Δελτίο Ελληνικής Γεωλογικής Εταιρίας τομ. XXX/5, 189-196, 1994
Πρακτικά 7ου Επιστημονικού Συνεδρίου, Θεσσαλονίκη, Μάιος 1994
Bulletin of the Geological Society of Greece vol. XXX/5, 189-196, 1994
Proceedings of the 7th Congress, Thessaloniki, May 1994

SHEAR WAVE VELOCITY MODELS FROM RAYLEIGH WAVE DISPERSION IN THE NORTHERN AEGEAN

I. Kalogeras* and P. Burton**

ABSTRACT

Rayleigh wave records generated by earthquakes at Chalkidiki (Greece) and Saros gulf (NE Aegean) and recorded at the Athens long period seismograph (ATH), were analyzed digitally to obtain group velocity dispersion curves, corresponding to two discrete propagation paths. Furthermore, these dispersion curves were inverted using the Hedgehog technique in order to determine shear wave velocity-depth models along the propagation paths which descraibe the structure of the crust and upper mantle of the northern Aegean. The shear wave velocity inversion profiles are reasonably constant for both propagation paths, although that for the Saros gulf to Athens is the better resolved and more stable. There is only slight evidence found for the onset of a sub-crustal zone of low shear wave velocity in the upper mantle.

ΣΥΝΟΨΗ

Εγγραφές κυμάτων Rayleigh από σεισμούς της Χαλκιδικής και του Κόλπου Σάρου, που εγγράφησαν από τον σεισμογράφο μακράς περιόδου της Αθήνας (ATH), αναλύονται ψηφιακά για να υπολογιστούν οι καμπύλες σκέδασης για δύο διαφορετικές διαδρομές διάδοσης. Ακολούθως, στις καμπύλες σκέδασης εφαρμόζεται η τεχνική Hedgehog της αντιστροφής για να προσδιοριστούν μοντέλα μεταβολής της ταχύτητας των εγκαρσίων κυμάτων σε συνάρτηση με το βάθος για τις εξεταζόμενες διαδρομές. Τα μοντέλα αυτά περιγράφουν τη δομή του φλοιού και του πάνω μανδύα του βόρειου Αιγαίου. Η δομή παρουσιάζεται περίπου όμοια και στις δυο διαδρομές διάδοσης, αν και η διαδρομή κόλπος Σάρου - Αθήνας δείχνει καλύτερη επίλυση. Επίσης βρέθηκαν ενδείξεις για την ύπαρξη ζώνης χαμηλής ταχύτητας στον ανώτερο μανδύα.

INTRODUCTION

The seismic surface waves generated by earthquakes or blasts, show dispersion along the propagation path, this means that the velocity by which the energy is propagated, i.e. the group velocity, varies as a function of frequency.

The estimation of the relationship between group velocity and frequency is of great importance because from this relationship the determination of the variations of the body wave velocity as a function of depth along the propagation path is possible.

The structure of the broader area of the Aegean and eastern Mediterranean has been investigated by previous authors using various methods and tech-

* National Observatory of Athens, Seismological Institute, P.O.Box 20048, 118 10 Athens, Greece.
** University of East Anglia, School of Environmental Sciences, Norwich NR4 7TJ, U.K.

niques. Some of the first investigations of the velocity structure were based on surface wave dispersion and the conclusions can be summarized as follows. Papazachos et al. (1967) and Papazachos (1969) concluded that the mean thickness of the crust of the area varies between 35 and 45 km. Payo (1967, 1969) characterized the Aegean as an area of continental crust which is covered by a rather thick sedimentary layer. Calcagnile et al. (1982) proposed further research for the determination of a crust-mantle transition zone in the Aegean, the existance of which they accepted in other areas of the eastern Mediterranean. Ezen (1983, 1991a,b) studied the influence of crustal thickness on Rayleigh wave records and proposed a P-wave velocity model for western Turkey. Kalogeras et al. (1992) determined the mean dispersion curve for a Dodecanese - ATH propagation path and concluded that the continental structure of the SE Aegean shows, at its deepest parts, a possible contamination by oceanic material.

The recent studies on geodynamic processes in the Aegean area (e.g. Makropoulos & Burton, 1984; Ligdas et al, 1990; Christova & Nikolova, 1993; Hatzfeld et al., 1993) show that the Hellenic arc and the adjacent areas are tectonically more complicated than had previously been thought, and it should be emphasized that there is no generally accepted single geotectonic model which gives explanation for all of the geological and geophysical observations.

The purpose of this study is to obtain a shear wave velocity-depth structure for the northern Aegean by applying an inversion technique to measurements of Rayleigh wave dispersion.

DATA AND ANALYSIS

Twelve records of Rayleigh waves generated by five earthquakes at Chalkidiki peninsula and seven earthquakes at Saros gulf, all recorded by the long period vertical component of the WWSSN station at Athens (ATH), were used in this study. These two groups of earthquakes represent two discrete propagation paths crossing the northern Aegean. Table I gives the source parameters of the earthquakes as taken from the I.S.C. monthly bulletins and Figure 1 shows the epicenters of the earthquakes and the propagation paths to ATH.

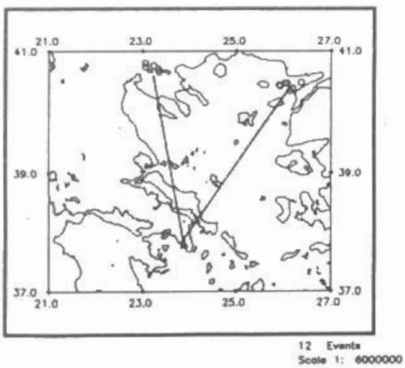

Fig. 1: Map of epicenters of the earthquakes and the Rayleigh wave propagation paths, which were used in this study.

Σχ. 1: Χάρτης επικέντρων των σεισμών και οι διαδρομές διάδοσης των κυμάτων Rayleigh, που χρησιμοποιήθηκαν στην παρούσα μελέτη.

The records have been chosen so that they show high signal-to-noise ratio. They were digitized manually at unequal time intervals, taking the first noticeable onset of the record as the first point of digitization. Linear interpolation and baseline correction were then applied in order to obtain signals digitized at a rate of two samples per second. This determines a Nyquist frequency of $f_N = 1$ Hz.

The digitized seismograms are transformed into the frequency domain using the Fast Fourier Transform algorithm of Cooley and Tukey (1965) and the spectra obtained corrected for the instrument response using the Espinosa et al. (1965) technique. According to this technique the instrument parameters are determined from

Table I: The parameters of the earthquakes, which were used in this study. (Source: I.S.C. bulletins)

Πίν. I: Οι παράμετροι των σεισμών οι εγγραφές των οποίων χρησιμοποιήθηκαν στην παρούσα μελέτη.

DATE	ORIGIN TIME	GEOGRAPHICAL COORDINATES		FOCAL DEPTH	EPICENTRAL DISTANCE	MAGNITUDE M_S
		φ°	λ°	km	d°	
24/08/65	23:57:35.4	40.39	26.20	18	3.09	4.2
28/09/68	00:53:28.0	40.49	26.38	28	3.26	4.4
16/03/75	08:37:16.3	40.36	26.14	5	3.04	4.3
17/03/75	02:06:39.1	40.48	26.03	2	3.08	4.5
27/03/75	19:42:42.5	40.48	26.08	5	3.11	4.5
24/05/78	02 12 28.1	40.71	23.34	8	2.75	4.8
19/06/78	10:31:05.5	40.71	23.24	10	2.82	5.3
21/06/78	12:29:43.1	40.81	23.06	1	2.88	4.8
04/07/78	22:23:28.4	40.75	23.06	18	2.82	5.0
19/02/84	03:47:22.5	40.67	23.36	24	2.70	4.9
29/07/84	01:58:43.3	40.45	25.91	21	3.00	5.0
29/07/84	09:48:23.8	40.43	25.93	27	2.99	4.5

measurements taken from each record calibration pulse. Frequency harmonics extracted from the record are then determined at

$$f_j = jf_o$$

where fo is the fundamental harmonic and j=1,2,... As a prerequisite of the Fourier algorithm, the 250 points time series of a typical 2 minutes long record was increased to 2^{10} points. This means that the resulting digital record and its spectrum have four times more frequency points or harmonics than are required to uniquely determine it. For this reason, a smoothing factor of four is applied to decrease the spectral density. The new frequency values generated by this smoothing still correspond precisely to original Fourier harmonics, which are

$$4f_o,\ 8fo,\ ...,\ f_N$$

The fundamental harmonic fo is

$$f_o = f_N / 2^{10} = 0.001953 \text{ Hz}$$

These frequency values, after cosine tapering of each signal at both ends, correspond to 15 independent values of group velocity at a fixed set of frequencies for all seismograms analysed.

The signals were analyzed to obtain group velocity using the multiple filter technique of Dziewonski et al. (1969) as modified by Burton and Blamey (1972). The filters used (Gauss function) were of constant resolution. Estimation of the group velocities for the same set of Fourier harmonics for all the records allows the dispersion data to be averaged simply for each propagation path. Figure 2 shows the two mean dispersion curves for the two propagation paths, namely Chalkidiki to ATH and Saros gulf to ATH respectively. The estimated values of group velocity have been presented with 99.5% confidence intervals.

The two dispersion curves are characterized by different mean values of group velocity for the range of lower frequencies, which correspond to

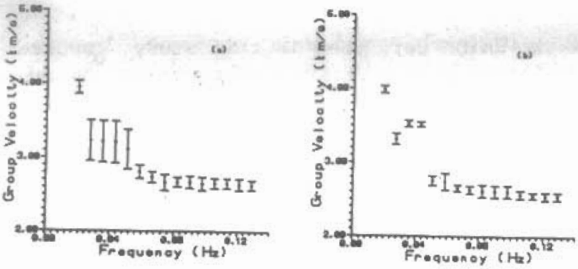

Fig. 2: Mean dispersion curves along the paths Chalkidiki-ATH (a) and Saros gulf-ATH (b) with corresponding 99.5% confidence intervals for each value of group velocity.

Σχ. 2: Οι μέσες καμπύλες σκέδασης για τις διαδρομές Χαλκιδική-ATH (α) και κόλπος Σάρου-ATH (β), με τα αντίστοιχα 99.5% διαστήματα εμπιστοσύνης για κάθε τιμή ταχύτητας ομάδας.

penetration into deeper parts of the lithosphere (about 40 - 60 km). These differences are not significant when the estimetes of uncertainty on the group velocities, particularly for the Chalkidiki to Athens path, are taken into account. However, these uncertainties may observe complexities of deeper structure which cannot be resolved by the present data.

INVERSION OF GROUP VELOCITY DATA

The two average dispersion curves are used to estimate the average distribution of the shear wave velocity with depth along each propagation path. The group velocity values are inverted using the Hedgehog inversion technique which is an improvement of the Monte-Carlo technique, as far as it tries to produce a connected region of acceptable solutions. The Hedgehog technique was developed by Keilis-Borok and Yanovskaja (1967) and Valyus (1972). Knopoff (1972) and Biswas and Knopoff (1974) have applied it to surface wave dispersion data.

For application of the technique it is necessary to parameterize the earth structure. The number of parameters specifying a structure which is described by a finite number of layers overlying a half-space are reduced by adopting relationships between the compressional wave velocity á and the shear wave velocity â and the density ñ. For this reason we set the Poisson ratio ó equal to 0.28 (this value has been proposed by Delibasis, 1982, for the northern Aegean), which gives a relation á = 1.81â. Furthermore we adopt the relationship (Stuart, 1978)

$$\rho = 0.286\ \beta + 1.736$$

The algorithm searches for the points in the parameter space which are successful, i.e. the quantities

$$\left|\frac{U_i - U_{oi}}{\Delta U_{oi}}\right| < a \quad , \qquad \sqrt{\frac{1}{M}\sum_{i=1}^{M}\left(\frac{U_i - U_{oi}}{\Delta U_{oi}}\right)^2} < \sigma$$

for M values of frequency are within the appropriate precision levels. In these quantities, Uoi and Ui are the observed and the theoretical Rayleigh wave group velocity values respectively and ΔUoi is the standard error on the observed values of Uoi.

The Hedgehog nets for each of the propagation paths have been set up taking into account the velocity model proposed by Panagiotopoulos (1984) for the Aegean. This model assumed a crust of two layers (with thicknesses of 18.5 km and 12.5 km) overlaying the mantle. For the purpose of this study this model is modified as follows: the upper layer is devided into two layers of 7.0 km and 11.5 km, which are followed downwards by the layer of 12.5 km plus two more layers of 14.0 and 15.0 km overlaying the half-space. The depth of 60 km, to the upper surface of the half-space, has been selected taking into account Knopoff's relationship (1972):

$$pd = 0.4\ \lambda = 0.4U\ /\ f$$

where pd (in km) is the effective maximum penetration depth of the Rayleigh wave for which the shear wave velocity results are reliable, ë (in km) is the wave length, U (in km/s) is the group velocity and f (in Hz) is the frequency. According to this relationship, our dispersion data give a maximum penetration depth of the order of 80 km for reliable results.

REGION OF SEARCH:

H	LIMIT1	LIMIT2	STEP
7.0	2.60	4.60	0.40
11.5	2.60	5.00	0.40
12.5	3.00	5.40	0.40
14.0	3.20	5.60	0.60
15.0	3.40	6.00	0.60
10.0	3.60	6.00	0.60

HEDGEHOG SOLUTION:

H	LIMIT1	LIMIT2
7.00	3.00	3.00
11.5	3.40	3.40
12.5	3.40	5.00
14.0	3.80	5.00
15.0	4.00	5.80
10.0	3.60	5.40

REGION OF SEARCH:

H	LIMIT1	LIMIT2	STEP
7.0	2.60	4.60	0.40
11.5	2.60	5.00	0.40
12.5	3.00	5.40	0.40
14.0	3.20	5.60	0.60
15.0	3.40	6.00	0.60
10.0	3.60	6.00	0.60

HEDGEHOG SOLUTION:

H	LIMIT1	LIMIT2
7.00	2.60	3.00
11.5	3.40	3.80
12.5	3.80	4.20
14.0	4.40	5.00
15.0	4.00	5.20
10.0	4.20	4.80

Fig. 3: Shear wave velocity - depth profile along the propagation paths Chalkidiki-ATH (left) and Saros gulf - ATH (right) obtained by Hedgehog inversion of the dispersion curves of Fig. 2. The continuous line indicates the region of search and the dashed lines and shaded regions indicate the Hedgehog solutions.

Σχ. 3: Το μοντέλο μεταβολής ταχύτητας εγκαρσίων κυμάτων με το βάθος για τις διαδρομές Χαλκιδική-ΑΤΗ (αριστερά) και κόλπος Σάρου - ΑΤΗ (δεξιά) όπως προκύπτουν από την αντιστροφή Hedgehog των καμπύλων σκέδασης του Σχ. 2. Οι συνεχείς γραμμές ορίζουν την περιοχή αναζήτησης και οι διακεκομένες γραμμές και οι γραμμοσκιασμένες περιοχές ορίζουν τις λύσεις Hedgehog.

RESULTS AND DISCUSSION

Figure 3 shows the shear wave velocity-depth profiles obtained for the propagation paths Chalkidiki - ATH (left) and Saros gulf - ATH (right). The upper layer for both propagation paths is characterized by a rather low shear wave velocity (no more than 3.0 km/s), which could be assigned to the thick sediments (3-6 km) which fill the basins of the northern Aegean (Lalechos & Savoyat, 1977). A generalized map of the eastern Mediterranean compiled by Christova & Nikolova (1993), in which the surface heat flow extremes and relative velocity anomalies are shown, indicates that the western northern Aegean area is characterized by low velocities. There is an increase in shear wave velocity from the first to the second layer from the most 3.0 km/s in layer one to at least 3.4 km/s in layer two, which is clear in both velocity - depth inversion profiles. The velocity in this second layer (in the range of 3.4 - 3.8 km/s) is higher than the typical velocity of a "granitic" material. There may be two explanations for this.

Firstly, the "granitic" layer may be thinner than was previously assumed and the "basaltic" layer may start closer to the surface. Secondly, according to Kiriakidis (1988), ophiolitic bodies exist in the crust of the northern Aegean and these could increase the mean velocity along the propagation paths.

A significant increase in the shear wave velocity is observed with the transition from layer three to layer four at around 31 km depth. This is particularly clear in the Saros gulf - ATH inversion. Previous studies (Makris, 1973; Kiriakidis, 1984; Brooks & Kiriakidis, 1986; Kiriakidis, 1988) assumed that the crustal thickness in the northern Aegean varies between 26 and 30 km. This noticeable increase in shear wave velocity is attributed to transition from crust to mantle.

The mean shear wave velocity in layers four, five and six for depths greater than 31 km along the path Saros gulf - ATH remains almost constant, around 4.6 km/s. On average, could slight evidence of a decrease with depth from about 4.7 to 4.5 km/s. These values, and the ranges within individual layers, are consistently within the enveloping range of the Chalkidiki - ATH inversion, which is less well resolved at these depths due to the relatively large uncertainty in the frequency range (0.028 - 0.052 Hz) of group velocities. Papazachos (1969) also found a shear velocity of 4.5km/s at depths greater than 35 km and assumed a low velocity zone within the upper mantle along the path Instabul - ATH in order to explain the observation that the velocity remains constant for periods larger than 35 s. However, we found no noticeable evidence for the existence of a low shear wave velocity layer at depths shallower than 45 km although there is some consistent evidence in both inversions of reduction in shear wave velocity at greater depths.

It is apparent from these observations that the inversion of the dispersion curves of Rayleigh wave records contributes to knowledge of the structure of the crust and upper mantle. This can be further enhanced by results obtained from other methods (e.g. geophysical methods, P-wave arrival times, etc.). Although the use of one station methods has some inherent uncertainty, this can be reduced by both the good quality and high quantity of the available data. The long period standard seismograph of the ATH station fulfils these prerequisites.

REFERENCES

BISWAS, N.N and KNOPOFF, L. (1974). The structure of the upper mantle under the United States from the dispersion of Rayleigh waves. *Geophys. J. R. astr. Soc., 36, 515-539.*

BROOKS, M. and KIRIAKIDIS, L. (1986). The north Aegean trough subsidence: an alternative view. *J. Geol. Soc. Lon., 146, 23-27.*

BURTON, P.W. and BLAMEY, C. (1972). A computer program to determine the spectrum and a dispersion characteristic of a transient signal. *HMSO AWRE Report No. 0-48/72.*

CALCAGNILE, G., D'INGEO, F., FARRUGIA, P. and PANZA, G.F. (1982). The lithosphere in the central - eastern Mediterranean area. *Pure appl. Geophys., 120, 389-406.*

CHRISTOVA, C. and NIKOLOVA, S.B. (1993). The Aegean region: deep structures and seismological properties. *Geophys. J. Intern., 115, 635-653.*

COOLEY, J.W. and TUKEY, J.W. (1965). An algorithm for the machine calculation of complex Fourier series. *Maths Comput., 19, 297-301.*

DELIBASIS, N.D. (1982). Seismic wave attenuation in the upper mantle beneath the Aegean region. *Pure appl. Geophys., 120, 820-839.*

DZIEWONSKI, A., BLOCH, S. and LANDISMAN, M. (1969). A technique for the analysis of transient seismic signals. *Bull. Seism. soc. Am., 59, 427-444.*

ESPINOSA, A.F., SUTTON, G.H. and MILLER, H.J. (1962). A transient technique for seismograph calibration. *Bull. Seism. soc. Am., 52, 767-779.*

EZEN, U. (1983). An interference phenomenon in Rayleigh wave trains associated with the earthquakes in and around the Aegean Sea. *Bull. Intern. Inst. Seism. Earthq. Engin., 20, 33-62.*

EZEN, U. (1991a). Crustal structure of western Turkey from Rayleigh wave dispersion. *Bull. Intern. Inst. Seism. Earthq. Engin., 25, 1-21.*

EZEN, U. (1991b). Surface wave dispersion and upper crustal structure along N-S direction in western Turkey from Burdur earthquake of 12 May 1971. *Bull. Intern. Inst. Seism. Earthq. Engin., 25, 39-59.*

HATZFELD, D., BESNARD, K., MAKROPOULOS, K. and HATZIDIMITRIOU, P. (1993). Microearthquake seismicity and fault-plane solutions in the southern Aegean and its geodynamic implications. *Geophys. J. Intern., 115, 799-818.*

KALOGERAS, I.S., DRAKOPOULOS, J.K and BURTON, P.W. (1992). Dispersion curves for the path Dodecanese islands - ATH as inferred from the analysis of the Rayleigh wave records. *Proc. 6th Congress of the Geol. Soc Greece, Athens, 25-27 May (in Greek).*

KEILIS-BOROK, V.I. and YANOVSKAJA, T.B. (1967). Inverse problems of seismology (structural review). *Geophys. J. R. astr. Soc., 13, 223-234.*

KIRIAKIDIS, L.G. (1984). Geophysical studies of the eastern margin of the Vardar zone in Central Macedonia, Greece. *Ph.D. thesis, University of Wales, pp.372.*

KIRIAKIDIS, L.G. (1988). The structure of the crust in northern Greece. *Proceed. of the 1st Symposium "On the new evolutions on Seismology and Geophysics in Greece", 1-3 July, Thessaloniki, Greece, (in Greek).*

KNOPOFF, L. (1972). Observation and inversion of surface wave dispersion. In: *A.R. Ritsema (edit.), The upper mantle, Tectonophysics, 13 (1-4), 497-519.*

LALECHOS, N. and SAVOYAT, E. (1977). La sedimentation Neogene das le Fosse Nord-Egeen. *Proc. 6the Coll. on the geology of the Aegean region, I.G.M.E., Athens, 591-603.*

LIGDAS, C.N, MAIN, I.G. and ADAMS, R.D. (1990). 3-D structure of the lithosphere in the Aegean region. *Geophys. J. Int., 102, 219-229.*

MAKRIS, J. (1973). Some geophysical aspects of the evolution of the Hellenides. *Bull. Geol. Soc. Greece, 10, 206-213.*

MAKROPOULOS, K.S. and BURTON, P.W. (1984). Greek tectonics and seismicity. *Tectonophysics, 106, 275-304.*

PANAGIOTOPOULOS, D.G. (1984). Travel time curves and crustal structure in the southern Balkan region. *Ph.D. Thesis, Univ of Thessaloniki, pp.173, (in Greek).*

PAPAZACHOS, B.C. (1969). Phase velocities of Rayleigh waves in southeastern Europe and east Mediterranean sea. *Pure appl. Geophys., 75, 47-55.*

PAPAZACHOS, B., POLATOU, M. and MANDALOS, N. (1967). Dispersion of surface waves recorded in Athens. *Pure appl. Geophys., 67, 95-106.*

PAYO, G. (1967). Crustal structure of the Mediterranean Sea by surface waves. *Bull. Seism. soc. Am., 57, 151-172.*

PAYO, G. (1969). Crustal structure of the Mediterranean Sea by surface waves. Part II: Phase velocity ant travel times. *Bull. Seism. soc. Am., 57, 151-172.*

STUART, G.W. (1978). The upper mantle structure of the North Sea region from Rayleigh wave dispersion. *Geophys. J. R. astr. Soc., 52, 367-382.*

VALYUS, V.P. (1972). Determining seismic profiles from a set of observations. In: *Methods in Computational Seismology. Edit. Keilis-Borok, 114-118.*