Evidence for the seat of the strain-producing forces

A. G. GALANOPOULOS

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SUMMARY. — Evidence is presented which favours the theory that the seat of the strain-producing forces is in the low-rigidity layer near the top of the mantle.

RIASSUNTO. — La nota serve a confermare la teoria secondo la quale le forze deformanti vengono localizzate nello strato a bassa rigidità, prossimo al mantello superiore (sotto la superficie di Mohorovicic).

INTRODUCTION.

Báth and Duda (1964) in an effort to improve Benioff's method (1951a), being developed for strain release studies, were led to the conclusion that the earthquake volume $V$, identified with the total aftershock volume, increases with magnitude $M$, according to the following equation:

$$\log V = 9.58 + 1.47 M.$$  

For the aftershock area $S$, Báth and Duda derived a new equation:

$$\log S = 4.95 + 1.21 M,$$

which improves a previous relation:

$$\log S = 5.09 + 1.02 M,$$

found by Utsu and Seki (1955). Considering that $V = LWH$ and $S = LW$, where $L$, $W$ and $H$ are respectively, the length, the width and the vertical extent of aftershock zone in cm, we may immediately
derive from the two relations given by Bäth and Duda for the earthquake volume and the aftershock zone, the following expression:

$$\log H = 4.63 + 0.26 M.$$ 

The equation derived implies that for earthquakes of magnitude 7.7 to 8.7 the vertical extent of aftershock zone reaches to at least 43 to 78 km depths. Taking this for granted and another very interesting result of Bäth's and Duda's investigation that "The ratio of fault plane area to the vertical section through the aftershock zone, i.e. $F/L_H$, increases with magnitude, approaching unity for the largest shocks"; it might be concluded that the middle of the fault plane of the great shocks is – at least in most cases – immediately below the Mohorovite discontinuity, i.e. in the low-rigidity layer near the top of the mantle. This implication is strongly supported by the fact that all shocks of magnitude $> 7$ occurred in the area of Greece are of intermediate focal depth.

The Alaskan earthquake of March 27, 1964, with Richter magnitude of 8.4 to 8.6, had a focal depth of about 50 km. In a recent investigation, F. Press (1965) was led to the conclusion "on the basis of the very gradual reduction of vertical deformation with distances that the fault could not have extended to depths as shallow as 50 km and that 100 to 200 km are more likely values. The fault probably came to within 15 to 25 km of the surface". Thus the vertical extent found for the fault of the Alaskan earthquake exceeds the values previously found for other earthquakes. According to Press "The larger magnitude associated with the Alaskan earthquake ($M = 8.4$) as compared with the others may partially explain the difference".

The fact that mantle surface waves and free oscillations are excited only by the larger earthquakes strengthens the notion that the primary faulting associated with these shocks extends far below the earth's crust.

Another evidence are the empirical relations of $I_k$ to $M$ derived for constant depths of loss by V. Kneel (1964):

$$h = 3 - 5 \text{ km, } M = 0.36 I_k + 0.45$$
$$h = 6 - 10 \text{ km, } M = 0.36 I_k + 0.83$$
$$h = 11 - 15 \text{ km, } M = 0.37 I_k + 0.83$$
$$h = 19 - 30 \text{ km, } M = 0.39 I_k + 1.75$$
$$h = 31 - 50 \text{ km, } M = 0.49 I_k + 2.36$$
$$h = 51 - 82 \text{ km, } M = 0.29 I_k + 3.77 \text{ (}M_{\text{al}}\text{ without } \gamma M\text{)}$$
$$h = 83 - 150 \text{ km, } M = 0.33 I_k + 3.23 \text{ (}M_{\text{al}}\text{ without } \gamma M\text{)}$$
The relations derived for \( M = M_{LH} + \frac{1}{2}M^2 \) without depth corrections, \( M_{LH} \), have approximately a common intersection near \( I = XI \) and \( M = 7 \). This implies that in case of shallow shocks the maximum intensity ever observed, \( I = XI \), is attained by shocks of magnitude 7; in other words there are no shallow shocks with magnitude greater than 7.

**DATA USED.**

In the following table we give all shallow and intermediate earthquakes of magnitude \( \geq 5^{1/2} \) occurred in the area of Greece during the 120-years interval, 1843-1962, for which period the available data were proved to be fairly homogenous. In the intermediate earthquakes we have included all earthquakes of focal depth \( \geq 40 \) km.

During the time interval considered there were released: 454 shallow shocks with \( M > 5^{1/2} \), 210 with \( M > 6 \), 83 with \( M > 6^{1/2} \), 25 with \( M > 7 \), 12 with \( M > 7^{1/2} \). During the same period, 1843-1962, there were released: 74 intermediate shocks with \( M > 5^{1/2} \), 48 with \( M > 6 \), 39 with \( M > 6^{1/2} \), 17 with \( M > 7 \), 11 with \( M > 7^{1/2} \), and 7 with \( M > 8 \). The data given above may be summarized as follows:

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<th>( M )</th>
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<td>( N_1 )</td>
<td>3.78</td>
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<td>0.14</td>
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<tr>
<td>( \log N_1 )</td>
<td>—0.21</td>
<td>—0.40</td>
<td>—0.49</td>
<td>—0.35</td>
<td>—1.04</td>
<td>—1.23</td>
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<tr>
<td>( \log N_2 )</td>
<td>—1.43</td>
<td>+0.82</td>
<td>(8 — M)</td>
<td>+0.66</td>
<td>+0.06</td>
<td>+0.42</td>
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where \( N_1, N_2 \) is respectively the number of shallow and intermediate shocks of magnitude \( M \) or greater per one year. These values fit rather closely to:

\[
\log N_1 = [-1.43 + 0.82 (8 - M)] \pm 0.65 = -1.43 \pm 0.66 + (0.82 \pm 0.02)(8 - M)
\]
\[
\log N_2 = [-1.23 + 0.42 (8 - M)] \pm 0.66 = -1.23 \pm 0.63 + (0.42 \pm 0.01)(8 - M)
\]

The logarithm of the ratio of the number of smaller shallow shocks to that of intermediate shocks in the area considered is approximately 3.06; this makes the ratio of numbers about 1000: 1. However, the logarithm of the ratio of the number of shallow shocks of magnitude 8 and over, to that of intermediate shocks is approximately — 0.20; this makes the ratio of numbers about 0.63:1, i.e. roughly 60% of shocks...
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Table I - Catalogue of shallow earthquakes of magnitude $\geq 5\frac{1}{4}$ occurred in the area of Greece during the period 1843-1862.
**EVIDENCE FOR THE SEAT OF THE STRAIN-PRODUCING FORCES**

Table I (cont.)

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of magnitude 8 and over occurred in the area of Greece are of intermediate focal depth. The regression equations for shallow and intermediate shocks define two curves crossing each other at $M = 7\frac{1}{2}$.

Using the data given in Table I and II and applying the relations:

$$\log E^s = 5.9 + 0.75 M,$$

and

$$S \approx \Sigma E^s,$$

where $E$ is the seismic wave energy, $M$ the earthquake magnitude and $S$ the strain release in units $10^{11}$ (ergs)$^{1/2}$, we find that the average strain release per shallow and intermediate earthquake, i.e. $S/N$, for the period considered, amounts to 0.4 and 2.1, respectively. For the 60-years interval, 1903-1962, the corresponding values are 0.3 and 1.0.

Thus the average strain release per earthquake of intermediate focal depth is 3 to 5 times higher than that per shallow earthquake.
Table II - Catalogue of earthquakes of magnitude $\geq 5/4$ with focal depth $\geq 40$ km occurred in the area of Greece during the period 1843-1962.

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Discussion.

Assuming with Báth and Duda (1964) that "the main difference between large and small earthquakes is not to be found in the strain but
in the total volume involved", it might be possible to think that the higher average strain release per intermediate earthquake is due to the larger ability of deformation of the low-rigidity layer of the upper mantle. However, considering that a large amount of deformation in weak layers is relieved by plastic flow, i.e. that the possibilities of strain storage in the upper mantle are not very good (Blöth and Duda, 1963/III), the pronounced maximum of average strain release per earthquake at 50 to 150 km focal depths might be due to a combination of stronger strain accumulation and greater seismic gain ratio. The greater "seismic gain ratio", i.e. the greater ratio between seismic energy and elastic strain energy in the upper mantle, is evidenced by the very small number of aftershocks. Owing to the lower breaking strength of the low-velocity layer of the upper mantle the strain accumulated in a very large volume is probably completely relieved in almost one earthquake. A stronger strain accumulation at 50 to 150 km depths combined with a smaller ability of strain storage implies that the seat of the strain producing forces is in the upper mantle. It is reasoned therefore that convection currents are probably the prevailing agent in producing a strained region in the Earth's interior. This evidence is fairly corroborated by the fact that in Greece the periods of greater seismic activity are initiated by intermediate shocks, i.e. the seismic activity in the area of Greece is induced by processes occurring under the Earth's crust (Galanopoulos, 1956).

Later on Blot (1963) was led to the same conclusion for other regions of the globe where intermediate and deep foci exist: Southern Pacific, America, Japan, Indonesia, Indo-Kush ... According to Blot "The earthquakes of very great magnitude are preceded by deep earthquakes of a magnitude superior to 7, or by several deep earthquakes of a lesser magnitude".

Recently L. Don Leet and Florence J. Leet (1965), based on other data were led with a different reasoning to believe that "the fundamental cause of earthquakes is movement in the subaqueous mantle", and even more that "when computational procedures are further refined, it may turn out that all earthquakes are basically mantle ruptures, even when some displacements are coupled to the surface".

Benioff (1951b) has already put forward evidence that earthquakes of magnitude exceeding 8, may not be entirely independent events, but may be related in some form of global stress-system. This suggestion is very well understood in the assumption that the seat of the strain producing forces is in the upper mantle.
ACKNOWLEDGMENTS.

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REFERENCES


