revista mexicana de física 27 no. 2 (1981) 129-142

AN IMPROVED DETERMINATION OF THE THICKNESS OF THE SEDIMENTARY LAYER OF THE SONORAN EMBAYMENT

Javier A. Aldaz, Robert G. McIntyre, and H. S. Slusher

Physics Department,
The University of Texas at El Paso
El Paso, Texas 79968

and

Universidad Autónoma de Cd. Juárez

(recibido 25 de marzo, 1980)

ABSTRACT

Earthquakes from the Gulf of California to El Paso, Texas-Juárez, México were analyzed to give a more definitive estimate of the thickness of México's Sonoran Embayment. Subtracting the data filtered by a long Parzen window from the raw data (corrected to time of transit of the embayment) yields a zero mean stochastic process. Using multiple selective filtering a composite seismogram was obtained which was then analyzed by both Savarensky's method and by Fourier spectral analysis (after the

traditional and highly questionable normalization of the variance to produce an essentially stationary process). Identical estimates of a uniform thickness of about 2.5 ± 0.5 km were obtained from the two methods with a greater probability for the lower estimate.

RESUMEN

Siete sismogramas de terremotos originados en el Golfo de California y observados en El Paso, Texas - Juárez, México, fueron analizados para estimar definitivamente el espesor de la capa de Sonora. Los datos fueron filtrados con el filtro Parzen de larga apertura y posteriormente fueron substraidos de los datos originales (corregidos con respecto al tiempo de transmisión por la capa sonorense) para obtener un proceso aleatorio de promedio cero. Aplicando filtración múltiple selectiva se construyó un sismograma compuesto, el cual fue analizado por el método de Savarensky y el método espectral del análisis de Fourier. Ambos métodos resultaron en estimaciones idénticas para el espesor uniforme, de aproximadamente 2.5 ± 0.5 Km. con mayor probabilidad el menor valor estimado.

INTRODUCCION

The objective of this study was to try to make more definite the estimate of the thickness of the sedimentary layer of the Sonoran Embayment, using the seismic recordings of seven earthquakes in the Gulf of California by means of group-velocity dispersion of Rayleigh waves.

Oliver and Ewing[1] demonstrated that sedimentary layers have a strong effect on the velocity of Rayleigh waves with periods less than 20 seconds. Shurbet[2] first used Rayleigh-wave propagation from the Gulf of California to Lubbock, Texas to estimate the thickness of the sedimentary rocks of the Sonoran Embayment based on a method developed by Ewing and Press[3]. His estimate of eight kilometers is far too high mainly because of the method used but also because the waves suffered considerable dispersion in the path from the eastern edge of the Sonoran Embayment to Lubbock, Texas. Also for this segment of the path he had to make an unconfirmed estimate for the velocities of the waves, which could result in incorrect travel times throughout the Sonoran Embayment, leading to errors in the corresponding group-velocity estimates.

Wilhelm[4] arrived at an estimate of six kilometers for the sedimentary thickness of the Sonoran Embayment using both Savarensky's method and Fourier Spectral Analysis. This estimate was too high for several reasons, however, a principal reason being faulty estimates of the wave velocities in the Gulf of California and the Sierra Madre Occidental leading to errors in group velocity estimates in the Sonoran Embayment.

Wilhelm, McIntyre and Slusher[5] corrected the estimates of velocities of the waves in the Gulf of California and Sierra Madre Occidental by a study of one pair of co-linear events using a cross-covariance analysis. Their estimates of two to four kilometers with unsureness on the high limit are found to be good ball-park figures.

THE DATA

The events studied in this work were recorded at the John W. Kidd Memorial Seismological Observatory of The University of Texas at El Paso during the year 1964. The records were taken by a continuous Benioff vertical-component seismometer with a period $T_0 = 1$ second and recorded with a galvanometer with a period $T_g = 15$ seconds.

Seven earthquakes were found with normal depths, their locations are shown in Fig. 1. Table I gives pertinent information about the events as extracted from pamphlets of The United States Coast and Geodetic Service. The records of these earthquakes appear much weaker than those studied by Wilhelm, McIntyre and Slusher[5] and were, in fact, rejected by them as not being strong enough for analysis. The objective in this work was really two-fold. First, a study was made to show that with such weak signals useful results could be obtained. Secondly, a successful effort is made to extract information from the data and use it to make more definitive the estimate of Wilhelm, McIntyre and Slusher[5] of the thickness of the sedimentary layer of the Sonoran Embayment.

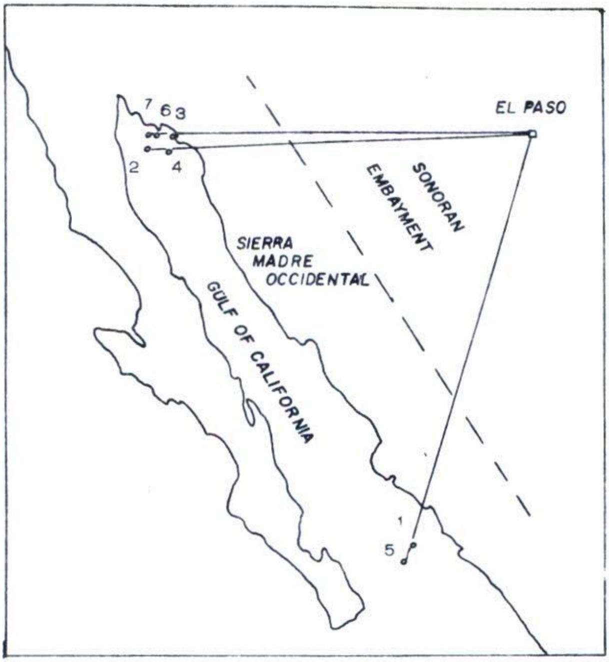
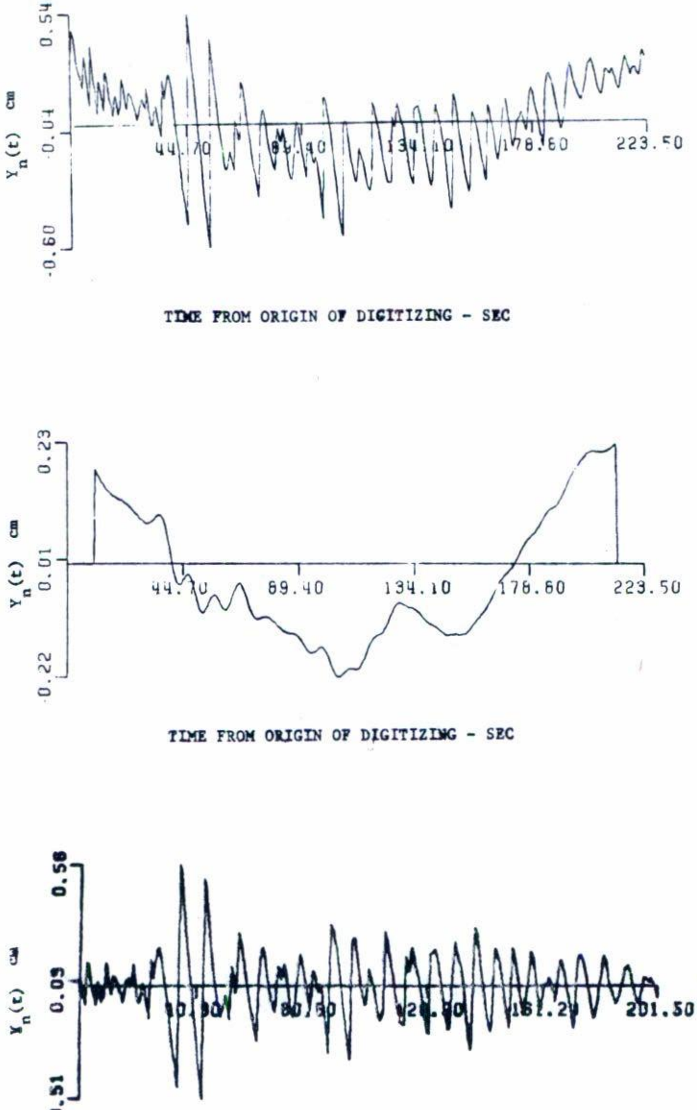


Fig.1 Map with location of epicenters and wave paths to El Paso.

TABLE I

U.S. Coast and Geodetic Survey information on earthquakes and on distances through major geological surface features from the Gulf of California to El Paso, Texas - Juarez, Chihuahua, Mexico.

Earthquake	Date	Time at Origin	Epicenter		Magnitude	Depth	Estimated Distance Through		
Number	D - M - Y	H - M - S	N°	W°		(KM)	Gulf of Calif.	Sierra Madre	Sonoran Embayment
1	30-01-64	05 39 44.6	24.5	108.6	4.5	49	80	270	530
2	04-02-64	05 40 23.3	31.1	114.3	4.5	14	110	165	475
3	16-04-64	07 03 34.0	31.3	113.7	4.6	33	0	210	480
4	16-04-64	09 18 12.0	31.1	113.8	4.3	29	65	165	475
5	04-09-64	09 50 06.6	24.2	108.6	4.7	33	115	215	530
6	03-02-64	09 15 42.0	31.3	114.2	---	14	35	220	480
7	03-02-64	13 51 07.4	31.3	114.3	4.2	14	60	210	480



2a

2b

2c

Fig.2 Earthquake number five showing:
(a) digitized seismogram
(b) filtered seismogram with Parzen filter length P = 45
(c) reduced seismogram.

DIGITAL REDUCTION OF DATA

The records of the events are optical tracings on photographic paper where along the time axis 1 mm = 2 seconds. An x-y reading traveling microscope was assembled reading to within .01 mm along both x and y axes. For earthquake No.5, Fig. 2 a-c shows (a) the raw digitized data, (b) the filtered seismogram using a Parzen filter (P = 45) and (c) the reduced seismogram derived from subtracting (b) from (a). The sampling interval, Δt, is 1/2 second giving a Nyquist frequency of one cycle per second, well beyond the frequency limit of Rayleigh waves capable of propagating long distances.

In making a preliminary inspection of the data, one sees that there is a need to massage the data to more closely meet the criteria of a stationary process, i.e. that it has a zero mean independent of time and that the variance be constant. Wilhelm[4] did not concern himself sufficiently with the former of these two criteria. He merely averaged the data and subtracted this value from each data point.

A great deal of literature exists on removing "trends" in data with probably very insignificant differences in their value in most cases. A very simple procedure was used in this work which did effectively remove trends and as well filtered out extremely long period (greater than 20 seconds) waves having essentially no relationship to the parameters of interest in the sedimentary rocks of the Sonoran Embayment. The filter used in this work is the Parzen filter of length 45 data points

$$w(\mu) = \begin{cases} 1 - 6\left(\dfrac{\mu}{M}\right)^2 + 6\left(\dfrac{|\mu|}{M}\right)^3, & |\mu| \leq \dfrac{M}{2} \\[2ex] 2\left(1 - \dfrac{|\mu|}{M}\right)^3, & \dfrac{M}{2} < |\mu| < M \\[2ex] 0, \quad |\mu| > M, & \end{cases}$$

which for a given value of M the smoothed data is the time series

$$Y_n' = \sum_{\mu=-M}^{M} Y_{n+\mu}(t)w(\mu) ,$$

as taken from Jenkins and Watts[6].

The problem of normalizing the variance shall be discussed in the next section.

ANALYSIS OF DATA

The analysis of the data was performed using two standard methods. The first method, introduced by Savarensky[7] simply consists of selecting peaks of an incoming signal. The time interval between the peaks yields the period. The mid-point between the peaks is conventionally taken as the time of arrival of that component of the wave. Picking all the signal peaks yields a set of group velocities which may be plotted against their corresponding periods. The group-velocity dispersion curve derived may then be used for interpretation, as will be discussed later. The second method introduced to seismology by Schneider, Mueller and Knopoff[8] consists of computing the Fourier phase spectrum. Since arrival times are derivatives of the phase with respect to angular frequency, the group-velocities can be calculated directly, knowing the distance traveled by the earthquake, again leading to a group-velocity dispersion curve.

At this point in the analysis two important problems arise. Firstly, inasmuch as the signals are weak, one must be very careful to determine just where is the signal. The problem of separating signal from noise is difficult enough without admitting to the event parts of the record not made by the surface Rayleigh waves. This problem can be partly resolved by filtering.Fig. 3 a-f inclusive show for earthquake No. 5 reduced seismograms filtered with Parzen filters with lengths 45, 35, 25, 20, 15 and 10 respectively. Examination of the filtered event using the 45 point filter shows that the first peak in the dispersive Rayleigh wave appears at about 55 seconds. The first detectable peak using the 35 point filter appears at about 81 seconds. Using shorter and shorter filter lengths the first detectable dispersive wave appears at later and later times. The last discernible peak also appears at later and later times with shorter filter lengths. The overlap of detectable regions of the dispersive wave permits the creation of a composite using all the appropriate filtered waves, allowing one to expand the range of periods over which group-velocities can be determined and, hence, to increase the length of the group-velocity dispersion curve. Filtering naturally removes the harmonics. In the power spectra for each of the filtered waves, for the respective filter lengths the range over which the power appears, keeps moving to the right in a power vs frequency plot (not shown), which again served to illustrate the validity of the multiple filtering technique.

The second problem, normalizing the variance of the process, requires very careful consideration. The method generally followed in the literature and that used by Wilhelm, McIntyre and Slusher(5) involves picking the times of peaks and valleys using some fixed optimum filter lenght ("optimum" being a subjective judgement). The only variation on this paper is the multiple selective filtering technique where each peak or valley is marked on the filtered seismogram with the most appropriate filter for that part of the incoming surface Rayleigh wave. From these times of peaks and valleys half-wave sine curve segments are fitted with amplitude one at each extremum. A synthetic seismogram is thus developed meeting the requirements of zero mean and constant variance. Experience in performing this technique, calculating the phase spectrum and then deriving the group-velocity dispersion curve for such a synthetic seismogram, does indeed yield positive results. Leaving the interpretation of results relating to geologic structure to a later section a comparison of results of the two methods is made in order to assess their relative effectiveness. Fig. 4 gives the group-velocity dispersion values as calculated for earthquake five using both Savarensky's method and Fourier spectral analysis showing seemingly indistinguishable results. However, a careful analysis causes one to favor Savarensky's method for two reasons. Firstly, the range of periods over which points are obtained is slightly greater for Savarensky's method (due mostly to loss of points in smoothing in the calculations of the spectra). Secondly, the curves calculated by Savarensky's method have a character closer to that of the theoretically calculated curves discussed later and shown in Fig. 5. Therefore the conclusion is made that no advantage is gained in performing the sophisticated spectral analysis over the empirical Savarensky's method. It should

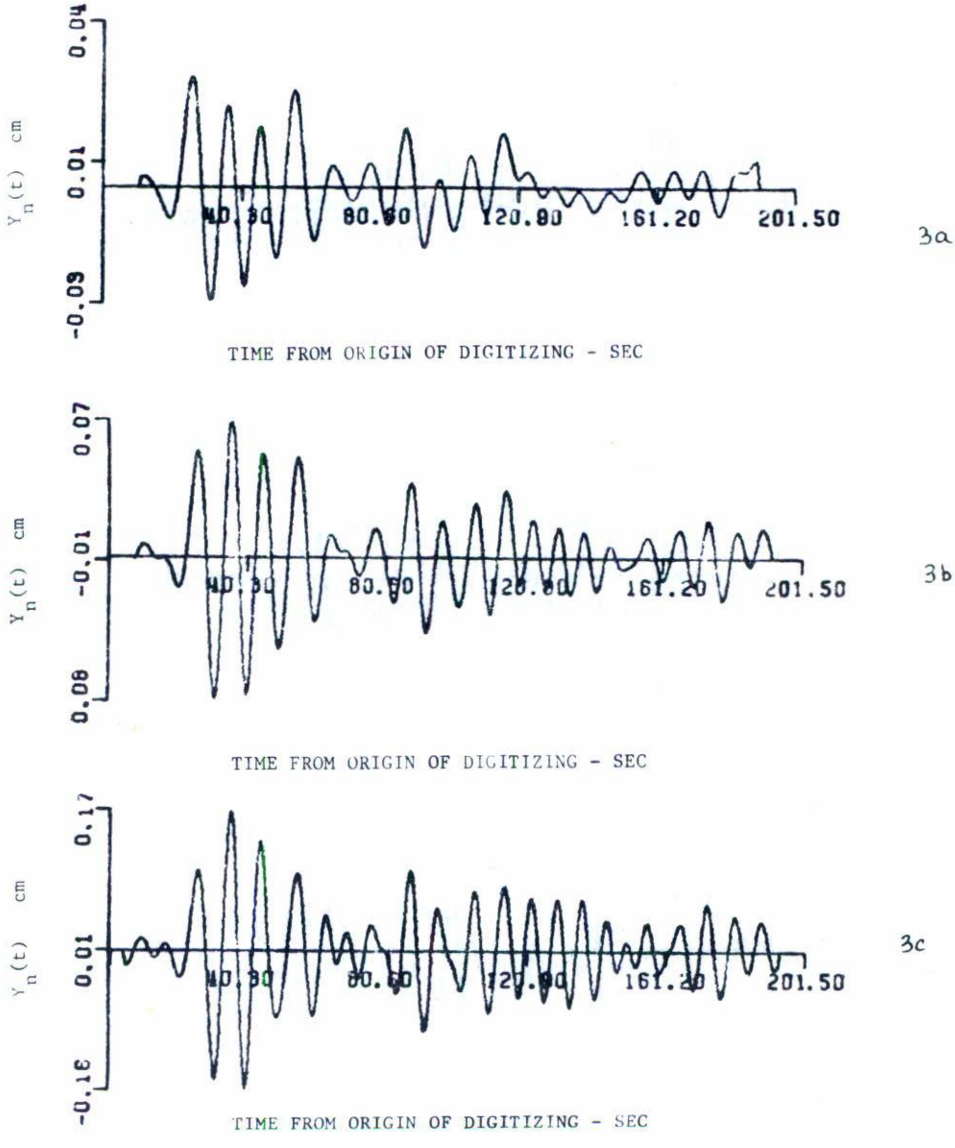


Fig. 3 Reduced seismogram of earthquake number five filtered with Parzen filter length:

(a) P = 45 (b) P = 35 (c) P = 25

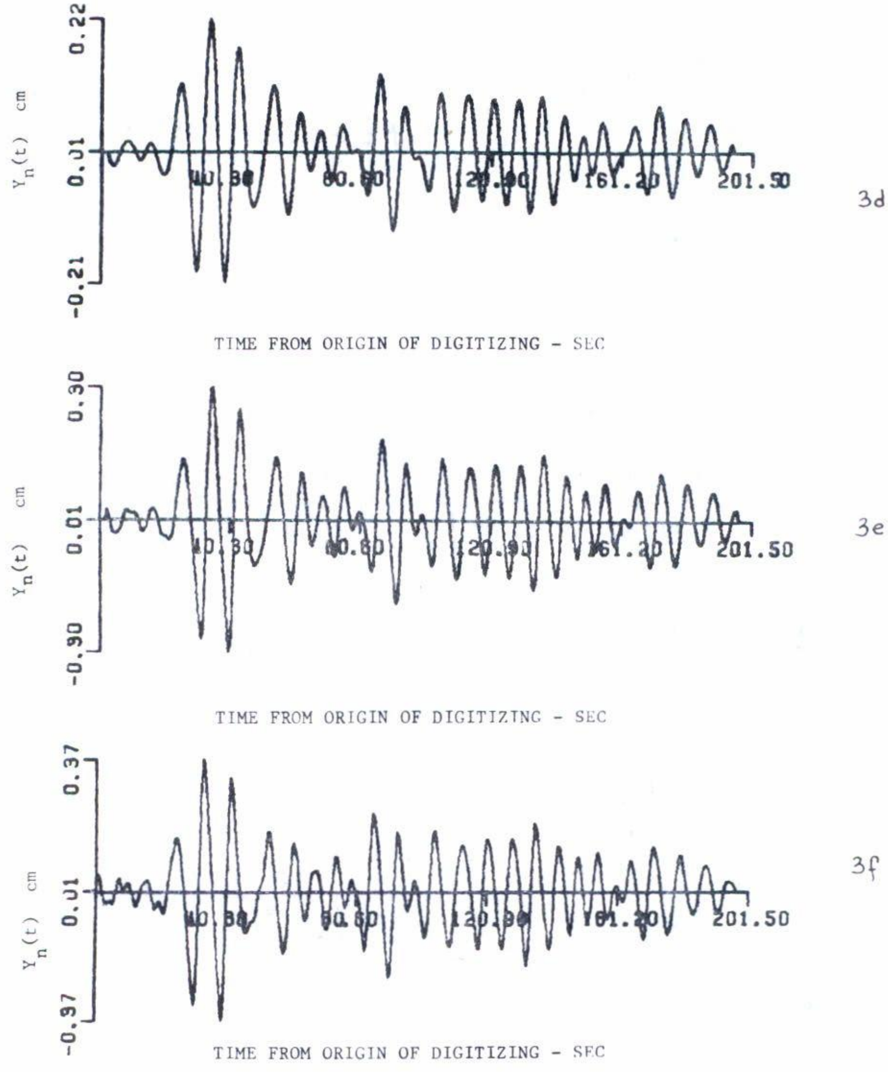


Fig. 3 Reduced seismogram of earthquake number five filtered with Parzen filter length:

(d) P = 20 (e) P = 15 (f) P = 10

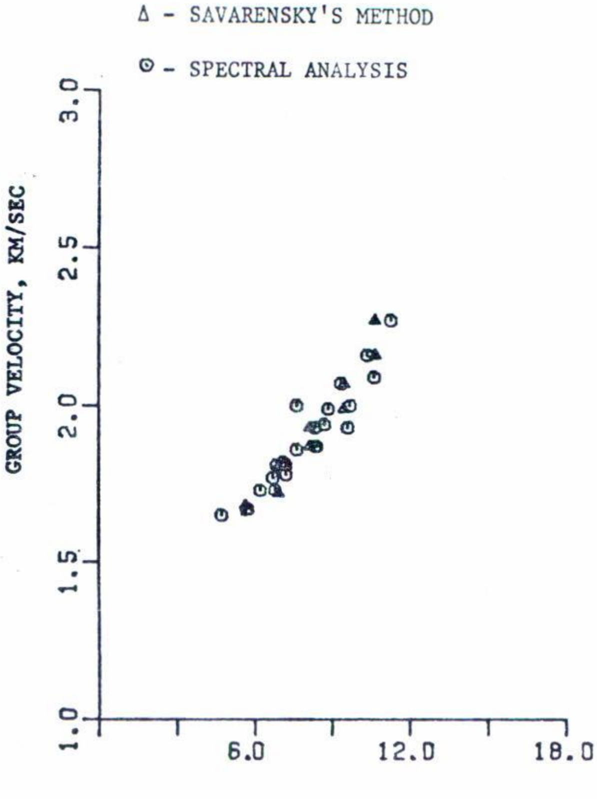


Fig. 4 Group-velocity dispersion values as calculated for earthquake number five using both Savarensky's method and Fourier spectral analysis.

be noted that the peaks and valleys were picked in exactly the same manner for the two methods and that this is all of the available information. All of the information was used in the Savarensky's method and one would logically expect this method to yield results at least as good as any other method using the same information. The weakness in the Fourier spectral analysis was introduced in the attempt to normalize the variance. Until a better method for performing this operation is introduced to seismology the method will not be superior to the more empirical Savarensky's method. It should be noted that Wilhelm[4] and Wilhelm et al.[5] claim an advantage of the Fourier spectral method over Savarensky's method in that the former shows the inversely dispersing branch of the group-velocity dispersion curves, i.e. a branch corresponding to the negative slope segments in Fig. 5b. This simply is not true. No method will show this branch under normal circumstances because those components (at such high frequencies) are quickly attenuated and do not come in. If they had come in they would have been picked by Savarensky's method as well since they are picked in the same manner for the two methods. Inspection of the papers of Wilhelm[4] and Wilhelm et al.[5] show that nowhere in their results does an inversely dispersing branch appear.

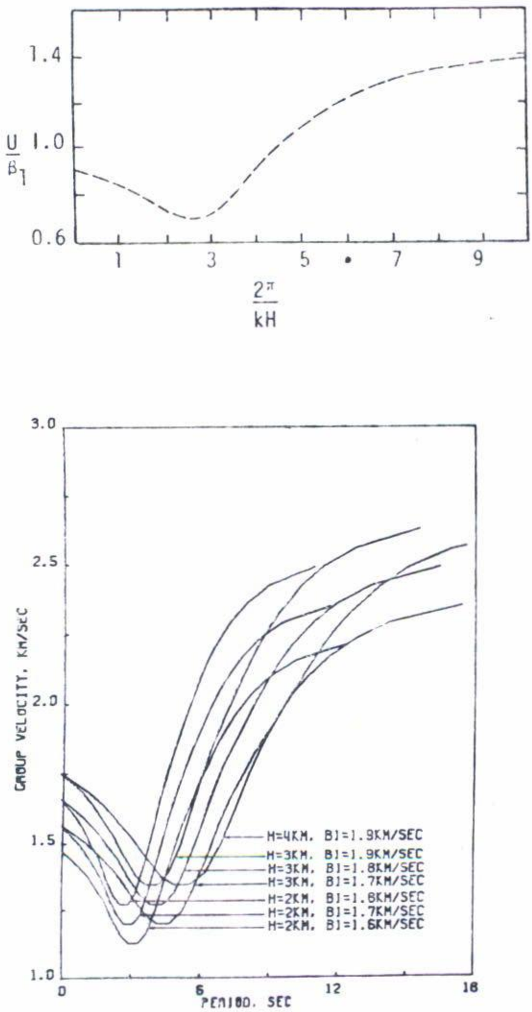


Fig.5 (a) Dimensionless group-velocity curve (after Kanai[9])
(b) Group-velocity dispersion curves for indicated thickness H and shear-wave velocity B1 (Wilhelm et al.[5]).

INTERPRETATION OF RESULTS

In order to translate observed dispersion curves into geologic structure, comparison is made with theoretically calculated group velocity dispersion curves. The model used is a homogeneous single layer over a semi-infinite substratum. Fig. 5a gives the dimensionless theoretical group-velocity dispersion curve derived by Kanai [9], for the model where the parameters U, β_1, k and H are: Rayleigh group-velocity, S-wave velocity, the propagation constant for the arriving Rayleigh wave and the top layer thickness, respectively. When specific values are chosen for the parameters β_1 and H the dimensionless curve can be converted to a two parameter family of curves as illustrated in Fig. 5b where each member curve maps group-velocity versus period of the arriving Rayleigh wave.

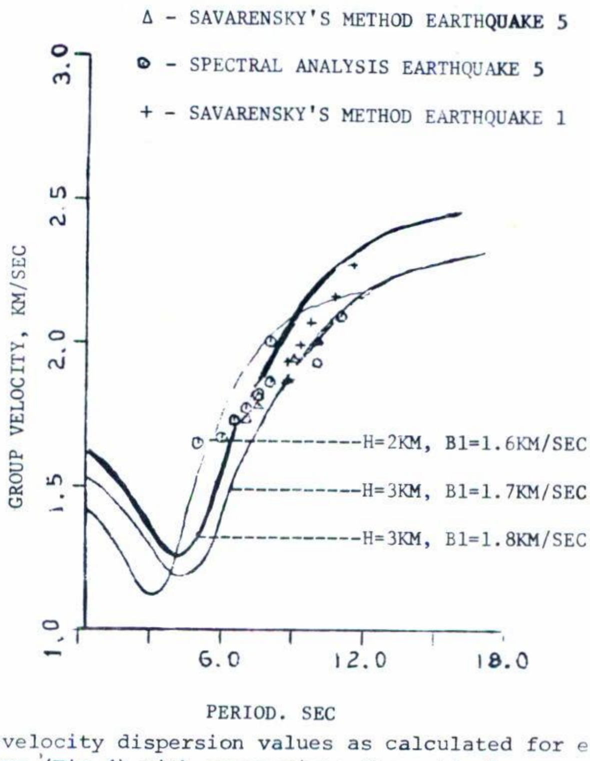


Fig.6 Group-velocity dispersion values as calculated for earthquake number five (Fig.4) with appropriate theoretical group velocity dispersion curves for indicated thickness H and shear-wave velocity B_1 (from Fig. 5b). Also values for earthquake number one are shown.

Fig. 6 shows the group-velocity dispersion points from earthquake 5, together with appropriate members of the family of theoretical curves for the purpose of comparison and interpretation. Also shown are points from earthquake 1 using Savarensky's method.

All of the events studied yield a very low estimate for the thickness of the sedimentary layer of the Sonoran Embayment, very consistently having a value of 2.5 ± 0.5 kilometers with the estimate leaning slightly to the lower side.

REFERENCES

1. J. Oliver and M. Ewing, Bull. Seism. Soc. Am. 48 (1958) 339.
2. D. H. Shurbet, J. Geophys. Res. 66 (1961) 899.
3. M. Ewing and F. Press, Bull. Seism. Soc. Am. 42 (1952) 315.
4. R. Wilhelm, "Determination of the Sedimentary Thickness of the Sonora Geosyncline by Rayleigh Wave Dispersion" (M.S. Thesis, University of Texas at El Paso, 1972) unpublished.
5. R. Wilhelm, R. G. McIntyre and H. S. Slusher, Bull. Seism. Soc. Am. 65 (1975) 733.
6. G.M. Jenkins and D.G. Watts, "Spectral Analysis and its Applications", (Holden-Day Pub. Co., San Francisco, 1968).
7. E.F. Savarensky, Izvestiya Acad. Sci. USSR, Geophys. Ser. 1958 (1957) 1102.
8. G. Schneider, S. Mueller and L. Knopoff, Z. Geophysik, 32 (1966) 33.
9. K. Kanai, Bull. Earthquake Res. Inst., Tokyo 29 (1951) 49.