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Fault-plane solutions for earthquakes (1956–1995) in Croatia and neighbouring regions

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The study presents (re)evaluation of fault-plane solutions for 40 earthquakes that occurred in the period 1956–1995 in Croatia and neighbouring regions. All events were analyzed in the same manner, using the best available velocity models and the most recently updated earthquake catalogue for that region. For the most important earthquakes our solution is briefly discussed and compared to the results of previous studies when they were available. The results are presented with all related data thus enabling estimation of each solutions' reliability.

Mehanizmi pomaka u žarištu potresa (1956–1995) u Hrvatskoj i susjednim područjima

U radu su objavljena rješenja mehanizama u žarištu za 40 potresa koji su se dogodili u razdoblju 1956–1995 u Hrvatskoj i susjednim područjima. Svi su potresi analizirani na isti način koristeći najbolje dostupne modele razdiobe brzina seizmičkih valova s dubinom, kao i najpotpuniji katalog potresa. Rješenja koja se odnose na najznačajnije potrese kratko su diskutirana i uspoređena s rezultatima dosadašnjih studija. Prikazani su i svi popratni podaci koji omogućuju procjenu pouzdanosti pojedinog rješenja.

1. Introduction

The fault-plane solutions (FPS) provide essential data for single earthquake source studies as well as for hazard assessment or research related to contemporary tectonic stress field. It is therefore of importance to collect as many FPS as possible for a particular region and present them in a uniform manner. No such collection has yet been published for Croatia and the neighbouring regions. For some of events in this area FPS were reported by researchers dealing with the tectonics of the Balkans, Adriatic or the Pannonian basin (*e.g.* McKenzie, 1972; Ritsema, 1974; Anderson and Jackson, 1987; Gerner, 1995), but many important earthquakes have not been taken into account. Furthermore, the methodologies and data sets used varied significantly, often leading to uncomparable and widely differing solutions for the same event.

In this paper we (re)evaluate FPS for 40 earthquakes in Croatia and adjacent areas that occurred in the period 1956–1995. All events were processed in the same manner using local velocity models, and parameters are given to asses each solution's reliability.

2. Data and method

The earthquakes considered (listed in Table 1) ranged in magnitude from M_L=3.5 to M_L=6.8. Most of them were too weak to be recorded at teleseismic distances, so we had to rely on data reported mainly by local and regional stations. As P_n is the phase that arrives first at regional distances the resolution in the emergence angle space was rather poor. The angles at which rays emerge towards the stations were computed using the best available – but still rather simple – local velocity models (Herak and Herak, 1995) and the most recently updated version of the Croatian earthquake catalogue (Herak et al., 1996). The quality of the velocity models influences the results much more for P_g, whose ray path is determined by relatively inhomogeneous structure of the upper crust, than for P_n for which the angle of emergence from the focus depends on quantities that have small spatial variability.

The data on the first arrival polarity were read from the original seismograms (mostly from Croatian, but also for some Albanian, Italian, Montenegrin and Slovenian stations) or were taken from various available bulletins and other published material.

The best fitting fault-plane solution was determined by a combination of random and guided search in the (φ, δ, λ) space (φ – fault's strike azimuth, δ – fault's dip, λ – rake, as defined in Aki and Richards, 1980).

The best fitting solution was defined to minimize

$$s = g / b$$

where g (good) is the sum of weights for observations with polarities that agree with the theoretical ones, while b (bad) is the same for non-fitting data. The weights, w were calculated after

$$w = w_1 w_2$$

where w_1 = 1.0 for *i* (impetus) or w_1 = 0.5 for *e* (emergent) type of onset and w_2 ranges from 0.2 for data on nodal lines to 1.0 for data with the largest theoretical radiation pattern amplitudes (*i.e.* in the middle of the respective radiation quadrant). In the initial part of the algorithm 450 000 random solutions are tested. The guided search then takes over, limiting the search space to a progressively narrowing »cone« centered around the best solution so far, until a total of 750 000 (φ, δ, λ) triplets have been tested.

Table 1. List of earthquakes
(BH – Bosnia and Herzegovina, CR – Croatia, MN – Montenegro, SL – Slovenia)

No.	Date (d.m.y)	Time (UTC)	Lat. (°N)	Lon. (°E)	Depth (km)	M_L	Region
1	15.08.56.	12:02:56.1	43.210	15.950	14.0	5.75	Vis island, CR
2	22.06.61.	00:56:04.0	42.320	19.260	24.0	4.90	MN
3	07.01.62.	10:03:12.9	43.200	16.880	10.0	5.90	Makarska – Hvar island, CR
4	11.01.62.	05:05:00.2	43.150	16.940	10.0	6.10	Makarska – Hvar island, CR
5	21.01.62.	02:51:32.0	43.090	16.950	14.0	5.15	Makarska – Hvar island, CR
6	17.04.62.	10:03:46.0	42.150	17.070	21.0	5.15	Gargano ridge, Adriatic Sea
7	11.06.62.	07:15:43.0	43.600	18.400	8.0	6.00	Treskavica Mt., BH
8	14.02.63.	13:18:53.5	44.260	15.170	15.0	4.80	Pag island, CR
9	19.05.63.	10:00:04.0	46.190	14.720	14.0	4.80	Kamnik, SL
10	13.04.64.	08:30:00.0	45.242	18.026	11.0	5.65	Dilj gora, CR
11	05.08.66.	17:47:43.0	42.100	18.800	35.0	5.00	Adriatic Sea, MN
12	26.10.69.	15:36:47.7	44.850	17.280	10.0	6.00	Banja Luka, BH
13	27.10.69.	08:10:55.8	44.930	17.240	18.0	6.40	Banja Luka, BH
14	25.08.70.	01:40:11.0	43.350	18.410	13.0	5.00	Zelengora, BH
15	15.04.79.	06:19:45.8	42.020	19.070	13.0	6.80	Adriatic Sea, MN
16	15.04.79.	14:43:05.7	42.210	18.680	4.0	5.80	Adriatic Sea, MN
17	24.05.79.	17:23:18.1	42.140	18.760	5.0	6.10	Adriatic Sea, MN
18	11.03.84.	11:55:31.5	45.830	15.470	6.1	4.20	Kostanjevica, SL
19	13.05.84.	12:45:54.6	42.970	17.800	13.4	5.40	Hutovo Blato, BH
20	21.04.85.	18:13:20.5	43.840	16.543	18.2	4.15	Dinara Mt., CR – BH
21	25.11.86.	13:59:40.7	44.077	16.345	9.4	5.50	Knin, CR
22	27.11.86.	12:10:32.4	44.053	16.340	15.7	4.40	Knin, CR
23	24.12.86.	16:48:03.6	43.997	16.220	9.7	4.70	Knin, CR
24	26.04.88.	00:53:45.7	42.341	16.641	0.0	5.30	Gargano ridge, Adriatic Sea
25	16.12.88.	11:35:50.3	44.708	15.033	6.0	4.50	Velebit Mt., CR
26	06.12.89.	05:33:12.4	43.661	16.965	9.1	4.80	Kamešnica Mt., CR – BH
27	03.09.90.	10:48:32.1	45.923	15.922	12.8	4.80	Donja Stubica, CR
28	27.11.90.	04:37:57.7	43.833	16.635	7.9	5.60	Dinara Mt., CR
	27.11.90.	04:51:37.2	43.861	16.650	9.1	5.50	Dinara Mt., CR
29	27.04.91.	18:44:53.0	46.596	15.199	11.6	3.70	Pohorje, SL
30	08.09.91.	19:45:23.5	42.242	18.899	11.3	4.30	Adriatic Sea, MN
31	21.02.92.	20:50:32.4	45.472	14.349	13.0	4.10	Klana, CR – SL
32	11.06.92.	00:20:21.8	45.919	14.925	13.4	3.50	Trebnje, SL
33	30.10.92	05:38:27.1	42.378	19.046	13.8	4.50	Skadar Lake, MN
34	06.04.93.	23:24:48.4	43.011	17.830	12.6	4.05	Hutovo Blato, BH – CR
35	01.06.93.	19:51:09.9	46.232	16.547	18.8	4.70	Ludbreg, CR
36	01.10.93.	04:13:09.2	43.399	17.662	3.7	4.25	Mostar, BH
37	25.02.94.	16:03:05.9	43.654	16.679	10.6	4.55	Sinj, CR
38	13.05.95.	10:16:01.0	43.155	15.274	8.7	4.40	Jabuka island, Central Adriatic Sea
39	22.05.95.	11:16:53.4	45.620	14.260	18.9	4.30	Snežnik, SL
40	22.05.95.	12:50:31.0	45.612	14.242	18.5	4.70	Snežnik, SL

The stability of the best solution was qualitatively assessed by accepting all solutions that have up to 5% less »good« data then the best one does. Out of these, 100 were randomly chosen and for them P (pressure) and T (tension) axes positions were defined by their strike (φ_P, φ_T) and dip (δ_P, δ_T). For well defined solutions, a small perturbation of data set as described above, would induce only minor variation of P and T positions, while the opposite holds for unstable solutions. The stereographic plots showing the positions of 100 P and T axes computed in this way are given for all solutions in Fig. 2.

3. Results

An overview map of obtained FPS is presented in Fig. 1, while detailed plots for each of them is given in Fig. 2. In the following, we shall discuss some of the solutions obtained and compare our results to those previously published.

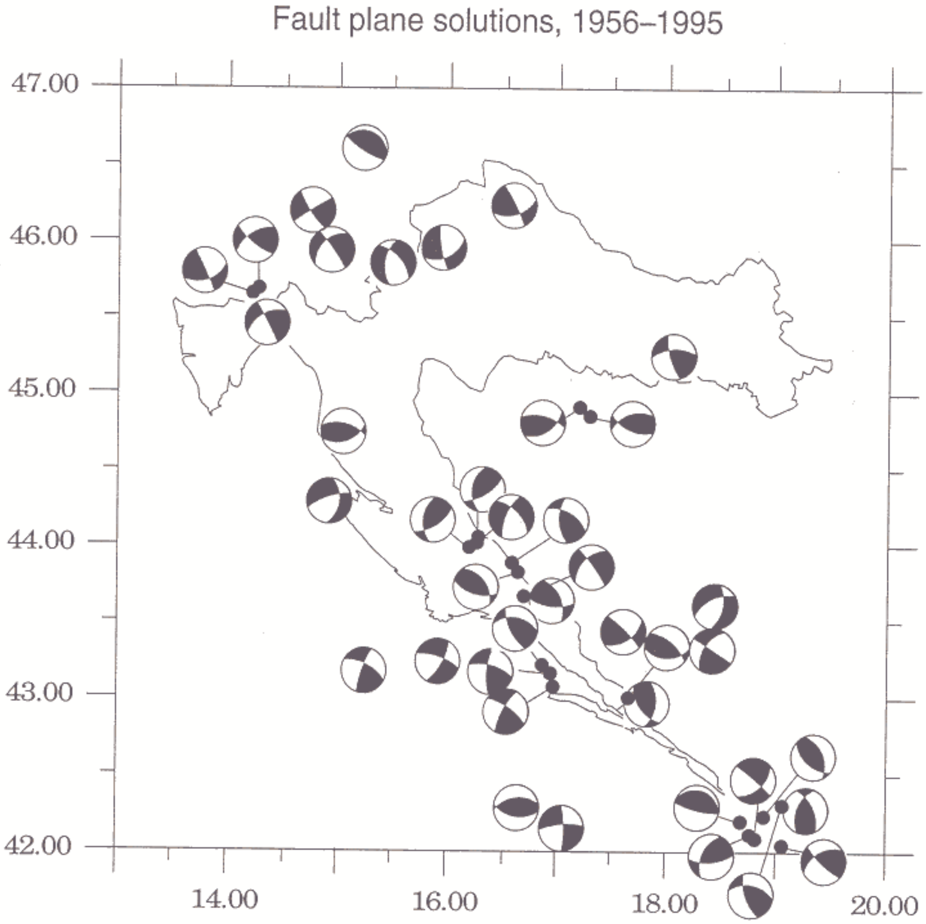
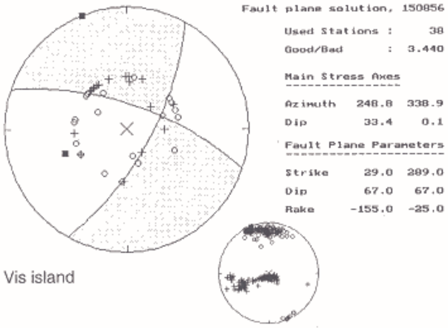


Figure 1. Fault-plane solutions obtained in this study (lower hemisphere stereographic projection beach-ball plots). Compressive quadrants are shaded.

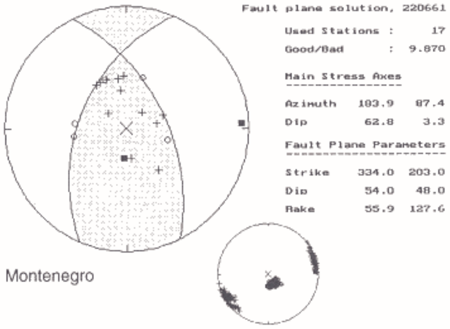
⟶

Figure 2. Lower hemisphere stereographic projection plots. Compressions are indicated as '+' (shaded quadrants), dilatations as 'o'. The earthquakes' occurrence dates are given in the upper right corner of each subplot (in the format ddmmyy), see Table 1. Main parameters of the best solution are listed in a table to the right of the plot. The small subplot presents positions of P- and T-axes ('+' and 'o', respectively) for 100 random solutions satisfying acceptance criteria in a perturbed data set (see text for details). Figure continues on five pages.



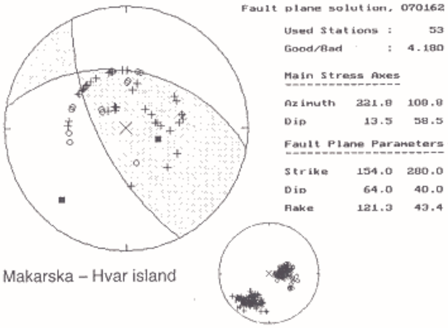
```
Fault plane solution, 150856
          Used Stations :       38
          Good/Bad      :    3.440

          Main Stress Axes
          ----------------
          Azimuth    248.8   338.9
          Dip         33.4     0.1
          Fault Plane Parameters
          ----------------------
          Strike      29.0   289.0
          Dip         67.0    67.0
          Rake      -155.0   -25.0
```

Vis island



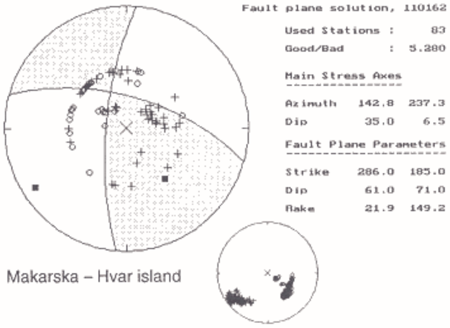
```
Fault plane solution, 220661
          Used Stations :       17
          Good/Bad      :    9.870

          Main Stress Axes
          ----------------
          Azimuth    183.9    87.4
          Dip         62.8     3.3
          Fault Plane Parameters
          ----------------------
          Strike     334.0   203.0
          Dip         54.0    48.0
          Rake        55.9   127.6
```

Montenegro



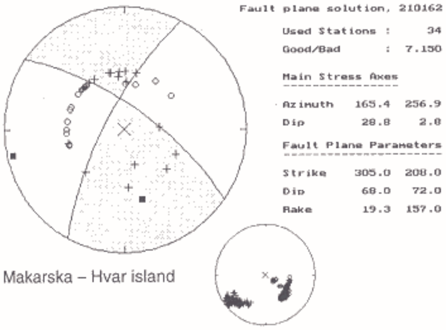
```
Fault plane solution, 070162
          Used Stations :       53
          Good/Bad      :    4.180

          Main Stress Axes
          ----------------
          Azimuth    221.8   108.8
          Dip         13.5    58.5
          Fault Plane Parameters
          ----------------------
          Strike     154.0   280.0
          Dip         64.0    40.0
          Rake       121.3    43.4
```

Makarska – Hvar island



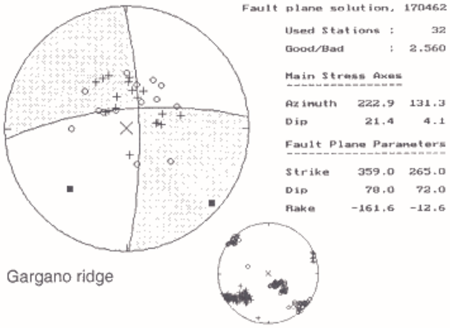
```
Fault plane solution, 110162
          Used Stations :       83
          Good/Bad      :    5.280

          Main Stress Axes
          ----------------
          Azimuth    142.8   237.3
          Dip         35.0     6.5
          Fault Plane Parameters
          ----------------------
          Strike     286.0   185.0
          Dip         61.0    71.0
          Rake        21.9   149.2
```

Makarska – Hvar island



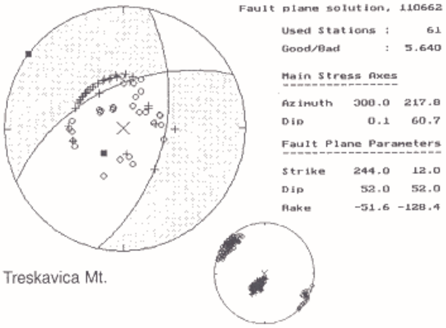
```
Fault plane solution, 210162
          Used Stations :       34
          Good/Bad      :    7.150

          Main Stress Axes
          ----------------
          Azimuth    165.4   256.9
          Dip         28.8     2.8
          Fault Plane Parameters
          ----------------------
          Strike     305.0   208.0
          Dip         68.0    72.0
          Rake        19.3   157.0
```

Makarska – Hvar island



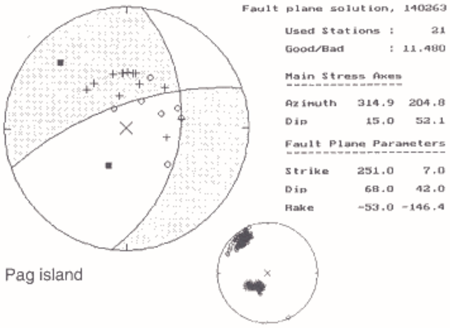
```
Fault plane solution, 170462
          Used Stations :       32
          Good/Bad      :    2.560

          Main Stress Axes
          ----------------
          Azimuth    222.9   131.3
          Dip         21.4     4.1
          Fault Plane Parameters
          ----------------------
          Strike     359.0   265.0
          Dip         78.0    72.0
          Rake      -161.6   -12.6
```

Gargano ridge



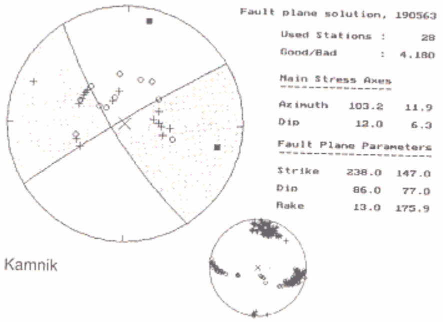
```
Fault plane solution, 110662
          Used Stations :       61
          Good/Bad      :    5.640

          Main Stress Axes
          ----------------
          Azimuth    308.0   217.8
          Dip          0.1    60.7
          Fault Plane Parameters
          ----------------------
          Strike     244.0    12.0
          Dip         52.0    52.0
          Rake       -51.6  -128.4
```

Treskavica Mt.



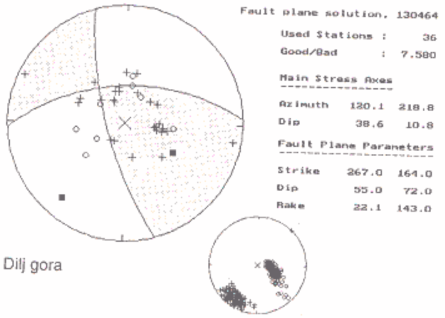
```
Fault plane solution, 140263
          Used Stations :       21
          Good/Bad      :   11.480

          Main Stress Axes
          ----------------
          Azimuth    314.9   204.8
          Dip         15.0    52.1
          Fault Plane Parameters
          ----------------------
          Strike     251.0     7.0
          Dip         68.0    42.0
          Rake       -53.0  -146.4
```

Pag island



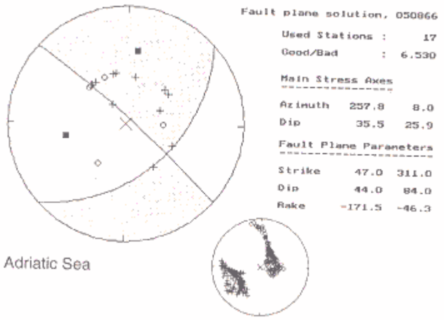
```
Fault plane solution, 190563
          Used Stations :       28
          Good/Bad      :  4.180

          Main Stress Axes
          ----------------
          Azimuth   103.2   11.9
          Dip        12.0    6.3

          Fault Plane Parameters
          ----------------------
          Strike    238.0  147.0
          Dip        86.0   77.0
          Rake       13.0  175.9
```

Kamnik



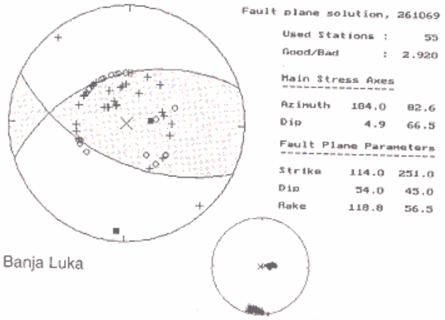
```
Fault plane solution, 130464
          Used Stations :       36
          Good/Bad      :  7.580

          Main Stress Axes
          ----------------
          Azimuth   120.1  218.8
          Dip        38.6   10.8

          Fault Plane Parameters
          ----------------------
          Strike    267.0  164.0
          Dip        55.0   72.0
          Rake       22.1  143.0
```

Dilj gora



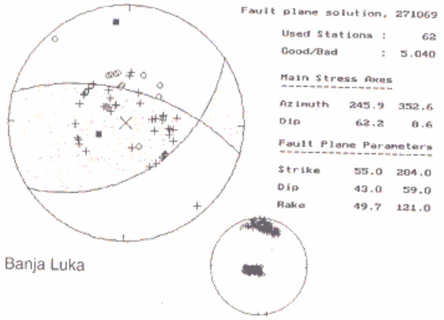
```
Fault plane solution, 050866
          Used Stations :       17
          Good/Bad      :  6.530

          Main Stress Axes
          ----------------
          Azimuth   257.8    8.0
          Dip        35.5   25.9

          Fault Plane Parameters
          ----------------------
          Strike     47.0  311.0
          Dip        44.0   84.0
          Rake     -171.5  -46.3
```

Adriatic Sea



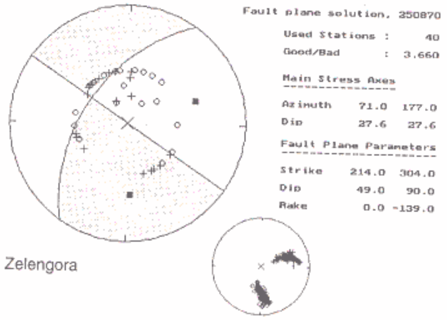
```
Fault plane solution, 261069
          Used Stations :       55
          Good/Bad      :  2.920

          Main Stress Axes
          ----------------
          Azimuth   184.0   82.6
          Dip         4.9   66.5

          Fault Plane Parameters
          ----------------------
          Strike    114.0  251.0
          Dip        54.0   45.0
          Rake      118.8   56.5
```

Banja Luka



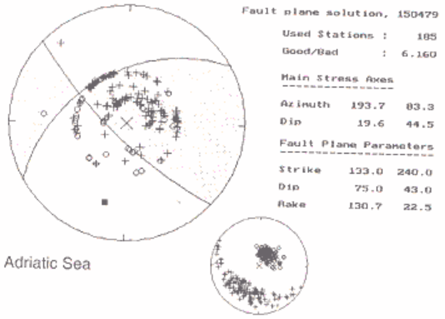
```
Fault plane solution, 271069
          Used Stations :       62
          Good/Bad      :  5.040

          Main Stress Axes
          ----------------
          Azimuth   245.9  352.6
          Dip        62.2    8.6

          Fault Plane Parameters
          ----------------------
          Strike     55.0  204.0
          Dip        43.0   59.0
          Rake       49.7  121.0
```

Banja Luka



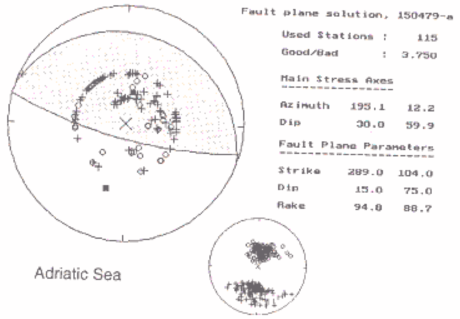
```
Fault plane solution, 250870
          Used Stations :       40
          Good/Bad      :  3.660

          Main Stress Axes
          ----------------
          Azimuth    71.0  177.0
          Dip        27.6   27.6

          Fault Plane Parameters
          ----------------------
          Strike    214.0  304.0
          Dip        49.0   90.0
          Rake        0.0 -139.0
```

Zelengora



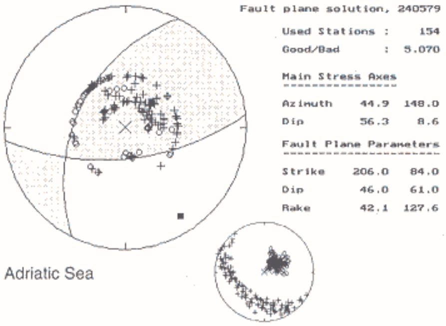
```
Fault plane solution, 150479
          Used Stations :      185
          Good/Bad      :  6.160

          Main Stress Axes
          ----------------
          Azimuth   193.7   83.3
          Dip        19.6   44.5

          Fault Plane Parameters
          ----------------------
          Strike    133.0  240.0
          Dip        75.0   43.0
          Rake      130.7   22.5
```

Adriatic Sea



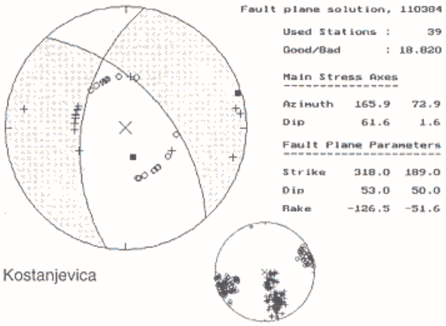
```
Fault plane solution, 150479-a
          Used Stations :      115
          Good/Bad      :  3.750

          Main Stress Axes
          ----------------
          Azimuth   195.1   12.2
          Dip        30.0   59.9

          Fault Plane Parameters
          ----------------------
          Strike    289.0  104.0
          Dip        15.0   75.0
          Rake       94.8   88.7
```

Adriatic Sea



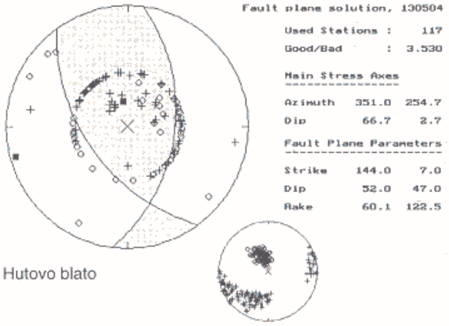
```
Fault plane solution, 240579

Used Stations :      154
Good/Bad      :    5.070

Main Stress Axes
----------------

Azimuth    44.9   148.0
Dip        56.3     8.6

Fault Plane Parameters
----------------------

Strike    206.0    84.0
Dip        46.0    61.0
Rake       42.1   127.6
```

Adriatic Sea



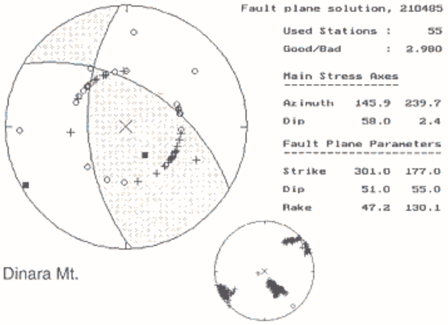
```
Fault plane solution, 110384

Used Stations :       39
Good/Bad      :   18.820

Main Stress Axes
----------------

Azimuth   165.9    73.9
Dip        61.6     1.6

Fault Plane Parameters
----------------------

Strike    318.0   189.0
Dip        53.0    50.0
Rake     -126.5   -51.6
```

Kostanjevica



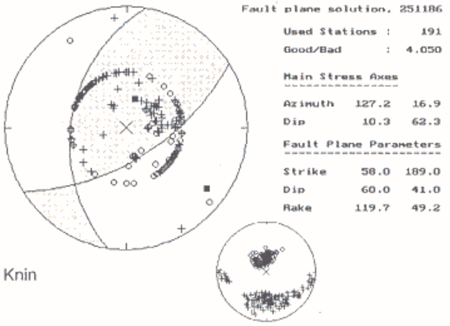
```
Fault plane solution, 130504

Used Stations :      117
Good/Bad      :    3.530

Main Stress Axes
----------------

Azimuth   351.0   254.7
Dip        66.7     2.7

Fault Plane Parameters
----------------------

Strike    144.0     7.0
Dip        52.0    47.0
Rake       60.1   122.5
```

Hutovo blato



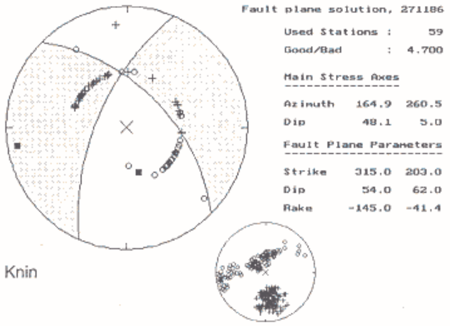
```
Fault plane solution, 210485

Used Stations :       55
Good/Bad      :    2.980

Main Stress Axes
----------------

Azimuth   145.9   239.7
Dip        58.0     2.4

Fault Plane Parameters
----------------------

Strike    301.0   177.0
Dip        51.0    55.0
Rake       47.2   130.1
```

Dinara Mt.



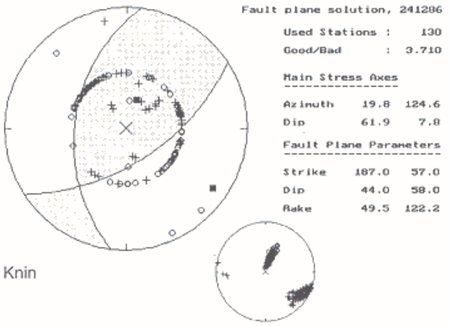
```
Fault plane solution, 251186

Used Stations :      191
Good/Bad      :    4.050

Main Stress Axes
----------------

Azimuth   127.2    16.9
Dip        10.3    62.3

Fault Plane Parameters
----------------------

Strike     58.0   189.0
Dip        60.0    41.0
Rake      119.7    49.2
```

Knin



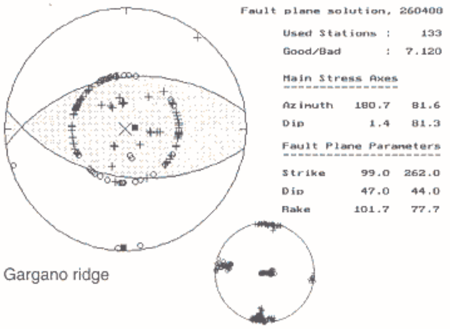
```
Fault plane solution, 271186

Used Stations :       59
Good/Bad      :    4.700

Main Stress Axes
----------------

Azimuth   164.9   260.5
Dip        48.1     5.0

Fault Plane Parameters
----------------------

Strike    315.0   203.0
Dip        54.0    62.0
Rake     -145.0   -41.4
```

Knin



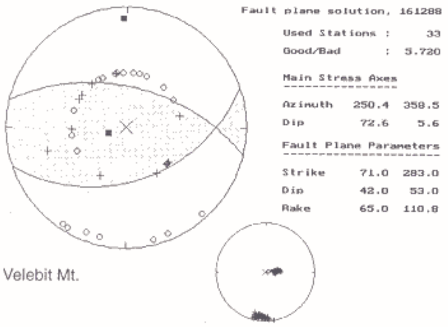
```
Fault plane solution, 241286

Used Stations :      130
Good/Bad      :    3.710

Main Stress Axes
----------------

Azimuth    19.8   124.6
Dip        61.9     7.8

Fault Plane Parameters
----------------------

Strike    187.0    57.0
Dip        44.0    58.0
Rake       49.5   122.2
```

Knin



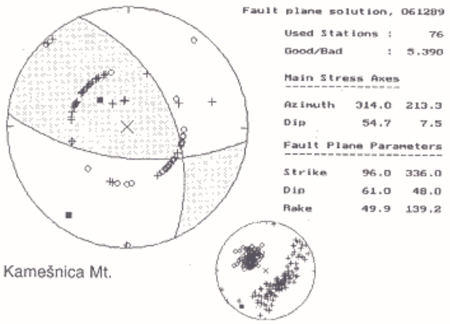
```
Fault plane solution, 260400

Used Stations :      133
Good/Bad      :    7.120

Main Stress Axes
----------------

Azimuth   180.7    81.6
Dip         1.4    81.3

Fault Plane Parameters
----------------------

Strike     99.0   262.0
Dip        47.0    44.0
Rake      101.7    77.7
```

Gargano ridge



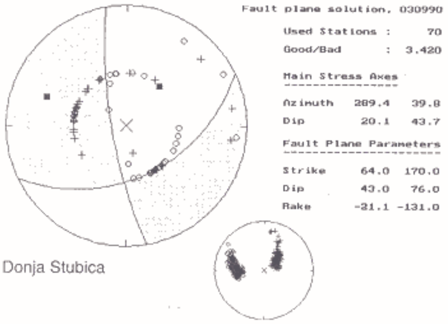
```
Fault plane solution, 161288
        Used Stations :      33
        Good/Bad      :   5.720

        Main Stress Axes
        ----------------
        Azimuth   250.4  358.5
        Dip        72.6    5.6

        Fault Plane Parameters
        ----------------------
        Strike     71.0  283.0
        Dip        42.0   53.0
        Rake       65.0  110.8
```

Velebit Mt.



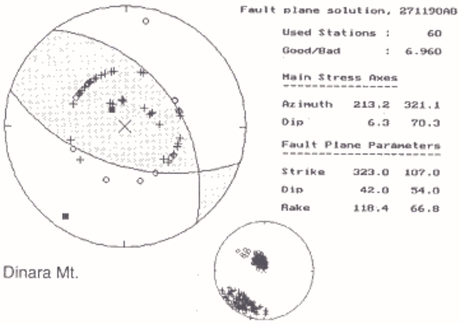
```
Fault plane solution, 061289
        Used Stations :      76
        Good/Bad      :   5.390

        Main Stress Axes
        ----------------
        Azimuth   314.0  213.3
        Dip        54.7    7.5

        Fault Plane Parameters
        ----------------------
        Strike     96.0  336.0
        Dip        61.0   48.0
        Rake       49.9  139.2
```

Kamešnica Mt.



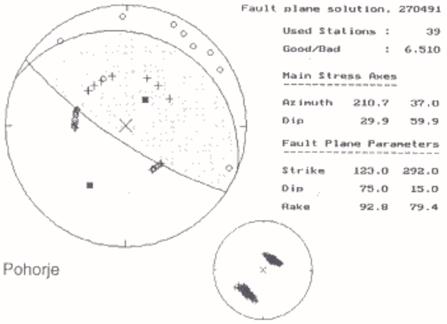
```
Fault plane solution, 030990
        Used Stations :      70
        Good/Bad      :   3.420

        Main Stress Axes
        ----------------
        Azimuth   289.4   39.8
        Dip        20.1   43.7

        Fault Plane Parameters
        ----------------------
        Strike     64.0  170.0
        Dip        43.0   76.0
        Rake      -21.1 -131.0
```

Donja Stubica



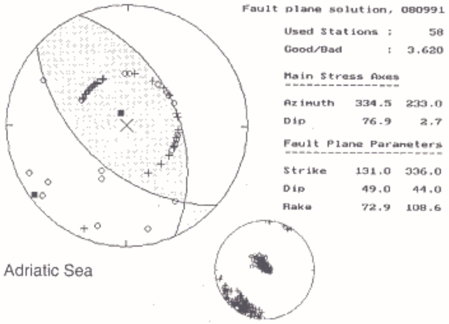
```
Fault plane solution, 271190AB
        Used Stations :      60
        Good/Bad      :   6.960

        Main Stress Axes
        ----------------
        Azimuth   213.2  321.1
        Dip         6.3   70.3

        Fault Plane Parameters
        ----------------------
        Strike    323.0  107.0
        Dip        42.0   54.0
        Rake      118.4   66.8
```

Dinara Mt.



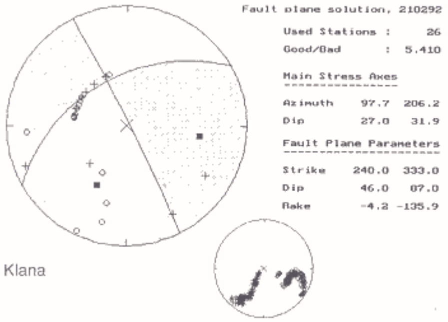
```
Fault plane solution, 270491
        Used Stations :      39
        Good/Bad      :   6.510

        Main Stress Axes
        ----------------
        Azimuth   210.7   37.0
        Dip        29.9   59.9

        Fault Plane Parameters
        ----------------------
        Strike    123.0  292.0
        Dip        75.0   15.0
        Rake       92.8   79.4
```

Pohorje



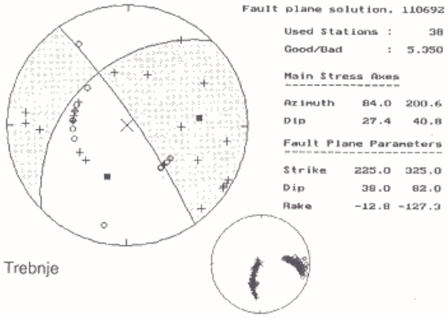
```
Fault plane solution, 080991
        Used Stations :      58
        Good/Bad      :   3.620

        Main Stress Axes
        ----------------
        Azimuth   334.5  233.0
        Dip        76.9    2.7

        Fault Plane Parameters
        ----------------------
        Strike    131.0  336.0
        Dip        49.0   44.0
        Rake       72.9  108.6
```

Adriatic Sea



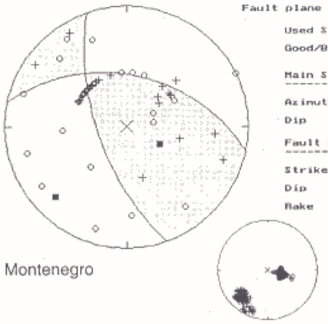
```
Fault plane solution, 210292
        Used Stations :      26
        Good/Bad      :   5.410

        Main Stress Axes
        ----------------
        Azimuth    97.7  206.2
        Dip        27.0   31.9

        Fault Plane Parameters
        ----------------------
        Strike    240.0  333.0
        Dip        46.0   87.0
        Rake       -4.2 -135.9
```

Klana



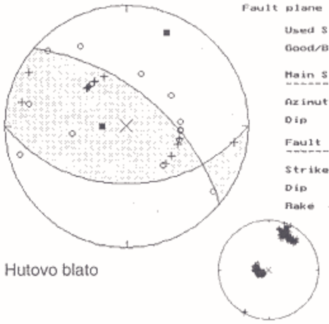
```
Fault plane solution, 110692
        Used Stations :      38
        Good/Bad      :   5.350

        Main Stress Axes
        ----------------
        Azimuth    84.0  200.6
        Dip        27.4   40.8

        Fault Plane Parameters
        ----------------------
        Strike    225.0  325.0
        Dip        38.0   82.0
        Rake      -12.8 -127.3
```

Trebnje



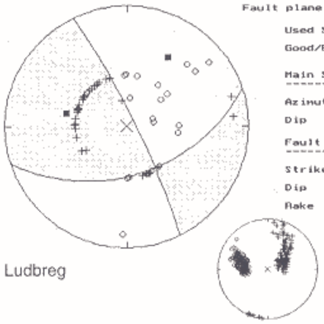
```
Fault plane solution, 301092
          Used Stations :       54
          Good/Bad      :   3.180

          Main Stress Axes
          ----------------
          Azimuth   118.8  225.4
          Dip        55.7   11.0
          Fault Plane Parameters
          ----------------------
          Strike    282.0  161.0
          Dip        44.0   63.0
          Rake       40.2  126.5
```

Montenegro



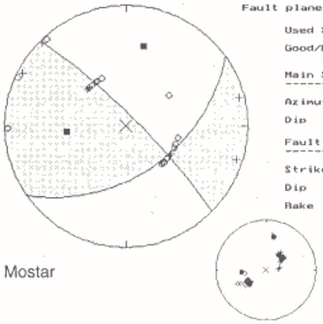
```
Fault plane solution, 060493
          Used Stations :       29
          Good/Bad      :   3.940

          Main Stress Axes
          ----------------
          Azimuth    23.1  268.1
          Dip        10.0   67.4
          Fault Plane Parameters
          ----------------------
          Strike    310.0   90.0
          Dip        58.0   39.0
          Rake      113.9   57.0
```

Hutovo blato



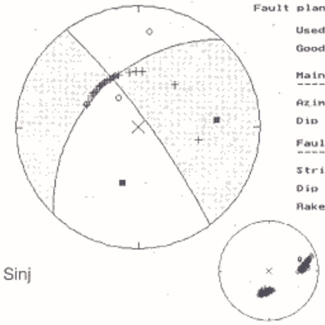
```
Fault plane solution, 010693
          Used Stations :       63
          Good/Bad      :   9.460

          Main Stress Axes
          ----------------
          Azimuth    30.8  282.6
          Dip        23.1   36.1
          Fault Plane Parameters
          ----------------------
          Strike    334.0   72.0
          Dip        82.0   46.0
          Rake      135.4   11.3
```

Ludbreg



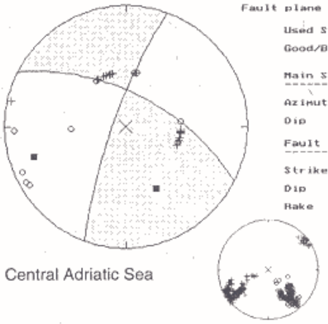
```
Fault plane solution, 011093
          Used Stations :       27
          Good/Bad      :   4.550

          Main Stress Axes
          ----------------
          Azimuth    12.4  264.4
          Dip        21.6   37.9
          Fault Plane Parameters
          ----------------------
          Strike    315.0   55.0
          Dip        80.0   46.0
          Rake      135.1   14.1
```

Mostar



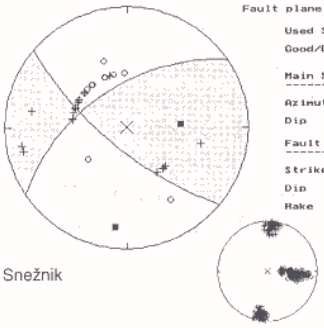
```
Fault plane solution, 250294
          Used Stations :       34
          Good/Bad      :   7.110

          Main Stress Axes
          ----------------
          Azimuth    85.2  196.2
          Dip        23.9   39.0
          Fault Plane Parameters
          ----------------------
          Strike    224.0  324.0
          Dip        43.0   81.0
          Rake      -13.4 -132.2
```

Sinj



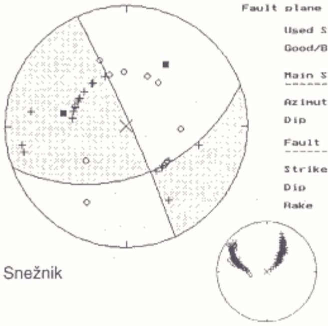
```
Fault plane solution, 130595
          Used Stations :       31
          Good/Bad      :   6.870

          Main Stress Axes
          ----------------
          Azimuth   154.1  251.7
          Dip        30.6   12.6
          Fault Plane Parameters
          ----------------------
          Strike    297.0  200.0
          Dip        59.0   78.0
          Rake       13.9  148.3
```

Central Adriatic Sea



```
Fault plane solution, 220595a
          Used Stations :       32
          Good/Bad      :  10.310

          Main Stress Axes
          ----------------
          Azimuth   186.5   86.8
          Dip        10.6   41.9
          Fault Plane Parameters
          ----------------------
          Strike    130.0  236.0
          Dip        70.0   53.0
          Rake      140.1   25.4
```

Snežnik



```
Fault plane solution, 220595b
          Used Stations :       38
          Good/Bad      :  11.150

          Main Stress Axes
          ----------------
          Azimuth   282.1   32.4
          Dip        33.9   27.4
          Fault Plane Parameters
          ----------------------
          Strike     70.0  336.0
          Dip        44.0   86.0
          Rake        5.7  133.9
```

Snežnik

15 August 1956 – This is the earliest event considered, and has been analyzed previously by *e.g.* Constantinescu et al. (1966), Ritsema (1974) and Udias et al. (1989). Our solution obtained by using 38 data is very similar to Ritsema's who used 33 readings. The solution represents a strike slip faulting with a small normal component, although data do not rule out strike slip dominated reverse fault, as obtained by Constantinescu et al. (1966). This is an important event that contributed to the knowledge of tectonics of the active region in the Central Adriatic Sea.

7 January, 11 January and 21 January 1962 – These events belong to the most important series of earthquakes in Croatia in the second half of this century. All three earthquakes were studied before (*e.g.* McKenzie, 1972; Ritsema, 1974; Anderson and Jackson, 1987) and most of the published FPS agree within few degrees. The three solutions obtained here are also similar, but were computed using more data and by taking significantly revised hypocentral locations (Herak et al., 1995) into account. They define mostly strike-slip faulting (with a reverse component) on a steeply dipping fault that is either parallel or roughly perpendicular to the coastline. Both solutions are plausible as main tectonic structures are oriented NW–SE, while the aftershock epicentres, as well as isoseismals are elongated NE–SW. All three solutions are well constrained indicating subhorizontal, SW–NE directed pressure axis.

17 April 1962 – The earthquake occurred in the Gargano ridge area that seems to be the most active region of the Adriatic platform. To our knowledge only Ritsema (1974) studied it previously. Using the same number of readings as we did he obtained considerably different solution, probably due to differences in the velocity models. As our solution is rather poorly constrained it is difficult to give preference to either of them (especially since both solutions are characterized by only slightly different P-axis position).

14. February 1963 – Again, only Ritsema (1974) calculated FPS for this event near the Pag Island in the Northern Adriatic. We obtained almost the same result, with well constrained stress axes, that indicates normal faulting with comparable dip-slip and strike-slip components. This is an important earthquake as it is the only solution available for this area.

13 April 1964 – This is very important event that occurred in the Slavonian mountains region known for rare events with magnitudes up to $M \approx 6.0$. Previous studies of FPS for this earthquake were published by McKenzie (1972), Ritsema (1974), Gangl (1975), and Anderson and Jackson (1987). All available solutions indicate reverse faulting but are considerably different from each other, and ours is the most similar to the one of Gangl (1975). This area is characterized by mostly W–E to SW–NE striking structures (Prelogović et al., 1985), and the faults show predominantly left lateral movement which is consistent with the strike-slip motion on a W–E striking fault as obtained here. The azimuth of the P-axis is constrained to SSW–NNE direction, and its dip indicates predominantly horizontal pressure.

26 and 27 October 1969 – These two strong (M_L =6.0 and 6.4) events occurred near Banja Luka in Bosnia and Herzegovina, and were the subject of numerous studies (*e.g.* Mc Kenzie, 1972; Ritsema, 1974; Gangl, 1975; Cagneti et al., 1976; Udias et al., 1989). Their solutions range from pure strike-slip to predominantly dip-slip reverse faults. The quality of our solution for the first event is considerably lower (s = 2.92) then for the subsequent earthquake (s = 5.04). The two FPS for these events were found by all researchers mentioned above to be practically identical. Both of our results give well constrained positions of P and T axes indicating horizontal pressure in the N–S direction. This is compatible with the respective results obtained in previous studies.

April–May 1979 – The earthquake that occurred on 15 April 1979 (M_L = 6.8) is the largest event in the region in this century. It is located on the margin of the area considered in this paper, but we decided to include it (and two of the aftershocks) due to its size and importance for hazard studies of the Dubrovnik area. This is the first event that we studied for which a Centroid Moment Tensor (CMT) solution is available (Dziewonski et al., 1987a). The numerous previous studies of FPS for this series of earthquakes include those of Boore et al. (1981), Anderson and Jackson (1987), Dziewonski et al. (1987a) , Mele et al. (1990), Papazachos et al. (1991) and Muço (1994). The CMT solution for the main shock indicates pure dip-slip faulting on a vertical, NW–SE trending fault. This fault is identified in all other solutions (including ours) but the sense of motion varies between pure dip-slip and an oblique reverse rupture. Although the main shock is by far the strongest event considered here, and the solution may be rated rather high regarding the s-value of 6.16, the confidence limits for the stress axes are the largest ones observed – P-axis may lie anywhere between the NW and SE direction while the T-axis is confined to the first quadrant. This is probably due to the complexity of faulting since the earthquake is considered to be a double or triple event, and the nearest stations reported onsets related to the initiation of faulting. It therefore seems reasonable to adopt the CMT solution as representative for this event.

11 March 1984 – The earthquake occurred in Slovenia near the Croatian border. The first FPS was published by Živčić et al. (1985) who obtained a solution (using 22 data) somewhat different from ours. Both solutions, however, describe normal faulting, probably on a fault striking NW–SE, in accordance with geologic features and distribution of aftershocks. The T-axis is well constrained, and data do not constrain the dip of the P-axis.

25 November 1986 (and aftershocks) – The FPS for the main Knin earthquake has been reported and analyzed by Herak and Jukić (1993), who obtained practically the same solution as we did in this study. The CMT solution given in Dziewonski et al. (1987b) differs significantly from ours (see also Herak and Jukić, 1993). The largest aftershock of 24 December yields the same solution but with much better constrained stress axes positions (in spite of lower 'good'/'bad' ratio). The FPS for the aftershock of 27 November indicates normal faulting (unusual for that area) – it is however poorly defined and solutions equal to the two aforementioned events fall within the confidence limits of the solution.

26 April 1988 – An important event in the active boundary region (Gargano ridge zone) in the Central Adriatic. The CMT solution is given in Dziewonski et al. (1989). FPS indicating larger strike-slip component was published by Favali et al. (1993). Our solution is very similar to the CMT result. The distribution of hypocentres agree with the strike and dip of the southwards dipping plane (Herak et al., 1995).

16 December 1988 – This is one of rare solutions for earthquakes from the Velebit Mt. area. The strike of the northward dipping fault agrees with the strike of the Bakovac fault. The data constrain the stress axes very well.

6 December 1989 – The Kamešnica Mt. earthquake's FPS was analyzed in detail by Herak et al. (1991), and our solution is very similar. It should however be noted that data poorly define the P-axis position, constraining it only to directions between NE and SW. It is interesting that the best solution (for P-axis) lies at the edge of the cloud of permissible solutions.

3 September 1990 – This is the only earthquake from the very important Zagreb epicentral area for which FPS is available. Using essentially the same dataset as Markušić et al. (1993) did, we obtained a different solution – while our result indicates strike-slip or normal fault, the one in Markušić et al. (1993) describes reverse faulting with equal strike-slip and dip-slip components. The inspection of the distribution of stress axes reveals that the type of faulting (normal or reverse) is very poorly constrained by data, making a strike-slip mechanism most probable. Both results indicate as one of possible seismogenic faults a SW–NE striking one that could correspond to the major Žumberak–Medvednica–Kalnik fault.

27 November 1990 – The solution presented is the composite FPS for two main shocks that occurred beneath the Dinara Mt. 14 minutes apart. These earthquakes were studied in detail by Markušić et al. (1993) who obtained similar FPS as we did. The CMT solution (Dziewonski et al., 1991d) for the first shock and the FPS for the second one reported by Gerner (1995) also yielded essentially the same results.

21 February 1992 – The earthquake occurred near the Croatian-Slovenian border. The solution obtained is rather poorly defined and allows interpretation both in terms of reverse (as reported by Gerner, 1995) or normal faulting with expressed strike-slip component. The most important regional faults strike NW–SE, which is compatible with the solution of Gerner (1995) as well as with the one reported here.

1 June 1993 – This event occurred in the well known Ludbreg epicentral zone, probably on the northern part of the large, SW–NE striking Žumberak–Medvednica–Kalnik regional fault system. The solution obtained here is practically the same as reported by Gerner (1995) and describes reverse or strike-slip faulting.

13 May 1995 – The earthquake occurred in the Central Adriatic Sea near the small, isolated island of Jabuka. The earthquakes there are rare, which makes this solution important for the stress-regime and other related studies of that area. Azimuths of the stress axes are well constrained. The FPS is very similar to the one for the earthquake of 15 August 1956 near Vis Island, some 50 km to the east.

4. Conclusions

The detailed interpretation of results obtained here is beyond the scope of this paper. In particular, the analysis of the inferred stress pattern will be reported in subsequent study. Let us only note here that for most of the well constrained solutions (especially in the coastal part of Croatia) reverse or strike-slip faulting is indicated with a sub-horizontal P-axis lying in the 3rd quadrant, mostly between the SW and S directions. This is in agreement with other studies of the contemporary stress field in this part of Europe (*e.g.* Grünthal and Stromeyer, 1992), and is compatible with the tectonic model of the collision of the Adriatic Platform with the Dinarides.

5. References

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