Problems of quick identification of the fault plane for earthquake on Rhodos Island, Greece (July 15, 2008, Mw 6.4)

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A simple geometrical method has been suggested recently (Zahradnik et al., 2008) to quickly identify the earthquake fault plane without waiting for aftershocks or studying directivity. The method is based on mutual position of the hypocenter H, centroid C and two orthogonal planes, passing through C, defined by the strike and dip of the centroid moment tensor solution (CMT). That plane which encompasses H is assumed to be the fault plane. Thus the name 'H-C method'. For limitations of the method, see the reference.

The method has been applied to a number of M6 events in Greece (January 6, February 14, February 20, June 8, 2008), with quick reports posted on the EMSC web page (Earthquake news & highlights, http://www.emsc-csem.org/index.php?page=current&sub=recent).

In contrast to the listed events, which occurred within a region relatively densely covered by local seismic stations, this report is devoted to a more problematic earthquake, with severe data limitations towards S and SE. Therefore, this is not a 'quick' report, but a study using locations and CMT calculations available one week after the event, and focusing rather on methodical problems. In fact, in this case, the fault plane is suggested with some doubts.

Three hypocenter locations were considered: EMSC, THE and NOA, all manually reviewed by the reporting agency; Table 1, Figure 1. The EMSC location makes use of many stations. On the other hand, THE and NOA include near stations, some of them with both P and S readings, thus are considered more reliable. In particular, NOA contains P and S from two stations within 1-degree distance, ARG and KARP, and the resulting P and S residuals are small (e.g., 0.1 sec for ARG). Note that the THE and NOA solutions have almost identical epicenter position, but they differ very much in hypocenter depth (31 and 56 km, respectively). Therefore, below we also include variations of the hypocenter depth (30, 40, 50, 60 km).

Table 1: Hypocenter position from locations (manually reviewed) by various agencies.

Agency	Lat(deg)	Lon(deg)	Depth(km)
EMSC	35.96	27.86	60
THE	35.83	28.03	31
NOA	35.85	27.92	56

The following CMT solutions were considered: Harvard (HRV), USGS, Mednet (MED), UPSL; Table 2, Figure 1. The UPSL solution was calculated with ISOLA software (Sokos and Zahradnik, 2008), at periods 20 to 66 seconds, using 11 stations[1]. It is different from the preliminary solution posted by UPSL to the EMSC web page. The current solution includes three stations east of Rhodos Island (IKL, CSS, KUL), and it was calculated through grid search for the best spatial position of the centroid. All these solutions are characterized by very similar strike-dip-rake angles, with one nodal plane almost vertical (strike ~265 deg, dip ~ 85, plotted in green and hereafter referred to as the 'green' plane), and the other one dipping less steeply (strike ~355 deg, dip ~ 50, the 'red' plane). Nevertheless, the C positions differ significantly, both in horizontal direction and depth.

Table 2: Centroid positions and focal mechanism by various agencies. The strike-dip-rake angles I and II are for the so-called 'green' and 'red' plane, respectively.

Agency	Lat (deg)	Lon (deg)	Depth (km)	Strike I (deg)	Dip I (deg)	Rake I (deg)	Strike II (deg)	Dip II (deg)	Rake II (deg)
HRV	35.7	27.68	36	261	85	–44	356	47	–173
USGS	35.92	27.33	34	262	84	–41	358	48	-171
MEDNET	35.79	27.6	37	268	89	–39	358	51	-179
UPSL	35.87	27.75	60	262	90	-38	352	52	-180

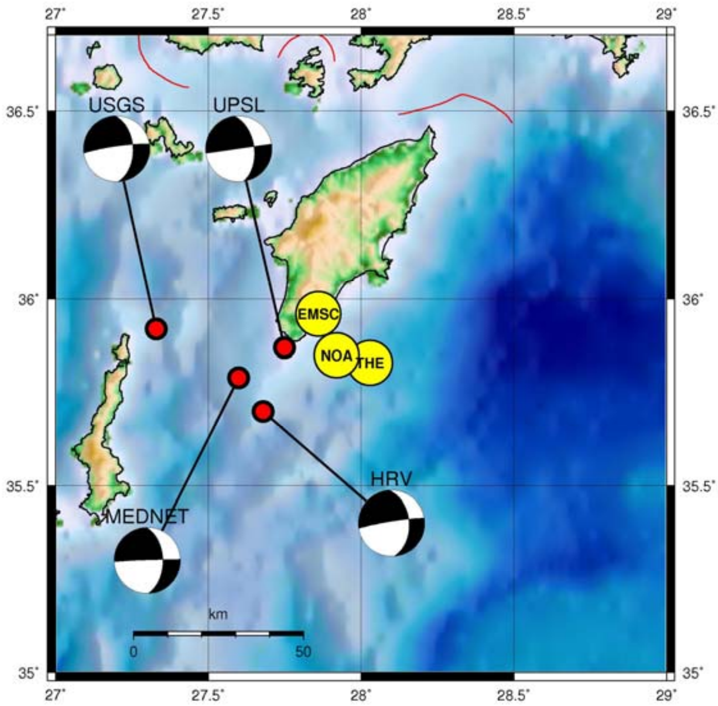


Figure 1: Epicenter (yellow circle) and plane view of centroid (red circle) by various agencies. The fault plane solutions are shown by 'beach balls' connected with the corresponding centroid positions.

The two most important concepts of the method are the H-C consistency and the collective solutions. We seek the *H-C consistent solutions*, e.g. the cases where H is on (or close to) the 'red' or 'green' plane. What is 'close' is relative and depends on the event solved, but usually the distance of about 5 km between the hypocenter and the plane is considered small. The 5km threshold is also used in this report. Inconsistent solutions, whose H distance from none of the two planes is small, are rejected; rejection takes place also when the distance is small, but same with respect to both planes. The concept of *collective solutions* means that we have to take into account possible errors in the H and C position, and in orientation of the two planes. The error can be estimated in two ways: (i) assessing uncertainty of each solution separately, and varying the parameters correspondingly, (ii) assessing

[1] ZKR, SIV, KAR, DYR, VLX, DID, LTK, APE, IKL, CSS, KUL.

uncertainty from the variation among the agency reports. Method (i) is suitable for users who made the location and CMT solution themselves, hence understand their limitations. Below we use mainly (ii), i.e. we assume that the scatter among agency reports represents the data uncertainty.

First, we construct a collective solution combining all agency hypocenter determinations and CMT solutions of Tables 1 and 2 (Figures 2a,c). Additionally, in Figures 2b,d we also allow each hypocenter depth to vary.

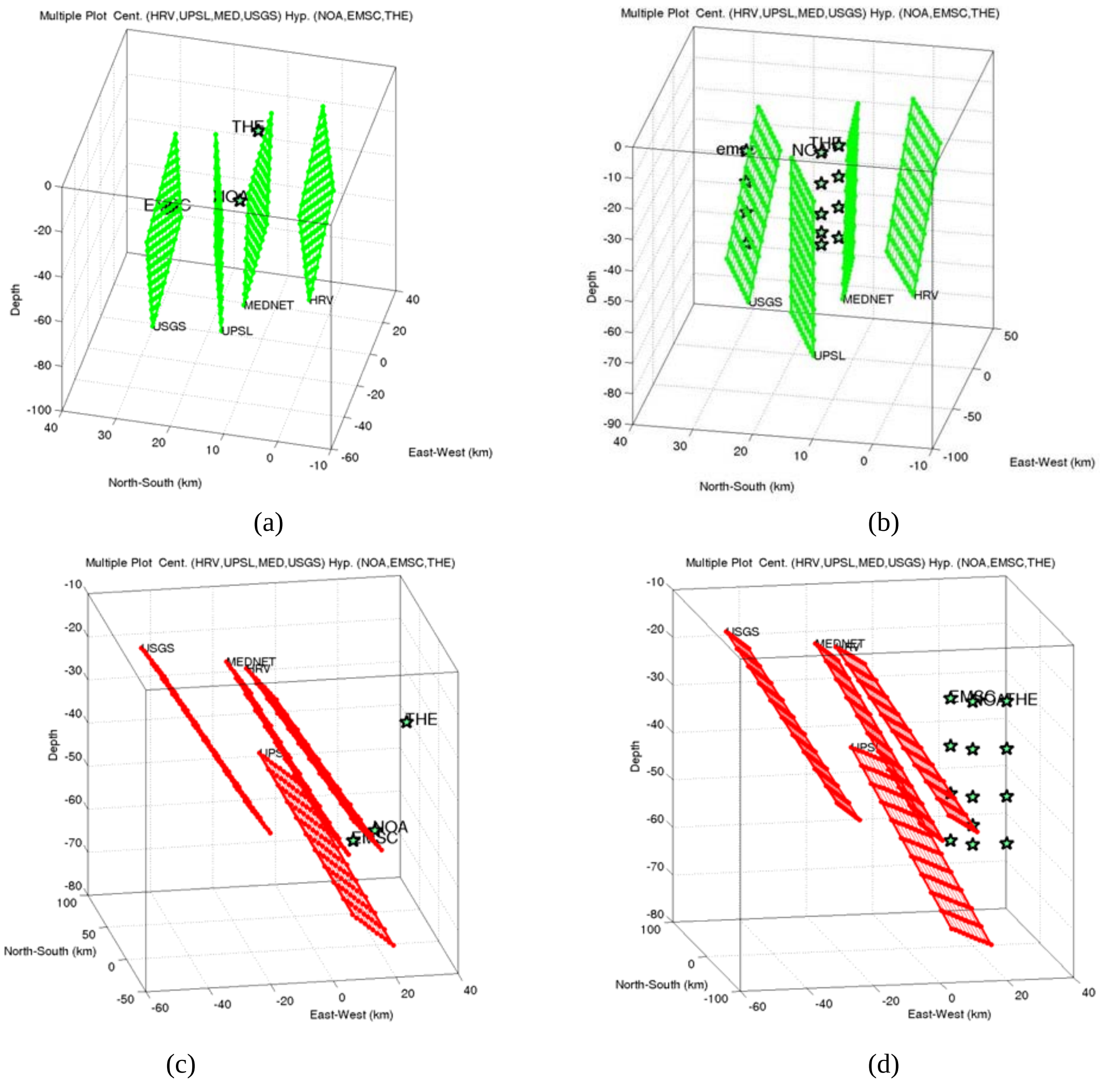


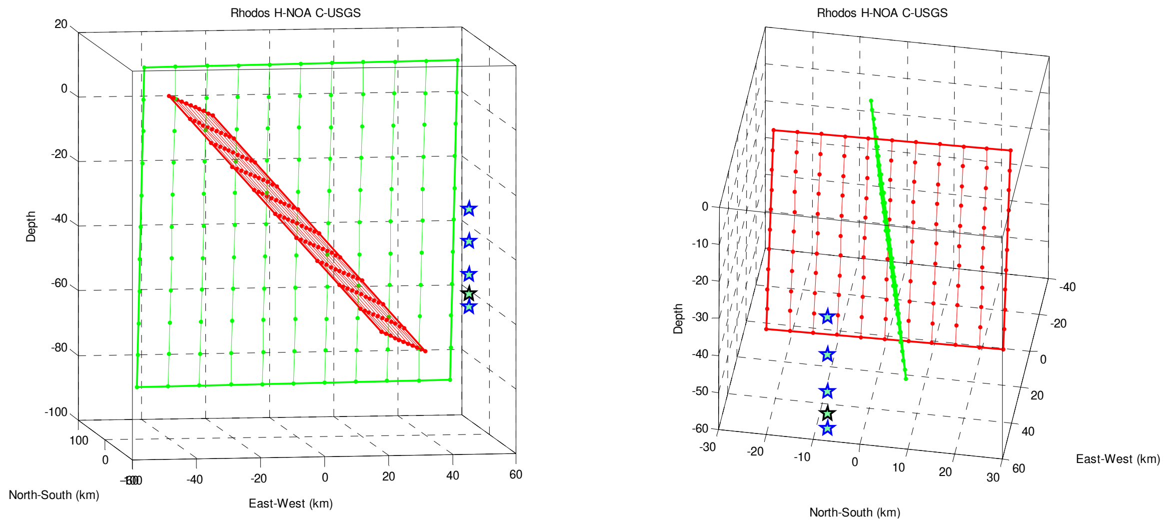
Figure 2. The HC plot combining all hypocenter solutions (stars) and CMT solutions. Centroid is always in the middle of the plane (not shown by any symbol). Panel (a) shows the hypocenters according the agency repots. Panel (b) allows variation in the hypocenter depth (30, 40, 50 and 60 km). The axis marked East-West is positive to east, North-South to north, and the Depth axis is negative down. Panels (c) and (d) show the same for the 'red' planes.

From Figure 2 we find that the scatter of the agency solutions is too large, so it does not allow any conclusion. Therefore, in the following, we separately inspect the individual combinations of each single H and single C, Table 3, and collectively discuss the results at the end.

Step 1 – Eliminating inconsistent solutions. We exclude the combination of H-NOA with C-USGS (i.e. using hypocenter of NOA and centroid of USGS), because for neither the reported hypocenter, nor its varied depth, we find a H-C consistent solution; H does not fall to any nodal plane; see Figure 3. The distance of H from the green and red plane is H-green = 17 km and H-red = 25 km, respectively, see Table 3. For the same reason, we exclude the combinations H-THE with C-USGS, H-THE with C-HRV, and H-EMSC with C-UPSL.

Table 3: Relations between hypocenter (H), Centroid (C) and the considered planes. H-green and H-red are distances of hypocenter from the 'green' and 'red' plane (see the text), H-C is the distance between hypocenter and centroid. The 'Preference' column shows that 5 and 3 combinations suggest the green and red plane, respectively. The combination H-NOA with C-UPSL is highlighted because we believe that NOA provided the most reliable H, the H-green distance is small, and the H-C distance is reasonable.

H(agency)	**C(agency)**	**H-green(km)**	**H-red(km)**	**H-C(km)**	**Preference**
NOA	HRV	11	3	34	red
NOA	USGC	17	25	58	none
NOA	MED	6	11	35	green?
NOA	**UPSL**	**4**	**14**	**16**	**green**
EMSC	HRV	24	4	41	red
EMSC	USGS	5	18	55	green
EMSC	MED	18	5	38	red
EMSC	UPSL	9	9	14	none
THE	HRV	10	27	35	none
THE	USGS	21	49	64	none
THE	MED	4	34	40	green
THE	UPSL	7	37	39	green?



(a) (b)

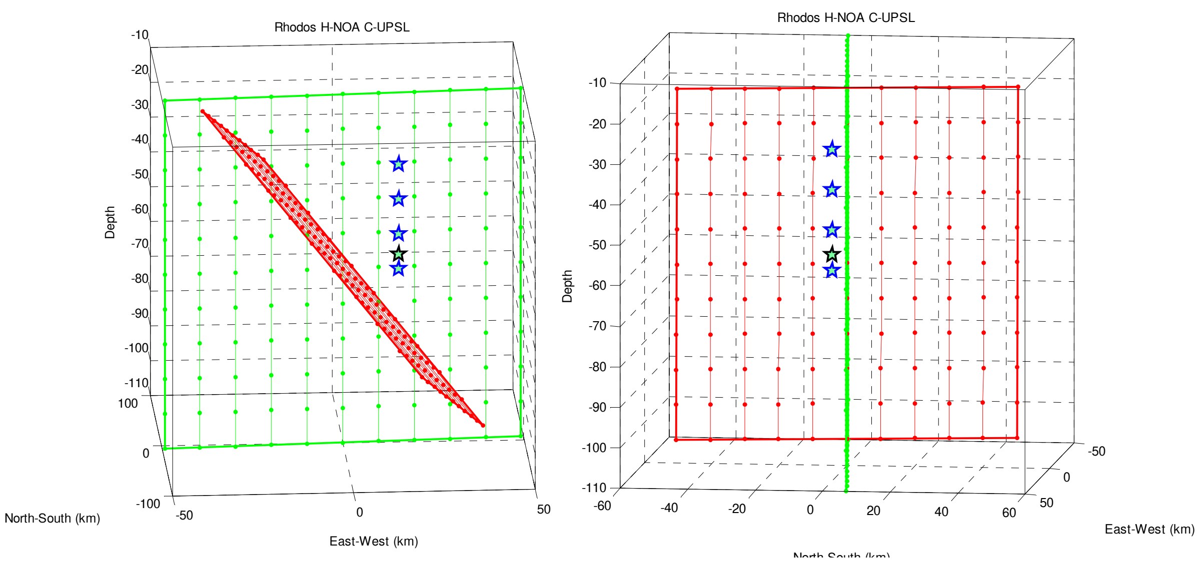
Figure 3. The HC plot for the hypocenter NOA and the CMT solution USGS. This is an example of H-C inconsistent solution, because H (green star) is too far from both green and red planes: H-green = 17km and H-red = 25km. The same is true for the varied hypocenter depths (blue stars). Panels (a) and (b) are two different spatial views of the same configuration.

Step 2 – Identifying consistent solutions. Combining, for example, H-NOA and C-UPSL yields an H-C consistent solution, Figure 4. The H-green and H-red distances are 4 and 14 km, respectively. Indeed, it clearly rejects the red plane, and it strongly prefers the **green** plane (even if we allow the depth of H to vary from 30 to 60 km). An advantage of our 'own' CMT solution UPSL is that we can also study uncertainty of this individual solution. Thus we know that when grid searching the centroid C at a shallower depth, say 50 km, its horizontal position stays unchanged, and the waveform misfit is just a bit less good than at the optimum 60 km depth. It means that we should count also with the C depth of 50km. Importantly, with such a change, the green plane is still preferred, although less strongly (H-green 4km, H-red 8km).

The green plane is preferred also for H-THE with C-MED and H-EMSC with C-USGS. See again Table 3. The combination H-NOA with C-MED seems to weakly prefer the green plane; 'weakly' means that H-green = 6 km is slightly above the 5 km threshold mentioned above.

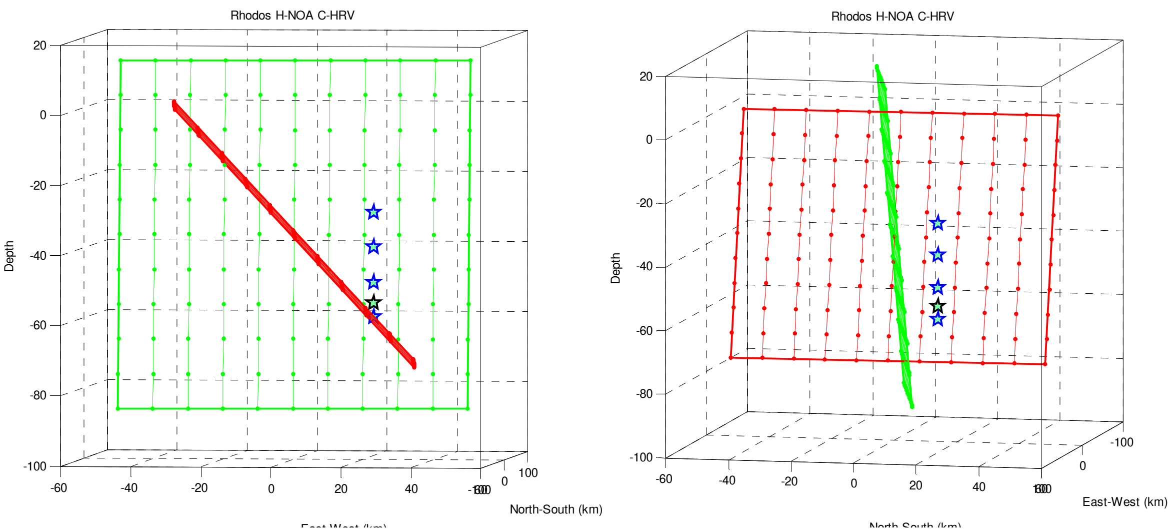
On the contrary, when checking H-NOA with C-HRV, we find a very strong preference of the **red** plane (Figure 5): H-green = 11km and H-red = 3km. Analogously for H-EMSC with C-MED, and H-EMSC with C-HRV.

Therefore, when considering the whole variety of the available H and C solutions, identification of the fault plane (preference of the green or red plane) seems impossible for this event, unless we add some constraints.



(a) (b)

Figure 4. The HC plots for the hypocenter NOA and the CMT solution UPSL. This is an example of H-C consistent solution, with H (green star) close to the **green** plane and far from the red one: **H-green = 4km** and H-red = 14km. The distance between H and C, is H-C = 16km. The preference of the green plane persists also for the varied hypocenter depth (blue stars). Panels (a) and (b) are two different spatial views of the same configuration.



(a) (b)

Figure 5. The HC plots for the hypocenter NOA and the CMT solution HRV. This is an example of H-C consistent solution, with H (green star) close to the **red** plane and far from the green one: H-green = 11km and **H-red = 3km. The** H-C distance is 34km. Panels (a) and (b) are two different spatial views of the same configuration.

Step 3 – Preference of the NOA location. So far we have assumed that all the three considered agency locations are equally plausible for the studied earthquake. To more strongly constrain the solution, we re-analyze the hypocenter determinations. For reasons explained above in relation to Table 1, we decided to prefer the NOA solution (near stations, S readings, small residuals). Let us therefore summarize all solutions using H-NOA:

- H-NOA and C-USGC (Figure 3) is H-C inconsistent
- H-NOA and C-MED weakly prefers the green plane
- H-NOA and C-UPSL (Figure 4) strongly prefers the green plane
- H-NOA and C-HRV (Figure 5) strongly prefers the red plane

Obviously, preference of a single location result (NOA) still does not resolve the ambiguity; use of C-UPSL and C-HRV yields opposite result, and we have no strong reasons to prefer C-UPSL over C-HRV (perhaps just due to shorter periods in the UPSL solution, thus a better spatial resolution).

Step 4 – An additional constraint? A possible solution of the puzzling situation is to constrain the distance between H and C. This is a **new** concept, initially not introduced in the method (Zahradnik et al., 2008). According to empirical relations, the fault area for this magnitude is about 300 km^2, e.g. a circle of radius 10 km, or a rectangle 12x24 km, etc. In this sense, a H-C distance larger than ~20 km is unlikely. Applying this constraint to the two concurrent solutions of the previous paragraph, H-NOA with C-HRV, and H-NOA with C-UPSL, whose H-C distances are 34 and 16 km, respectively, points to the latter; hence preference of the **green** plane.

This solution is highlighted in Table 3. In the CMT solution of UPSL this plane is characterized by strike 262 deg and dip 90 deg. With H and C practically in the same depth (~60 km), and C encountered west of H (Figure 1), we might interpret the event as an oblique-slip rupture (rake –38 deg) propagating predominantly westward. This is schematically shown in Figure 6.

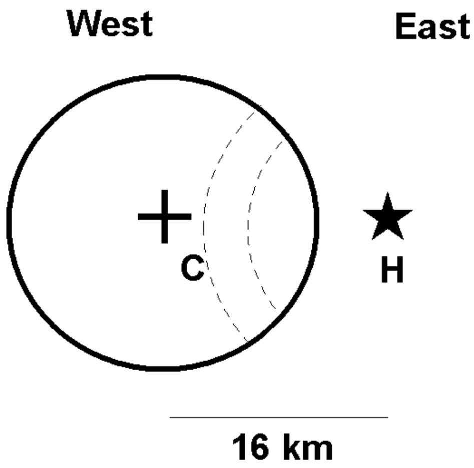


Figure 6. Schematic source model suggested by the H-C method. Hypocenter (H) east of centroid (C), C is a point-source representation of a finite fault whose size approximately reflects the moment magnitude, all in a vertical plane striking at 262 degrees. Rupture (rake –38 deg) starts at H and propagates over the fault predominantly westward, as illustrated by dashed lines.

Conclusion

The Rhodos earthquake did not allow an easy solution in terms of the quick fault-plane identification. Although the fault plane solutions (strike, dip, rake) by various agencies are almost identical, there is a significant difference in the centroid position, both horizontally and vertically. The same is true for the three analyzed hypocenter positions. The variety comes from insufficient data south and southeast of the earthquake. As such, it is difficult to unequivocally say whether hypocenter was closer to the almost vertical plane (strike ~265 deg, dip ~85 deg), or the gently dipping plane (strike ~355 deg, dip ~50 deg). Even when concentrating on the likely most reliable hypocenter (NOA), we find two concurrent CMT's providing a H-C consistent solution, but with opposite result: the Harvard solution, pointing to the plane of strike ~355 deg, and the UPSL solution preferring the almost vertical plane of strike ~265 deg. Only when further constraining the H-C distance we resolve the ambiguity and arrive at **preference of the almost vertical fault plane**, as suggested by the combination H-NOA with C-UPSL, whose H-C distance of 16 km is reasonable. With H and C practically in the same depth (~60 km), and C encountered west of H, we might interpret the event as an oblique-slip rupture propagating predominantly westward. Obviously, due to demonstrated problems, the preferred model strongly requires an independent support by finite-source modeling or stress analysis.

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