NON-REVIEWED CONTRIBUTION

SHALLOW EARTHQUAKES: SHALLOWER THAN EXPECTED?

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1. INTRODUCTION

The space and time distribution of earthquakes represents a key input for seismo-tectonic models, but also for the seismic hazard assessment. Earthquake depths belong to the most important factors. For example, the depth distribution serves for delimiting the so-called 'seismogenic layer' (*Chiarabba et al., 2005*). *Marone and Scholz (1988)* emphasized importance of the upper cutoff in seismicity between 3–5 km, related with the state of stress, fluids and frictional stability on faults. According to their paper, only well-developed faults exhibit the upper cutoff in seismicity. Poorly developed faults, with insignificant gouge zones, exhibit seismicity up to surface. Specifically, in the Gulf of Corinth, Greece, dealt with in this paper, so far most events have been reported to occur at depths greater than 5 km (e.g., *Hatzfeld et al., 2000*; *Lyon-Caen et al., 2004*; *Novotný et al., 2008*). The upper cutoff seems to be very well developed there (Fig. 16 of *Latorre et al., 2004*).

Shallow events are often responsible for heavier earthquake losses (e.g., *Zheng-Xiang at al., 2005*). However, the relation between depth and damaging effects is not straightforward. Large events at very shallow depths, or even accompanied with surface ruptures, may (perhaps surprisingly) generate weaker ground motions than buried events of the same magnitude. It is because buried earthquakes may have larger effective stress drop and higher slip velocities (*Kagawa et al., 2004*). The tsunami generation is also very much dependent on the proximity of the fault to the Earth's surface (*Geist, 2002*). As shown by *Tselentis et al. (2006)* for the Corinth Gulf, their Table 2 (and references therein), for the top of fault shallower than 2 km, the sea-bottom vertical displacement will be about twice as large as compared to the fault top below 5–6 km.

In spite of importance of the earthquake depth, just this parameter is less accurately determined than the epicenter position. The reason is principal because inverse problem of the arrival times has its least eigenvalue related just with the depth. Moreover, knowledge of the crustal structure, employed in most of the location procedures, is often fairly limited. Specifically, the objective of this paper is to show that some shallow crustal earthquakes might be in fact 'shallower' than routinely calculated. The main tool will be combination of the arrival-time location and the moment-tensor calculations; see also (*Olivieri and Ekström, 1999*). Main questions to be addressed in this paper are as follows: (i) where the erroneous depth estimates might come from, (ii) how to detect problematic cases, (iii) how to find more relevant depths. The study is based on a selected weak earthquake from the western Corinth Gulf, Greece, and a synthetic experiment.

Table 1. Location of the studied event.

Model	Latitude [°N]	Longitude [°E]	Depth [km]
R[*]	38.3373	21.8903	5.4
N[**]	38.3348	21.8863	3.2

[*] *Rigo et al. (1996), Vp/Vs* = 1.80
[**] *Novotný et al. (2001), Vp/Vs* = 1.80

2. EVENT 20021203: INCONSISTENCY BETWEEN LOCATION AND MOMENT-TENSOR ANALYSIS

Motivation for this study came from our previous investigations of weak earthquakes in the Corinth Gulf (*Zahradník et al., 2008*). One of them featured a strange behavior in terms of its location, first-motion polarities and fault-plane solution. This is the *Mw* 3.4 earthquake that occurred in the western part of the gulf on December 3, 2002 (23:04:39 UTC). It attracted attention already in *Bernard et al. (2006)*; based on nearby strain measurements, the event was classified as a fast episode of a slow earthquake of equivalent magnitude 5.5, lasting almost two hours.

Location (Table 1). Here we locate the earthquake using 'manual' picking of arrival times at eight stations at epicentral distances up to 25 km: 5 stations (AGE, DIM, ALI, KAL, TEM) of the short-period network of the Corinth Rift Laboratory, CRL (*Lyon-Caen et al., 2004*), 2 stations (UNI, NAF) of the short-period network of the University of Patras, PATNET (*Tselentis at al., 1996*) and Rodini station belonging to the RASMON network (National University of Athens), Fig. 1. The location was made with HYPOPC71 code (*Lee and Valdés, 1985*; *Lee et al., 2003*) and the crustal model of Fig. 2, hereafter denoted R (*Rigo et al., 1996*), routinely employed in the CRL network. The hypocenter parameters are given in Table 1 (the depth of 5.4 km). To investigate uncertainty of the source depth, the event was relocated using the "fixed depth" approach, where the depth was changed from 1 km to 8 km with the step of 0.5 km. The resulting misfit is shown in Fig. 2. We find a clear minimum at the depth near 5 km, in agreement with the HYPO location with free depth. If the nearest station Rodini is not used (or missing in the data set) the depth would be 14 km. This was the alarming case of our very preliminary study, similar to the experience of *Husen et al. (2003)*.

Moment tensor (Table 2). The MT was obtained by inverting complete waveforms at three nearest broadband stations RLS (NOA - National Observatory of Athens), SER, MAM (Prague-Patras project, *http://seis30.karlov.mff.cuni.cz/*), (Fig. 1) using the same crustal model, R, as above. The frequency range 0.08–0.15 Hz was used; the frequencies lower than 0.08 Hz have poor *S*/*N* ratio, and the frequencies higher than 0.15 Hz do not allow successful modeling with the available crustal models. The ISOLA software was applied (*Sokos and Zahradník*, *2008*). A set of trial depths below the epicenter, 0.3 to 4.8 km, with the step of 0.5 km, indicated notable variation of the fault-plane solution (Fig 3). Shallow depths (< 2.5 km), with normal-fault mechanisms, were preferred against the larger depths and strike-slip mechanisms. The optimum solution (depth 1.3 km) is in Table 2. Although only 3 broadband stations were available due to small size of the earthquake, the results proved stable when repeatedly removing one station. The first-

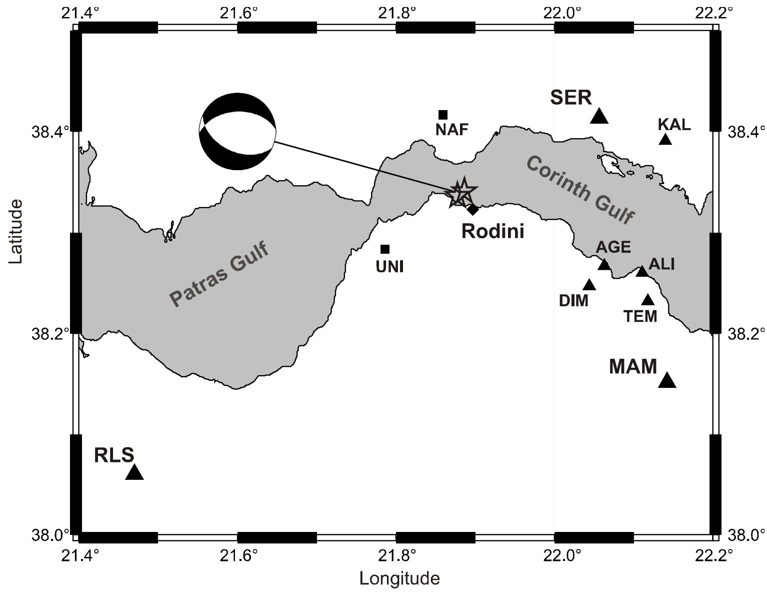

Fig. 1. Studied region in western Greece. Short-period stations used for location are shown by small triangles (CRL stations), squares (PATNET stations) and diamond (RASMON station). Broadband stations used for moment tensor inversion are shown by large triangles. Epicenters of the 20021203 event (solutions for the R- and N-model, respectively) are denoted by the stars. The MT obtained by inverting complete waveforms at three nearest broadband stations SER, MAM, RLS using the crustal model R, is shown by the 'beach ball'.

motion polarities also supported the shallow normal faulting mechanisms (Fig. 3). Comparing with the location depth (5.4 km), we arrive at an important inconsistency.

2.1. Event 20021203: Possible Effects of Shallow Low-Velocity Layers

How to explain the inconsistency between the MT and location results? The working hypothesis is that the discrepancy comes from the topmost crustal layers, whose correct description is very critical for location of a shallow event, but less critical for the (relatively low-frequency) MT calculation. To prove the latter, we move to another crustal model, hereafter denoted N (*Novotný et al., 2001*), containing pronounced low velocity layers at its top; Fig. 2. Without claiming that model N is more plausible for the studied region it has been simply chosen as a distinct counterpart to model R, quite homogeneous and relatively fast in its topmost 4 kilometers (Vp = 4.8 km/s). As expected, although the two models differ enough, the overall pattern of the MT variation with depth is similar (compare panels a, b of Fig. 3); depths < 3.5 km are preferred. For the best-fitting solution the depth is 2.3 km, where also the first-motion polarities are satisfied in model N, see Table 2.

As a next step, let us try to understand the effect of the topmost layers on the earthquake location, too. Using HYPO location of the same earthquake, but now in

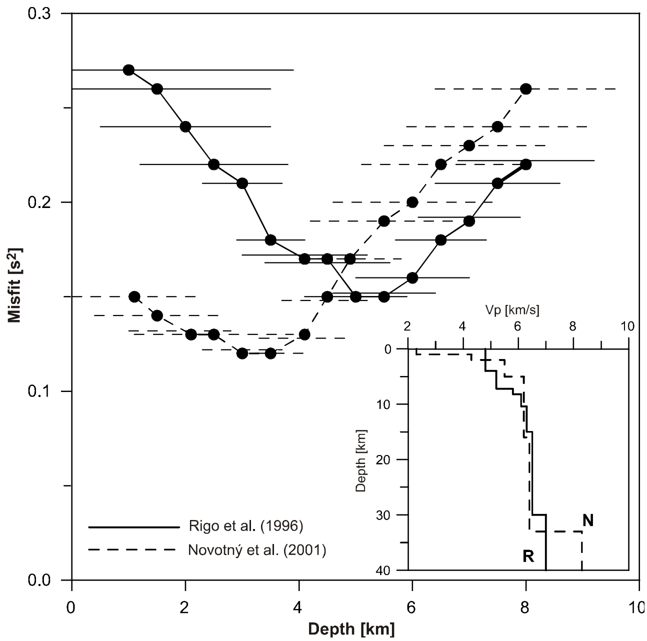

Fig. 2. Location of the 20021203 earthquake. Misfit as a function of depth obtained during the HYPO location with the fixed depth in model R (*Rigo et al., 1996*) - solid line and model N (*Novotný et al., 2001*) - dashed line. Note preference of the shallower depth in model N. The corresponding crustal velocity models are shown in the inset. Note the low velocity layers in the upper crustal part of model N. The horizontal bars show the standard error of each depth.

Table 2. Fault-plane solution of the studied event.

Model	Depth* [km]	Strike [°]	Dip [°]	Rake [°]	*Mo* [Nm]	*Mw*
R	1.3	267	47	–110	1.05×10^{14}	3.4
N	2.3	267	48	–113	0.96×10^{14}	3.4

* The depth providing the optimum waveform fit and satisfying polarities.

model N, we arrive at a shallower optimal depth, of about 3 km (Table 1). It is again supported by the repeated location with the fixed depth, see Fig. 2. If the nearest station Rodini is not used (or missing) the depth would be 12 km.

Compared to the stable MT calculations, the location results are considerably more sensitive to the absence/presence of the shallow low-velocity layers of the crust. While the MT gives a stable depth estimate, < 3.5 km (confirmed also by the first-motion polarities), different crustal models provide different hypocenter depths. None of the two tested models located the earthquake at the MT-preferred depth, but the trial model with shallow low-velocity layers (model N) moved the location-derived depth much closer to the MT-preferred depth. The other factor efficiently reducing the depth discrepancy was the availability of a very near station.

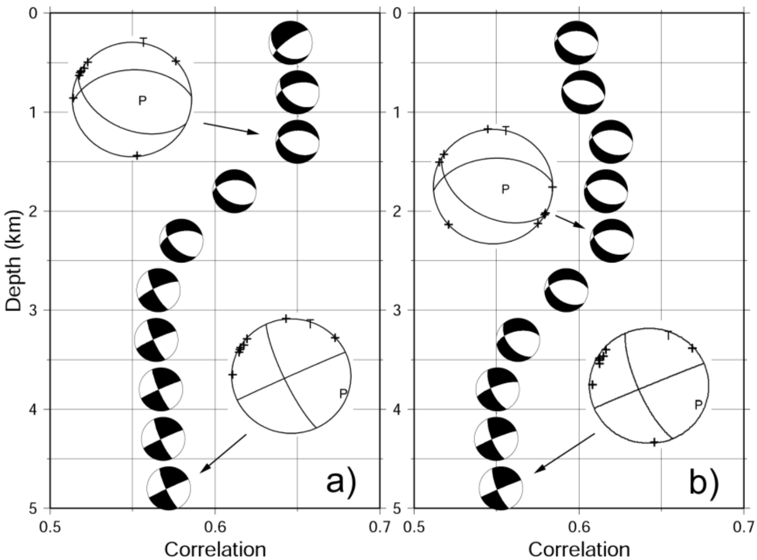

Fig. 3. Moment-tensor solution of the 20021203 earthquake. Correlation between the observed and synthetic waveforms is shown as a function of the trial depth. Also plotted are the fault-plane solutions. Panel a) - model R, panel b) - model N. Note preference of the shallow depths (< 2.5 km and 3.5 km in model R and N, respectively). Four large 'beach balls' show the first-motion polarities (all being compression), clearly violated at the depth of 4.8 km, while satisfied at the MT-preferred shallow depths. All 'beach balls' show the usual top view of the lower hemisphere, i.e., they are not rotated into the vertical cross section.

2.2. Synthetic Experiment: Mislocation of Very Shallow Events

To find out whether we are at real risk to systematically mislocate shallow events, we make the following synthetic experiment: First, a set of artificial events is 'prescribed', at known positions, in a known crustal structure (in the so-called 'true' crustal model). Further, synthetic arrival times are calculated to mimic the situation that the events are recorded at the studied seismic stations. Finally, the arrival times are inverted in a 'wrong' crustal model, to see the effect upon the inferred hypocenter position, mainly depth. Stimulated by the previous section of this paper, we are particularly interested in the situation that the 'true' model contains the low-velocity shallow layers, while these are absent in the 'wrong' (simpler) model.

The experiment has been designed to model the real situation of the 20021203 event. A set of 36 hypocenters was prescribed, composed of four rectangular grids, each one consisting of nine events (Fig. 4). The first two grids were situated at the depth of 2.5 and 3.5 km, representing shallow events. The third and four grid, were placed at the depth of 5.5 and 6.5 km, representing deeper events, i.e. events with "usual" depth. The stations "recording" the individual events were kept as in the real case, including the phase weights. The synthetic arrival times were calculated in model N, but inverted (by HYPO code) in model R. As a result, Fig. 4, deeper events do not change their depth very much, but the shallow events are shifted considerably to larger depth. The shift is further analyzed in Fig. 4, panel d, where the relocated depth is given as a function of the epicentral distance of the nearest station. It shows that depth shift (mislocation) of the shallow events considerably increases if the nearest-station distance increases.

The experiment manifested a possible, systematic and notable mislocation of the shallow events when the adopted crustal model does not appropriately reflect the shallow crustal layers. Deeper events are much less vulnerable to these problems; first because the deeper layers are relatively well described by the existing models, and, second, because the effect of the shallow layers upon the location of deeper events is less strong.

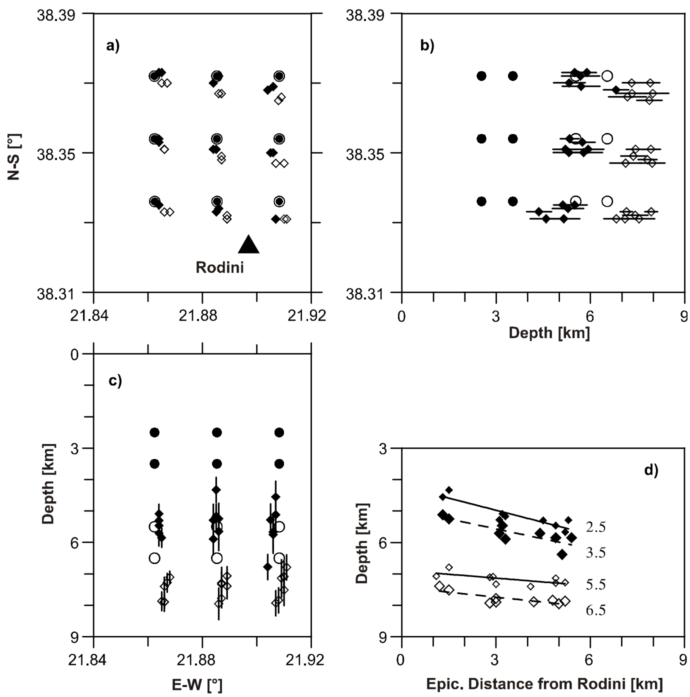

Fig. 4. Synthetic experiment. The 36 prescribed synthetic hypocenters (arranged in 4 rectangular grids of 9 events, placed at the depths of 2.5, 3.5, 5.5 and 6.5 km) are shown by dots (shallower) and circles (deeper), respectively. Shown are the map view (**a**) and two vertical cross sections (**b**, **c**). The Rodini station in panel **a)** is the nearest station. The 36 retrieved synthetic hypocenters are shown by full diamonds (shallower) and empty diamonds (deeper), respectively. The bars show the standard error of each depth. Arrival times of synthetic events were calculated for the studied seismic stations in 'correct' model N, containing the shallow low-velocity layers. Then the arrival times were inverted in a 'wrong' crustal model, without the shallow layers, to see the effect upon the inferred hypocenter position, mainly depth. The overall effect is that shallow events are shifted deeper. However, details depend on the proximity of the nearest station, see panel **d)**, where the depths are plotted as a function of epicentral distance of the Rodini station. The prescribed depth (in km) is shown at right. It is clearly seen that the misclocation of the shallower events (those originally at 2.5 and 3.5 km) is more severe.

3. CONCLUSION

An *Mw* 3.4 earthquake of western Corinth Gulf, Greece, was analyzed as an example of a relatively rare event for which the moment-tensor (MT) calculation and the arrival-time location yield inconsistent results, in particular a very shallow MT-preferred depth. To better understand the real data case, a synthetic experiment was also made. Both together they provide answers to the three questions formulated in the introduction.

i) Where the erroneous depth estimates might come from? A likely reason for a wrong depth is the case when a shallow earthquake is located in an available crustal model, not appropriate enough in terms of the shallow low-velocity structure, and if the nearest station is relative distant from the epicentre. Deeper events are much less vulnerable to these problems.

ii) How to detect problematic cases? Discrepancies between very shallow MT-preferred depths and the location-derived hypocenter depths may efficiently signalize the problem. In particular, when complemented by an analogous evidence from the first-motion polarities.

iii) How to find more relevant depths? In absence of the crustal models accurately describing the first few kilometers of the crust, it is basically impossible to guarantee relevant depths. The very shallow earthquakes might be systematically mislocated, i.e. moved to larger depths. In general, the only way is to improve crustal models, e.g. with the help of controlled-source measurements.

Similarly to the studied case, inadequacy of the models in the shallow crust, combined with often sparse location networks (thus missing very near stations) might systematically bias the seismicity pattern in many regions of the world. For example, delineation of the top of the seismogenic layer might be less certain than believed so far. Limitations of this kind may seriously affect not only tectonic studies, but also the seismic-hazard assessment and expected strong ground motions. The same is true for the tsunami scenarios.

Usefulness of the combined location and moment-tensor studies is an important finding of this paper. Success of this technique follows from the fact that it represents a combination of the high- and low-frequency seismic information. Stable depth estimate from the relatively low-frequency moment tensors, independent of the inaccurately known subsurface layers, has not been broadly recognized as a tool to improve the accuracy of the shallow seismicity pattern.

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