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Fault-plane solution for the earthquake of 25 November 1986 near Knin, Croatia

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By analysing the P-wave first motion polarities we have obtained the fault plane solution for the Knin earthquake of 25 November 1986. The fault plane/auxiliary plane ambiguity was resolved by comparing the solutions to the known geological features of the area. We were able to obtain practically the same result by modeling the first 10 s of the P-wave as recorded on the broad-band instrument at GRF, thus confirming the relatively poorly constrained classical solution parameters. The earthquake has probably occurred on the northern section of the NW-SE striking right lateral reverse Knin fault. The pressure axis corresponding to the fault plane solution does not lie in the direction of the regional compressional stress field as reported by others, thus indicating strong deformation of the local stresses that is probably the result of interaction of numerous block structures present in that area.

Mehanizam u žarištu potresa od 25. studenog 1986 pokraj Knina

Mehanizam pomaka u žarištu potresa od 25. studenog 1986 pokraj Knina određen klasičnim načinom (analizom prostorne razdiobe prvih pomaka P-valova) ukazuje da se potres vjerojatno dogodio na sjevernom dijelu Kninskoga rasjeda pružanja SZ–JI, što je u skladu s lokalnim geološkim značajkama toga područja. Os najvećega tlaka ne podudara se sa smjerom regionalnog polja tektonskih napetosti, što ukazuje na njegovu jaku deformiranost lokalnim uvjetima. Gotovo jednako rješenje dobili smo modeliranjem prvih 10 s širokopojasnog seizmograma kninskog potresa zabilježenog na postaji GRF, čime je dodatno potvrđeno relativno slabo definirano klasično rješenje.

1. Introduction

The $M = 5.5$ earthquake of 25 November 1986 with the epicentre near Knin (lat. = 44.07 °N, long. = 16.32 °E) is the strongest known event in this particular region of External Dinarides. The seismicity of the region and associated with this earthquake series was studied by D. Herak et al. (1988) D. Herak and M. Herak (1990), M. Herak and D. Herak (1990), while its macroseismic field was investigated by Cvijanović et al. (1989).

The Knin epicentral area is located within the zone where the Adriaticum geotectonic unit is overthrusted by Dinaricum structures (M. J. Herak, 1986). The geotectonic setting of the area is quite complex (Aljinović et al, 1990; see Fig 1, top). The largest faults predominantly strike NW-SE, but the area is intersected by numerous smaller faults striking NE-SW, thus dividing it into

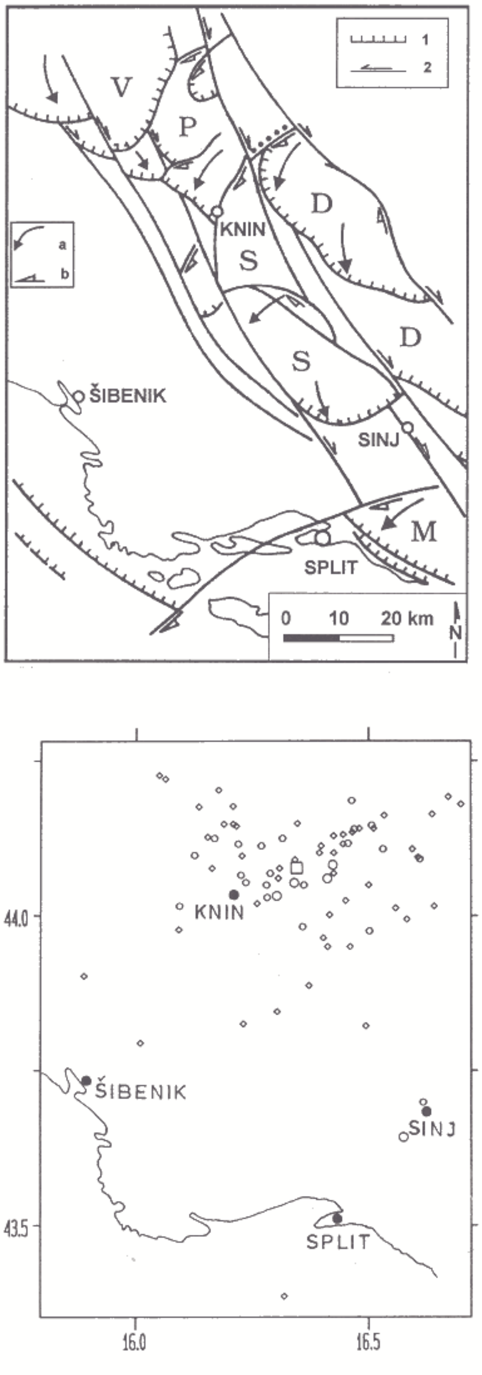

Figure 1. top) Structural map of the greater Knin area (modified, after Aljinović et al, 1990). 1 – reverse faults, 2 – faults with horizontal displacements; a – rotation direction of structures on the surface, b – displacement direction of structural margins; Thrust structures: V – Southern Velebit, P – Plavno, D – Dinara, S – Svilaja, M – Mosor. The northern section of the Knin fault is marked by a dotted line.
bottom) Epicentres of earthquakes in the investigated area in 1986 and 1987. (revised, after Herak D. et al, 1988). ◊ $M < 3.0$, ◦ $3.0 \le M < 4.0$, ○ $4.0 \le M < 5.0$. The Knin main shock is shown as an empty square(□).

smaller structural blocks which move and rotate relative to each other. The surface structures indicate anticlockwise relative rotation of overthrusting units, which is consistent with large-scale tectonic features of the Adriatic region (Anderson and Jackson, 1987).

The Knin earthquake series occurred near the junction of the Dinara, Svilaja and Plavno thrust structures (Fig. 1). Most of the aftershocks were located in a belt some 5 km wide, stretching parallel to the northern section of the Knin fault (indicated by a dotted line in the top part of Fig. 1), but considerable activity was recorded also to the west of the main shock epicentre, in the Plavno structure.

The purpose of this note is to use available data to estimate the kinematics of the Knin earthquake source and to compare it to the relative motions of structural blocks inferred on the basis of geological investigations. This would hopefully enable us to identify the seismogenic fault, and gain insight into the contemporary stress field in the area.

2. Data and methods

The Knin earthquake was recorded by most regional stations and by a number of teleseismic ones. We were able to collect a total of 191 P-wave first motion polarity readings which were used to estimate the strike (φ) and dip (δ) of the fault and the direction of relative motion (rake, λ) of the fault's surfaces. The best fitting values of φ, δ and λ were found by random search in the (φ, δ, λ) space by minimizing the »quality of fit« ratio, q:

$$q = \frac{S_o}{S_1} \tag{1}$$

where S_o is the sum of weights for observations which have different polarities than theoretically predicted (for given φ, δ, λ), and S_1 is the same for observations whose polarites agree with the theoretical ones. The weight assigned to the $\boldsymbol{i}$-th observation is defined as

$$w_i = w_{1i}\, w_{2i} \tag{2}$$

where w_{1i} has the value of 1.0 for *impetus* and 0.5 for *emersio* first onsets, while w_{2i} is proportional to the theoretical radiation pattern, i.e. it depends on the position of the station within the respective quadrant. We have chosen w_{2i} to linearly increase from 0.2 for the data on the nodal line to 1.0 for the ones in the centre of the quadrant. In this way we give preference to solutions where the non-fitting observations are close to nodal lines, while the ones which have the same polarity as theoretically predicted lie as far from nodal lines as possible.

The best fitting solution obtained after testing 1 000 000 random cases is: $\varphi_o = 53°$, $\delta_o = 59°$, $\lambda_o = 123°$ for the fault plane, and $\varphi_o' = 181°$, $\delta_o' = 44°$, $\lambda_o' = 48°$ for the auxiliary plane (we shall substantiate the fault/auxiliary plane attribution later). The minimum obtained value for q was $q_o = 0.247$, and the best solution successfully explains 78% of available polarities. The data and nodal planes are shown in lower-hemisphere Schmidt projection in Fig. 2.

The very important question – how well do the data resolve the fault parameters? – may be answered, at least qualitatively, by looking at Fig. 3 where φ, δ and λ are displayed against q. We see that for the fault plane the best resolved parameter is the dip, while the worst resolution is obtained for its strike (note the difference in horizontal scales for dip vs strike and rake!). It is very clear that the fault is a reverse one since all solutions with $q<0.31$ correspond to $0 \le \lambda \le 180°$. We may quantify this analysis by choosing an arbitrary threshold level of $1.1q_o = 0.272$ (indicated by the horizontal line in Fig. 3). Then, inspecting Fig. 3 we obtain: $\varphi_o = 53° \pm 22°$, $\delta_o = 59° \pm 10°$, $\lambda_o = 123° \pm 12°$, and $\varphi_o' = 181° \pm 12°$, $\delta_o' = 44° \pm 6°$, $\lambda_o' = 48° \pm 19°$. These confidence limits are quite high, and the situation would become worse if the threshold level was increased, especially in the case of the fault's dip.

We therefore decided to estimate the fault's parameters also by modeling the first 10 seconds of the observed vertical component broad band record of

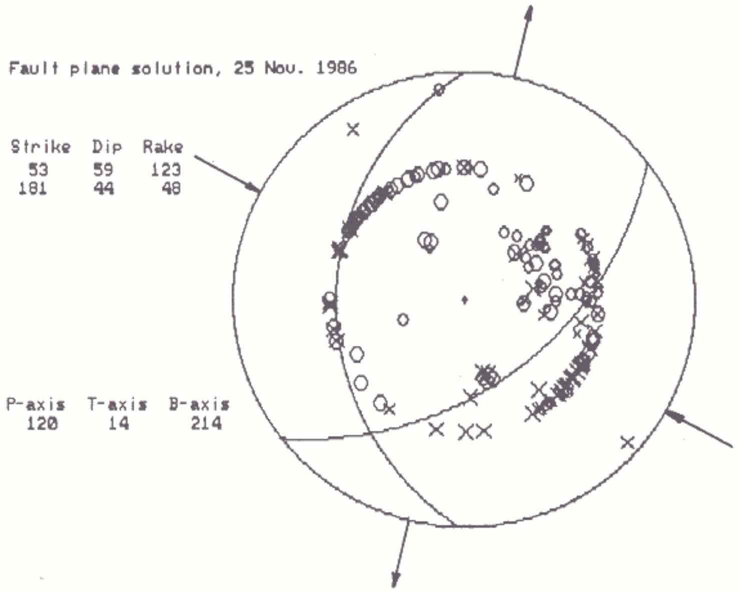

Figure 2. The lower hemisphere Schmidt projection plot of data and the fault plane solution for the 25 November 1986 Knin earthquake. Circles and crosses mark compressions and dilatations, respectively; the arrows show the azimuths of P- and T-axes.

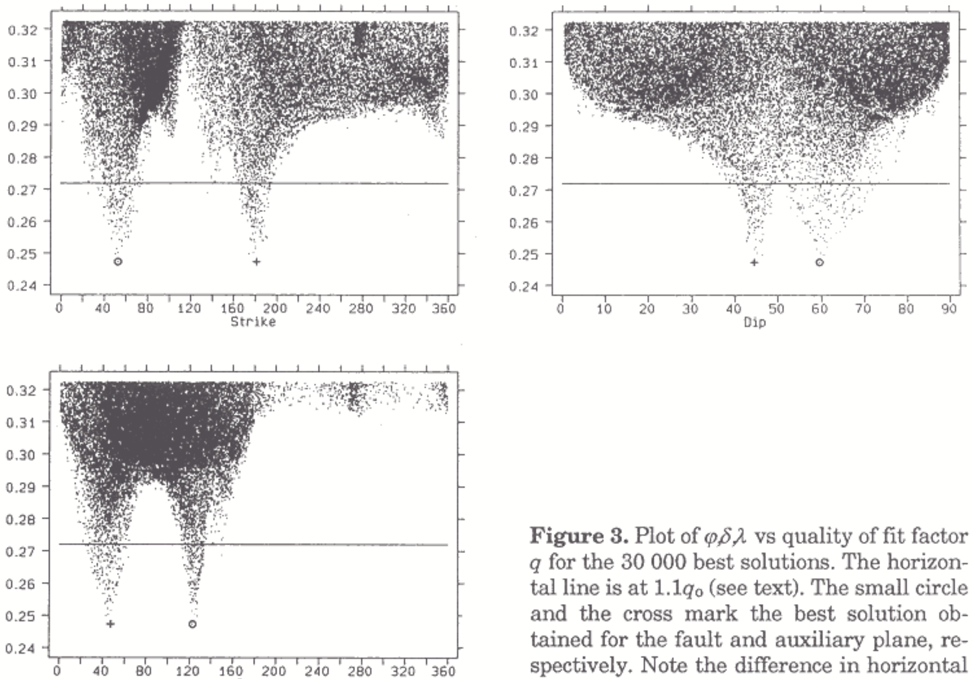

Figure 3. Plot of $\varphi\delta\lambda$ vs quality of fit factor q for the 30 000 best solutions. The horizontal line is at $1.1q_0$ (see text). The small circle and the cross mark the best solution obtained for the fault and auxiliary plane, respectively. Note the difference in horizontal scale for strike and rake vs dip.

the Knin earthquake at GRF A1 seismic station (distance = 736 km, azimuth = 330°), and matching it to the synthetic one obtained by using the slightly modified SNERT computer program (Kennett, 1988). The input data were the following: focal depth = 13 km (D. Herak et al, 1988), frequency band: 0.2–5.5 Hz, slowness interval: 0.117–0.250 s/km, trapezoid source function of a total duration of 6 s, and the crust/upper mantle model as shown in Table 1. The model was constructed by combining properties of the model proposed for the Balkan region (B.C.I.S, 1972), the PREM model (Dziewonski and Anderson,

Table 1: The crust and upper mantle model used to compute synthetic seismograms. v_P and v_S are P- and S-wave velocity; Q_α and Q_β are quality factors for P- and S-waves.

layer	v_P (km/s)	v_S (km/s)	density ρ (g/cm^3)	thickness d (km)	Q_α	Q_β
1	5.30	3.05	2.60	2	350	150
2	5.85	3.45	2.85	28	450	200
3	6.70	3.88	3.15	10	580	250
4	8.10	4.50	3.38	20	770	330
5	8.08	4.47	3.37	20	1100	500
6	8.06	4.46	3.37	∞	1400	590

1981) and the models D1 and D5 for the area of Mid Europe and External Dinarides, respectively (D. Herak and M. Herak, in preparation). The SNERT program was modified to generate theoretical ground velocity time history for a suite of predefined sets (φ, δ, λ). Each of them was compared to the observed seismogram and the one which minimized the value of

$$s = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} (A_{\mathrm{oi}} - A_{\mathrm{si}})^2 \tag{3}$$

was retained. A_{oi} and A_{si} are normalized amplitudes of observed and synthetic waveforms, and N is the number of digitized points (N = 300, $\Delta t = 0.033$ s). The (φ, δ, λ) space was than systematically scanned around the retained solution, and the proces was repeated until the minimum of $s = 0.103$ was found for

$$\begin{array}{lll} \varphi_1 = 50°\pm25°, & \delta_1 = 68°\pm15°, & \lambda_1 = 138°\pm30° \\ \varphi_1' = 159°, & \delta_1' = 52°, & \lambda_1' = 29°. \end{array}$$

The observed vs synthetic waveforms are shown in Fig. 4. We see a good match of long period (3–4 s) components, and a poor one for periods below 2 s, which is probably caused by describing the inelastic attenuation by Q-factors which do not depend on frequency. The overall fit could certainly also be improved by modifying other input data – model parameters, source function, slowness interval considered... This would require different approach and better computing facilities, and our goal was only to see whether it is possible

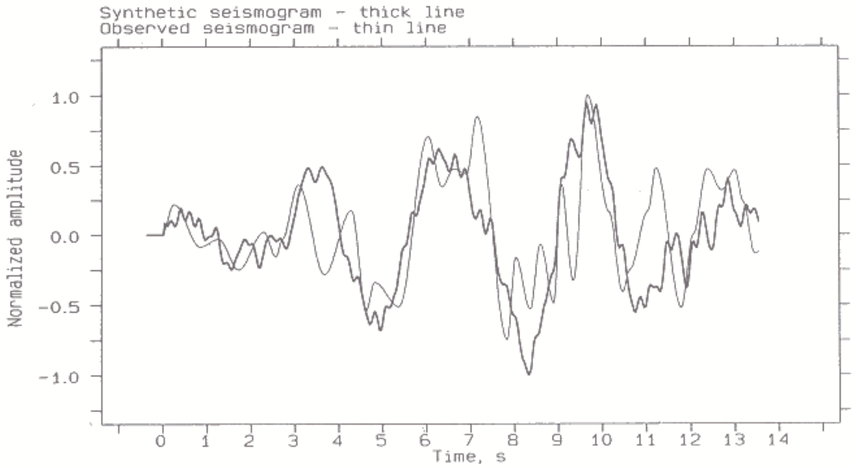

Figure 4. Comparison of the P-wave synthetic seismogram (ground velocity) obtained by assuming φ = 50°, δ = 68° λ = 138° and the one observed at GRF.

to model general characteristics of the observed ground motion by assuming reasonable input parameters.

If $(\varphi_1, \delta_1, \lambda_1)$ are compared to $(\varphi_o, \delta_o, \lambda_o)$ we see that they differ less than the corresponding confidence limits, i.e. we have basically obtained the same solution as in the case of P-wave first motion polarity analysis.

3. Discussion and conclusions

The solution obtained in the previous section describes a relatively steeply dipping right lateral fault striking approximately NE-SW with predominantly dip-slip motion. The alternative solution is a N-S striking left-lateral thrust fault. Since there are no N-S striking structures in this part of External Dinarides, and the faults in the Knin area are all right lateral ones (see Fig. 1), we have resolved the fault-plane/auxiliary plane ambiguity as mentioned before. Furthermore, the strike of $\varphi \approx 50\text{–}55^\circ$ agrees with the strike of the northern section of the Knin fault, and the indicated sense of relative motion of the Dinara, Svilaja and Plavno structures are consistent with the slip direction as obtained here. We can also estimate the Knin fault's dip – by measuring the average distance of the aftershocks from the fault's surface projection (7–8 km, see Fig. 1) and taking the focal depth of 13 km we obtain the dip of $\delta = \arctan(13/7.5) = 60^\circ$, again in agreement with our findings.

The P-axis corresponding to this fault plane solution lies at an azimuth of 120°, indicating ESE-WNW directed local pressure field. It is approximately perpendicular to the direction of P-axes reported by Anderson and Jackson (1987) for events in the near-by regions of External Dinarides, and to the lines of maximal horizontal compressional stress as given by Grünthal and Strohmeyer (1992). This means that the regional stress field (generated primarily by underthrusting of the Adriatic platform under the Dinaricum structures) was strongly deformed in this particular region, probably by a complicated interaction of numerous blocks present there.

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