Note on Strain Release Variation with Depth

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Ricevuto il 26 Ottobre 1963

Summary. — In the present paper an attempt is made to approach the problem of the upper mantle structure by studying the strain release variation with depth. If the method and data used in this paper are adequate, we may be allowed to say that although there is no strain release evidence for the depth of the upper boundary of the asthenosphere zone on account of lack of adequate accuracy in the determination of focal depths, nevertheless there is ample indication of a discontinuity at about 125 km depth. The abrupt change in the rate of decrease in the strain release with depth near this level clearly indicates that a sudden decrease in the yield strength of the material in the earth should occur at about this depth. It might even be possible to think that the melting point of some kind of crystal grains or rocks in the earth is attained at that depth. However, this does not involve a completely molten state. This state should rather occur at depths where there is a complete lack of strain release. Regionally this state is attained at different depths, but in some regions the partially molten state, i. e. the heterogeneity of the mantle, probably recurs or increases due to the pressure increase or some other reason and reaches a minor maximum beyond which it might be possible to speculate that the heterogeneity of the mantle falls off rapidly and a continuous layer of material in molten state covers the whole earth. If data from other sources will confirm this structure, there will be good reasons to think of redefining the upper boundaries of surface and intermediate shocks at depths of 125 and 425 km or thereabouts, respectively.

Résumé. — La présente note est un essai de rapprocher le problème de la structure du manteau supérieur par l'étude de la variation du soulagement des tensions en fonction de la profondeur. Si la methode et les données utilisées sont suffisantes, nous pouvons nous permettre de dire que malgré l'absence d'une indication de la profondeur de la limite supérieure de la zone de l'asthénoshère, a cause du manque d'une précision suffisante dans la détermination des profondeurs focales, il y a un ample indice d'une discontinuité a la profondeur de 125 km environs. La variation abrupte de la décroissance du soulagement des tensions en rapport à la profondeur près de ce niveau, indique clairement qu'une décroissance brusque de la

résistance des materiaux dans la terre devrait etre apparue environs a cette profondeur. On pourrait penser de meme que le point de fusion de certaines especes de grains cristallins ou de rochers dans la terre est atteint a cette profondeur. Pourtant, ce-ci, ne comprend pas un état de fusion complete. Cette condition peut se manifester plutot a des profondeurs où un soulagement des tensions manque completement. Régionellement cette condition est atteinte a des profondeurs differentes; mais dans certaines régions un retour ou un incrément de l'etat du fusion partielle, c'est a dire de l'hetérogénéité du manteau, dû a l'augmentation de la pression ou a d'autres raisons, peut se produire et atteindre un maximum sécondaire, au dela du quel on peut speculer sur la possibilité que l'heterogenéité du manteau s'efface rapidement et qu'une couche de materiaux a l'etat de fusion couvre toute la terre. Si des donnees provenantes d'autres sources confirment cette structure, il y aurait de bonnes raisons de penser a rédefinir la profondeur sepérieure des sécousses superficielles et intermediaires aux profondeurs respectives de 125 et 425 km environs.

Riassunto. — Nella presente nota si è tentato di affrontare il problema della struttura del mantello superiore della terra, studiando il variare delle tensioni liberate con la profondita.

Se il metodo ed i dati usati sono sufficienti ci si puo permettere di dire che, malgrado non si conosca la profondita del limite superiore dell'astenosfera per l'insufficiente determinazione delle profondita ipocentrali, esistono molte prove dell'esistenza di una discontinuità alla profondita di circa 125 km.

La brusca variazione, intorno a questo livello, del decremento delle tensioni liberate con la profondità, indica chiaramente che, sempre intorno a detto livello, dovrebbe avvenire un'altrettanto brusca diminuzione di resistenza del mezzo. Si potrebbe forse pensare che alla suddetta profondita, si raggiunga il punto di fusione di alcune specie cristalline o di roccia, tuttavia ciò non implica uno stato di fusione completa. Questa condizione può piuttosto manifestarsi ad una profondita dove manchi completamente una liberazione di tensioni.

Regionalmente questa condizione è raggiunta a diverse profondità: ma in alcune regioni lo stato di fusione parziale, cioè l'eterogeneita del mantello, torna a manifestarsi o aumenta a causa di un aumento di pressione o per altre ragioni e può raggiungere un massimo secondario. Al di là di quest'ultimo, dovrebbe essere possibile indagare sull'eventualita che l'eterogeneita del mantello si estingua rapidamente e che uno strato continuo di materiale allo stato di fusione ricopra tutta la terra.

Se dati provenienti da altre fonti confermassero questa struttura, vi sarebbero buone ragioni per collocare il limite superiore della profondità per terremoti superficiali e intermedi, rispettivamente a 125 km e 425 km.

Introduction.

A sufficient number of different methods developed in the last decade indicate the existence of a "low-velocity layer" in the upper mantle. Gutenberg (1948, 1959; for further references consult the latter publication) is the first who endeavoured to prove the existence of this layer by analysing time distance curves for P and S waves and by de-

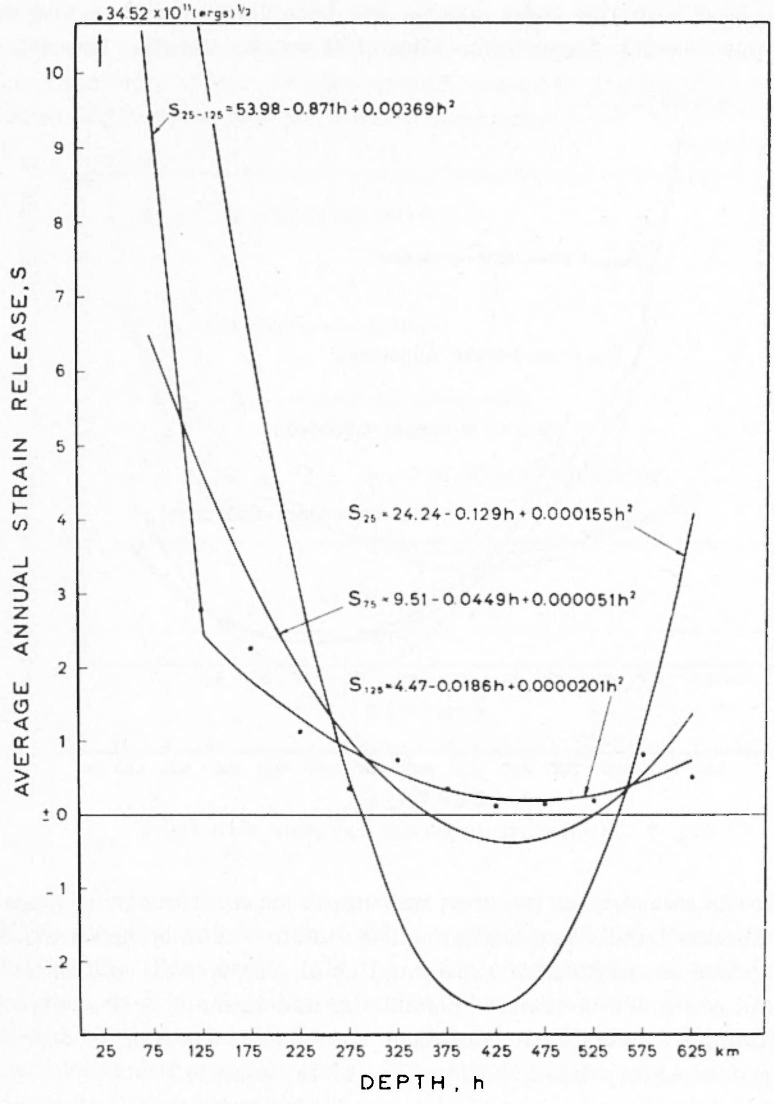

Fig. 1 – Global strain release variation with depth.

fining their " shadow zones ". Caloi (1954) succeded to point out special phases of P and S waves which seem to be guided by a low-velocity channel in the mantle at depths of between 50 and 250 km. Investigations of dispersion of mantle Rayleigh waves by Takeuchi and associates (1959) provided an additional evidence of the existence of the asthenosphere channel. Another support of the hypothesis of a " low-velocity layer " in the upper mantle has been found by Press (1959) from group-velocity dispersion studies of *G* waves. Similar investiga-

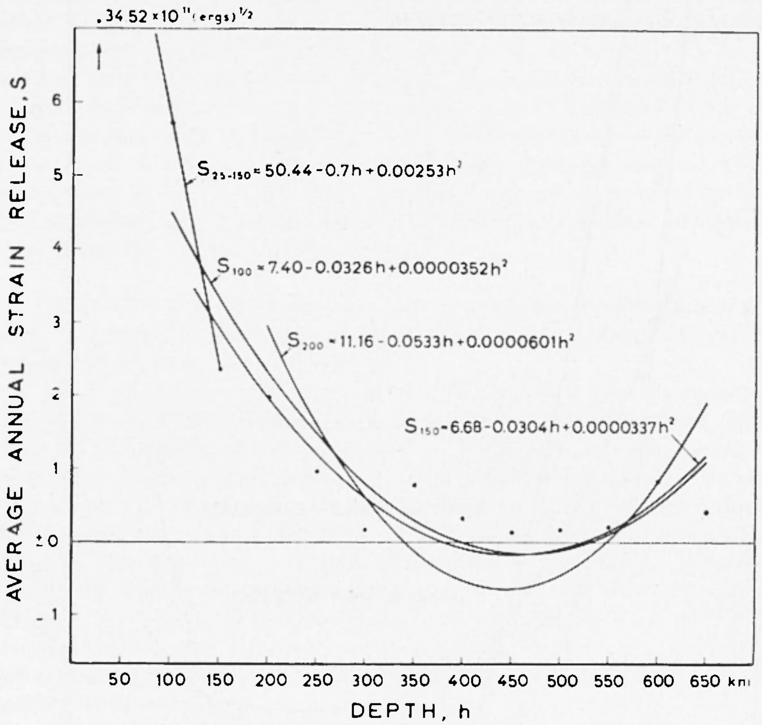

Fig. 2 – Global strain release variation with depth.

tions on the structure of the crust and upper mantle through propagation studies by Landisman and Sato (1958) and by many other scientists (Vesanen and associates, 1959; Dorman et al., 1960; Ness and others, 1961) and controlled tests made possible by underground nuclear explosions (Romney, 1959) have confirmed Gutenberg's concept of a low-velocity, low-rigidity layer near the top of the mantle.

Although the existence of the mantle low-velocity layer is now well established, there is no unanimity for the depth and the thickness of this channel. According to seismic studies hitherto made, it seems highly likely that the depth of the mantle low-velocity layer as well as the depth of isostatic compensation varies from one region to another.

There is also evidence that the asthenosphere low-velocity layer is not a continuous shell covering the whole earth but includes many portions in which a molten or partially molten state is attained (Rikitate, 1962). Regarding this point, it is worth to note that Gass and Mason-Smith (1963), in explaining the pre-Tertialy and perhaps pre-Cretaceous ultrabasic material of the Troodos massif, postulate a complete or partial fusion of the upper mantle in the Cyprus area.

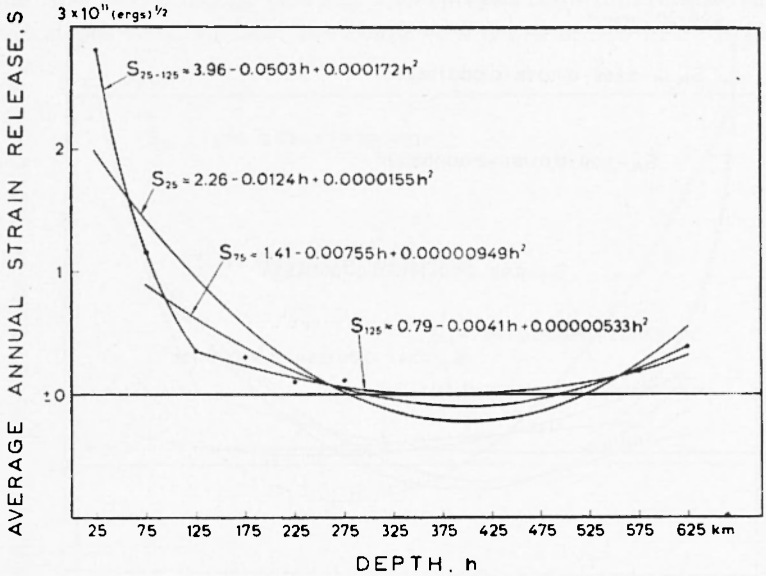

Fig. 3 – Strain release variation with depth in South America.

DATA USED.

In the present paper an attempt is made to approach the problem of the upper mantle structure by studying the strain release variation with depth. Considering that the strain accumulation in each layer is governed to a considerable extent by the state of the layer, it might be possible to get some clues as to the depth and the thickness of the low-velocity asthenosphere channel by plotting global and regional strain release as a function of depth.

The strain release is taken, after Benioff (1951), as proportional to the square root of E. The energy released in the individual shocks was computed by the formula

$$\log E = 11.8 + 1.5\ M\ ,$$

where M is the magnitude and E is the energy of the shock in ergs. The magnitude data were taken from Tables XIII, XIV, XV, and XVI given by B. Gutenberg and C. F. Richter in the " Seismicity of the Earth and Associated Phenomena ", 1954. The Tables include shallow, intermediate and deep shocks of magnitude 7 or over, 1904 to 1952, for the whole world.

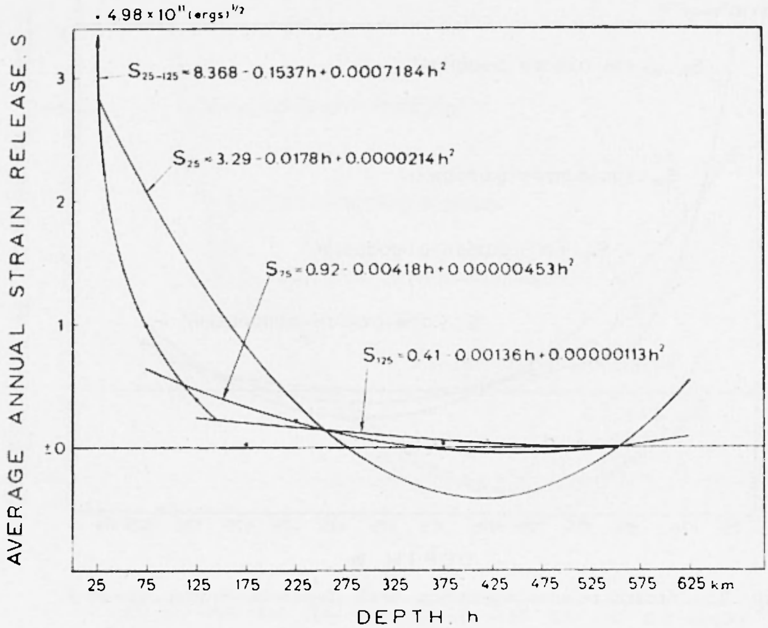

Fig. 4 – Strain release variation with depth in the region Japan to Kamtchatka.

For investigating the strain release variation with depth, the average annual strain release, S, in the depth intervals 0-50, 51-100, ..., 601-650 was calculated in 10^{11} $(\text{ergs})^{1/2}$ units. These values of S were considered as the average annual strain release at the middles of the intervals, that is, at the depths 25, 75, ..., 625 km. Then the same procedure was followed but this time for the depth intervals 76-125, 126-175, ..., 626-675. The calculated strain release at the depth interval 26-75 km, being very uncertain (Gutenberg, 1957), was rejected. All shallow shocks of class a in Table XIII were taken at a depth of 25 km.

RESULTS.

The average annual strain release, S, at various depths, h, was found to fit in two curves both of the type:

$$S = a - bh + ch^2 .$$

The first curve, $S_{25\text{-}125}$ (see Fig. 1), expresses the strain release variation with depth from surface downward to a depth of 125 km. Below this

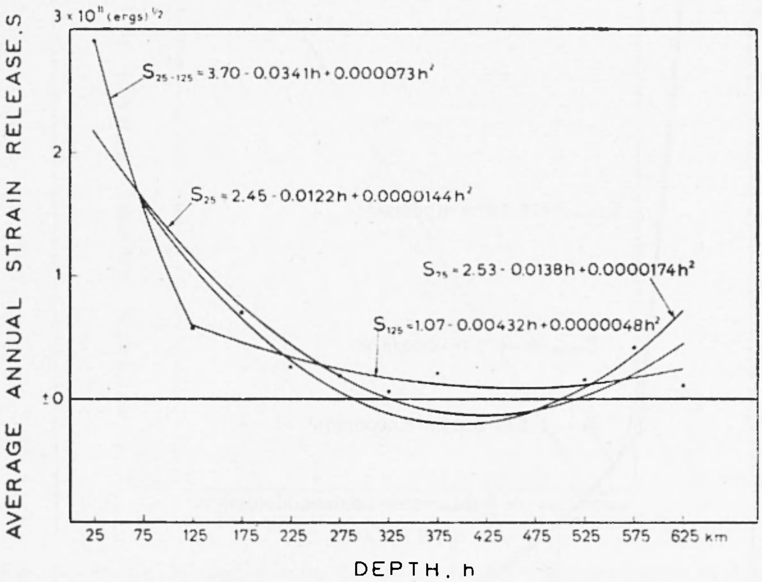

Fig. 5 – Strain release variation with depth in the regions Kermadek-Tonga, Fiji and New Hebrides.

depth the rate of decrease of strain release changes abruptly and the data fit in another curve, S_{125}, of the same type. The regression equation S_{125} is the only one wich gives the strain release variation with depth with the smallest standard deviation of a single observation. The strain release curve $S_{25\text{-}125}$ intersects the curve S_{125} at a depth of about 130 km.

The scattering of the values obtained from the regression equations S_{100} and S_{150} (see Table VI), is comparatively too large. The strain release curve $S_{25\text{-}150}$ (see Fig. 2) intersects the curves S_{100} and S_{150} at depth of about 130 and 140 Km, respectively.

For reasons of comparison we have plotted the annual strain release against depth for different regions of the globe. The magnitude data were taken from the regional Tables XVII and XVIII of shallow, intermediate and deep shocks of magnitude 7 or over for the regions 9 (South America), 19 (Japan to Kamchatka) and 12-14 (Kermadek-

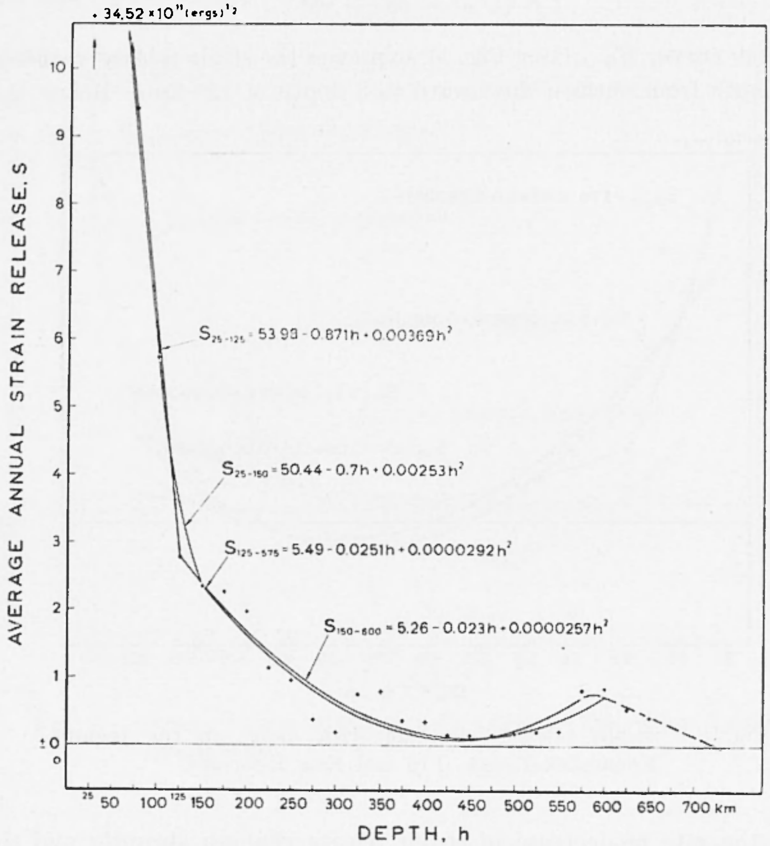

Fig. 6 – Global strain release variation with depth.

Tonga, Fiji and New Hebrides) given by B. Gutenberg and C. F. Richter (1954). Data on shocks of magnitude less than 7 being rather incomplete were not used. All data used fit in two curves $S_{25\text{-}125}$ and S_{125} of the same type. The strain release curve $S_{25\text{-}125}$ for the region 9 and 12-14 (see Fig. 3 and 5) intersects the corresponding curve S_{125} at a depth of about 125 km. In the region 19 (see Fig. 4) the intersection of the two curves occurs at a depth of about 150 km. Thus the rapid downward decrease of the strain release and the abrupt change in the rate of decrease between depths of 125 and 150 km appears to be a common feature for the global and regional strain release variation with depth.

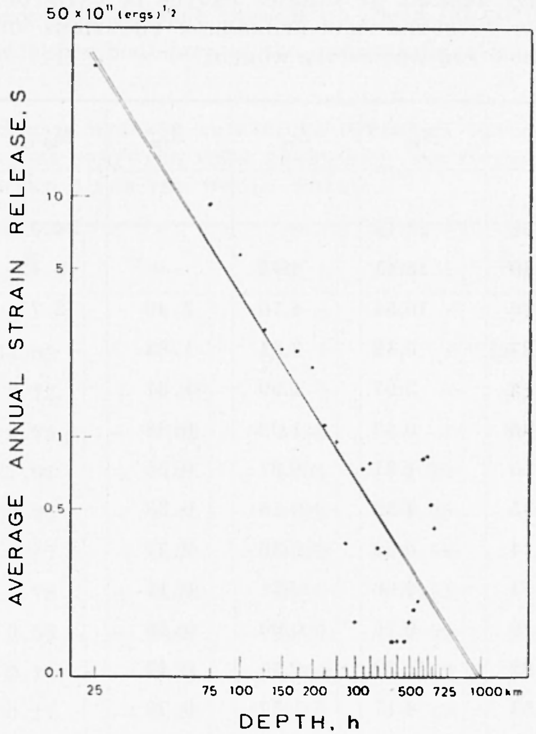

Fig. 7 – Strain release versus depth in double log-coordinate system.

Below the depth of about 125 km the global strain release decreases relatively slowly and reaches to a minimum between depths of 425 and 450 km; below this depth range the strain release increases very slowly to a second minor maximum between depths of 575 and 600 km, beyond which the strain release falls off rather rapidly. These general results are in accordance with those obtained by B. Gutenberg and C. F. Richter (1954) by the use of the total number of shocks listed at various depths.

The regional strain release minimum appears mostly at the same depth level (see Fig. 4 and 5) but there are regions in which the minimum strain release occurs much higher, between depths of 375 and 400 km (South America). There are also regions in which the strain release minimum is near zero and the minor maximum either appears or does not appear at all (see Fig. 4).

Table I – STRAIN RELEASE AT VARIOUS DEPTHS IN UNITS OF 10^{11} (ERGS)$^{1/2}$ AND VALUES COMPUTED FROM REGRESSION EQUATIONS GIVEN IN FIGURES 1 AND 6 FOR THE WHOLE WORLD.

Depth h	S	S_{25}	S_{75}	S_{125}	$S_{25\text{-}125}$	$S_{125\text{-}575}$
25	34.52	+ 21.12	—	—	34.52	—
75	9.40	+ 15.44	+ 6.43	—	9.42	—
125	2.79	+ 10.54	+ 4.70	2.46	2.77	2.81
175	2.27	+ 6.42	+ 3.21	1.84	—	1.99
225	1.13	+ 3.07	+ 1.99	1.31	—	1.32
275	0.36	+ 0.49	+ 1.02	0.88	—	0.83
325	0.75	— 1.31	+ 0.31	0.55	—	0.41
375	0.35	— 2.33	— 0.16	0.33	—	0.19
425	0.14	— 2.58	— 0.36	0.20	—	0.09
475	0.14	— 2.06	— 0.31	0.17	—	0.15
525	0.19	— 0.76	± 0.00	0.25	—	0.36
575	0.82	+ 1.32	+ 0.55	0.43	—	0.71
625	0.53	+ 4.17	+ 1.37	0.70	—	—

If we drop the value of global strain release occurring beyond the minor maximum, the annual strain release below the depth of 125 km fits in the curve $S_{125\text{-}575}$ as well as in the curve $S_{150\text{-}600}$ (see Fig. 6) with almost the same scattering (see Table VI). The strain release curve beyond the minor maximum is just schematic. We are inclined to believe that the strain release decreases to zero not just below the depth of about 720 km below which no foci are known, but at the depth of about 950 km, " where the relatively rapid increase in wave velocity with depth in the outer mantle changes to a more slow increase in its deeper portion " (Gutenberg, 1957). This appears to be well substantiated by plotting S versus h in the double log-coordinate system (see Fig. 7).

Discussion.

If the method and data used in this paper are adequate, we may be allowed to say that although there is no strain release evidence for the depth of the upper boundary of the asthenosphere zone on account of

Table II – Strain release at various depths in units of 10^{11} (ergs)$^{1/2}$ and values computed from regression equations given in figures 2 and 6 for the whole world.

Depth h	S	S_{100}	S_{150}	S_{200}	S_{25-150}	$S_{150-600}$
25	34.52	—	—	—	34.52	—
100	5.72	+ 4.49	—	—	5.74	—
150	2.35	+ 3.30	+ 2.88	—	2.30	2.39
200	1.97	+ 2.28	+ 1.95	+ 2.90	—	1.69
250	0.96	+ 1.45	+ 1.19	+ 1.60	—	1.12
300	0.17	+ 0.79	+ 0.59	+ 0.58	—	0.67
350	0.78	+ 0.30	+ 0.17	— 0.13	—	0.36
400	0.33	— 0.01	— 0.09	— 0.54	—	0.17
450	0.14	— 0.14	— 0.18	— 0.65	—	0.11
500	0.17	— 0.10	— 0.10	— 0.47	—	0.18
550	0.21	+ 0.12	+ 0.15	+ 0.04	—	0.38
600	0.84	+ 0.51	+ 0.57	+ 0.82	—	0.71
650	0.42	+ 1.08	+ 1.16	+ 1.91	—	—

lack of adequate accuracy in the determination of focal depths, nevertheless there is ample indication of a discontinuity at about 125 km depth. The abrupt change in the rate of decrease in the strain release with depth near this level clearly indicates that a sudden decrease in the yield strength of the material in the earth should occur at about this depth. It might even be possible to think that the melting point of some kind of crystal grains or rocks in the earth is attained at that depth. However, this does not involve a completely molten state. This state should rather occur at depths where there is a complete lack of strain release. Regionally this state is attained at different depths, but in some regions the partially molten state, i.e. the heterogeneity of the mantle, probably recurs or increases due to the pressure increase or some other reason and reaches a minor maximum beyond which it might be possible to speculate that the heterogeneity of the mantle falls off rapidly and a continuous layer of material in molten state covers the whole earth.

Table III – Strain release at various depths in units of 10^{11} (ergs)$^{1/2}$ and values computed from regression equations given in figure 3 for the region South America.

Depth h	S	S_{25}	S_{75}	S_{125}	$S_{25\text{-}125}$
25	2.81	+ 1.96	—	—	2.81
75	1.15	+ 1.42	+ 0.89	—	1.16
125	0.36	+ 0.95	+ 0.62	+ 0.36	0.36
175	0.30	+ 0.56	+ 0.38	+ 0.23	—
225	0.10	+ 0.25	+ 0.19	+ 0.14	—
275	0.11	+ 0.02	+ 0.05	+ 0.06	—
325	—	— 0.13	— 0.04	+ 0.02	—
375	—	— 0.21	— 0.09	± 0.00	—
425	—	— 0.21	— 0.09	+ 0.01	—
475	—	— 0.13	— 0.04	+ 0.05	—
525	—	+ 0.02	+ 0.07	+ 0.11	—
575	0.19	+ 0.25	+ 0.21	+ 0.19	—
625	0.39	+ 9.56	+ 0.40	+ 0.31	—

The existence of a very prominent region of low shear velocity between depths of about 100 to 200 km (Gutenberg, 1959), the observed large regional variations in the shear velocity of the upper mantle and the relatively downward increase of shear velocity between depths of about 400 to 500 km (Dorman et al., 1960) appear to support the above suggested structure of the earth. If data from other sources will confirm this structure, there will be good reasons to think of redefining the upper boundaries of surface and intermediate shocks at depths of 125 and 425 km or thereabouts, respectively.

The existence of a discontinuity at about 125 kilometers below the earth's surface is strongly supported by the independent evidence found by Ritsema (1953) from the change of phase of elastic waves at about this depth. Recently Lehmann (1961) found abundant evidence from observations of S at small epicentral distances that in Europe the upper

Table IV – STRAIN RELEASE AT VARIOUS DEPTHS IN UNITS OF 10^{11} (ERGS)$^{1/2}$ AND VALUES COMPUTED FROM REGRESSION EQUATIONS GIVEN IN FIGURE 4 FOR THE REGION JAPAN TO KAMCHATKA.

Depth h	S	S_{25}	S_{75}	S_{125}	$S_{25\text{-}125}$
25	4.98	+ 2.86	—	—	4.97
75	0.88	+ 2.08	+ 0.63	—	0.88
125	0.39	+ 1.40	+ 0.47	0.25	0.38
175	0.03	+ 0.83	+ 0.33	0.20	—
225	0.22	+ 0.37	+ 0.21	0.16	—
275	—	+ 0.02	+ 0.11	0.12	—
325	0.23	— 0.23	+ 0.04	0.09	—
375	0.03	— 0.37	— 0.01	0.06	—
425	—	— 0.41	— 0.04	0.03	—
475	—	— 0.33	— 0.04	0.01	—
525	—	— 0.15	— 0.02	0.01	—
575	—	+ 0.13	+ 0.02	0.00	—
625	—	+ 0.53	+ 0.08	0.00	—

boundary of the low velocity layer in the upper mantle seems to be at a depth of about 140 km. For northeastern America it was assumed tentatively that the low-velocity layer begins at 120 km depth. Dispersion of mantle Rayleigh waves with periods from 100 to 400 seconds shows the minimum velocity occurring at a depth of about 140 kilometers (Press, 1961). On the other hand Love wave phase velocity data indicate that the upper mantle in the Canadian shield has a high-velocity layer with shear velocity of 4.72 kmps down to about 115 km, below wich the low velocity channel has a shear velocity of about 4.5 kmps down to a depth of about 315 km (Brune and Dorman, 1963). *Pn* velocity studies from the data of recent southeast Missouri earthquakes also allow " a low velocity layer for *P* beginning at some depth greater than about 100 kilometers below the base of the crust " (Stauder and Bollinger, 1963).

Table V – Strain release at various depths in units of 10^{11} $(\mathrm{ergs})^{1/2}$ and values computed from regression equations given in figure 5 for the regions Kermadek-Tonga, Fiji and new Hebrides.

Depth h	S	S_{25}	S_{75}	S_{125}	$S_{25\text{-}125}$
25	2.90	+ 2.16	—	—	2.90
75	1.56	+ 1.62	+ 1.60	—	1.55
125	0.58	+ 1.15	+ 1.08	0.60	0.58
175	0.70	+ 0.76	+ 0.65	0.46	—
225	0.26	+ 0.44	+ 0.31	0.34	—
275	0.19	+ 0.19	+ 0.06	0.24	—
325	0.06	+ 0.01	— 0.11	0.18	—
375	0.21	— 0.10	— 0.19	0.12	—
425	—	— 0.13	— 0.19	0.10	—
475	—	— 0.09	— 0.09	0.10	—
525	0.16	+ 0.02	+ 0.09	0.12	—
575	0.42	+ 0.20	+ 0.35	0.18	—
625	0.11	+ 0.45	+ 0.71	0.24	—

Whether now the petrological model for the upper mantle proposed by Ringwood (1962), in the light of recent high pressure experiments that pyroxene in the mantle will break down to olivine + stishovite around 400 km and that olivine will invert to the spinel structure at about 600 km, may account for the observed strain release minimum and the minor maximum at about the same depths is left for further discussion to the specialists. However, it is necessary to mention that the rate of cooling by conduction to the surface is expected to be most rapid between about 400 and 600 km (Birch, 1954). Therefore, the postulated increase or recurrence of the partially molten state in this depth range may be depended upon such cooling.

Table VI – DIFFERENCES BETWEEN GLOBAL AND REGIONAL STRAIN RELEASE VALUES IN UNITS OF 10^{11} (ERGS)$^{1/2}$ COMPUTED FROM REGRESSION EQUATIONS GIVEN IN FIG. 1 TO 6 AND THE CORRESPONDING VALUES DETERMINED FROM MAGNITUDE DATA TAKEN FROM "SEISMICITY OF THE EARTH" BY B. GUTENBERG AND C. F. RICHTER (1954).

Strain Release	N	$\bar{\delta}$	S. E.	S. D.
Global, S_{100}	12	— 0.00	± 0.18	± 0.62
Global, S_{125}	11	+ 0.03	± 0.09	± 0.28
Global, S_{150}	11	— 0.01	± 0.13	± 0.42
Global, $S_{125\text{-}575}$	10	+ 0.01	± 0.08	± 0.24
Global, $S_{150\text{-}600}$	10	+ 0.01	± 0.08	± 0.26
South America, S_{125}	11	— 0.00	± 0.02	± 0.05
Japan to Kamchatka, S_{125} . . .	11	— 0.00	± 0.03	± 0.09
Kermadek-Tonga, Fiji and New Hebrides, S_{125}	11	— 0.00	± 0.04	± 0.13

N = number of depths used;
$\bar{\delta}$ = mean difference;
S.E. = Standard error of the mean;
S.D. = Standard deviation of a single observation.

ACKNOWLEDGEMENTS.

The author wishes to epress his sincere thanks to Drs. W. Stauder and O. Nuttli for reading the manuscript of this paper and to Dr. B. Papazachos for useful suggestions.

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