A LAYERED MODEL OF THE UPPER CRUST IN THE AIGION REGION OF GREECE, INFERRED FROM ARRIVAL TIMES OF THE 2001 EARTHQUAKE SEQUENCE

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ABSTRACT

The western part of the Gulf of Corinth attracts attention due to its seismically active fault system and considerable seismic hazard. Detailed studies of the seismic activity of the region have been carried out especially as part of the so-called Corinth Rift Laboratory (CRL) Project. For standard earthquake locations, the CRL uses the HYPO algorithm and a special structural model that is composed of homogeneous layers (Rigo et al., 1996). This model was derived from a passive seismic experiment in a broader area around the western part of the Gulf. A significant part of the seismic activity is concentrated close to the town of Aigion, which was damaged by a strong earthquake in 1995. A sequence of smaller earthquakes occurred to the south of this town in the year 2001. In the present paper, we have used this sequence to derive an improved structural model for the region in the vicinity of the town of Aigion. This new model is based on the minimization of travel-time residuals. In particular, we used arrival times from a subset of 88 events recorded by at least 5 stations of the southern part of the CRL network, had magnitudes of over 2.3, and were recorded at the nearest station (station code AIO). A variant of the method of conjugate gradients has been used for this purpose. In comparison with the model derived by Rigo et al. (1996), the new model is characterized by a higher v_P/v_S velocity ratio and by higher velocities to a depth of about 7 km. The new model was derived with the aim to get more accurate locations of future events in the vicinity of the town of Aigion.

Key words: crustal structure, arrival times, Greece, Gulf of Corinth, conjugate gradients, 1-D model

1. INTRODUCTION

The Gulf of Corinth is one of the most active seismic regions of Europe, as evidenced by the M_L6.2 earthquake that struck the town of Aigion in the western part of the Gulf on June 15, 1995 (*Tselentis et al., 1996*). The geological setting and Quaternary evolution of the Gulf of Corinth have been described in detail by *Armijo et al. (1996).* In the region of the town of Aigion, major tectonic elements include ESE-WNW oriented normal faults, steeply dipping to the NNE. Many smaller faults can also be distinguished at the surface. Moreover, some faults have also been hypothesized at depth (*Rietbrock et al., 1996*; *Rigo et al., 1996*). This geologically complicated fault system and the related seismic hazard call for detailed studies of this area.

In 1991, a passive seismological experiment was performed in the western part of the Gulf of Corinth, covering a 45×45 km area extending roughly from 21°45′ to 22°15′E and from 38°08′ to 38°33′N (*Rigo et al., 1996*). Using 51 digital stations and a set of 850 events these authors derived the optimum 1-D crustal velocity model, based on minimalization of travel time residuals. The model derived is composed of homogeneous layers and represents an average model for the whole area of the western Corinth Gulf. Hereinafter we refer to this model as RM. Its *P*-wave velocities and layer thicknesses are given in Table 1. The ratio of *P*- to *S*-wave velocities, v_P/v_S, is equal to 1.80 in all layers of the model.

Detailed seismological investigations in the broader vicinity of Aigion have been carried out as part of the Corinth Rift Laboratory (CRL) Project using records from a special seismic network (*Lyon-Caen et al., 2004*). The main aim of this project is to associate the well located events with the hypothesized deep faults. For routine location in the broader region, the CRL uses the RM model. However, the RM model is unable to accentuate detailed features of the individual subregions of the broader area.

A sequence of smaller earthquakes occurred to the south of the town of Aigion in 2001 (Fig. 1). In the present paper, we shall use this sequence to derive a local model of the upper crust in the vicinity of Aigion by modifying the RM model. Thus, the new model will again be composed of the same number of homogeneous layers as the RM. We shall proceed in the following steps.

Table 1. Parameters of the initial structural model (RM) and of the final model for the Aigion region (AM): i is the sequential number of the layer, v_i is the *P*-wave velocity in km/s, and d_i is the layer thickness in km. The *P*- to *S*-wave velocity ratio is equal to 1.80 in all layers of model RM, but is equal to 1.83 in all layers of model AM. The standard deviations of the individual parameters of the AM model, estimated by delete-one jackknifing, are given in parentheses. The thickness of the fifth layer of model AM is taken so that the bottom of this layer is situated at the same depth as in model RM.

i	RM		AM	
	v_i	d_i	v_i	d_i
1	4.8	4.0	5.36 (0.18)	3.55 (0.07)
2	5.2	3.2	5.37 (0.02)	3.10 (0.07)
3	5.8	1.0	5.59 (0.05)	1.37 (0.21)
4	6.1	2.2	5.97 (0.08)	2.20
5	6.3	4.6	6.3	4.78
6	6.5	15.3	6.5	15.3

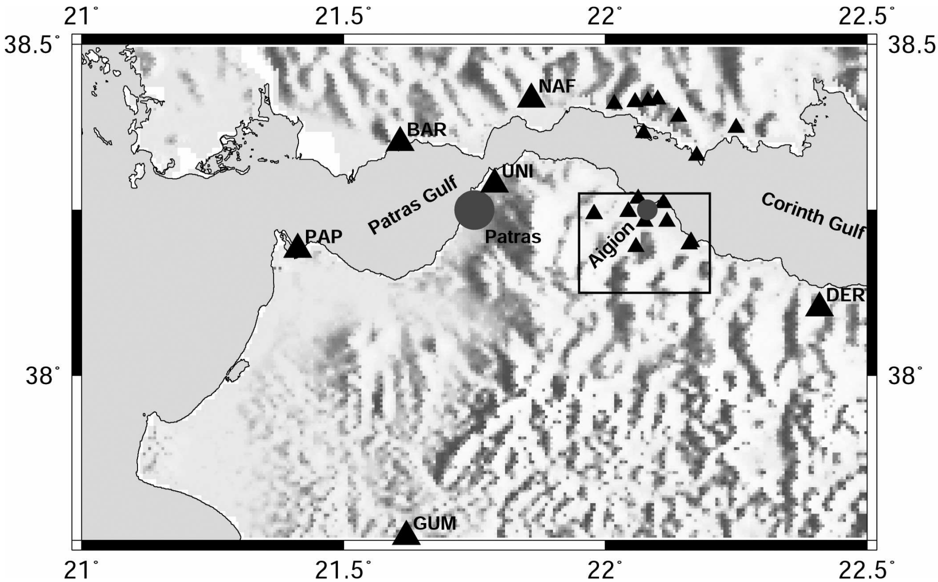

Fig. 1. Broader view of a part of the Gulf of Corinth with the area of interest delimited by the square. Positions of the CRL stations are shown as triangles, and the position of the nearest PATNET stations, up to a distance of 70 km from the town of Aigion (circle), are shown as larger triangles.

Firstly, in order to reduce the number of unknown structural parameters, we shall restrict ourselves to a model with a constant ratio of *P*- and *S*-wave velocities, v_P/v_S, in all layers. Note that model RM also belongs to this category of models. However, a new value of the ratio will be sought by the Wadati method (*Wadati, 1933*). Secondly, model RM will be used as the initial structural model, but a new mean value of v_P/v_S will be adopted for it. All earthquakes will be located in this model, using the HYPO program (*Lee and Valdés, 1989*). These locations will serve as the initial hypocentral parameters in the next step. Thirdly, an inversion of the arrival times will be performed for simultaneous estimation of a new structural model and new locations of earthquakes (e.g., *Crosson, 1976*). A variant of the method of conjugate gradients will be used for this purpose. Finally, the accuracy of the new structural model will be estimated using delete-one jackknifing (*Tichelaar and Ruff, 1989*).

2. DATA

The whole 2001 Aigion sequence was composed of many hundreds of events. In the first step, we selected from them a subset of 104 events, marked by circles in Fig. 2. These are all the events that were recorded by at least 5 stations of the southern part of the CRL network (CRLNET), had local magnitudes of over 2.3, and were recorded at the nearest station AIO. The northern stations of the network were not used in this study because we are interested only in the crustal structure of a local region near Aigion.

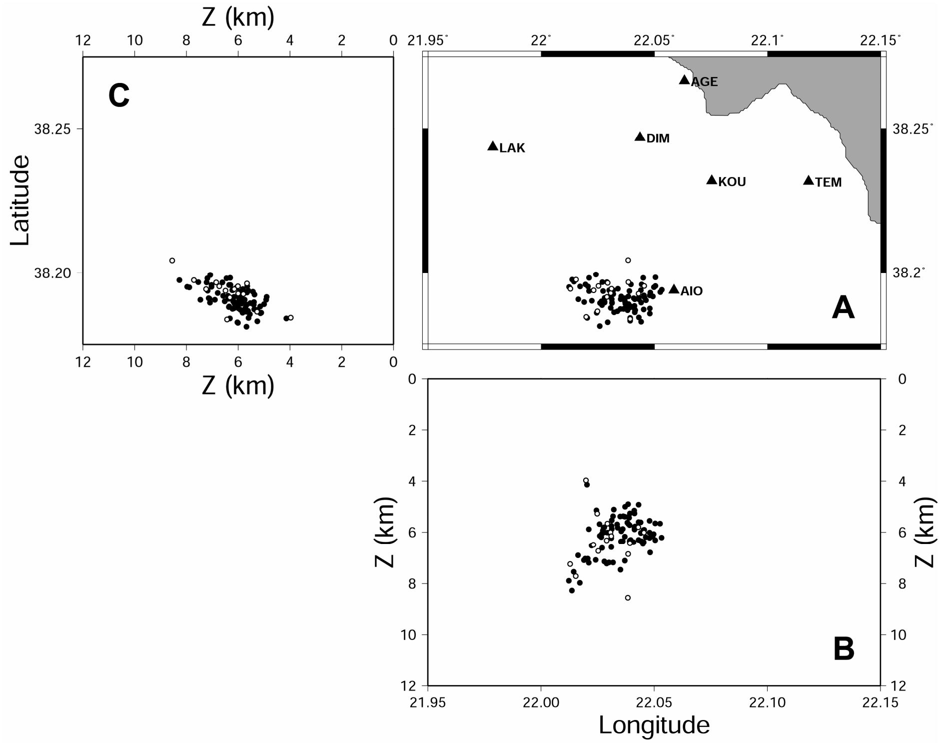

Fig. 2. Sequence of earthquakes that occurred in the region of Aigion in 2001: **A)** CRLNET stations used in this study (triangles) and the epicentres of the 104 stronger events (circles). The selected 88 events are shown as black circles. **B)** Projection of the hypocentres onto the longitude-depth plane. **C)** Projection of the hypocentres onto the latitude-depth plane.

In the present study, we have restricted ourselves only to records from the stations with codes AGE, AIO, DIM, KOU, LAK and TEM, since these stations recorded almost the entire earthquake sequence (Fig. 2). The other southern CRLNET stations recorded only a small portion of the sequence and, therefore, have not been used in this study.

The seismic stations considered were equipped with three-component digital short-period seismometers (*Lyon-Caen et al., 2004*). The sampling frequency was 125 Hz.

Figure 2 shows that the seismic stations used, with the exception of station AIO, are distributed mostly to the NE of the epicentral area. This distribution of seismic stations is not optimal for earthquake location and structure determination. The azimuthal gaps can amount to as much as 295° in the worst case. This disadvantage is only partially compensated by numerous readings of the *S*-wave onsets in our data set. There are no nearby stations situated to the SW that could record "Aigion" earthquakes and decrease the azimuthal gap. Note that the seismic activity in western Greece is monitored by the seismic network of the University of Patras (PATNET; see *http://geology.upatras.gr*), but the nearest stations of the PATNET in the SW direction from our sequence are too distant to be useful in our study (Fig. 1).

3. RATIO OF SEISMIC VELOCITIES DETERMINED BY THE WADATI METHOD

Let t_P and t_S be the arrival times of the *P*- and *S*-waves at a station, respectively. Assuming the ratio of the *P*- and *S*-wave velocities, v_P/v_S, to be constant, the Wadati method *(Wadati, 1933)* yields a linear relation between the time difference $t_S - t_P$ and the arrival time t_P. We computed this linear relation using the method of least squares, and determined the deviations for the individual seismic stations. Systematic deviations from the mean straight line were recognized for station DIM. Preliminary analysis indicated that this phenomenon could be associated with local geological conditions beneath the station that predominantly effected the *S*-wave arrivals. The solution to this problem is beyond the scope of this paper. Thus in the discussions that follow, we take into account only the t_P arrival times at the DIM station.

Some earthquakes were found to display considerable deviations from the linear Wadati relation, their *RMS* being larger than 0.10 s. By eliminating them from further considerations, our original subset of 104 events was reduced to 88 events (black circles in Fig. 2). Further in this paper we work only with this reduced subset of events. The v_P/v_S values for the individual earthquakes are shown in Fig. 3. The determination of the v_P/v_S values for all 88 events yielded a mean value of $v_P/v_S = 1.83$, with an *RMS* deviation of 0.04. This velocity ratio for the Aigion region is higher than the value of 1.80 for the broader region used in model RM.

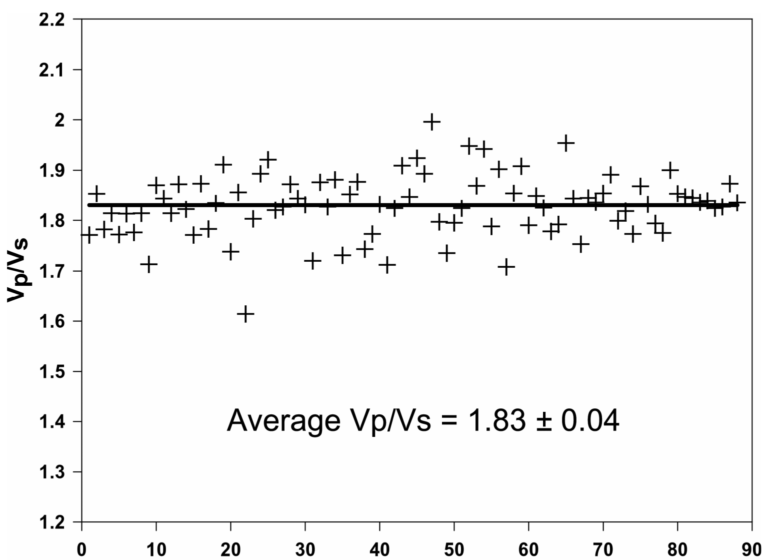

Fig. 3. The v_P/v_S ratios for the individual earthquakes obtained by the Wadati method.

Table 2. Number of Aigion events (total number is 88) recorded at the selected stations, and the corresponding sums of the total *P*- and *S*-wave weights.

Station	No. of Events	Sum of Weights	
		P Wave	*S* Wave
AIO	88	87.50	46.75
LAK	88	86.75	40.75
DIM	88	88.00	0.00
AGE	65	64.50	3.00
KOU	88	45.25	18.75
TEM	88	85.75	35.5

4. STANDARD RM MODEL AND HYPOCENTRAL PARAMETERS

Table 2 shows the number of records of the subset at the individual stations. Moreover, the table also contains the corresponding sums of weights of *P* and *S* onsets assigned to the records by the interpreter for the HYPO location procedure. The *S*-wave onset readings in our subset have, as a rule, lower weights as compared with the *P*-wave onsets, but are relatively numerous (owing to the three-component CRL stations).

The locations at the Corinth Rift Laboratory are routinely performed using the RM model and the HYPO algorithm. The upper part of model RM is shown in Fig. 4 as the thin solid line. The HYPO locations of our subset of 88 events in this model, using the standard v_P/v_S ratio of 1.80, are shown in Fig. 2 as black circles.

The hypocentres form a compact cluster that occupies a 2×4 km surface area and a depth range of 5 to 8 km. The average *RMS* of the arrival-time residuals equals 0.09 s. The average standard errors in the determination of the epicentre and depth are 0.59 km and 0.52 km, respectively (Table 3).

5. SEARCH FOR A NEW LAYERED MODEL USING THE METHOD OF CONJUGATE GRADIENTS

As the optimum 1-D model, we shall consider the model that yields the smallest sum of squares of the arrival-time residuals for all events and seismic stations (e.g., *Crosson, 1976*). Such model can be sought by various inverse techniques [e.g., genetic algorithms, the isometric inverse algorithm (*Málek et al., 2005*), the neighbourhood algorithm (*Sambridge, 1999*), methods of least squares, etc.].

The model search and locations in our study were performed by a generalised variant of the method of conjugate gradients. In computing the forward problem, only ray tracing had to be performed by a numerical method. The partial derivatives of the arrival times, which are needed in the gradient methods, were computed using analytical formulae. Their derivation followed the procedure in *Novotný (1980).* These analytical formulae guarantee high speed and accuracy in computing the required derivatives.

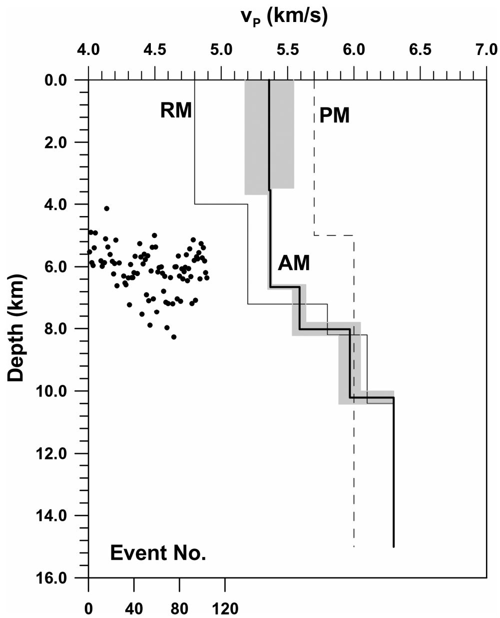

Fig. 4. *P*-wave velocity cross-sections: RM is the upper part of the model of *Rigo et al. (1996)*; AM is the local model found for the area of Aigion; PM is the upper part of the model used for earthquake location in western Greece by the PATNET. The shaded zone gives the standard deviations of the AM model obtained by delete-one jackknifing. The group of dots represents the depth distribution of the 88 hypocentres (the corresponding horizontal coordinates represent the sequential numbers of earthquakes).

Table 3. Average RMS of the time residuals, average standard errors in epicentre (ERH) and in depth (ERZ) for the 88 events located by the HYPO code for models RM and AM, respectively.

Model	RMS [s]	ERH [km]	ERZ [km]
RM	0.09	0.59	0.52
AM	0.07	0.55	0.47

Gradient methods are computationally fast, but require initial (starting) values of the parameters to be specified. As the initial model of the medium, we take the v_P velocities from the RM model, but with $v_P/v_S = 1.83$. As the initial hypocentral parameters (the coordinates and origin time), we have used locations obtained by the HYPO code in the RM model. Since all the events were shallow, we have restricted ourselves to the four upper layers of the RM model. In the inversion, we thus seek 8 structural parameters (the thicknesses and *P*-wave velocities of the four layers) and 352 hypocentral parameters of the 88 hypocentres.

In addition to the initial hypocentral and structural parameters, our generalisation of the method of conjugate gradients also requires the relative weights of the corresponding partial derivatives to be specified. On the basis of preliminary tests, we chose these weights as follows: 1.0 for each derivative of the hypocentral coordinates, 0.1 for the derivative of the hypocentral origin time, 0.8 for the derivatives of the layer thicknesses and 0.2 for the velocities. Note that the values of these parameters usually influence the speed of the iterative process, but do not change the final model significantly.

6. DISCUSSION AND CONCLUSIONS

First, we performed the inversion using all stations. The model obtained, which we shall denote as AM (Aigion model), is shown in Fig. 4 as the bold solid line. We see higher velocities in this model in comparison with model RM down to a depth of about 7 km (i.e. in the first and second layers).

The cluster of 88 hypocentres located by the HYPO in model AM (not shown) is shifted on average to shallower depths (by 0.43 km), to the west (0.13 km) and to the north (0.23 km), as compared with the same cluster located using the RM model. The difference in location of the individual events is more pronounced. It can reach up to 1.63 km in epicentre and 1.03 km in depth. The new locations are not significantly more clustered, the average deviation from the cluster centre being in both cases of about 0.86 km, 1.10 km and 0.56 km in depth, EW direction and NS direction, respectively.

The average *RMS* in time residuals, the average standard errors in epicentre and in depth for both these locations are given in Table 3. We have obtained slightly smaller error values for model AM. For example, the average *RMS* in time residuals for model RM is 0.09 s and was reduced to 0.07 s for model AM.

In order to estimate the model uncertainty bounds, we applied delete-one jackknifing (*Tichelaar and Ruff, 1989*) by repeating the inversion six times, omitting one of the recording stations each time. The standard deviations for the individual model parameters of the AM model obtained in this manner are graphically shown in Fig. 4 as the shaded area. Their numerical values are given in Table 1 by the numbers in parentheses. The standard deviations of the AM velocities in the individual layers are strongly connected to the number of hypocentres situated in these layers. In particular, the largest standard deviation is for the first layer, which is without hypocentres, and the smallest deviation is for the second layer, containing the majority of hypocentres. The reduced model resolution for the layer without hypocentres also agrees with some synthetic tests that show how the model resolution depends on the depth distribution of events (e.g., *Crosson, 1976*; *Janský et al., 2007*).

The AM and RM models differ in shallow depths, but are almost identical below a depth of 5 – 6 km. This indicates differences between the local structure of the Aigion area and the average regional structure represented by the RM model. Note also the negligible velocity contrast between the first and second layers of model AM.

The velocity of about 5.4 km/s in the first two layers of model AM is higher than the corresponding velocities of 4.8 km/s and 5.2 km/s in model RM. Nevertheless, the velocity of 5.4 km/s is still lower than the value of 5.7 km/s down to a depth of 5 km in the crustal model PM, which is routinely used in locating earthquakes in western Greece by the PATNET (Fig. 4).

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