to define the quality score (A–D) based on scatter of all solutions within the set.
For poorly constrained solutions, and if digital seismograms were available, the misfit function was modified to also include amplitude ratios of P and S waves on Z- and T-components ($A_1 = S_Z/P_Z$, $A_2 = S_T/P_Z$, $A_3 = S_Z/S_T$):

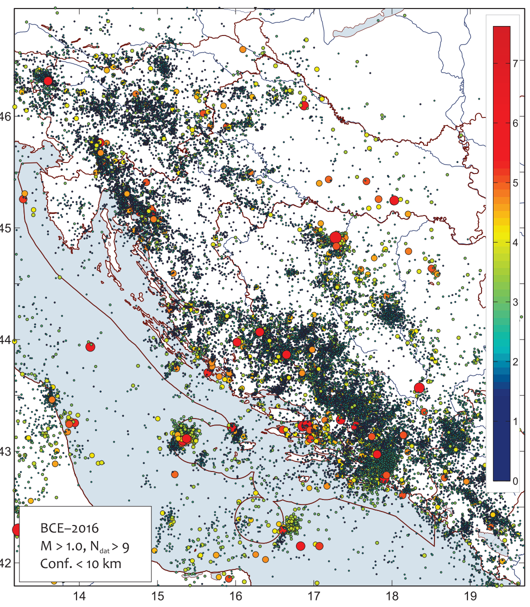
$$D'(\varphi,\delta,\lambda) = (1-W_A)\,D(\varphi,\delta,\lambda) + W_A \sum_j \log(A_{j,O}/A_{j,T})^2.$$

O and T denote observed and theoretical amplitude ratios, respectively. How much weight the amplitude ratios carry in the final misfit function is determined by W_A ($W_A < 1.0$).

Example

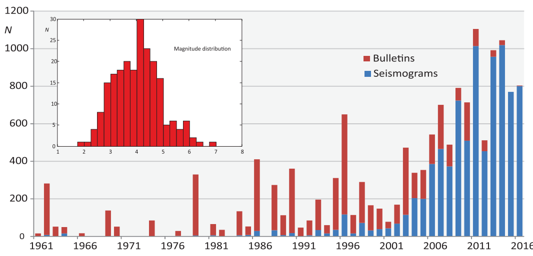


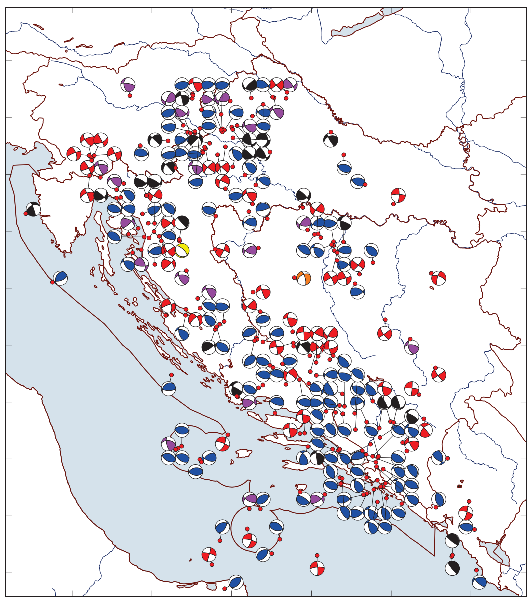


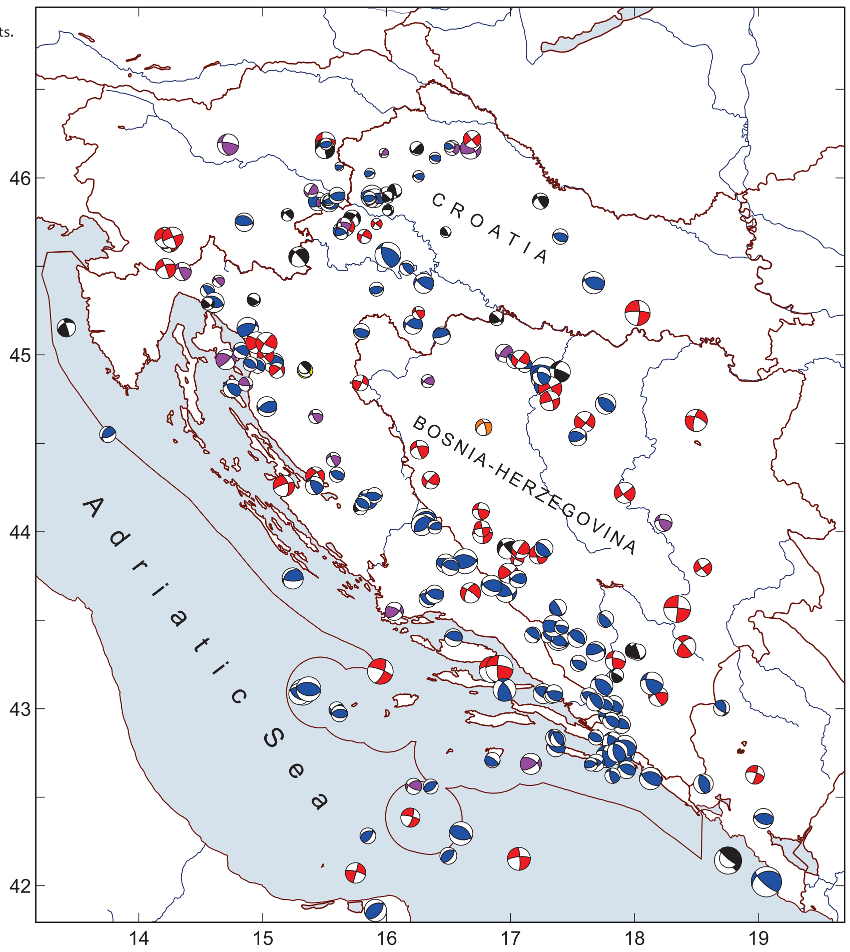


DATASET

- **242** earthquakes mostly from Croatia and Bosnia-Herzegovina (also Slovenia, Montenegro)
- Magnitudes range: 1.9–6.9
- **14 512** first motion data, of those:
- **8634** onset amplitudes manually read from seismograms and **5878** polarities read from bulletin reports.

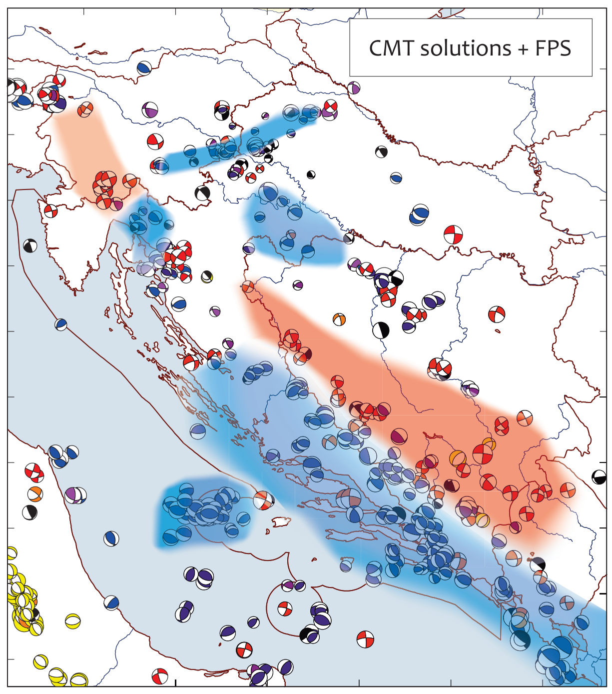


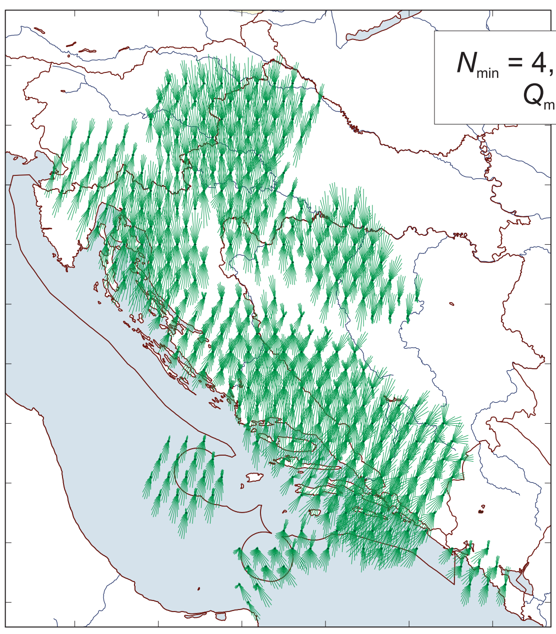


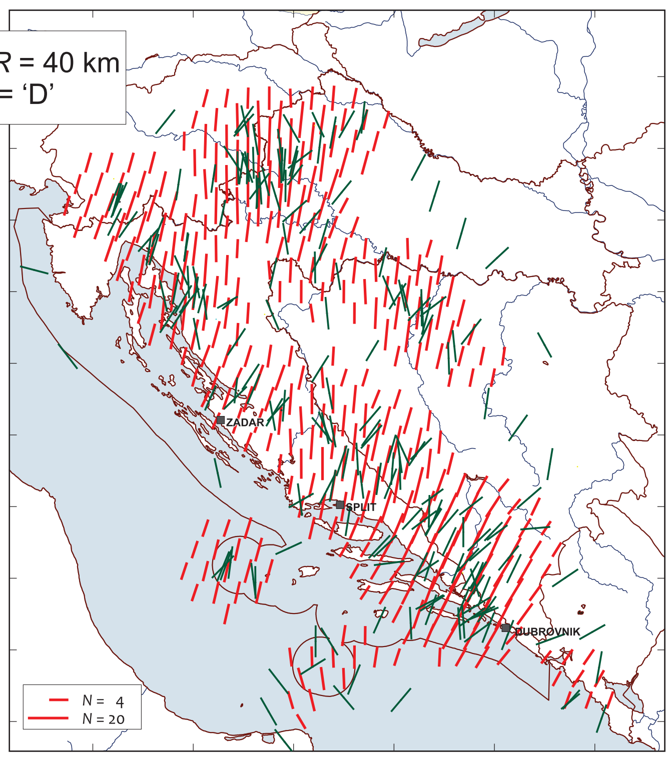


Maps of FPS

- Reverse
- Strike-slip
- Normal
- Transpression
- Transtension
- Undetermined
- Mostly reverse
- Mostly strike-slip







TOP: Angular histograms of all P-axis strike azimuths corresponding to solutions falling within 75% confidence limits, averaged on a regular grid. All events with quality 'D' or better and within 40 km of each grid node are considered. Only nodes with at least 4 such events are considered.

RIGHT: Angular average of spatially smoothed P-axis strike azimuths (red), and individual P-axes for each considered FPS (green).

CONCLUSIONS

1. Faulting mechanisms computed for 242 earthquakes in the greater region of Northen and Central Dinarides using data on first-motion polarity, its prominence, and amplitude ratios, considerably improve the density of available fault-plane solutions (FPS) in this region. Overall agreement between CMT solutions and FPS presented here (when both exist) is very good.

2. The data presented above indicate two distinct regions along the strike of the Dinarides, southeast of the Mt. Velebit. The external belt (collision zone between Adria and Europe) is characterised by prevalence of reverse or thrust faulting, whereas the earthquakes in the transition zone from External to Internal Dinarides mostly originate on strike-slip transfer faults. This is roughly in agreement with the recent models of active faults there (*e.g.* SHARE project, Basili *et al.*, 2013) and tectonic reconstructions (*e.g.* Handy *et al.*, 2015). To the northwest of Mt. Velebit mostly reverse dip-slip faulting abruptly changes to a strike-slip regime. Until more data is collected, the region of Mt. Velebit and its hinterland remains enigmatic, with a mixture of faulting-styles especially at its NW part. A similar situation is seen around Banja Luka in NW Bosnia and Herzegovina. FPS in the Central Adriatic (around the islet of Jabuka) indicate W–S striking reverse faults, which is not reflected in current regional fault-models.

3. Observed average strike of the best double-couple P-axes is SSW–NNE to S–N, which is in general agreement with the (rather sparse) data from the World Stress Map, or the modelled stress in Central Europe (Jarosiński *et al.*, 2006). Along the Croatian coast it is approximatelly perpendicular to the coastline, except in Central Dalmatia (between Zadar and Split), and in the NW-most part of the Mt. Velebit region where it turns to the S–N direction. More inland, in NW Croatia and N Bosnia and Herzegovina, P-axis is generally directed S–N.

FPS database and catalogue is updated constantly. It will hopefully help in better definitions of properties of seismogenic faults and modelling of seismotectonic processes.

References

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This study has been supported by the Croatian Science Foundation, grant number IP 2014-09-9666. The support is gratefully acknowledged.