

Seismological Institute
The University
Uppsala Sweden

Uppsala, July 10, 1963

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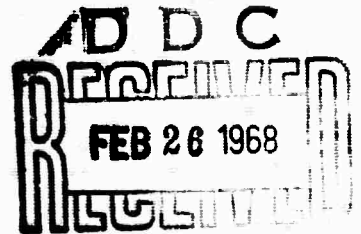
Third Semi-Annual Technical Report

(Report No. 16)

Period Covered: January 1-June 30, 1963

ARPA Order No. 180-62, Amendment No. 7, dated 3 Aug. 1961
Project Code Number: 8100
Name of Contractor: University of Uppsala
Uppsala, Sweden
Date of Contract: 1 May 1962
Contract Number: AF 61(052)-588
Amount of Contract: \$ 19,120.00
Contract Expiration Date: 30 June 1965
Name and Phone Number
of Project Scientist: Dr. Markus Båth
Seismological Institute
30258

Short Title of the Work: Rheologic Properties of the Solid Earth.



the following report

The investigations reported in the 2nd Semi-Annual Technical Report (Report No. 9) were continued during the above-mentioned period in the following directions:

1. strain release studies of the circum-Pacific seismic belt;
2. laboratory studies of the stress distribution in models of geological bodies.

Below we shall present the aim and the results obtained in the reported time interval in these directions of our investigations of the rheologic properties of the solid earth.

1. Strain release studies

a. Aim

The aim was mainly the same as that mentioned in the 2nd Semi-Annual Technical Report (Report No. 9), i.e. to increase our knowledge

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of the dynamics of strain release during earthquake sequences, and the mutual dependence of earthquake activity in adjacent areas. We included also investigations of strain release patterns preceding large earthquakes. The emphasis has usually been concentrated to the dynamics of aftershock sequences in earlier studies. However, it is our belief that much valuable information can be obtained by including phenomena preceding large earthquakes. In addition, a world-wide statistical study of strain release in dependence of depth was carried out for an interval of 35 years, the aim in this case mainly being to see if any weak layers in the mantle would exhibit minima in the strain-depth curve.

b. Results

The paper attached to the 2nd Semi-Annual Technical Report with the title: Strain release in the circum-Pacific belt: Kern County 1952, Desert Hot Springs 1948, San Francisco 1957, by Seweryn J. Duda and Markus Båth has been accepted for publication in the Geophysical Journal of the Royal Astronomical Society, London, England, and is at present in press.

Two additional papers have been prepared: Strain release in the circum-Pacific belt: Chile 1960, by Seweryn J. Duda, and: Strain release in relation to focal depth, by Markus Båth and Seweryn J. Duda. The first paper is favored for publication in the Journal of Geophysical Research, American Geophysical Union, Washington D.C., USA; the second paper, of which the complete manuscript constitutes an Appendix to the present report, is intended for publication in Geofisica pura e applicata, Milan, Italy.

The study of strain release in South America before and during the Chilean earthquake sequence starting on May 21, 1960, supported some older results, and gave some new ones. A distinct concentration of strain release was found towards the northern and southern end of the aftershock area. The segment with decreased activity in between was

slightly displaced in the interval of 32 months following the start of the sequence. The strain-release characteristic exhibits two branches with different shape, clearly separated in time. The strain release in the aftershock sequence occurred in the oscillatory manner previously found for a number of aftershock sequences.

The seismic activity in South America during 40 months preceding the Chilean earthquake sequence exhibited a repeated northward migration of the maximum strain release, the migration velocity increasing with time towards the start of the sequence. Four migration cycles could be observed, the pattern of which was practically destroyed by the beginning of the Chilean earthquake sequence. In particular, the region adjacent to the aftershock area in the north became quiet for more than two years after the start of the sequence.

In the Chilean sequence the totally accumulated strain was released by several strong (main) shocks and a relatively unimportant aftershock sequence, from the energetic point of view. This is in contradiction to some other circum-Pacific aftershock sequences, e.g. Kamchatka 1952 and the Aleutians 1957, where the totally accumulated strain was released by the main shock and a powerful aftershock sequence.

A similar investigation of strain release has been started for Western North America for the time interval 1955-1959. The strain release pattern prior to the strong Alaskan earthquake of July 10, 1958, has several features in common with the strain release in Chile up to May, 1960. Thus, three migration cycles could be stated in the investigated time interval before the Alaskan earthquake. The migration velocity increased towards the start of the sequence. The migration is directed away from the region with highest stress concentration, where later the important strain release occurred. The initial rupture in the main shocks was both in Alaska and in Chile directed oppositely to the migration direction. By the strong Alaskan shock the migration pattern

was also destroyed. A quietness could be observed in the region adjacent to the aftershock area.

This study is not yet finished. A detailed report is planned to be given in the near future.

The study of world-wide strain release in dependence of depth for 35 years was performed with the purpose to see, if the asthenosphere low-velocity layer, known from seismic wave propagation, gives rise to a smaller amount of strain release, than expected from a regular strain decay with depth in the corresponding depth range. The strain release was found to be highest in the uppermost 75 km of the earth. It decreases exponentially with depth between 75 and 400 km. After a pronounced minimum between 400 and 475 km it increases again approximately exponentially between 475 and 650 km. Thereafter it drops rapidly to zero. There is no pronounced minimum corresponding to the asthenosphere low-velocity layer.

The depth curve for the number of shocks is nearly parallel to the strain-depth curve. The average strain per earthquake shows only an insignificant decrease with depth.

As continuation of this part of our work it is planned to carry out a strain-release investigation for one further circum-Pacific earthquake sequence - the Kurile sequence, which started on November 6, 1958, and afterwards for two Asiatic earthquake sequences - the Mongolian sequence which started on December 4, 1957, and the Chinghai Province, China, sequence which started on May 21, 1962. Perhaps some additional smaller sequences will be included. One aspect of this research is to compare the strain released in the main shock to that of the aftershock sequence. We have already seen that these strains are different in different regions. This may give a clue to some of the dynamic characteristics of different seismic regions.

In all this research, Benioff's methods have been of basic importance. However, it would be desirable to improve the methods as far as possible. Especially, we aim at a relation between magnitude of a shock and the volume of strained rock, instead of assuming this volume as constant, as hitherto done in all such studies.

2. Laboratory investigations

a. Aim

Stress distributions in models of geological bodies can be obtained in an analytical form only in the case of simple forms, and usually under the assumption, that the material deformed by the stress is perfectly elastic. On the other hand, earthquake sequences, as well as tectonophysical processes in general, cannot be considered as perfectly elastic processes: it is necessary to introduce the time parameter into the stress-strain relation. This gives rise to essential mathematical difficulties. A different way to get quantitative information about the stress field and its changes with time is an analogue processing. We decided to apply the photoelastic method, first to the steady stress state in perfect elastic bodies, and thereafter in bodies with creep features.

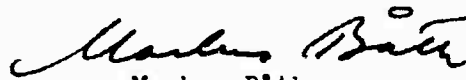
b. Results

Our collaboration with the photoelastic laboratory of the Royal Water Power Board (Kungl. Vattenfallsstyrelsen), Stockholm, gave the first result. A model of a crack in a plate, the plate being sufficiently large to be considered as an infinite plane, was prepared. It was subjected to a uniaxial compression under 45° to the crack axis. The isochromatic fringes were obtained in the polariscope and the principal stresses will be calculated for this case. This experiment permits determination of the stress distribution in the presence of shear stress at the crack. On the other hand, the analytical expressions

for the stress distribution, as given by C.E. Inglis (Stresses in a plate due to the presence of cracks and sharp corners, Trans. Inst. Naval Architects, Vol. 55, Pt. 1, 1913, pp. 219-230), and K. Wolf (Beiträge zur ebenen Elastizitätstheorie, Zeitschrift f. techn. Physik, Vol. 2, No. 8, 1921, pp. 209-216) are calculated under the assumption, that the crack boundaries are free. Our picture of isochromatic fringes was attached to the Ninth Monthly Status Report (Report No. 12). The experiments can easily be varied from pure tangential to pure normal stress at the crack.

The experiments, thus far performed, give the stress distribution in the static case. It is naturally of interest to enlarge these experiments, so as to be able to study also the dynamic processes at a crack, resembling the earthquake phenomena as much as possible, including the time factor. Different models, e.g. with zones with decreased strength, as well as varying stress fields are envisaged.

The third item of our investigations of the rheologic properties of the solid earth, i.e. the development of methods to measure stress and strain variations in the earth's crust, was not advanced much in the reported time. We have again consulted Professor Hast in Stockholm about his stress measurements and hope to embark on these problems in more detail when items 1 and 2 have been more advanced or finished.



Markus Bâth

Markus Bâth

Project Scientist

A P P E N D I X I

STRAIN RELEASE IN RELATION TO FOCAL DEPTH

Markus Båth and Seweryn J. Duda

Seismological Institute

University of Uppsala

Uppsala, Sweden

Contract No. AF 61(052)-588

July 10, 1963

PREPARED FOR

GEOPHYSICS RESEARCH DIRECTORATE

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

OFFICE OF AEROSPACE RESEARCH

UNITED STATES AIR FORCE

BEDFORD, MASSACHUSETTS

WORK SPONSORED BY ADVANCED RESEARCH PROJECTS AGENCY

PROJECT VELA-UNIFORM

ARPA Order No. 180-62

Project Code No. 8100, Task 2

Intended for publication in *Geofisioa Pura e Applicata*, Milan, Italy

Markus Båth, Project Scientist

STRAIN RELEASE IN RELATION TO FOCAL DEPTH

by MARKUS BÅTH ^(x) & SEWERYN J. DUDA ^(xx)

Summary - The world-wide strain release in relation to focal depth has been calculated for all shocks with magnitude 7 and over for the interval 1918-1952. The strain exhibits a strong maximum in the uppermost 75 km of the earth; it decreases exponentially with depth between 75 and 400 km, with an unimportant minimum corresponding to the asthenosphere low-velocity layer and another minimum at 275 km; after a pronounced minimum between 400 and 475 km it increases again approximately exponentially between 475 and 650 km, after which it drops rapidly to zero. The shape of the strain-depth curve is interpreted in terms of the physical conditions and the intensity of strain accumulation. In particular, the increase between 475 and 650 km is ascribed to a combined effect of temperature and pressure variation with depth with related phase changes and possible changes in composition. The depth curve for the number of shocks is nearly parallel to the strain-depth curve, and the average strain per earthquake shows only an insignificant decrease with depth.

Zusammenfassung - Es wird die Tiefenabhängigkeit der Deformationsauslösung in allen Erdbeben mit Magnitude 7 und darüber, im Zeitraum 1918-1952 untersucht. Die Deformationsauslösung hat ein ausgesprochenes Maximum in den obersten 75 km. Sie nimmt im Tiefenbereich zwischen 75 und 400 km exponential mit der Tiefe ab, wobei sich ein Minimum, das der

^(x) Dr. MARKUS BÅTH, Seismological Institute, Uppsala, Sweden.

^(xx) Mr. SEWERYN J. DUDA, Seismological Institute, Uppsala, Sweden.

On leave from SEISMOS G.m.b.H., Hanover, Germany.

Schicht mit niedriger Wellengeschwindigkeit entspricht, schwach angedeutet, und ein zweites Minimum bei 275 km liegt. Nach einem ausgeprägten Minimum zwischen 400 und 475 km Tiefe, steigt die Deformationsauslösung erneut, etwa exponential, im Tiefenbereich zwischen 475 und 650 km an, und nimmt danach schnell ab. Der Verlauf der Deformationsauslösung in Abhängigkeit von der Tiefe wird an Hand der physikalischen Verhältnisse im Erdkörper, sowie der Intensität der Deformationsaufspeicherung gedeutet. Insbesondere wird der Anstieg zwischen 475 und 650 km einer Änderung der Temperatur und des Druckes mit der Tiefe, bei Phasensprung und möglicher Änderung in der Zusammensetzung des Materials zugeschrieben. Die Tiefenabhängigkeit der Anzahl der Beben und der Deformationsauslösung verlaufen annähernd parallel; die mittlere Deformationsauslösung pro Erdbeben zeigt lediglich eine unbedeutende Abnahme mit der Tiefe.

1. Introduction - There is no doubt that seismological measurements offer the most reliable information about the physical conditions of the earth's deep interior. Determinations of travel times of seismic waves and of seismic wave velocities in the earth's interior constitute the most important contribution of seismology in this respect. But it is clear that amplitude measurements will furnish additional information of great value. For instance, attenuation of seismic waves depends on the material properties and it is often related to the frequency of the waves, causing a selective attenuation with ensuing changes of the wave spectrum during propagation.

Another application of amplitude measurements is made in determinations of magnitudes and strain release in earthquakes. The present paper is concerned with this problem, in particular the variation of the strain release with depth and its possible relations to the physical conditions. A starting-point for this piece of research was the question if any weak

layers with increased plastic flow would show up as minima in the curve relating strain release to focal depth.

Strain characteristics of the earth's interior have been studied earlier by several other authors (see e.g. BENIOFF & GUTENBERG, 1951, BENIOFF, 1954; GUTENBERG, 1958 a, 1959). Earthquake energy in relation to focal depth was studied by GUTENBERG (1956, 1957). To our knowledge, the only earlier investigation of strain-depth relations has been published by RITSEMA (1954). The present paper, however, differs from that one in several respects, as in methods used and in the discussion of the results.

2. Observed depth relation of strain release and of number of earthquakes - The material listed by GUTENBERG & RICHTER (1954) was used. In order to get a homogeneous set of data, we restricted ourselves to earthquakes with magnitude $M \geq 7$ in the interval 1918-1952. No separation according to earthquake regions has been made, as we only aimed at the world distribution of strain release with depth.

In calculating the strain release S , we used for comparison purposes the same formulae as in earlier similar studies, i.e., with J = seismic wave energy,

$$(1) \quad S \sim \sum J^{\frac{1}{2}}$$

extending the sum over all earthquakes of given depth in the range of time and magnitude as already defined, and

$$(2) \quad \log J^{\frac{1}{2}} = 4.5 + 0.9 M$$

Only logarithms to the base 10 are used in this paper.

Equation (1) implies that the following quantities are constant:

(a) the fraction of potential strain energy converted into seismic wave energy; (b) the elastic parameters; (c) the volume of strained rock for every earthquake (compare BATH & BENIOFF, 1958). The elastic

parameters certainly vary with depth, but within the depth range of 33-600 km the square root of the elastic parameters concerned varies roughly between 0.8 and 1.1. For this reason, assumption of constant elastic parameters is very well permitted in a first approximation and does not at all change the more important trends of the strain-depth curve. With regard to (c) it is known that the volume increases with the magnitude, but no very reliable relation has so far been given, and the assumption of constant volume is equally permitted in a first approximation. Effects of the factor (a) are discussed below.

Fig. 1 shows the results of the computations. The strain as well as the number of shocks with $M \geq 7$ has been plotted for every 25 km in depth, i.e. corresponding to the approximate accuracy of focal depth determinations.

The strain-depth curve in Fig. 1 exhibits a series of features for different ranges of the depth h :

(a) $h < 75$ km. The depths of shocks in this range are not well known and given only sparsely by GUTENBERG & RICHTER (1954). As a consequence no reliable curve can be constructed for this range. The total strain in this range is known with the same accuracy as for greater depths, but the depth variation is uncertain. In Fig. 1 a logarithmic decrease with depth is tentatively traced. Anyway, it is clear that the strain release far exceeds that of any greater depths and decreases with depth more rapidly than at greater depths. It is likely that the strain has a maximum at some shallow depth, perhaps around 25-30 km, and decreases to a low value closer to the surface of the earth ($h = 0$). This interpretation would agree with MATSUSHIMA's (1961) results. KONING's (1953) frequency-depth curve exhibits a relative minimum at 60-80 km and a relative maximum at 120 km depth, which is probably only an effect of insufficient knowledge of focal depth, especially in the shallower range.

(b) $75 \text{ km} \leq h \leq 400 \text{ km}$. The logarithm of the strain shows an approximately linear decrease with depth. A least-square solution, illustrated by the straight line A in Fig. 1, yielded the following equation, disregarding the proportionality factor in eq. (1):

$$(3) \quad \log S = (2.85 \pm 0.36) - (0.0040 \pm 0.0010) h$$

the unit for S being $10^{10} \text{ (ergs)}^{\frac{1}{2}}$. There are some superimposed variations in the lower part of this range, especially a minimum at $h = 275 \text{ km}$. However, the number of earthquakes is also quite small in this range, and greater fluctuations are to be expected. Local influences are then greater, and this minimum may for instance largely depend on the depth distribution in the Japanese area (see GUTENBERG & RICHTER, 1954).

(c) $400 \text{ km} < h < 475 \text{ km}$. There is no earthquake with $M \geq 7$ in this range and consequently no corresponding strain.

(d) $475 \text{ km} \leq h \leq 650 \text{ km}$. The strain exhibits a pronounced increase with depth, approximated here by the straight line B in Fig. 1, which corresponds to our least-square solution:

$$(4) \quad \log S = (-1.68 \pm 0.28) + (0.0054 \pm 0.0017) h$$

(e) $h > 650 \text{ km}$. There is no shock with $M \geq 7$ in this range. As is well known, no shock deeper than 720 km has been recorded, and the strain disappears completely at this depth and below.

Fig 1 shows also the depth variation of the number N of earthquakes with $M \geq 7$. This curve exhibits almost perfect parallelism with the strain-depth curve. This will be approximately true even if we had chosen a lower magnitude limit, because of the statistics given by GUTENBERG & RICHTER (1954, p. 17, eqs 5 and 6) for the earth as a whole. This means that the variation of strain with depth is mainly a consequence of the variation of the number of shocks with depth. As a result, the average strain release per earthquake, i.e. S/N , also given

in Fig. 1, shows only an insignificant decrease with depth. The least-square solution for the depth range $40 \text{ km} \leq h \leq 650 \text{ km}$ is shown by the straight line C in Fig. 1 and has the equation:

$$(5) \quad S/N = (11.97 \pm 2.94) - (0.0037 \pm 0.0033) h$$

There is only a minor decrease of the maximum magnitude with focal depth, as is evident from the following table:

| | | | | | | | | | | | |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| h km | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 500 | 550 | 600 | 650 |
| M max | 8.0 | 8.0 | 7.8 | 7.3 | 7.2 | 7.8 | 7.8 | 7.2 | 7.3 | 7.8 | 7.6 |

3. Physical interpretation of the strain-depth curve - Even if

our curves probably represent fair approximations to the general conditions within the earth, it must be born in mind that they are strictly true only for the limited interval of 35 years considered. In evaluating the physical implications of our results, we have to consider that only strain which has produced elastic waves, is involved in our observations. This strain depends on two main factors:

(a) The strain accumulation. Without accumulation, there will naturally be no release. The strain accumulation depends on slow relative motions in the earth's interior, the reasons for which we do not need to consider in this connection.

(b) The mode of strain release. Depending on their physical condition, the rocks are able to store larger or smaller amounts of strain. With increasing depth, plastic flow processes will become more and more important. Ultimately, they are prevailing and no (shearing) strain can be stored for any length of time of importance for earthquake generation.

Obviously, the variation of strain with depth depends on both factors, (a) and (b), which both vary with depth. This presents a major difficulty in interpreting the empirical strain-depth curve. If

(a) varies but (b) is constant, the frequency of shocks N will vary in parallelism with the intensity of strain accumulation, whereas the maximum magnitude will be essentially constant. Variations of magnitude require variations of the factor (b). Our empirical results would thus indicate that variations of (a) rather than of (b) are of dominating influence on our strain-depth curve.

The case with constant (a) but variable (b) can be better grasped with the following simple consideration. Compare two cases, 1 and 2, both having the same rate of strain accumulation, i.e. the same (a), but with more of plastic flow processes in 2 than in 1, i.e. (b) is different. Denoting the two cases by indices 1 and 2 and applying the equation for J expressed in M , we have

$$(6) \quad \log (N_1 J_1 / N_2 J_2) = b(M_1 - M_2) - \log (N_2 / N_1)$$

with the constant $b = 1.8$ according to eq. (2) but $= 1.4-1.5$ according to more recent determinations. In eq. (6) we have for simplicity assumed constant magnitudes: M_1 in case 1 and M_2 in case 2, corresponding to the breaking strength in the two cases. We now have that $M_1 > M_2$, because of the lower breaking strength in case 2. Moreover, the total strain energy is the same in the two cases, as (a) is the same. But, part of the total strain is dissipated by plastic flow in case 2, and therefore the fraction of total strain converted into elastic wave energy is then less, i.e. $N_1 J_1 / N_2 J_2 > 1$. Eq. (6) then reduces to the following condition:

$$(7) \quad b(M_1 - M_2) > \log (N_2 / N_1)$$

Thus, N_2 may be greater than N_1 , up to a limit defined by eq. (7). But it is not necessary that N_2 exceeds N_1 , contrary to some statements in the literature that a zone with lower breaking strength should be accompanied with a larger number of shocks.

In the real earth the cases 1 and 2 do not exist isolated but

may be adjacent to each other, which will modify the situation to some extent. If a layering corresponding to 1-2-1, i.e. a weak layer between two stronger layers, is subjected to a shearing strain, it will first break in the layer 2, i.e. the whole structure will roughly behave as only composed of its weakest material. This means that the effects of a weak layer extend upward and downward probably several times its own thickness. Beyond a certain distance the weak layer has no longer any effect on the strain release.

Penetrating into more detail, however, the conditions are rather complicated. The factors (a) and (b) cannot be considered as independent of each other. The time factor is of importance, and in fact (b) has to be taken as dependent on the factor (a). A given material under given physical conditions will behave differently according to the rate of strain accumulation.

The large strain release within the crust and upper mantle down to about 75 km depth is explained by large strain accumulation (in active earthquake areas) combined with large ability of strain storage. According to GUTENBERG & RICHTER (1954), "isostasy and post-glacial uplift indicate that the strength (resistance to plastic flow) below 80± kilometers is less than 1/100 of that near the surface".

The existence of the asthenosphere low-velocity layer at depths around 100-200 km is now generally recognized from wave propagation studies. It is considered as a weak zone, where one should expect plastic flow processes to be more important. The zone is characterized by minima of elastic wave velocities and of elastic parameters (BATH, 1956). However, our strain-depth curve does not exhibit any clear minimum to be ascribed to the asthenosphere low-velocity layer. There is only a small superimposed minimum between the depths 100 km and 225 km.

A probable reason is that the material in the asthenosphere still has sufficient strength to accumulate considerable amount of strain.

Various geophysical effects of a soft or weak layer in the upper mantle have been discussed by SCHEIDEGGER (1960), HALES (1961), SHIMOZURU (1963) and others. In evaluating effects of such a layer it is naturally essential to consider the time factor.

The strain minimum at 275 km depth could possibly be due to a weak layer in this depth range.

The most significant feature of the strain-depth curve is the pronounced minimum in the depth range of 400-475 km. Our curve is summed up for the whole earth. In many earthquake regions there are no deep shocks, i.e. the secondary maximum below 475 km does not occur. The reason is probably lack of strain accumulation at these depths in many regions. The accumulation is unevenly distributed over the surface of the earth, and its variation with depth is most likely also different in different areas. On the other hand, the physical properties at these depths in the earth are probably the same everywhere. In other words, the lack of deep earthquakes in some regions is rather to be ascribed to lack of strain accumulation than to plastic flow processes.

It remains to be explained why the material behaves in such a way as to give a pronounced strain minimum at 400-475 km depth and a strong increase between 475 km and 650 km. BULLEN's (1947) results indicate a second order discontinuity at a depth of 413 km with rapid downward increases of wave velocities, density and elastic parameters. This would imply increased strength of the material, possibly due to phase changes or changes in composition (BIRCH, 1961; RINGWOOD, 1962). For the interval 475-650 km this increase of strength will counteract the general tendency towards plastic flow with depth and will correspond to a greater ability to store strain. Below 650 km, plastic flow

processes again dominate the picture.

The strain increase between 475 km and 650 km may thus be traced back to the combined effect of pressure, temperature, phase changes and/or changes in composition. Increased pressure generally means increased strength, whereas increased temperature means decreased strength (MATSUSHIMA, 1961). If within the interval mentioned, the pressure effect dominates over the temperature effect, this would explain our results. As a matter of fact, the ratio of pressure increase (dp) to temperature increase (dT) with depth, increases rapidly below 400 km depth. Combining BULLEN's (1947) pressure curve and GUTENBERG's (1951) temperature curve, we find the values given in Table 1. With P = breaking strength, the condition for increasing strength without change of phase or composition is:

$$(8) \quad dp/dT > - (\partial P/\partial T)_p : (\partial P/\partial p)_T$$

Unfortunately, lack of knowledge of numerical values of the partial derivatives under the extreme conditions at great depth prevents further calculations. In addition, pressure and temperature variations with depth will determine any phase changes that may occur. If the phase change possibly in combination with a change in composition is spread out over a depth range of several hundred kilometers, it is not necessary to have a second order discontinuity, i.e. the velocity curves could be more in agreement with those of GUTENBERG (1958 b).

On the other hand, as emphasized by GUTENBERG (see BENIOFF & GUTENBERG, 1951), "deep-focus earthquakes do not necessarily require appreciable strength for an accumulation of stresses, but a high coefficient of viscosity is sufficient to permit the required accumulation of strain".

Explanations in terms of special strain accumulation patterns could also be imagined, but these could hardly be pushed above the purely

hypothetical level (see e.g. HESS, 1951).

4. Conclusions - The world-wide strain release in relation to focal depth for all earthquakes with $M \geq 7$ in the interval 1918-1952 has revealed the following features:

- (a) The maximum strain occurs within the uppermost 75 km of the earth, due to a combination of strong strain accumulation (in seismically active areas) and good possibilities of strain storage.
- (b) The asthenosphere low-velocity layer produces only a small, almost insignificant minimum in the strain-depth curve.
- (c) There is a secondary strain minimum at 275 km.
- (d) There is a pronounced minimum at 400-475 km depth with a rapid increase downwards between 475 and 650 km. These features are probably associated with the depth variation of pressure and temperature, in combination with possible phase changes or changes in composition.
- (e) The strain curve is almost parallel to the curve showing the variation of number of shocks with depth.
- (f) The average strain release per shock is practically independent of depth, the decrease found being statistically insignificant.

Acknowledgment - The research reported in this paper was carried out at the Seismological Institute, Uppsala, with the support and sponsorship of the Cambridge Research Laboratories of the Office of Aerospace Research, United States Air Force, through its European Office, as part of the Advanced Research Project Agency's Project VELA UNIFORM, under Contract No. AF 61(052)-588, the support and sponsorship being gratefully acknowledged.

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(Received July , 1963)

TABLE 1 - dp/dT for various depth ranges.

| h km | dp/dT 10^8 dynes/cm ² degree |
|---------|--|
| 200-300 | 3.5 |
| 300-400 | 4.4 |
| 400-600 | 8.7 |

(Caption for the figure 1)

Fig. 1 - Strain release, number of earthquakes and average strain in relation to focal depth.

Fig.1

