On the canalization of seismic energy (*)

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Summary. — The paper shows how the velocities of the channel waves P_a and S_a, as thus far calculated, are apparent velocities. From such apparent values it is easy to calculate the real velocities, which coincide with the minimum velocity of longitudinal and transversal waves, calculated by B. Gutenberg and by Miss I. Lehmann for the astenosphere.

The canalization of seismic energy is a general phenomenon which, in the case of strong earthquakes with focus ca. 100 km deep, may involve not only the astenosphere, but also the earth crust channels. Important examples are alleged.

The paper finally shows that also the energy developped by deep earthquakes (600 km deep and more) undergoes remarkable canalization. However, this concerns to a significant extent only the astenosphere.

Riassunto. — La nota mostra come le velocità delle onde canalizzate P_a ed S_a, finora calcolate, siano velocità apparenti. Dai valori ottenuti per queste ultime, è facile calcolare le velocità reali, le quali coincidono con la velocità minima delle onde longitudinali e trasversali calcolate da B. Gutenberg e Miss I. Lehmann, per l'astenosfera.

La canalizzazione dell'energia sismica è un fenomeno generale che, nel caso di forti terremoti con profondità ipocentrale di 100 km ca., può interessare non solo l'astenosfera ma anche i canali della crosta terrestre: a questo proposito nel testo si riportano notevoli esempi.

La nota, infine, mostra che anche l'energia sviluppata da terremoti a profondità di 600 km ed oltre, subisce una notevole canalizzazione; ad ogni modo, detta canalizzazione interessa in maniera significativa solo l'astenosfera.

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Canalized waves were the first discussed in 1953, when I made a communication to the Accademia dei Lincei on the existence of longitudinal and transversal waves guided by the astenosphere (1). I indicated such waves by P_a and S_a, Gutenberg, who soon confirmed their existence and my interpretation, suggested the symbols P_a and S_a, changing into a small letter the capital A, initial of " astenosphere ".

It is well known how, in my interpretation and in Gutenberg's, the proper physical condition for the diffusion of such waves is the existence of a wide low-velocity layer beneath the earth crust, which has been named by many " astenosphere ". Gutenberg devoted many periods of his hard-working life to the study of such zone, after 1926. The last study was carried out before his death (which was, as it is well know, on January 5th, 1960). In this paper, at page 351, the velocity values for longitudinal and transversal waves — at intervals of 10 km each — for increasing depth, from 40 to 400 km are reported.

According to Gutenberg's opinion, the minimum velocity for longitudinal waves (7.8 km/sec, at other times he had indicated it as 7.85-7.9 km/sec) should be found at a depth of 80-100 km, while the minimum velocity for transversal waves (4.4 km/sec) should be found at a depht of ca. 150 km (2).

The real waves velocities shall therefore be found within this range (7.9; 4.4 km/sec) respectively for P_a and S_a waves. Such were indeed, the average values which I found for the velocity of these waves in my first work on the subject (1).

However, later on, those who concerned themselves with these waves calculated higher values for their velocity; this started with Ewing and Press who studied them in 1954 separately from Caloi.

Of course, I shall not report here all the results obtained by the various scientists. I shall only mention two of the most accurate among such studies. Magnitsky and Khorosheva (3) processed the P_a and S_a waves's recordings taken by Russian seismic stations, drawn from the study of 9 earthquakes, for epicentral distances between 22° and 150°. The two Russian scientists found dromochrones for the P_a and S_a waves to be straight lines of equations

$$t_{(min)} = 0{,}9558 + 0{,}2205\,\Delta^{\circ} \qquad P_a$$

$$t_{(min)} = 0{,}3780 + 0{,}4180\,\Delta^{\circ} \qquad S_a\,.$$

From these, we may draw the velocities of 8.3 and 4.4 km/sec, respectively for the P_a and S_a.

R. R. Guidroz and R. G. Baker, in a chapter on " Channel Waves " (4) give the following results of P_a and S_a waves transfer times:

$$t_{(min)} = 0{,}85 + 0{,}223\ \Delta_o \qquad P_a$$
$$t_{(min)} = 0{,}96 + 0{,}403\ \Delta^o \qquad S_a$$

whence we may draw for P_a and S_a respectively the velocities of 8.31 km/sec and 4,59 km/sec (Fig. 1).

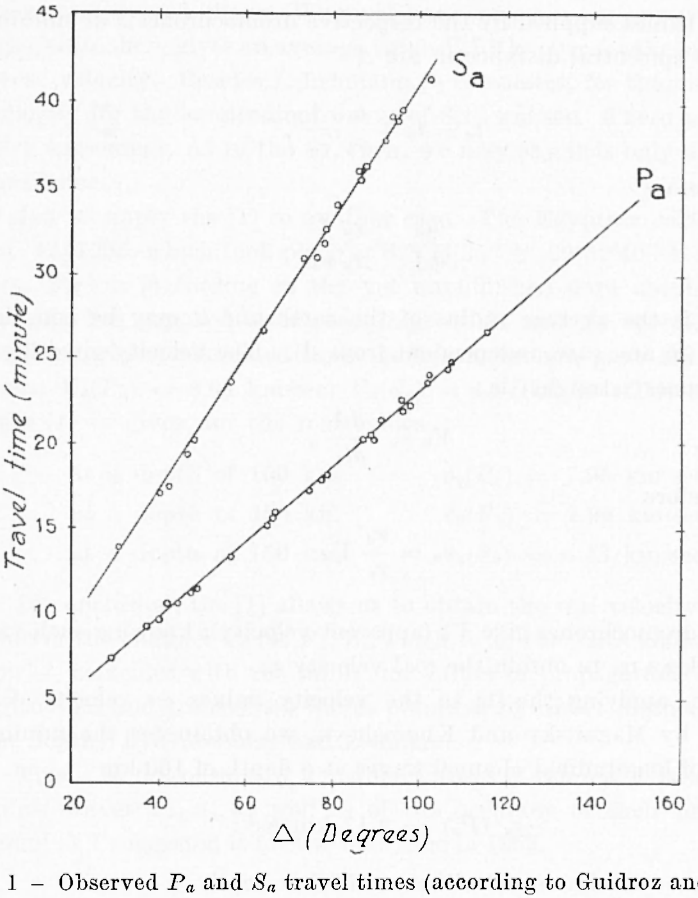

Fig. 1 – Observed P_a and S_a travel times (according to Guidroz and Baker).

On the other hand, this is the average value obtained for the velocity of these waves also in the study of recordings regarding a single earthquake. There seems therefore to exist a remarkable difference between the results achieved by Gutenberg — with methods connected with the propagation of body waves — for the minimum velocities in the astenosphere, and those supplied by the study of channel waves.

But are the velocities drawn directly from the arrival time curves of the P_a and S_a waves really the *true* velocities? It is easy to prove that they actually are only apparent velocities. In fact, if we indicate by r_a the radius of the astenosphere (in its section characterized by the minimum velocity) and by v_a the real propagation velocity on the circumference of such radius, if t_a are the times obtained on the surface for the propagation of longitudinal (or transversal) waves guided by the asthenosphere (times supplied by the respective dromochrones), we obtain (5), being the epicentral distance in arc Δ

$$t_a = t_o + \frac{t_a}{r_o} \frac{\Delta}{v_a} ,$$

and therefore

$$\frac{dt_a}{d\Delta} = \frac{r_a}{r_o} \frac{1}{v_a}$$

where r_o is the average radius of the earth and t_o may be considered constant (in any case, independent from Δ). The velocity given by the dromochrones (straight) is

$$V_a = \frac{d\Delta}{dt_a} ,$$

and therefore

$$v_a = \frac{r_a}{r_o} V_a . \qquad [1]$$

The dromochrones give V_a (apparent velocity); knowing such value, the [1] allows us to obtain the real velocity v_a.

Then, applying the [1] to the velocity values — velocity V_a — obtained by Magnitsky and Khorosheva, we obtain for the minimum velocity of longitudinal channel waves at a depth of 100 km

$$v_a\ (P_a) = 8{,}17 \text{ km/sec} ;$$

for the same minimum velocities at 150 km depth

$$v_a\ (P_a) = 8{,}1 \text{ km/sec} .$$

By calculating the real value of the transversal waves' velocity at 150 km depth, we obtain, on the basis of the apparent velocity obtained by the Russian scientists:

$$v_a\ (S_a) = 4{,}365 \text{ km/sec} .$$

Applying the [1] to the values calculated by Guidroz and Baker, for a minimum velocity at 150 km depth, we obtain

$$v_a(P_a) = 8{,}1 \quad \text{km/sec} ,$$
$$v_a(S_a) = 4{,}48 \ \text{km/sec} .$$

The velocity of the P_a, given lately by Gutenberg, is slightly inferior to the one reported above. We must however point out how, in previous works, Gutenberg gives an average value of 7,9 km/sec for the longitudinal waves' velocity. Besides I. Lehmann (6) calculates, for the same depth, a velocity for the longitudinal waves of 8,12 km/sec. There could be no better agreement. As to the S_a, then, we may say it is only a matter of coincidence.

Let us apply the [1] to another case. The Egyptian earthquake of Sept. 12, 1955, which took place at 32° 24′25″ N, 29°52′40″ E at a depth of ca. 25 km (according to the yet unpublished data obtained by L. Marcelli), has supplied clear recordings of P_a and S_a waves. The apparent velocities, calculated from the dromochrones, gave the following values: $V_a(P_a) = 8.08$ km/sec; $V_a(S_a) = 4.54$ km/sec. The application of the [1] — gives, for the real values:

at a depth of 100 km	$v_a(P_a) = 7.95$ km/sec
at a depth of 150 km	$v_a(P_a) = 7.90$ km/sec
at a depth of 150 km	$v_a(S_a) = 4.43$ km/sec .

In conclusion, the [1] allows us to obtain the *real* velocity of propagation of the channel waves P_a, S_a which — in the cases under consideration — coincides with the minimum values of propagation velocity of longitudinal and transversal waves obtained by direct methods (for the same depths) by Gutenberg and Lehmann.

This is to be considered a further witness of the real existence of the channel waves P_a, S_a, as well as of the accuracy of their propagation system, as I suggested it for the first time in 1953.

2. – In my opinion, the phenomenon of canalization or guide of seismic energy has not thus far received all the attention it deserves. Such phenomenon plays a role of primary importance in the acquisition of new knowledge on the physical and chemical aspects of the upper mantle. This may be achieved only after a careful study of the mantle itself, which is much wider than we are likely to believe so far. This is, however, only my own opinion.

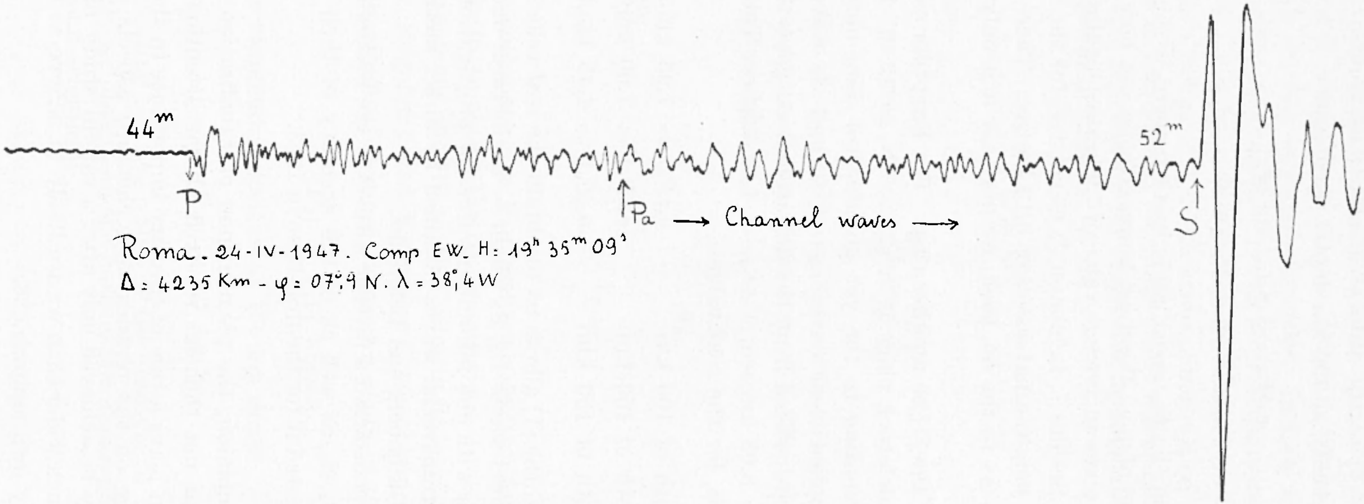

Fig. 2 – Channel waves on mixed path (atlantic and continental).

Being all conditions equal, the canalization concerns specifically the stratifications of the earth crust or the asthenosphere, depending upon whether the earthquake has its origin in the crust or at depths in the range of a few hundreds of km. In the case of earthquakes at intermediate depths, of sufficient intensity, all the upper section of the mantle, from the astenosphere up to the superficial crust stratification becomes the seat of canalization.

Let us consider the following examples.

Ewing, Press, Bath, Gutenberg ... have already shown that the surface stratification of the earth crust conducts transversal waves (L_g, L_R), though their propagation system be variously interpreted (multiples reflections or high-node surface waves according to Ewing, Press, Oliver...; zonal canalization with velocity flexion according to Gutenberg, Bath...).

These types of waves, having a rather short period, do not seem to propagate at great distances. In this very brief exposition, I shall only refer to waves having a rather long period (from ca. 10 seconds upwards).

What I want to show is that such phenomenon is not limited to the astenosphere. See the example supplied by the recordings caused in mediumperiod seismographs (i.e. the Galitzin I.N.G. in Rome) by the earthquake of the submersed dorsal in the Atlantic Ocean, on April 24, 1947 (Fig. 2). It shows very clearly how, beside the P_a, there are other phases which precede the S_a waves and cannot be ascribed to multiple reflections, but only to a part of the seismic energy captured and canalized by the earth crust canals.

In this particular case, as the earthquake has an Atlantic origin, the canalization is initially limited to the astenosphere, but we must believe that it has later on interested also the continental socle area, then extending also to the three continental layers.

But the canalization takes relevant proportions with earthquakes having their origin at about 100 km depth. An extremely interesting witness to this regard is the earthquake of July 25, 1960. See the seismogram reproduced in Fig. 3. It has been recorded by a long-period pendulum (ca. 90 sec.) operating still experimentally at the new seismic station of L'Aquila. This earthquake — (these are its characteristic date: α = 54 °N, λ = 159 °E, H = 11.12.00, h = 100 km ca., M = 7 – Pasadena, Rome) was about 100 km deep. Notice the long uninterrupted sequence of canalized waves from the asthenosphere and from the layers of the earth crust, both longitudinal and transversal. The seismogram may be divided into four separate sections: longitudinal body waves, direct and reflected, having short period (I); channel waves from the astenosphere and the earth crust, with a definitely longer period (II); transversal body waves direct and reflected (III), and transversal channel waves (IV). The last are to be considered the transversal analogues to the channel longitudinal waves of the II section (except the Lowe waves, which are recorded among them).

3. – In the case of deep earthquakes (focused at more than 350 km from the external surface according to Gutenberg's division), is there a possibility of canalization? If so, which zones does it interest?

I have studied, with this purpose in mind, the strong deep earthquake of the Japan Sea, which took place at 40°,0 N — 129°,7 E, on October 8th, 1960, — with an origin time H = 05.53.01,1 — at a depth of ca. 600 km, — according to the U.S.G.G.S. Its magnitude was evaluated, at Pasadena, between 6.5 and 7.5.

Limiting the exam, for the present, to the S_a waves, I noticed in the about 50 seismograms in my possession, and specially among the recordings taken with medium and long-period seismograms, conspicuous examples of transversal channel waves. After resolving their dromochrones with the method of the minimum squares I obtained

$$V_a(S_a) = 4{,}615 \text{ km/sec}$$

whence, by means of the [1],

$$v_a\,(S_a) = 4{,}41 \text{ km/sec} .$$

There are, therefore, channel waves from the astenosphere.

There are among the most evident phases of the seismograms I checked (Figg. 4a-4b); indeed, in many instances, the S_a appears to be the most remarkable phase in the whole seismogram (Figg. 4c-5). This proves that *upwards canalization is not only possible, but it has also the power of conveying a remarkable part of the seismic energy into the astenosphere.*

The S_a vertical component is always very strong (Figg. 4c-4d).

In the earthquake under consideration, no noticeable examples of canalization from the earth crust have appeared.

Finally, the canalization appears to be a general phenomenon, which plays a remarkable role in the propagation of seismic energy. It may concern both the earth crust stratifications and the astenosphere. It is most effective in correspondance of strong earthquakes originated in the astenosphere, that is, it can interest at the same time the crust canals beside the astenosphere.

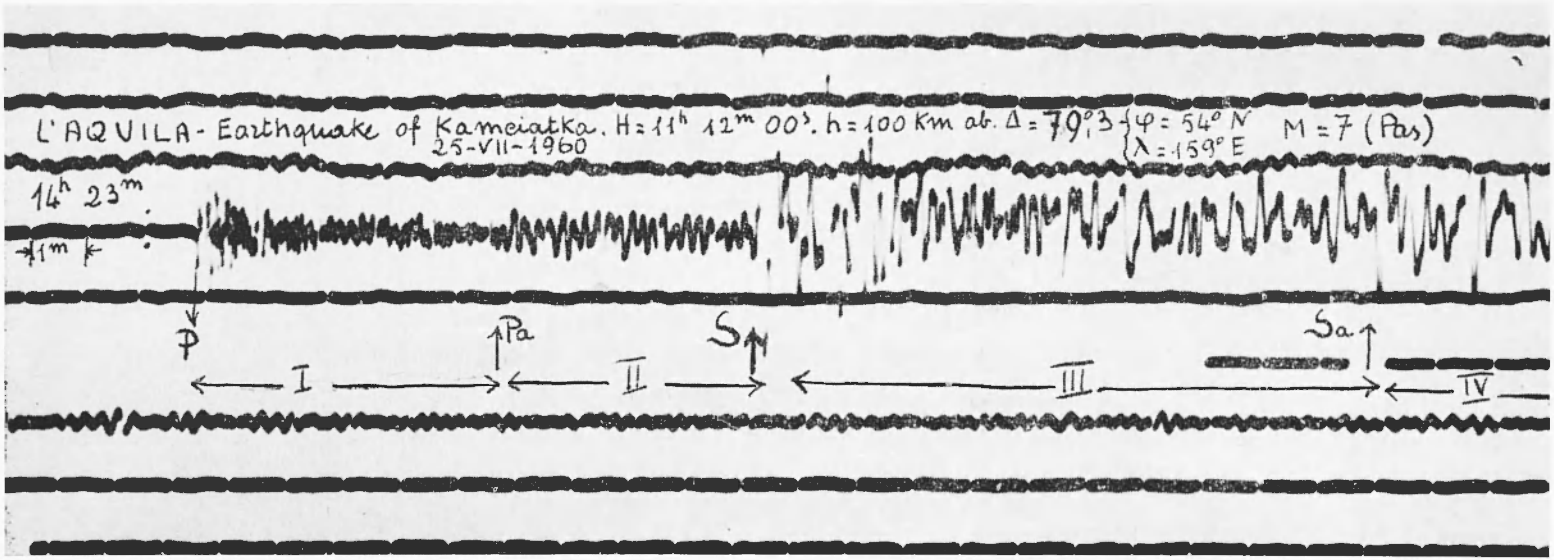

Fig. 3 – Seismic station of L'Aquila-Earthquake of 25th July 1960 – Kameiakta Region. A clear example of canalization concerning the astenosphere and the earth crust. Zone I: direct and reflected longitudinal waves. Zone II: channel waves. Zone III: direct and reflected transversal waves. Zone IV: channel transversal waves (beside L and R waves).

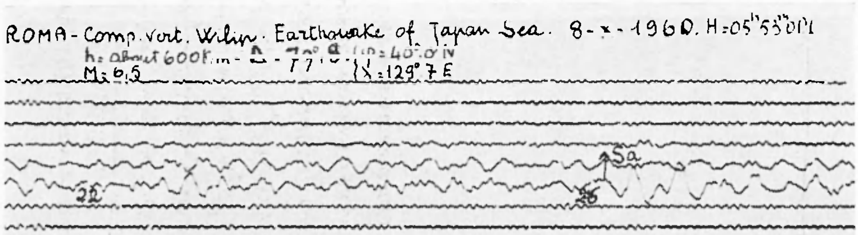

Fig. 4*a* – Records obtained in the seismic station of Rome — Wilip vert. component – Earthquake of 8th October 1960 – Japan Sea.

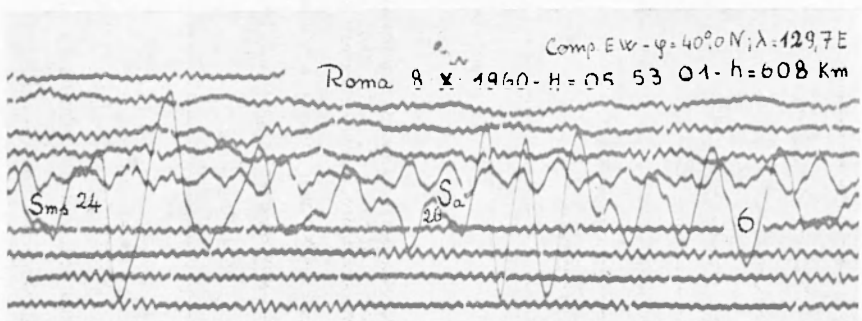

Fig. 4*b* – E-W component – The same earthquake.

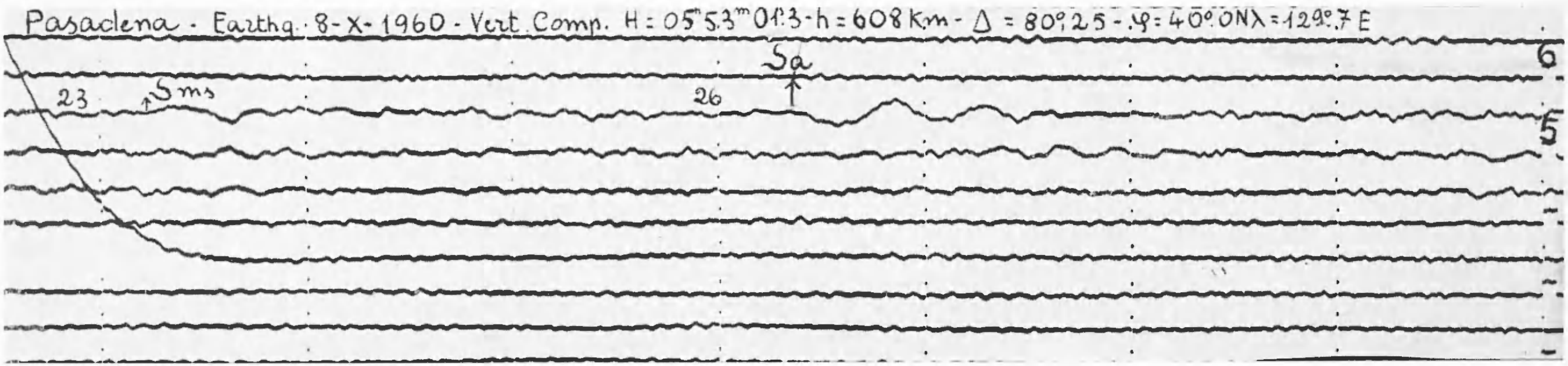

Fig. 4c – The Earthquake of 8 October 1960 – Station of Pasadena. Vert. component.

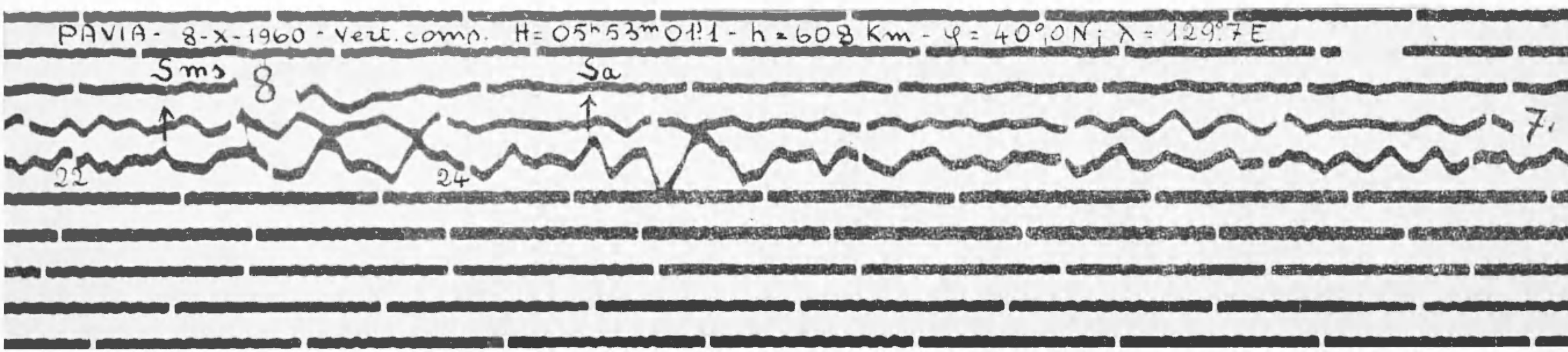

Fig. 4d – Station of Pavia. The same earthquake. Vert. component. In deep focus earthq., S_a appears to be the most remarkable phase in the whole seismogram; S_{ms} shear wave guided by «twenty degree discontinuity».

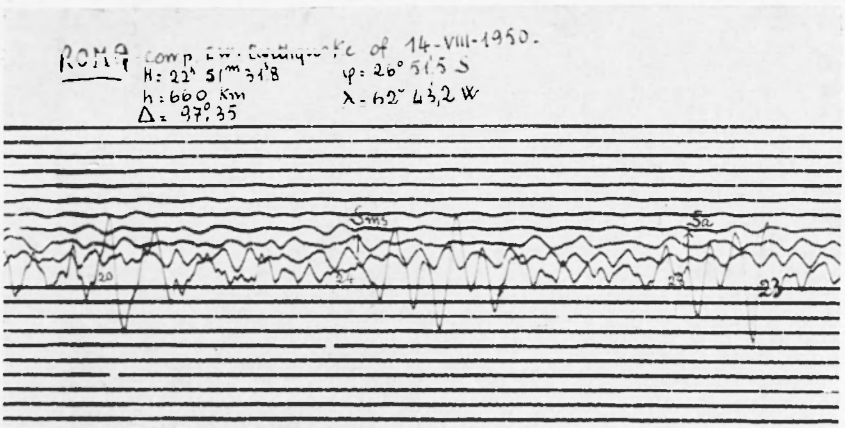

Fig. 5 – Record obtained in the seismic station of Rome – EW component – Earthquake of 14th August 1950.

In the case of deep focus earthquakes, canalization is especially remarkable only in the astenosphere.

RECTIFICATION.

In the last years some authors, while studying the canalization of the seismic waves (Bâth, Vesanen, Anderson) have attributed the discovery of this phenomenon to B. Gutenberg.

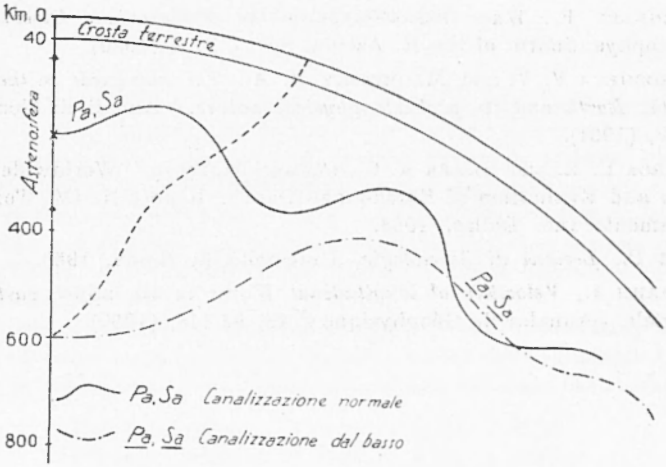

Fig. 6 – Examples of normal and deep focus canalization.

I think that a rectification is necessary. The priority of this discovery is of Caloi, who announced this phenomenon for the first time in 1953. Perhaps the cause of that confusion is due to the caption of Figure 4-7 (a), on pg. 87 of the " Physics of the Earth's Interior " — published by Gutenberg in 1959 — where the Author, quoting the scheme of the canalization, writes in brackets that this scheme has been suggested by Gutenberg (1954) and Caloi (1954).

Of course it is an oversight; in fact that scheme has been already pointed out by Caloi in the first work on this subject, on pg. 353 of the " Rendiconti dell'Accademia Nazionale dei Lincei " (Classe di Scienze fis., mat. e nat.) series VIII, vol. XV, numb. 6, 1953.

By the way that clearly appears in the same test of the book by Gutenberg. Moreover the same Gutenberg (" The asthenesphere low-velocity layer " « Annali di Geofisica », vol. XII, n. 4, 1959), on pg. 413, says what follows: " A very important discovery was made by Caloi (1953, 1954) when he observed and *explained correctly* two new phases . . ."

The note of Gutenberg on the canalization in fact came after the paper of Caloi and appeared for the first time in 1954.

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