Earthquake location from P-arrival times only: problems and some solutions

JAROMÍR JANSKÝ[1], OLDŘICH NOVOTNÝ[1], VLADIMÍR PLICKA[1], JIŘÍ ZAHRADNÍK[1]
AND EFTHIMIOS SOKOS[2]

1 Department of Geophysics, Faculty of Mathematics and Physics, Charles University in Prague, Ke Karlovu 3, 121 16 Praha 2, Czech Republic (jansky@seis.karlov.mff.cuni.cz, on@karel.troja.mff.cuni.cz, vp@karel.troja.mff.cuni.cz, jz@karel.troja.mff.cuni.cz)

2 Seismology Laboratory, Department of Geology, University of Patras, Patras, Greece (esokos@upatras.gr)

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ABSTRACT

Selected problems related to accurate hypocenter locations are discussed in the difficult case that only reliable P-wave readings are available. Near stations are usually only few, and often have a poor azimuthal coverage. As such, they are insufficient because the inversion is highly ill-posed, and the epicenter position strongly trades-off with depth. Thus more distant stations are also needed to obtain the correct epicenter. However, joint use of near and distant stations present another difficulty; it may yield a significantly incorrect depth estimate in case that the crustal model is not fully appropriate. In practice, the erroneous depth often remains unrecognized. An indication of the depth problem can be obtained by analyzing the travel-time residuals at individual stations. It is also useful to check fully independent depth estimates, for example those from the centroid-moment-tensor analysis. If the problematic crustal model is detected, and it is not easy to find a better one, the near- and distant station effects should be decoupled (a two-step location): the epicenter is calculated from all stations, kept fixed, and the source depth is grid-search beneath the epicenter by means of the near stations. The ideas are applied to the M_w 5.2 Efpalio (Western Greece) earthquake of January 18, 2010, and the following aftershock sequence.

Keywords: western Greece, station's distribution, two step location

1. INTRODUCTION

The motivation for this paper comes from our participation in the study of the M_w 5.2 Efpalio earthquake, Corinth Gulf, Greece (January 18, 2010), and the aftershock sequence following this event. The comprehensive investigation of these shallow crustal earthquakes was already done (*Sokos et al., The Efpalio 2010 earthquake sequence interpreted in terms of tectonics of the western Corinth Gulf, submitted to the*

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Tectonophysics, 2011). As one of the key issues was the identification of the fault plane, it was necessary to get a good estimate of the source depth. About 26 stations were available from almost zero epicentral distance (the saturated station EFP), up to ~80 km (Fig. 1). Most records did not allow reliable picking of S-wave arrivals, since S-wave onsets were obscured by complex wave trains following the P-wave group (see inset in Fig. 1), most likely due to combined effects of the shallow event depth and the complicated crustal structure. Despite attempts to use particle motion diagrams, filtration, etc., the S-wave readings remained highly uncertain; at some stations, including the near ones, the readings were within the interval of ±0.5 s. Therefore, although S waves obviously help to constrain the hypocenter depth, use of the unreliable S-wave needs down-weighting, which is almost identical to their omission. These difficulties suggest the investigation of possible sole use of reliable P-wave readings, especially if the latter are available also at relatively near stations. The limitation to P waves has also practical reasons: Automated phase picking is simpler for P than S, and many rapid agency locations are made almost exclusively from the P readings.

As such, the main objective of this paper is to understand problems related to the earthquake location from the P-wave onsets only, with main accent on the estimation of the source depth. Two factors have to be studied, viz the station distribution and the

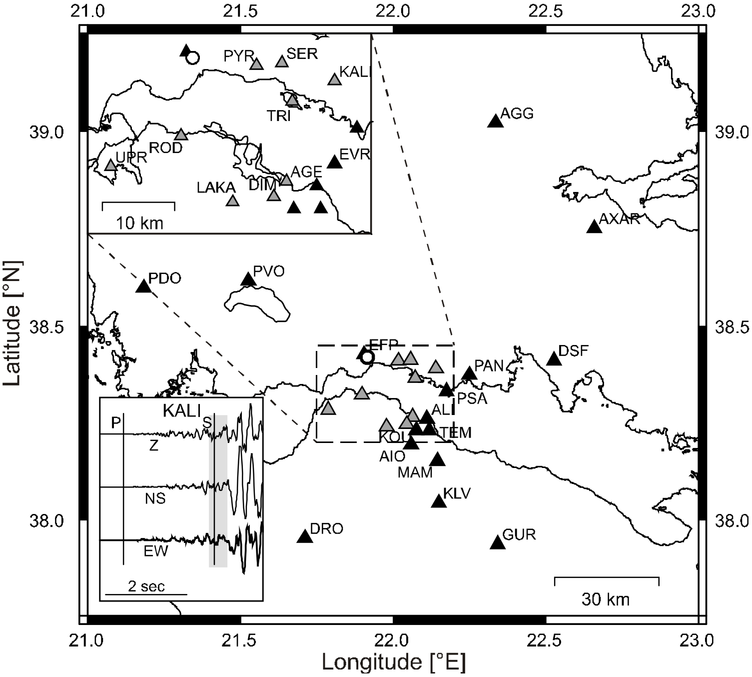

Fig. 1. Distribution of stations that recorded the Efpalio January 18, 2010 event. The position of epicenter No. 2 from Fig. 3 (row 2 in Table 1) is shown by circle. First inset shows in detail the position of the nearest 10 stations (gray triangles + EFP). The second inset shows the waveforms of the studied event, recorded at the station KALI. Note the uncertainty of the S-wave onset.

crustal model. We investigate a model situation where relatively distant stations with a good azimuthal coverage with respect to the studied event can be complemented with near stations, whose azimuthal distribution is poor. We discuss how to combine these two groups of observations. We also investigate effects of the crustal structure. Typically, one or a few 1D models are routinely used to locate earthquakes in a study region, and little attention is paid to the model reliability. Sometimes, a few alternative models are checked, and it is believed that the one providing smaller root-mean-squared (*RMS*) residuals is better (*Serpetsidaki et al., 2010*). We demonstrate some cases where even the relatively low-RMS results are still misleading. The Efpalio mainshock is used as a model of a shallow $M_W \sim 5$ event recorded in a near-regional network. The explanations are performed for this case study, but the main intention is to draw conclusions of a broader applicability.

The paper is structured as follows: First, location results from all stations and those from only near stations are critically compared. Second, independent depth estimates are introduced, and ways how to recognize the problematic location depth are shown. Third, effects of the crustal model is discussed, including examples of a model modification. Forth, to solve the situation that a better crustal model is not available, a two-step location is proposed as a 'first-aid' tool to reduce the depth deficiencies. The final part of the paper is devoted to the application of the ideas to the Efpalio aftershock sequence.

2. INITIAL UNCONSTRAINED LOCATIONS

The model situation is described in Fig. 1. We use a network of 26 stations, and try to locate a shallow event close to one of them (EFP). The network can be roughly characterized as composed from two groups of stations: the 'near' and 'distant' stations,

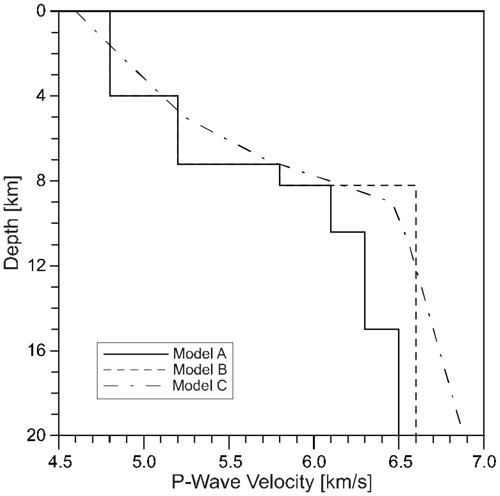

Fig 2. Crustal Models A, B and C used in the location. Model A (*Rigo et al., 1996*) was derived for the western part of the Corinth Gulf, Model B is an ad-hoc model of this paper, Model C is a 1D local approximation of the recent 3D tomography model of the studied area (*Latorre et al., 2004*).

Table 1. Locations of the Efpalio mainshock. *ERH* and *ERZ* stand for the standard error of the epicenter and depth, respectively.

Location Specification	Veloc. Model	No. of Stations	Lat. [°N]	Long. [°E]	Depth [km]	*RMS* [s]	*ERH* [km]	*ERZ* [km]
HYPO71PC								
Relative	A	16	38.4208	21.9228	5.93	0.04	0.3	0.2
Absolute	A	26	38.4198	21.9153	8.93	0.14	0.4	0.5
Absolute	A	10	38.4285	21.9075	8.66	0.12	1.7	1.6
Absolute	B	26	38.4115	21.9163	6.69	0.12	0.4	0.3
Two-steps	A	26/10	38.4198	21.9153	7.00	0.10	1.0	0.6
Synt. data	C/A	26	38.4250	21.9137	7.39	0.08	0.2	0.3
Synt. 2-steps	C/A	26/10	38.4250	21.9137	6.90	0.03	0.3	0.2
NonLinLoc								
Absolute	A	26	38.4192	21.9173	9.96	0.16	0.4	1.8
Absolute	A	10	38.4170	21.9182	6.64	0.10	7.8	13.3
Absolute	C	26	38.4160	21.9178	7.52	0.15	0.4	0.9

with epicentral distance up to about 22–30 and 80 km, respectively. The near stations are situated in a narrow azimuthal sector, while the distant stations are azimuthally distributed fairly well.

Three 1D crustal models will be used, A, B and C, see Fig. 2. The models are as follows: Model A (*Rigo et al., 1996*) was derived for the western part of the Corinth Gulf, and is routinely used to locate local events by the Corinth Rift Laboratory (CRL) seismic network (*Lyon-Caen et al., 2004*; *Bernard et al., 2006*). Model B is an ad-hoc model of this paper. It was derived by the trial-and-error to improve the depth estimates, so it has just a formal meaning. Model C is a 1D local approximation of the recent 3D tomography model of the studied area (*Latorre et al., 2004*). The A and B models are composed of homogeneous layers, while C has layers with constant velocity gradients.

Several location codes will be applied: HYPO71PC (*Lee and Valdés, 1989*), NonLinLoc (*Lomax and Curtis, 2001*; *Lomax, 2005, 2006*) and HYPOINVERSE (*Klein, 2000, 2002*). Only P-wave first-arrivals are used.

Experiment 1. In this experiment we compare two locations: the first one employing all 26 (near and distant) stations, and the other with only 10 (near) stations, respectively. (Similar results are obtained if taking in consideration 16 near stations of Fig. 1, instead of 10.) We use both HYPO71PC and NonLinLoc, see Figs. 3 (hypocentres), 4 and 5 (probability-density function - *PDF* of the NonLinLoc for 26 and 10 stations, respectively) and Table 1. It is quite obvious, especially from NonLinLoc, that 26-station case is strongly preferable. The horizontal and vertical uncertainties are significantly better than in the near-station case, clearly related to the azimuthal coverage. Note that reducing the 26 stations to 9 stations (3 near and 6 distant), while still keeping a regular azimuthal distribution of distant stations, would provide very similar results (not shown). As documented in Fig. 5 the problem of the near stations is in the strong trade-off between the epicenter position and depth. In other words, the uncertainty volume, mapped by the probability density function, is highly inclined, not sub-vertical, as compared with the case of the use of all 26 stations.

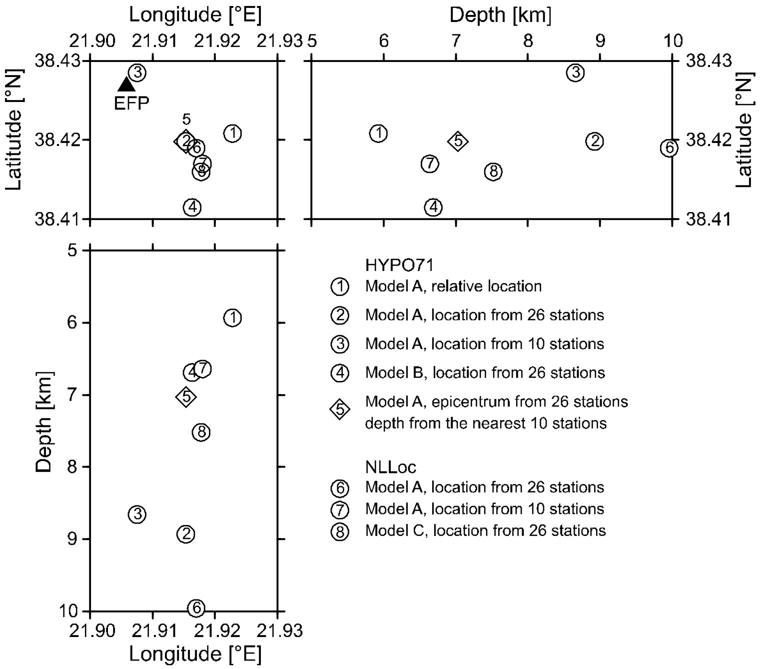

Fig. 3. The hypocenters of the Efpalio main shock as obtained with the location approaches used in this study, as specified in the legend.

Consequences of the ill-conditioning in the near-station case can be illustrated by comparing the HYPO71PC location with the optimum solution from the NonLinLoc; indeed, in the near-station case the two locations differ quite significantly, while the two methods give almost identical locations when all 26 stations are used (Fig. 3, Table 1). Possible bias between the depth and origin time, that users are often worrying about, is completely out of game for NonLinLoc because it employs the equal-differential-time (*EDT*) formulation, thus the origin time is fully eliminated.

So we may get the impression that the 26-station location is reliable, with the depth around 9–10 km. But we show that the situation is not as simple.

3. INDEPENDENT CONSTRAINTS ON THE HYPOCENTER DEPTH

As in any ill-posed problem, any additional constraint is useful. Typical data helping to estimate the depth of shallow events are the geodetic data (mainly applicable for larger magnitudes), centroid-moment tensor (CMT) solutions and relative locations. The advantage of the CMT solutions, inverted from low-frequency waveforms, is that their depth estimate is often less sensitive to the (poorly known) crustal structure (*Zahradník et al., 2008a*; *Janský et al., 2009*). The centroid depth is of course generally different from the hypocenter depth, but the difference is of the order of the fault size, hence small (less

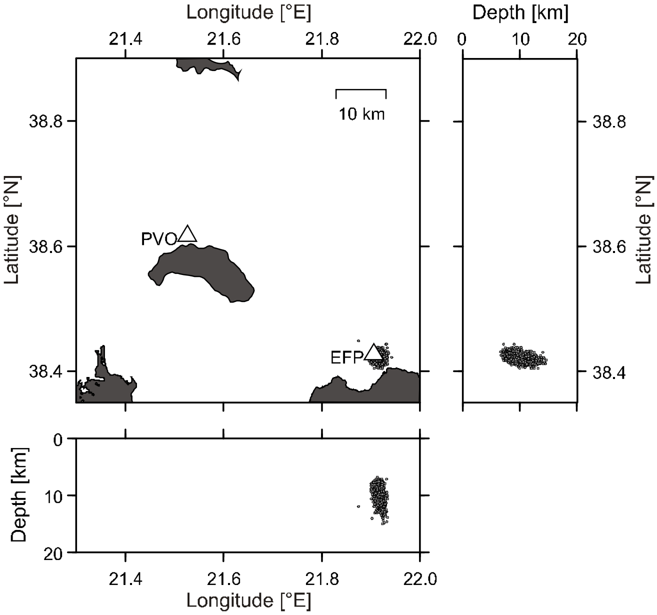

Fig. 4. Probability-density function (cloud of dots) for the main shock location by NonLinLoc in the Model A using all the 26 stations.

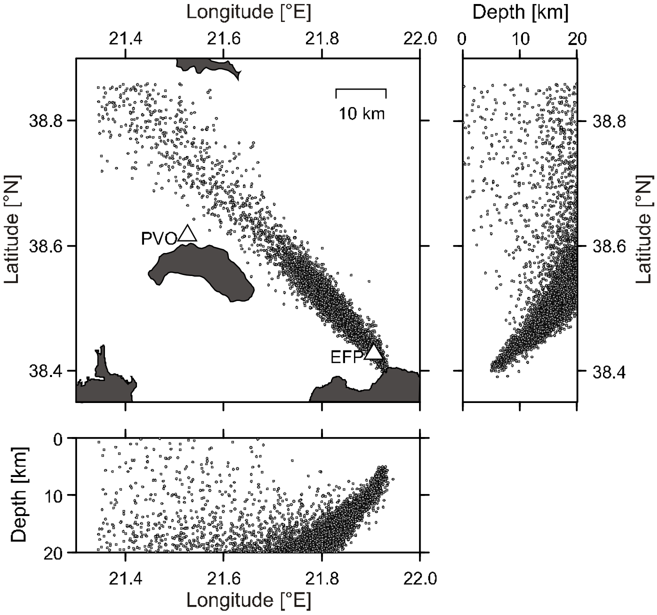

Fig. 5. The same as in Fig. 4, but using only the 10 nearest stations.

than ~2 km) for an $M_W \sim 5$ event. As for the relative locations, their advantage is in partially removing the poorly known crustal structure if a sufficiently close event of a better constrained depth is available, for example a foreshock. An advantage of a foreshock is its simpler waveform, enabling more reliable phase readings. Then the idea is to use the travel-time residuals of the foreshock as the station corrections when locating the mainshock (*Zollo et al., 1995*).

In case of the Efpalio earthquake both of these constraints are available. The CMT-depth inferred from near-regional stations at the frequency range of 0.05–0.10 Hz was 4.5 km (*Sokos et al., The Efpalio 2010 earthquake sequence interpreted in terms of tectonics of the western Corinth Gulf, submitted to the Tectonophysics, 2011*). A foreshock, which occurred 25 s before the mainshock, and was located using reliable P and S waves at the depth of 6 km enabled application of the relative method. It resulted in the mainshock depth of 5.9 km (Fig. 3, Table 1). It is in full agreement with *Lyon-Caen et al. (2010)*. The two pieces of evidence indicate that although the above derived depth of 9–10 km is confirmed by several methods, it was probably overestimated, and the more likely depth of the Efpalio mainshock is rather around ~6 km. Hereafter we call this the reference depth.

4. DETECTION OF THE PROBLEMATIC DEPTH: RESIDUALS OF INDIVIDUAL STATIONS

We obtained a relatively stable depth estimate from 26 stations, i.e. 9–10 km. The independent information says that this depth might be too large, likely by ~3–4 km. Is there any feature of the data, which would provide an indication that the 9–10 km depth is inappropriate?

Experiment 2. Consider the 26-station case, and calculate the *RMS* values separately for the first 10 near stations (stations ordered with increasing distance), and then for the most distant 10 stations. We obtain *RMS* = 0.13 s for both. This indicates a good balance between the solutions for the two groups. However, inspecting the travel-time residuals at the individual stations (Fig. 6 top), we find a significant difference in the polarity of the residuals. For the near stations the sum of positive residuals is 1.08 s, while the sum of negative residuals is only –0.20 s. The distant stations have an opposite relation, i.e. 0.16 s and –1.09 s, respectively; the negative residuals strongly prevailing. The prevalence of one sign at each group means that data of the whole network are matched in fact by balancing the near stations through the distant ones. The overall fit (*RMS*) is acceptable, but the location is likely to be biased. Hereafter we call this effect as internal inconsistency of the residuals. The inconsistency shows an inability to match observations close and faraway from the source, probably due to a limited applicability of the used crustal model (Model A).

In other words, inspecting the individual station residuals, or just the sum of their negative and positive values at the two station groups, we obtain a simple tool to recognize the location problem. The test is simple and efficient. It may preclude from adopting the low-*RMS* locations which are in fact inappropriate.

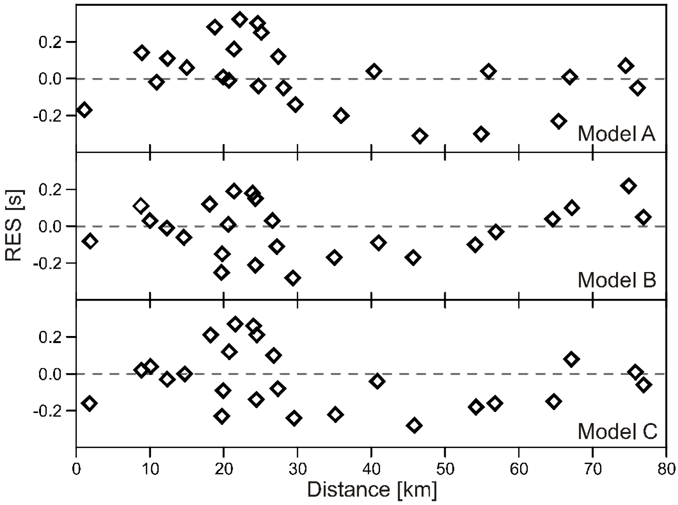

Fig. 6. Travel-time residuals as a function of epicentral distance. Upper part for location by HYPO 71PC in Model A; middle part for location by HYPO71PC in Model B; lower for location by NonLinLoc in Model C. Note prevalence of positive and negative residuals at near and distant stations, respectively, indicating problem of the corresponding crustal model in its lower part.

5. DEPTH IMPROVEMENT IN A MODIFIED CRUSTAL MODEL

The rays to distant stations propagate in our case from the source downwards. The domination of the negative residuals at these stations means that the computed travel times are to large, i.e. that the velocities in the corresponding part of the model are to slow. By closely inspecting the individual station residuals, one can infer by trial-and-error that a more suitable model, reducing the internal inconsistency of residuals, would be such, in which the P-wave speed increases at and below the depth of ~8 km. This is an "ad hoc" Model B (Fig. 2).

Experiment 3. Using Model B in HYPO71PC to locate from all 26 stations provides the hypocenter depth of 6.7 km. This value puts the location close to the reference depth of 6 km, indicated by the CMT and relative method. Moreover, using Model B we obtain not only smaller average residual *RMS* but also we balance the positive and negative travel-time residuals internally among the near stations (0.46 and –0.55 s), as well as internally among the distant ones (0.41 and –0.56 s, Fig. 6 middle).

There is no aspiration to present Model B as a result of a structural or geophysical importance. It merely shows how the internal inconsistency of the individual station residuals can be reduced, and how it may affect the depth. Nevertheless, it is possible that the 'ad hoc' Model B is not too far from reality. Indeed, a relatively steep increase of the P-wave velocity at the depth of about 8 km has been manifested in the 3D tomography model of *Latorre et al. (2004)*. Therefore, using panel (d) of their Fig. 16 as the most relevant one for the studied area, we derived and tested also a 1D approximation of their 3D model (our Model C, Fig. 2).

Experiment 4. Using Model C, 26 stations and NonLinLoc, we arrive at the depth of 7.5 km, again closer to the 6-km reference depth than the initial estimate 9–10 km. The balance of positive and negative travel time residuals (Fig. 6 bottom) is worse than for the Experiment 3 (an expected result, because the NLL-EDT does not explicitly balance the residuals as do L2-Least-Squares methods), but better than for the Experiment 2.

6. DEPTH IMPROVEMENT IN THE INAPPROPRIATE MODEL BY A 2-STEP APPROACH

It was found that the internal inconsistency of the travel time residuals at near and distant stations can be reduced by modifying the crustal model. Finding a better model is a research task, not feasible in routine practice. Thus a question arises if the deficiency of the crustal model cannot be ‘fixed’ by a simpler tool.

To find the tool, we have to understand the anatomy of the problem: readings from the near stations alone are of limited use because they yield a significant trade-off between the epicenter and depth (a highly ill-posed problem). At the same time, readings from distant stations (if azimuthally distributed well) provide a relatively well-posed inversion of the epicenter, but the depth is highly dependent on the crustal model. It follows that the problem can be regularized by decoupling the epicenter determination from the depth.

The so-called two-step method can be suggested, as follows: i) use all (26) stations (or a subset with good azimuthal coverage) and get the epicenter by any method, for example HYPO71PC. Then, ii) keep the epicenter from step i) fixed, and seek the hypocenter beneath by grid-searching the depth using the near stations. It is important that in step ii) only the near stations are used (although, as we learned, they are inappropriate for the full 3-parameter inversion of the epicenter and depth). Use of the sole near stations in step ii) eliminates negative effects of the bias between the near and distant stations in case of an inappropriate crustal model, hence reduces the risk of wrong depths. To further justify the two-step approach, we also make a synthetic test (below).

Experiment 5. We find that the two-step method applied to the (inappropriate) Model A does provide the source depth of 7.0 km, closer to the 6-km reference depth than the initial location (9–10 km). See Fig. 3 and Table 1, where the epicenter was obtained by HYPO71PC from the 26 stations in Model A, while the hypocenter depth (in the same model) was grid-searched using 10 near stations. The same ~7 km depth was obtained if, for example, we use only 3 or 5 nearest stations, confirming stability of the depth. Contrarily, recall that the free 3-parameter location from the 10 nearest stations was highly unstable, i.e. use of lower number of stations than 10 stations provided very different results (not shown).

7. SYNTHETIC TEST

To better demonstrate problems of the joint location from near and distant stations in an inaccurate crustal model, as well as to justify the two-step location, we set up the following synthetic test. ‘Data’ are represented by the P-wave travel times, forward simulated for the known (prescribed) position of the source at the depth of 6 km. The 26-station distribution is the same as in the real case above. The ‘data’ are calculated in

Model C, but, intentionally, their ‘inversion’ is performed with a different crustal structure, Model A.

Experiment 6. First, using the HYPO71PC, we invert all 26 stations for the epicenter and depth (one-step approach). Similarly to the real data case, the inaccurate crustal model weakly affects the epicenter (it shifts it only by 0.5 km), but it pushes the source by 1.4 km below the true one, i.e. from the depth 6.0 km to 7.4 km (Table 1). We also get predominantly positive travel-time residuals for the 10 nearest stations (0.46 and –0.07 s) and predominantly negative residuals (0.17 and –0.69) for the 10 most distant stations, i.e. we observe the internally inconsistent residuals, analogous to the real case.

Experiment 7. (The two-step approach) Now we keep the epicenter from Experiment 6 fixed, and obtain the best-fitting depth from the 10 nearest stations by grid search (again using the HYPO71PC), getting the value of 6.9 km. Comparing the above case of 7.4 km, the resulting value of 6.9 km is a bit closer to the prescribed depth of 6 km. Further, if we keep the epicenter fixed in its true (“synthetic”) position, and grid-search the depth beneath from the 10 nearest stations (still in the inaccurate Model A), we obtain the depth of 6.5 km, even closer to the 6-km true value.

In other words, we cannot expect that the two-step method will fully remove the problem of the model inaccuracy, and will always provide the perfect depth, but the method can reduce the undesired effects of the crustal model, and, most importantly, if the epicenter from the first step will approach the true value, also the depth in the second step will approach the correct value.

8. AFTERSHOCKS SEQUENCE LOCATION

Here we apply the above findings to 123 events of the Efpalio aftershock sequence from January 18 to February 17. Some additional temporary stations have been installed to complete the standard network for aftershocks location. These stations are shown in Fig. 7d. The main ideas to be proven by this analysis are the following: i) using Model A, whose validity is questionable for the joint location in the near and distant stations, we expect to obtain relatively large source depths. ii) Applying, instead, Model B or C, the foci will move upward. iii) If supplementing selected events by their CMT analyses (calculated using ISOLA software, *Sokos and Zahradník, 2008*), i.e. calculating their moment tensor for a series of depths and grid-searching the optimum one, we expect the CMT depths to be closer to those obtained from method ii), since the crustal model does not introduce significant bias to the CMT-derived depths (*Zahradník et al., 2008b*) and thus they present a better approximation of true depth. Furthermore the aftershocks used in the analysis have small magnitudes thus their location and centroid positions should be comparable.

Location of the aftershocks was done using the HYPOINVERSE code (*Klein, 2002*) and results are presented in Fig. 7. The change in depth distribution of the aftershocks obtained by the use of Model B or C in comparison to depths obtained by Model A is evident. Models B or C produce a decrease in mean event depth of the order of ~3 km (Fig. 7a–c). These results confirm the above mentioned expectations and provide validation of the mainshock depth. If we compare the location results using Model C with CMT-derived depths for selected events (i.e. the strongest aftershocks) we find that the differences between CMT depths and location depths lie between 0 and −2 km. The comparison proves the very good correlation between the two different approaches in deriving the event depth.

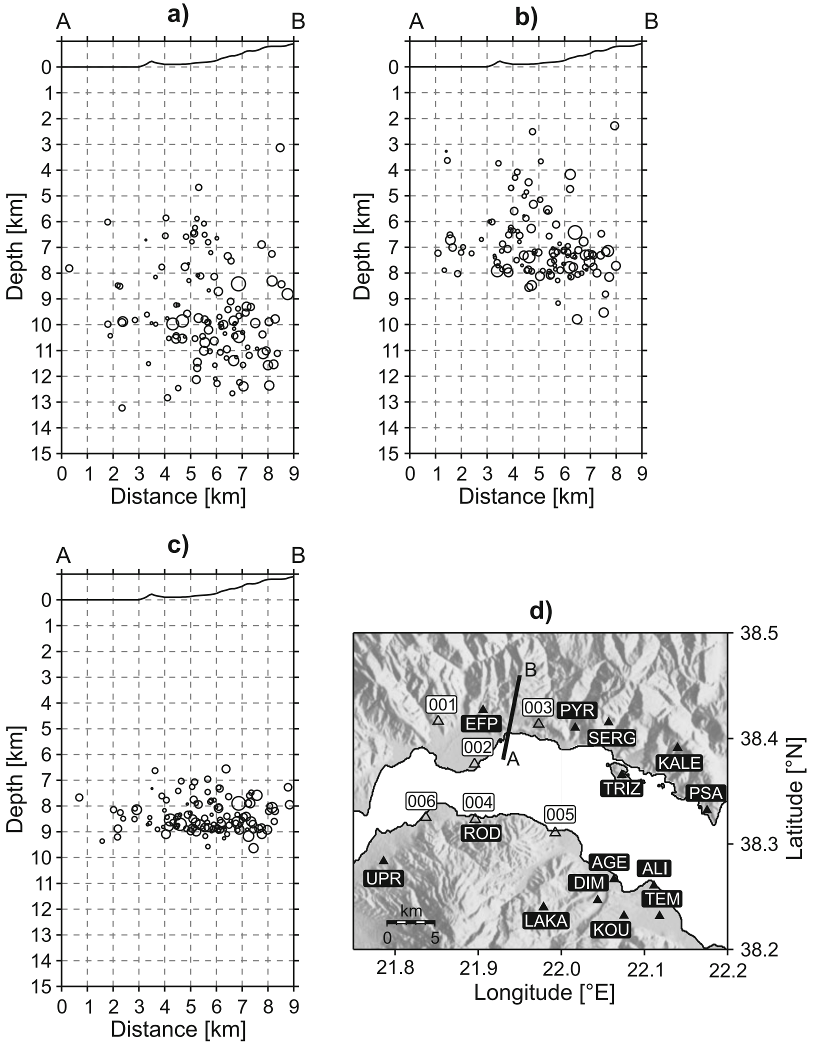

Fig. 7. **a)** The vertical crossection along the profile AB (marked in d)), showing the location of the aftershocks in the Model A; **b)** the same as in a), but for the Model B; **c)** the same as in a), but for the Model C. **d)** Part of the station network showing the position of the additional 6 stations (numbered triangles) installed to complete the standard network with the aim to improve the aftershocks location.

9. CONCLUSIONS

The paper provides an analysis of the problems related to the earthquake location with sole use of P waves. We concentrated on a $M_W \sim 5$ event recorded in a typical near-regional network, including ‘distant’ and ‘near’ stations, whose azimuthal coverage is good and bad, respectively. Another studied factor was the effect of the used crustal model. The Efpalio earthquake, January 18, 2010, western Corinth Gulf, served as an example, but we focused on findings of a broader applicability. These are as follows:

a) Using P-waves only we face the problem with the ill-conditioned source depth. If only near stations of a poor azimuthal coverage are used, a strong bias exists between the epicenter position and depth. A single linearized location may produce unstable results that depend e.g. on the choice of the first hypocenter approximation. Users of the codes like NonLinLoc will be informed about such a difficulty through the PDF shape (Fig. 5), but those who rely on HYPO71PC will only be warned by the larger formal error values. Moreover, they will see the standard error of the epicenter (*ERH*) and standard error of the depth (*ERZ*) values only for the ‘optimum’ depth, not being informed about strong variation of the error ellipsoids if the source position deviates form the formally detected one.

b) Joint use of near and distant stations brings another difficulty. It may provide the solution with a small formal uncertainty (both in the horizontal and vertical direction), but, at the same time, the depth may be significantly in error. The latter is the case if the crustal model is not fully appropriate for the given source and station configuration.

c) It is not easy to recognize the ‘wrong’ depth. Neither a small *RMS*, nor small residuals at the nearest stations, are sufficient. The best approach is to check independent estimates, for example the centroid-moment depth. If the latter indicates a significant deviation from the kinematic location, larger than expected for $M_W \sim 5$, it is necessary to analyse the problem in greater detail. We suggest a simple analysis of the travel time residuals of the individual station groups (Fig. 6). If there is a prevalence of residuals of equal sign for near stations, and prevalence of the opposite sign for the distant ones, then the location depth may be incorrect. Standard codes, used in routine locations, enable such a critical examination although they do not provide any ‘single-number’ warning.

d) When the problematic depth is identified, several procedures may be used to improve the depth determination. For example, if we locate a sequence, we can determine the mean difference between the location depths and CMT depths, and make a formal depth shift of the whole sequence, moving the location depths closer to the CMT-constrained ones. Alternatively, the user can try to find a more reliable crustal model. This may be a model among the existing ones, or a completely new one. Still another, perhaps simpler alternative, is a two-step location approach.

e) The two-step location is a simple practical way to (partly) reduce problems with the hypocenter depth when the crustal model is not good. It is based on the idea that we cannot use near and distant stations jointly, although we strongly need both these groups. The two-step approach consists of using all stations for the epicenter position (taking advantage of their good azimuthal distribution), keeping the epicenter fixed, and grid-searching the depth beneath, using near stations only. As proved by synthetic test, such an approach is useful because it treats the near and distant stations separately, and, the depth determination from the near stations is stabilized be decoupling the (otherwise strongly biasing) depth and epicenter position. Of course, the depth estimate from the second step improves with improving the epicenter estimate from the first step.

Specifically for the Efpalio earthquake sequence, these ideas led the following results. The mainshock (January 18): although the initial depth estimates from 26 stations (with the relatively small *RMS* values) were around 9–10 km, the final estimate is 6–7 km, significantly closer to the 6-km depth independently obtained from the CMT and from the foreshock-based relative location. These results were obtained by combining several approaches mentioned above, including the two-step method and the variation (modification) of the crustal model.

The aftershocks (123 events between January 18 and February 17): the final HYPOINVERSE locations (in Model C) were obtained with the focal depths comparable (on average) to those obtained from the CMT determination of ~30 events. As such they represent a relevant seismic information usable in tectonic interpretations.

Many events (even sequences) may have highly problematic depth determinations due to inappropriate station distributions and/or crustal models. Uncritical use of routine location algorithms in these cases may give results that can bias tectonic interpretations, and may sometimes even bias the earthquake hazard assessment (e.g., when shallow events are systematically mislocated to greater depths).

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