Dispersion of Rayleigh waves produced by nuclear explosions. Crustal structure of western Europe

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Summary. — Most of the nuclear explosion fired near Novaya-Zemlya island from September 1961 to January 1963 (21 in total) have been recorded on the seismographs of Toledo Observatory. The study of these records, mainly concerning the dispersion of Rayleigh waves, has been the purpose of this paper.

A crust-mantle structure for the Zemlya-Toledo path has been determined by means of group velocity curves and especially by the phase velocity ones obtained from Rayleigh waves of explosions. This structure supposes a crust of about 40 kms thick with an upper sedimentary layer with a thickness of about 5,5 kms and a shear velocity of 2,3 km/sec.

The average shear velocity in the granitic and basaltic layers jointly, is about 3,65 km/sec, permitting a small ambiguity at the position of the Conrad discontinuity between them.

A velocity of 4,5 km/sec has been assigned for the underlying crust material, but a better agreement with the data recorded is obtained by taking 0.28 for the Poisson ratio value.

Dispersion of Rayleigh waves of these explosions has been compared to the Rayleigh dispersion of some earthquakes of Eurasia, three of them with epicentral distances similar to those of the explosions and other four with the same azimuth in respect to that of Toledo-Zemlya, but more distants.

The results do not show any notable difference either in dispersion between explosion and earthquakes or in structure of the path considered.

The phase velocity between Toledo and Malaga Observatories supports the same above structure for this short path.

The velocity of Lg waves, which clearly appears on the record of the explosions, confirms this admitted structure, which serves to deduce the more probable transmission mechanism for these channel waves.

Also atmospheric pressure waves have been recorded on the three components with very notable amplitudes. The movement of the ground particle and the possible action mechanism on the records has been determined. The dispersion of these waves for the three more clear records, using the vertical component, has been calculated too.

RESUMEN. — La mayor parte de la explosiones nucleares hechas explotar en la isla de Nueva Zembla desde Septiembre de 1961 hasta Enero de 1963 (21 en total), han sido registradas por los sismografos del Observatorio de Toledo. El estudio de estos registros, principalmente en relacion con la dispersion de las ondas Rayleigh, es el objeto principal de este trabajo.

Se ha determinado una estructura Corteza-Manto para el trayecto Toledo-Zembla por medio de las curvas de velocidad de grupo y principalmente de las de velocidad de fase obtenidas de las ondas Rayleigh producidas por las citadas explosiones. Esta estructura supone una corteza de unos 40 km de espesor sobre la que se encuentra una capa sedimentaria de de unos 5,5 kms de gruesa y una velocidad de cizalla de 2,3 km/seg.

El promedio de la velocidad de cizalla en las capas granitica y basaltica conjuntamente es de 3,65 km/seg quedando fijada la posición de la capa de Conrad entre ellas con una cierta ambiguedad.

Para el material debajo de la corteza se le ha asignado una velocidad de cizalla de 4,5 km/seg, encontrandose la mejor coincidencia con los datos de registro si se considera 0.28 para el valor de a razon de Poisson.

Se ha comparado la dispersion de las ondas Rayleigh de estas explosiones con la de algunos terremotos de Eurasia, tres de ellos de distancias epicentrales parecidas a las de las explosiones y otros cuatro del mismo azimut que el trayecto Zembla-Toledo pero mas distantes.

Los resultados de estas comparaciones no muestran ninguna notable diferencia entre los terremotos y las explosiones en cuanto se refiere a la dispersion de las ondas Rayleigh, ó a la estructura de los caminos considerados.

Esta estructura cortical mencionada ha sido confirmada con en calculo de la velocidad de fase determinada con los registros de Toledo y Malaga conjuntamente.

Tambien la velocidad de las ondas Lg, que aparecen muy claras en algunos registros confirma esta estructura admitida, y ello contribuye a deducir el mecanismo mas probable de trasmision de estas ondas Lg.

Las ondas de presión atmosferica tambien han sido registradas con muy notables amplitudes. De estos registros se ha determinado el movimiento de la particula del suelo y el posible mecanismo de accion de estas ondas sobre los sismografos. Usando los tres registros mas claros hemos determinado la dispersion de estas ondas de presion, a partir solamente de la componente vertical.

RIASSUNTO. — La maggior parte delle esplosioni nucleari effettuate nell'isola della Nuova Zemlia dal Settembre 1961 al Gennaio 1963 (ventuno in tutto), è stata registrata dai sismografi dell'Osservatorio di Toledo. Lo studio di tali registrazioni, soprattutto in relazione alla dispersione delle onde Rayleigh, è appunto l'oggetto principale di questo lavoro.

Si e determinata una struttura Crosta-Mantello lungo il tragitto Toledo-Zemlia per mezzo delle curve di velocita di gruppo, e principalmente per mezzo di quelle di velocita di fase ottenute dalle onde di Rayleigh causate dalle esplosioni in oggetto. Tale struttura suppone una crosta di circa 40 km di spessore, al di sopra della quale si trova uno strato di sedimenti di circa 5,5 km di altezza con una velocita per le onde trasversali di 2,3 km al sec.

La media della velocita per le onde trasversali negli strati granitici e basaltici nel loro insieme e di 3,65 km al sec lasciando fra loro un piccolo margine, alla posizione della discontinuita di Conrad.

Per il materiale che si trova sotto la crosta, si e attribuita una velocita per le onde trasversali di 4,5 km al sec, riscontrando una migliore rispondenza con i dati registrati, se si da al rapporto di Poisson il valore di 0,28.

Si e confrontata la dispersione delle onde di Rayleigh di queste esplosioni con quella provocata da alcuni terremoti d'Eurasia, tre dei quali di distanza epicentrale pressoeche analoga a quella delle esplosioni, e altri quattro dello stesso azimut rispetto a quello Toledo-Zemlia, ma piu distanti.

I risultati trovati per le esplosioni e i terremoti non presentano alcuna notevole differenza ne per quanto riguarda la dispersione ne per i tragitti considerati. Questa struttura della crosta è stata confermata dal calcolo della velocita di fase, ottenuta dalle registrazioni degli Osservatori di Toledo e Malaga (per questo breve percorso).

Anche la velocita delle onde Lg, che appaiono molto chiare in alcune registrazioni, conferma la suddetta struttura e ciò contribuisce a dedurre il meccanismo piu probabile di trasmissione delle onde Lg.

Le onde di pressione atmosferica sono state registrate anche esse con ampiezze molto notevoli. Da queste registrazioni si e determinato il movimento della particella del suolo ed il probabile meccanismo d'azione di queste onde sui sismografi. Usando le tre registrazioni piu chiare si e determinata la dispersione di queste onde di pressione, partendo soltanto dalla componente verticale.

From September 1961 to January 1963, 21 nuclear explosions have been recorded on the seismographs of Toledo's Observatory, with very notable amplitudes.

In an exhaustive sutdy of Dr. Bath's about atomic explosions it is suggested among other important conclusions, that there is a considerable delay in the arrivals of the Rayleigh waves of the explosions to the Swedish Stations, probably due to lateral refraction. Therefore we have considered it interesting to study both the group and phase velocities of these Rayleigh waves in order to determine a crustal structure for the Zemlya-Toledo path. We also compare the dispersion of surface waves of these bombs with the surface wave dispersion as shown by earthquakes, either of similar distances or of similar paths.

The four explosions dated August 5 and 27, and September 8 and 27, 1962 have been principally chosen to carry out this study because they are clearer than the others.

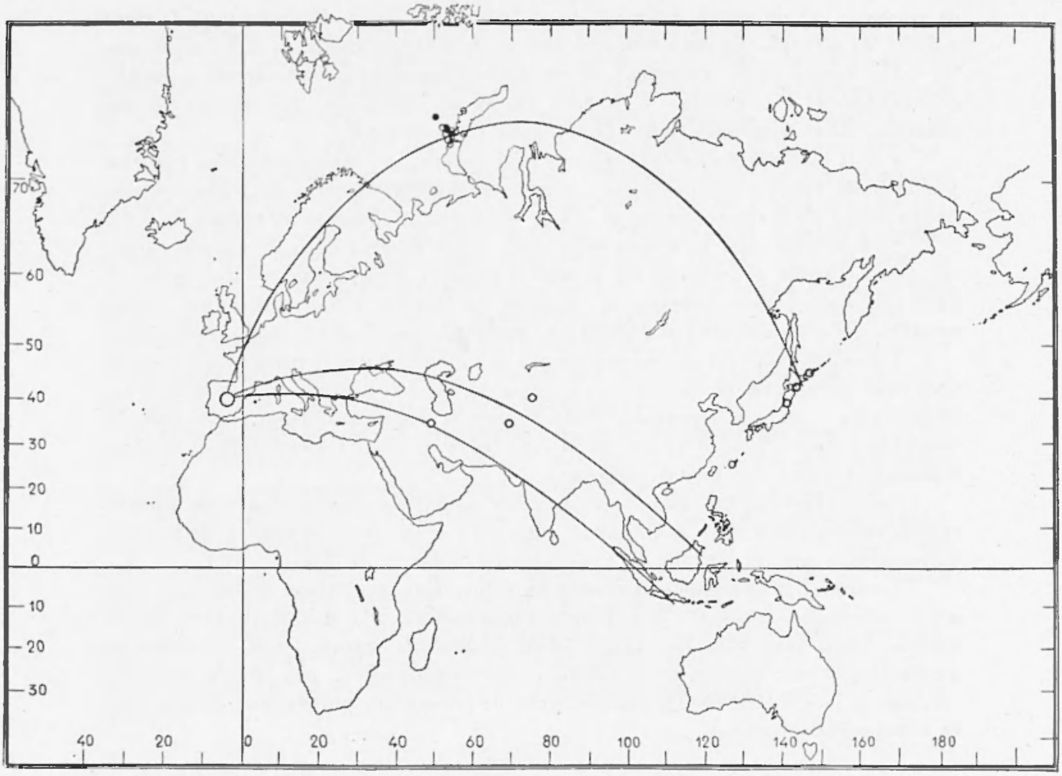

Fig. 1 – Eurasie map, showing locations and azimuts of considered explosions and earthquakes.

Really all these records are similar, above all concerning the dispersion; nevertheless we have chosen four explosions to better guarantee the result.

Movement of the underground particle shows clear Rayleigh waves, giving, on the horizontal plane, a retrograde ellipse with the larger axis fitting well into the ezimuth Toledo-Zemlya (20° about).

Comparing the Rayleigh waves dispersion curve (calculated by Press-method) for the group velocity of these four explosions with the theoretical curve computed by Press for his structure 6 EG, we find it to agree fairly well with the dispersion curve which supposes a crust 45 kms thick (Figs. 2-3) Really this seems too large a thickness for

Table I. – RECORDED EXPLOSIONS.

Date	Origin Time H M S	φ	λ	Distance	Magnitud	Clear recorded phases
1961						
Sept. 10	09 00 04	74 4° N	52.5° E	4.800	4.6 (Upp)	Lr_N, M_N.
» 18	07 59 33	74.4° N	52.5° E	4.800	4.4 (Upp)	Lr_N
» 20	08 12 09	74.4° N	52.5° E	4.800	4.3 (Upp)	Lr_N
October 6	07 00 08	74.4° N	52.5° E	4.800	4.7 (Upp)	Lr_N, M_N.
» 23	08 21 21	74.4° N	52.5° E	4.800	5.1 (Upp)	Lr_N, M_N.
» 30	08 33 26	74° N	53.3° E	4.820	5.4 (Upp)	iP_Z, eS , eSS_N, , Lr_N, Lg1 , Lg2 .
» 31	08 29 22	73 8° N	54° E	4.805	4.7 (Upp)	Lr_N, M_N.
» 31	08 37 54	(75.2°) N	57.9° E	5.920	—	
November 4	07 20 21	74.2° N	54.2° E	4.805	4.4 (Upp)	Lr_N, M_N.
1962						
August 5	09 08 45,8	74.2° N	52.5° E	4.785	—	aP_Z, ePP_Z, $iPcP_Z$, eS_Z, iSS_Z, Lr_Z, Lg1 , Lg2 , M_Z.
» 27	09 00 50,9	74.7° N	50.3° E	4.745	—	Lr_Z.
Sept. 8	10 17 57,7	73.7° N	53.8° E	4.795	4 3/4 (Pal)	Lr_Z.
» 15	08 02 13,9	74.4° N	51.5° E	4.770	—	$e(S)_Z$, Lr_Z, M_Z.
» 16	10 59 10,5	74.2° N	51.6° E	4.760	4 3/4-5 (Pal)	Lr_Z
» 18	08 29 02,7	73.2° N	54.7° E	4.820	—	Lr_Z
» 19	11 00 56,4	73.8° N	53.8° E	4.805	5-5 1/4 (Pal)	eP_Z, ePP_Z, eS_Z, eSS_Z, iLr_Z, Lg , M_Z.
» 21	— — —	—	—	—	—	Lr_Z, M_Z.
» 25	13 02 31,7	73.7° N	55° E	4.805	5 1/4 (Pal)	eP_Z, ePP_Z, eS_Z, eSS_Z, iLr_Z, Lg , M_Z.
» 27	08 03 16,4	74.3° N	52° 4 E	4.795	5 1/4-5 1/2(P	eP_Z, ePP_Z, eS_Z, iSS_Z, Lr_Z, Lg , M_Z.
October 22	09 06 10,1	73.4° N	54.9° E	4.815	5-5 1/3 (Pal)	L_N.
Dec. 24	11 11 42	73.6° N	57.5° E	4.900	—	L_Z, M_Z.

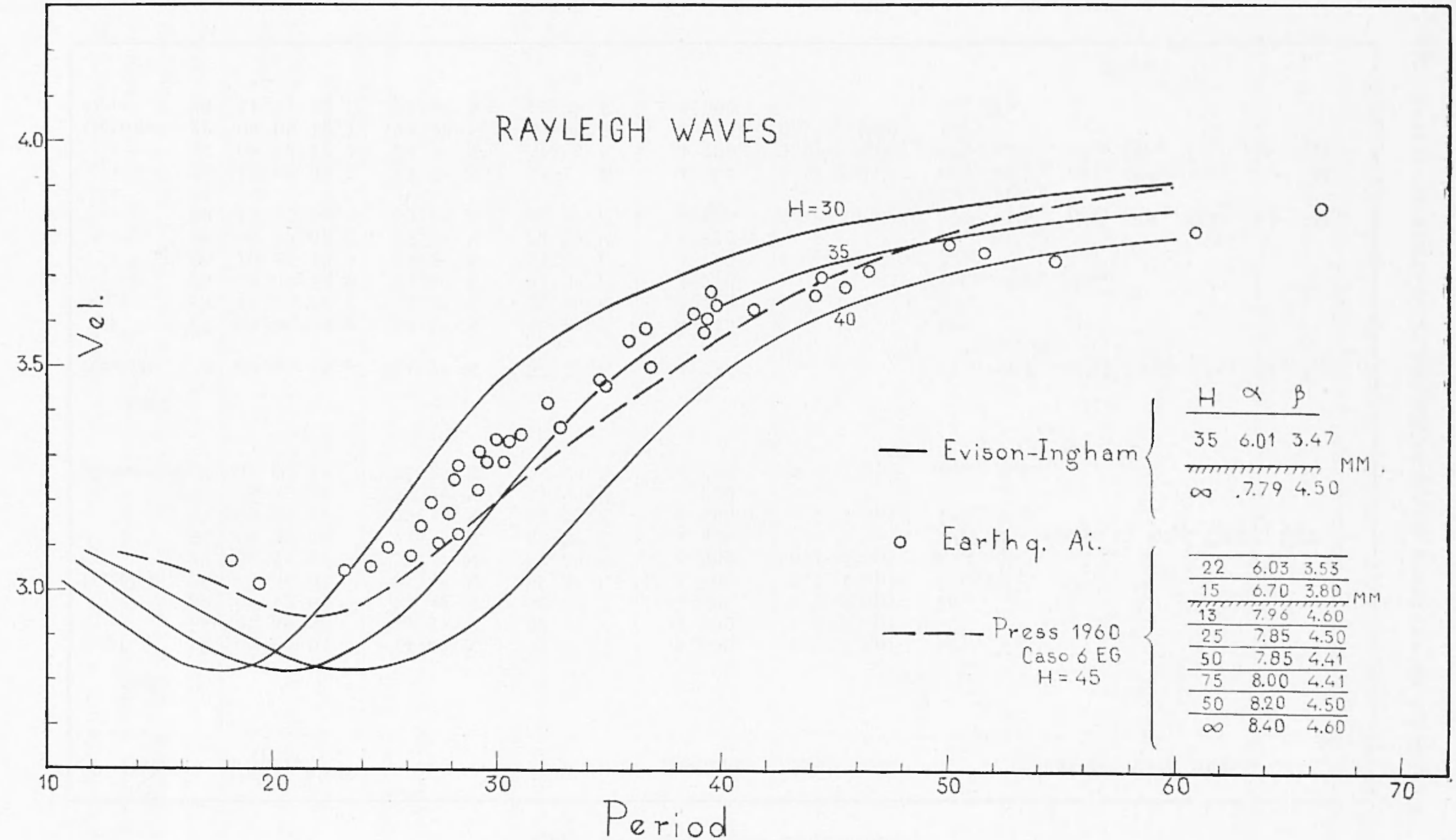

Fig. 2 – Group velocity of Rayleigh waves.

Table II

Earthq.	Date	Coordinates		Origin time	Distance	Mag.	Location
A_1	14 VI 62	$26^{\circ}4$ N	$126^{\circ}5$ E	22 14 10,9	11.037	—	Islas Ryukyu
A_2	30 IV 62	$38^{\circ}8$ N	$140^{\circ}9$ E	02 26 30	10.555	—	Honshu. Japón
A_3	17 VII 62	$43^{\circ}1$ N	$144^{\circ}5$ E	17 20 11,9	10.355	—	Hokkaido. Japón
A_4	7 V 62	$45^{\circ}3$ N	$146^{\circ}7$ E	17 39 50,3	10.080	$6\,^3/_4$ (Pas) 7 (Berk)	Islas Kuriles
B_1	4 IX 62	$35^{\circ}6$ N	$49^{\circ}7$ E	13 30 10,9	4.665	—	NW del Irán
B_2	12 IX 62	$36^{\circ}5$ N	$69^{\circ}2$ E	20 57 00,4	6.245	($6\,^1/_2$-$6\,^3/_4$ pas). 6 (Pal)	Hindu Kush
B_3	1 VII 62	40° N	$75^{\circ}4$ E	21 23 41,7	6.535	—	Province of Sinkiang. China

this path which is of course of continental structure (Fig. 1) as shown by the clear records of Lg waves.

In order to confirm this agreement with the Press curve we have calculated the phase velocity by the method of Brune, Nafe and Oliver (2) (*) for 0,5 - 1,0 - 1,5 - 2,5, as n value.

The result was the exact coincidence between dispersion curve of phase velocity for Press structure ($H = 45$) and the curve of phase velocity calculated for $n = 1{,}0$. This result can not be admitted because we must suppose that an explosion in the atmosphere produces a compression at the origin (n half-integer) as is shown, on the other hand, by the P waves recorded being compressional.

If we suppose this crust thickness to be 35 kms and the 45 kms obtained to be due to an effect of lateral refraction, then the Zemlya-Toledo distance ought to be considered about 500 kms greater than the maximal circle path. This seems too much especially if we take into account that, the continental borders are almost perpendicular to this path.

In order to find if there is some difference between the travel-time or Rayleigh waves of explosions and earthquakes, we have chosen 4 earthquakes of northern Japan (Table II, earthquakes A_i) that exhibit clear trains of Rayleigh and Love waves, and whose azimuth is the same as the Toledo-Zemlya one. In Fig. 2 can be seen that their group velocity is very similar to that of the explosions. In order to check this coincidence once more we have chosen three new earthquakes of Inner-Asia (Earthq. B_i Table II) whose epicentral distances are more or less equal to that of the explosions. In Fig. 3 their Rayleigh wave dispersion curves are compared with the dispersion shown by the explosions, as well as with a dispersion curve deduced from A_i earthquakes, after the path Toledo-Japan has been considered as composed of two segments and the necessary correction has been made in the dispersion for the segment Zemlya-Japan. This correction was made using the Press-Dewart method and the empirical dispersion curve computed by Evison-Ingham (1960) ($H = 32$).

The results shown in Fig. 3 indicate that there is not an important difference between the dispersion of these earthquakes and explosions.

Hence, we explain the first unsuitable results by the crustal structure of Press (6 EG) that we have used being inappropriate for this occidental-european border.

(*) (See bibliography at last).

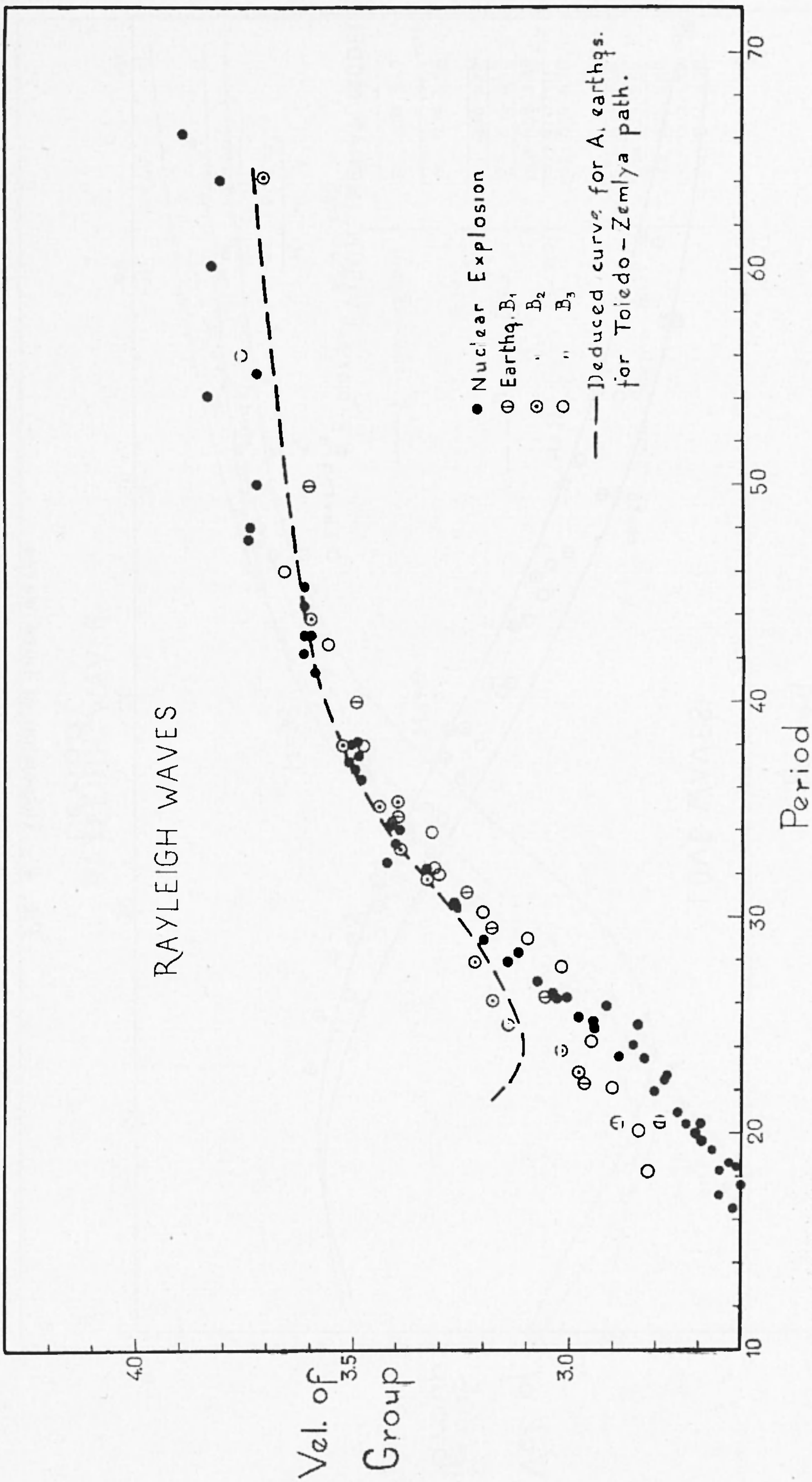

Fig. 3 – Comparison of group velocity between explosion and earthquakes.

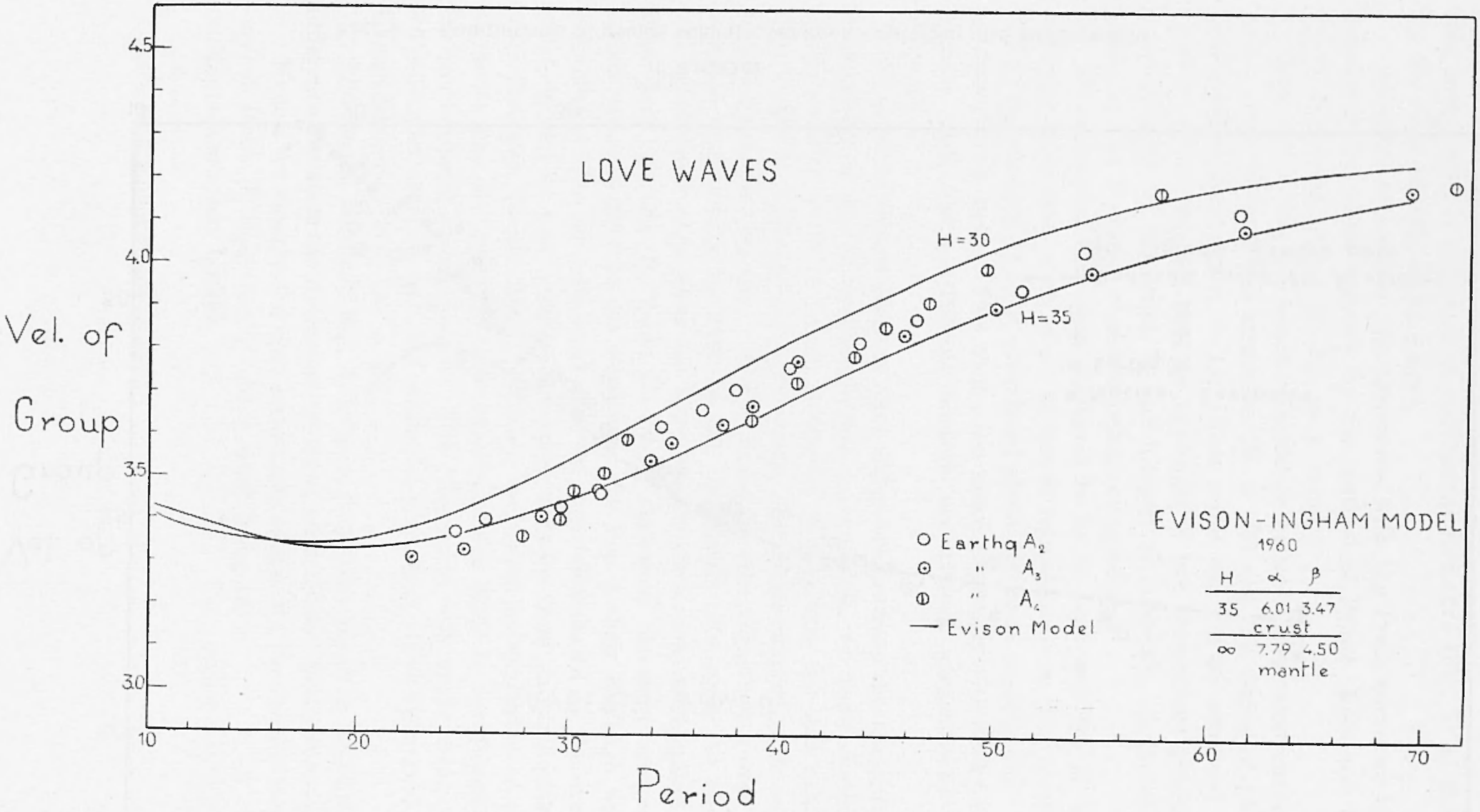

Fig. 4 – Dispersion of Love waves.

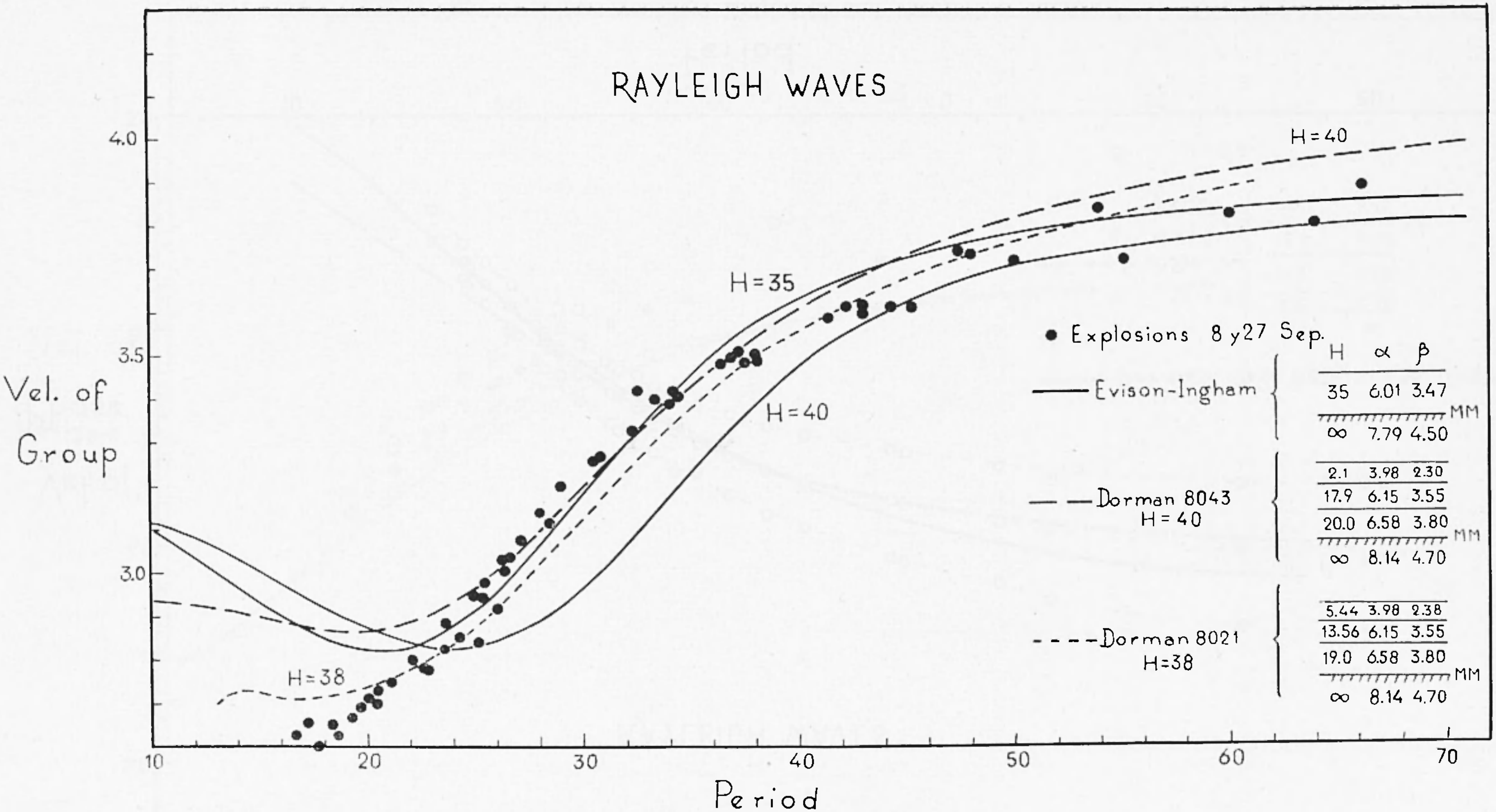

Fig. 5 – Group velocity of explosions as compared with different models.

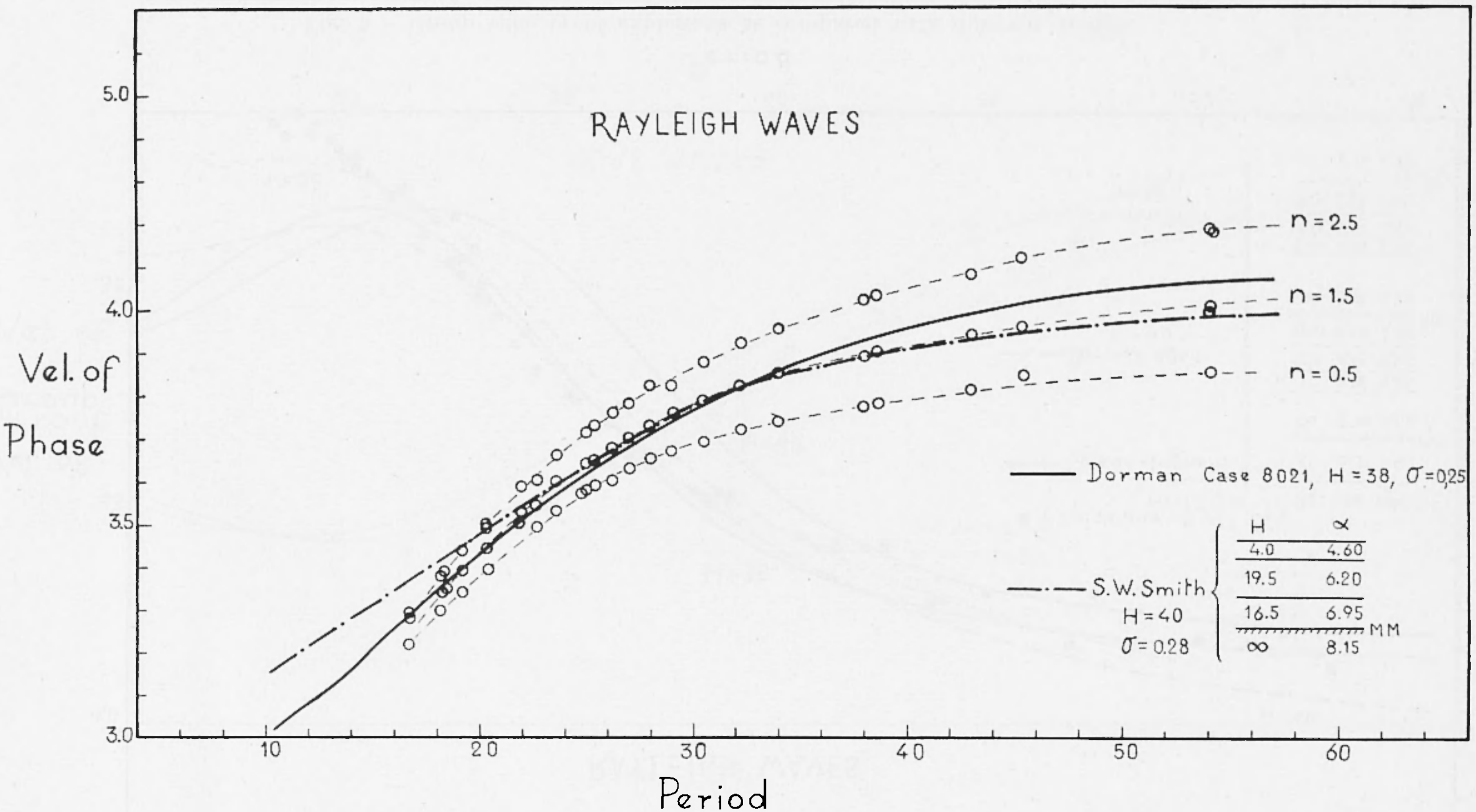

Fig. 6 – Phase velocity. Empirical and theoretical curves.

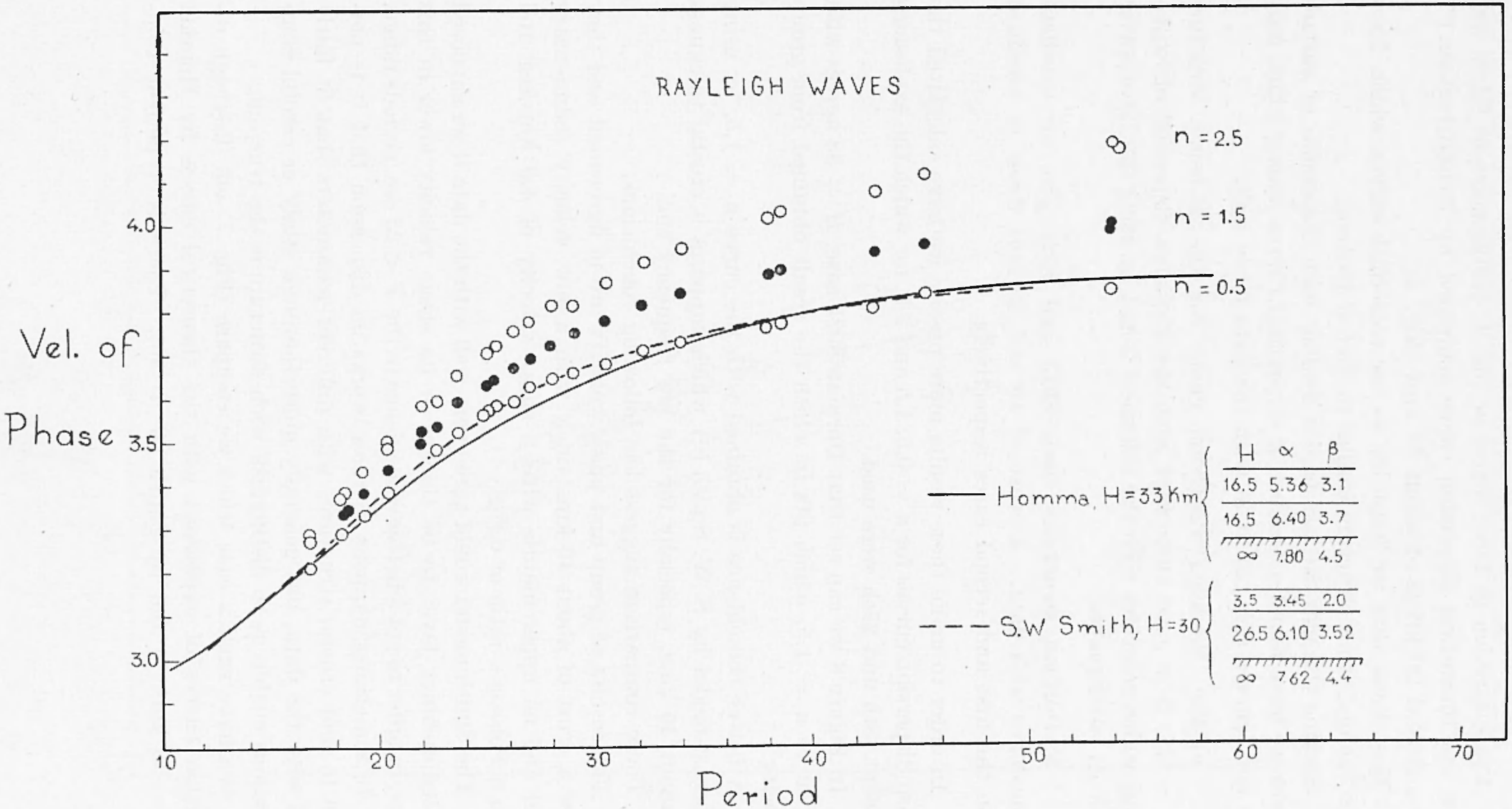

Fig. 7 – Phase velocity. Empirical and theoretical curves.

The dispersion of Love waves of the A_t earthquakes fit fairly well with the theoretical dispersion curve computed by Evison-Ingham [10] for a crustal thickness of about 34 kms (Fig. 4).

This shows that we must try to use teoretical curves which have been calculated for structure similar to that of Evison.

Seeking through the last papers dealing with dispersion of surface waves we have found a number of theoretical curves among which only the next curves (Fig. 5) fit in with the data fairly well:

a) The Rayleigh dispersion curve for the Evison's structure ($H = 35$) is in good agreement with the Rayleigh dispersion of explosions, which coincides with the thickness found by using the Love waves from A_t earthquakes.

b) Dorman structures cases 8043 and 8021 give an excellent coincidence with data. A crust of 40 and 38 kms thick is obtained from the first and second cases respectively.

In order to make these results more precise we have calculated the phase dispersion curves for $n = 0{,}5$, $1{,}5$ and $2{,}5$, for which the explosions on Sept. 8th and 27th were used.

In Figure 6 we can see that Dorman 8021 case, $H = 38$ agrees with the curve $n = 1{,}5$, which fits in whith the result obtained from group velocity.

A better coincidence is obtained with the curve $n = 1{,}5$, by using the crust-model by S. W. Smith [12] which supposes a crustal thickness of about 40 kms, especially for the low frequency end.

These comparison suggest the following conclusions:

The results of group and phase velocity are in agreement and they show a crust of about 40 kms thick with a low velocity sedimentary layer and un upper mantle with a shear velocity of 4.5 kms/seg and with a Poisson's ratio of 0.28.

The Smith model would agree very well with the data if we supoosed its sedimentary layer to be thicker or its shear velocity lower in this layer, in order to get a better coincidence in the $T < 23$ sec. periods range.

It sometimes happens in these works on dispersion that it is possible to find crustal structures with different parameters that fit fairly well with the data, but generally more thorough study or careful computations enable us to distinguish wich structure is the true one.

We have such a case when we compare (Fig. 7) our Rayleigh dispersion curves of explosions with the theoretical curves by Homma $H = 33$ kms [13] and by Smith ($H = 30$). There is a perfect coin-

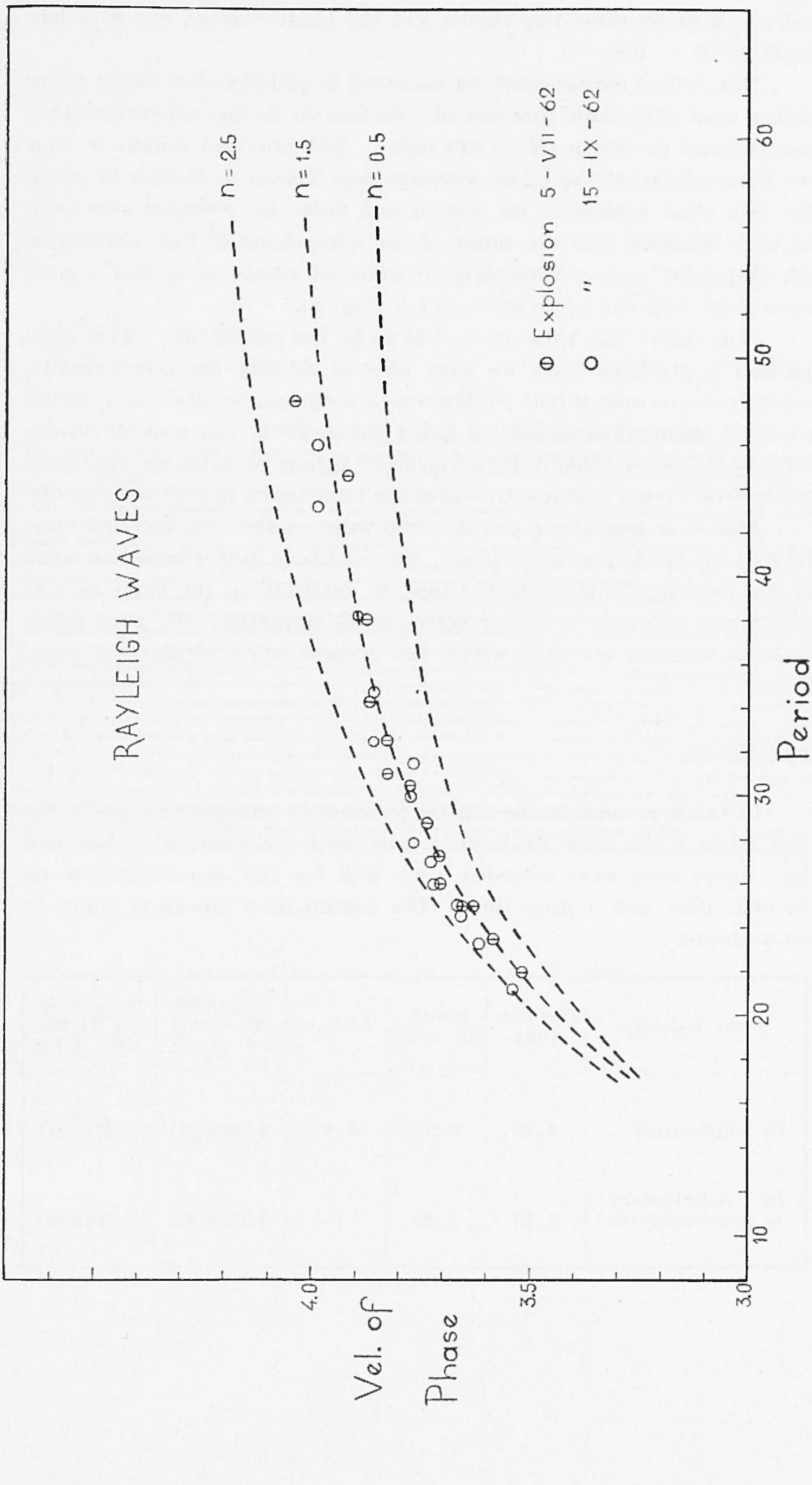

Fig. 8 – Phase velocity calculated from Toledo and Malaga Observatories.

cidence between these two curves and the phase velocity curves calculated for $n = 0.5$.

This fact of course could be admitted in principle but really many things exist that show this second structure to be less convenient that the Dorman or Smith ($H = 40$) ones. The principal reason is that we have calculated the phase velocity from Toledo to Malaga by using the two clear explosions on Aug. 5 and Sept. 15, recorded very well at both Stations, and the result of the comparison of this velocity to the dispersion curves calculated for different values of n, was a good agreement with the curve for $n = 1.5$ (Fig. 8).

That shows this value ($n = 1.5$) to be the proper one. This comparison is available since we were able to identify the corresponding crests in the records of both Stations accurately and because the maximal circle of Malaga-Toledo-Zemlya being the same it was possible to determine the phase velocity from Toledo to Malaga by using the simplified method by Press (4) which correlates the same crests in different records.

Also, it is possible to get the true value of the n at the first crest by making use of the Airy's phase, that was very well recorded on some of the records. This method, based on determining the value of n at the Airy's phase (2), is rather nevertheless imprecise. We have calculated it and got $n = 22.5$ which also gives $n = 1.5$ at the first crest.

Lg Wawes.

In order to confirm the crustal parameters admitted by us for the first layers in the crust we hawe a calculated the velocity of Lg1 and Lg2 waves that were recorded very well for the two explosions on 30 Oct. 1961 and 5 Aug. 1962. The confirmation has been found to be accurate.

Shear velocity	Dorman 8021	Smith (H = 40)	Evison	Explosion 30 X 961 vel. of Lg.	Explosion 5 VIII 962 Vel. of Lg
In whole crust	3.49	3.58	3.47	3.48(Lg1)	3.47(Lg1)
In sedimentary + granitic layers	3.19	3.28	—	3.27(Lg2)	3.26(Lg2)

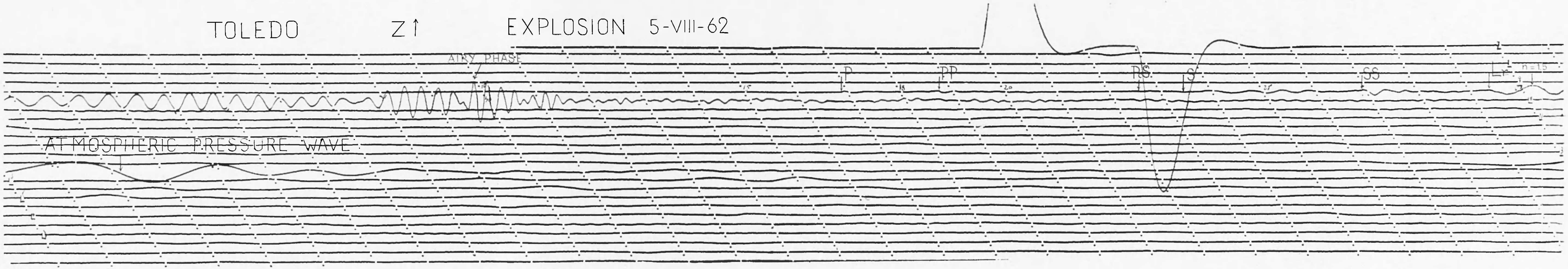

Fig. 9 – An example of records.

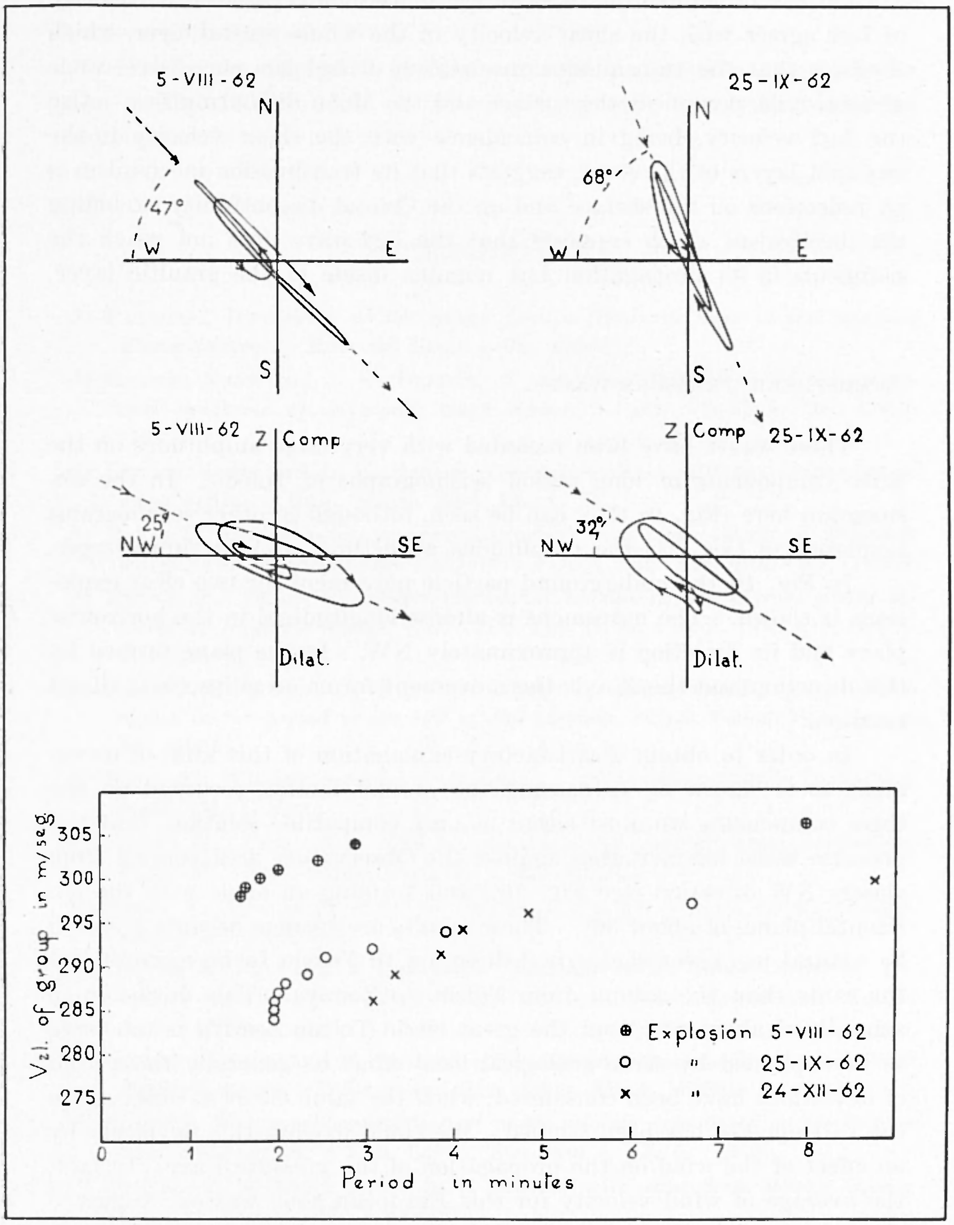

Fig. 10 – Particle motion of the ground, direction and atmospheric pressure waves dispersion for some of the explosions recorded in Toledo.

On the other hand as we can see in the above table, the velocity of Lg1 agrees with the shear velocity in the whole crustal leyer, which confirms that the transmission mechanism of Lg1 is a successive range of total reflections near the surface and the Moho discontinuities. Also the Lg2 velocity, being in coincidence with the shear velocity in the two first layers of the crust, suggests that its transmission mechanism is by reflections on the surface and on the Conrad discontinuity excluding the mechanism which supposes that the Lg2 wave does not reach the sediments in its propagation but remains inside of the granitic layer.

Atmospheric pressure waves.

These waves have been recorded with very large amplitudes on the three components of long period seismographs of Toledo. In the seismogram here (Fig. 9) they can be seen, although in other seismograms (explosion of Dec. 24) the amplitudes were three or four times larger.

In Fig. 10 the underground particle movement for two clear explosions is shown. The movement is almost longitudinal in the horizontal plane and its direction is approximately NW. In the plane formed by this direction and the *Z* axis the movement forms an ellipse with direct rotation.

In order to obtain a satisfactory explanation of this kind of movement as is shown by composing the ground motion recorded on the three components we must admit as only compatible solution, that the pressure wave has actuated against the Observatory area coming from closely NW direction (see Fig. 10), and forming an angle with the horizontal plane, of about 30°. These results are strange because it would be natural to expect the arrival direction to Toledo to be more or less the same than the azimut from Toledo to Zemlya. This deviation in azimuth of about 65° from the great circle Toledo-Zemlya is too large to be explained by some geological local effect as generally these kind of deviations have been considered, when the same effect as observed in the earthquakes has been studied. We could explain this deviation by an effect of the wind on the propagation of the pressure wave. In fact, the average of wind velocity for this European zone was on August 5 about 14 km/h and coming from NE direction which could deviate the trajectory of the pressure wave. On the other hand the wind on Sept. 25 was weaker (8 km/h) which agrees with the fact that the deviation at this day was smaller (Fig. 10) besides, its principal direction this day was

ES which probably would increase the angle of vertical incidence as we have seen to happen.

Finally the dispersion of these atmospheric pressure waves can be seen in Fig. 10, for some of the clearer records, taken from vertical components.

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