Evidence for the seat of the strain-producing forces

A. G. Galanopoulos

Ricevuto il 1 Settembre 1965

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.

Båth 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, Båth and Duda derived a new equation:

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

which improves a previous relation:

$$\log S = 5.99 + 1.02\ M\ ,$$

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 Båth 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 Båth's and Duda's investigation that " *The ratio of fault plane area to the vertical section through the aftershock zone, i.e. F/LH, 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 Mohorovicic discontinuity, i.e. in the low-rigidity layer near the top of the mantle. This implications is strongly supported by the fact that all shocks of magnitude $\geqslant 7^3/_4$ 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 20 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_o to M derived for constant depths of foci by V. Karnik (1964):

$$\begin{array}{llll}
h = 3 - 5 \text{ km}, & M = 0.56\, I_o + 0.45 & & \\
h = 6 - 10 \text{ km}, & M = 0.56\, I_o + 0.83 & & \\
h = 11 - 18 \text{ km}, & M = 0.57\, I_o + 0.85 & & \\
h = 19 - 30 \text{ km}, & M = 0.50\, I_o + 1.75 & & \\
h = 31 - 50 \text{ km}, & M = 0.40\, I_o + 2.36 & & \\
h = 51 - 82 \text{ km}, & M = 0.29\, I_o + 3.77 & \multirow{2}{*}{\Big\}} & \multirow{2}{*}{M_{LH} without ∂M^h} \\
h = 83 - 150 \text{ km}, & M = 0.33\, I_o + 3.23 & &
\end{array}$$

The relations derived for $M = M_{LH} + \delta M^h$ without depth corrections, δM^h, have approximately a common intersection near $I_o = \text{XI}$ and $M = 7$. This implies that in case of shallow shocks the maximum intensity ever observed, $I_o = \text{XI}$, 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 $\geqslant 5^1/_2$ 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 $\geqslant 40$ km.

During the time interval considered there were released: 454 shallow shocks with $M \geqslant 5^1/_2$, 210 with $M \geqslant 6$, 83 with $M \geqslant 6^1/_2$, 25 with $M \geqslant 7$ and 12 with $M \geqslant 7^1/_2$. During the same period, 1843-1962, there were released: 74 intermediate shocks with $M \geqslant 5^1/_2$, 48 with $M \geqslant 6$, 39 with $M \geqslant 6^1/_2$, 17 with $M \geqslant 7$, 11 with $M \geqslant 7^1/_2$ and 7 with $M \geqslant 8$. The data given above may be summarized as follows:

M	$5\,^1/_2$	6	$6\,^1/_2$	7	$7\,^1/_2$	8
N_1	3.78	1.75	0.69	0.21	0.10	—
N_2	0.62	0.40	0.325	0.14	0.092	0.058
log N_1	0.58	0.24	— 0.16	— 0.68	— 1.00	—
log N_2	— 0.21	— 0.40	— 0.49	— 0.85	— 1.04	— 1.23

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:

$$\log N_1 = [-1.43 + 0.82\,(8 - M)] \pm 0.05 = -1.43 \pm 0.06 + (0.82 \pm 0.02)(8 - M)$$

$$\log N_2 = [-1.23 + 0.42\,(8 - M)] \pm 0.06 = -1.23 \pm 0.03 + (0.42 \pm 0.01)(8 - M).$$

The logarithm of the ratio of the number of smaller shallow shocks to that of intermediate shocks in the area considered is approximately 3.00; 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

Table I – Catalogue of shallow earthquakes of magnitude $\geqslant 5^1/_2$ occurred in the area of Greece during the period 1843-1962.

No	Date	Magnitude adopted	No	Date	Magnitude adopted
1	1843, Sept. 5	$6\,{}^1/_4$	51	March 6	$6\,{}^1/_4$
2	Oct. 18	$6\,{}^3/_4$	52	March 13	$5\,{}^1/_2$
3	1845, June 23	$6\,{}^1/_4$	53	March 25	5.7
4	Oct. 11	6.8	54	Dec. 4	$6\,{}^3/_4$
5	1846, June 10	7.2	55	1867, Jan. 27	$6\,{}^3/_4$
6	June. 13	$6\,{}^1/_4$	56	March 7	6.7
7	1848, — —	$6\,{}^1/_4$	57	March 30	$6\,{}^1/_4$
8	1851, Jan. 20	$6\,{}^1/_4$	58	Oct. 22	5.9
9	Febr. 28	$6\,{}^3/_4$	59	1868, Apr. 20	$6\,{}^3/_4$
10	Oct. 12	7.1	60	May 3	$5\,{}^1/_2$
11	Oct. 17	$6\,{}^3/_4$	61	Oct. 3	5.6
12	Dec. 29	$6\,{}^1/_4$	62	1869, March 18	$5\,{}^1/_2$
13	Dec. 29	$6\,{}^1/_4$	63	Aug. 14	$6\,{}^3/_4$
14	1852, Aug. 26	$6\,{}^1/_4$	64	Sept. 1	$6\,{}^1/_4$
15	1853, Aug. 18	7.2	65	Dec. 1	$7\,{}^1/_2$
16	1854, July 30	6.6	66	Dec. 28	6.9
17	1856, Nov. 13	$6\,{}^3/_4$	67	1870, Aug. 1	$7\,{}^1/_2$
18	1858, Febr. 21	$7\,{}^1/_2$	68	Sept. 28	6.2
19	Apr. 5	$6\,{}^1/_4$	69	1871, Jan. 22	$6\,{}^1/_4$
20	Sept. 20	6.9	70	Apr. 8	$6\,{}^1/_4$
21	Oct. 10	6.8	71	June 7	$6\,{}^1/_4$
22	1859, March 13	$6\,{}^1/_4$	72	Oct. 8	6.9
23	Aug. 13	$5\,{}^1/_2$	73	1872, Febr. 11	$7\,{}^1/_2$
24	Aug. 21	6.4	74	1873, Jan. 31	6.6
25	Sept. 12	$6\,{}^1/_4$	75	July 25	$6\,{}^1/_4$
26	1860, Apr. 10	$7\,{}^1/_2$	76	Oct. 25	6.1
27	Apr. 15	$5\,{}^1/_2$	77	1874, Jan. 17	$5\,{}^1/_2$
28	Apr. 16	$6\,{}^1/_4$	78	March 18	$5\,{}^1/_2$
29	May 16	$6\,{}^1/_4$	79	Nov. 16	7.3
30	Aug. 6	$5\,{}^1/_2$	80	1875, Apr. 24	$5\,{}^1/_2$
31	1861, Dec. 26	$7\,{}^1/_2$	81	July 7	$6\,{}^3/_4$
32	1862, March 14	$7\,{}^1/_2$	82	1876, June 26	$6\,{}^1/_4$
33	Oct. 4	$6\,{}^3/_4$	83	1877, July 2	$5\,{}^1/_2$
34	1863, Aug. —	$6\,{}^1/_4$	84	Oct. 13	$5\,{}^1/_2$
35	1864, June 14	$5\,{}^1/_2$	85	Oct. 13	$6\,{}^1/_4$
36	July 17	$5\,{}^1/_2$	86	1880, July 29	6.6
37	Aug. 21	$5\,{}^1/_2$	87	1881, Apr. 3	6.3
38	1865, July 23	6.6	88	1883, Oct. 15	6.4
39	Oct. 10	$6\,{}^1/_4$	89	1885, Febr. 18	$5\,{}^1/_2$
40	Oct. 11	$5\,{}^1/_2$	90	March 28	6.0
41	Nov. 11	$6\,{}^1/_4$	91	Dec. 14	$5\,{}^1/_2$
42	1866, Jan. 2	$6\,{}^3/_4$	92	1886, Sept. 4	$5\,{}^1/_2$
43	Jan. 13	6.8	93	Nov. 27	$5\,{}^1/_2$
44	Jan. 31	6.1	94	1887, May 14	6.5
45	Febr. 2	$6\,{}^1/_4$	95	Oct. 3	6.3
46	Febr. 6	$6\,{}^1/_4$	96	1888, Sept. 9	5.8
47	Febr. 28	$6\,{}^1/_4$	97	1889, Apr. —	$5\,{}^1/_2$
48	March 2	$6\,{}^1/_4$	98	Aug. 25	6.3
49	March 2	$6\,{}^3/_4$	99	Oct. 25	6.9
50	March 2	$5\,{}^1/_2$	100	1890, May 21	$5\,{}^1/_2$

Table I (cont.)

No	Date	Magnitude adopted	No	Date	Magnitude adopted
101	1890, May 26	6.6	152	1907, Aug. 16	6 1/4
102	Dec. 14	6.5	153	1909, March 8	5 1/2
103	1891, May 11	6.1	154	May 30	5.9
104	June 27	5 1/2	155	July 15	5.8
105	Sept. 18	5 1/2	156	1910, Oct. 27	6 1/4
106	1892, Jan. 9	5.5	157	1911, Febr. 18	7.1
107	Dec. 27	5 1/2	158	March 9	5 1/2
108	1893, Jan. 31	6.4	159	Oct. 22	5 1/2
109	Febr. 1	6 3/4	160	1912, Febr. 13	7.0
110	Febr. 9	5.9	161	Febr. 15	6 1/4
111	March 12	5 1/2	162	Apr. 1	5 1/2
112	Apr. 17	6.4	163	Apr. 19	5 1/2
113	May 23	6.1	164	Apr. 21	5 3/4
114	June 14	7 1/2	165	Aug. 9	7 3/4
115	Oct. 13	5 1/2	166	1913, May 25	5 1/2
116	1894, Apr. 20	6.7	167	1914, Oct. 17	6.0
117	Apr. 27	6.9	168	Oct. 17	5.9
118	July 26	6 1/4	169	1914, Nov. 23	5 1/2
119	1895, May 13	6 3/4	170	Nov. 27	6.1
120	May 14	6 1/4	171	Dec. 2	5 1/2
121	May 14	7 1/2	172	1915, Jan. 27	6.0
122	May 15	6.4	173	June 4	5.7
123	June 21	6 1/4	174	Aug. 7	6.3
124	Aug. 6	6 3/4	175	Aug. 10	6.1
125	Aug. 19	6 1/4	176	Aug. 10	6.1
126	Sept. 5	6 1/4	177	Aug. 11	6.4
127	1896, Febr. 10	5 1/2	178	Aug. 11	5.5
128	Febr. 10	6 1/4	179	Aug. 19	5.7
129	Febr. 10	6 1/4	180	1916, Sept. 27	5.5
130	Febr. 11	5 1/2	181	1917, March 14	6 1/4
131	Febr. 11	6 1/4	182	March 26	5 1/2
132	March 18	6 1/4	183	Sept. 23	5 1/2
133	Oct. 27	6.2	184	1918, Jan. 17	5 1/2
134	Nov. 13	5 1/2	185	Sept. 11	5 1/2
135	1897, Febr. 12	6.1	186	Nov. 20	5 1/2
136	June 30	5 1/2	187	1919, Febr. 24	5.7
137	1898, Febr. 11	5 1/2	188	Oct. 25	6.0
138	June 2	6.4	189	Nov. 18	5 3/4
139	July 31	6.2	190	1920, Oct. 18	6 1/4
140	Nov. 9	6.0	191	Oct. 21	5.9
141	1899, Jan. 22	6.7	192	Nov. 15	6.1
142	Sept. 20	6 3/4	193	Nov. 25	5 1/2
143	1902, July 5	6.6	194	Nov. 26	6.4
144	Nov. 5	5 1/2	195	Nov. 28	5 1/2
145	1904, Apr. 4	7 1/2	196	Nov. 29	6.2
146	1905, June 1	5 1/2	197	Dec. 18	6 3/4
147	June 3	6.0	198	Dec. 23	6 1/4
148	Oct. 8	6.4	199	1921, March 30	5.5
149	Nov. 8	7.0	200	July 6	5.5
150	1906, March 3	6 1/4	201	1921, Sept. 13	5.5
151	1906, Sept. 28	6 1/4	202	Oct. 21	6 1/4

Table I (cont.)

No	Date		Magnitude adopted	No	Date		Magnitude adopted
203	1922,	Aug. 11	5 3/4	254		May 11	6 1/4
204	1923,	Jan. 7	6 1/4	255		Aug. 17	6.3
205		May 6	6.3	256	1934,	Febr. 4	5 1/2
206		Dec. 5	5.7	257		Febr. 21	5 1/2
207		Dec. 27	5 1/2	258		Nov. 21	5 3/4
208	1925,	Febr. 7	5 1/2	259	1935,	Jan. 4	6 1/4
209	1926,	March 18	6.9	260		Jan. 4	5.8
210		March 18	5 1/2	261		Jan. 4	6.0
211		March 19	5 1/2	262		Febr. 18	5.5
212		Dec. 17	6.2	263		March 30	6.0
213		Dec. 17	6.5	264		May 2	5 1/2
214	1927,	March 24	5 1/2	265		Nov. 7	6.0
215		June 30	5.5	266	1936,	Apr. 8	6.0
216	1928,	Jan. 23	5.5	267		Apr. 15	5.7
217		March 31	6 1/4	268	1937,	Jan. 2	5 1/2
218		Apr. 18	6 3/4	269		May 23	5.7
219		Apr. 18	5 1/2	270		July 6	6.0
220		Apr. 22	6.8	271	1938,	Jan. 30	5.9
221		Apr. 25	5 1/2	272		Febr. 10	5 3/4
222		Apr. 28	5 1/2	273		March 11	5.8
223		Dec. 10	5.6	274		March 13	5.7
224	1930,	Jan. 23	5.7	275		May 12	5 1/2
225		Jan. 28	6 3/4	276		June 20	5.7
226		Febr. 23	5.7	277		July 2	5.8
227		March 31	6.1	278		July 20	5 3/4
228		Apr. 17	5.8	279	1939,	May 20	5 1/2
229		June 25	5 1/2	280		June 23	5 1/2
230		Nov. 21	6.0	281		Aug. 9	6.1
231		Nov. 21	6 1/4	282		Sept. 22	6 1/2
232		Dec. 2	6 3/4	283	1940,	Jan. 6	5.6
233	1931,	Jan. 4	5.6	284		Febr. 23	5 1/2
234		March 7	6.0	285		Febr. 29	6.0
235		March 8	6 3/4	286	1941,	March 1	6 1/4
236		July 12	5.8	287		May 14	5 1/2
237	1931,	Sept. 13	6.0	288		May 16	5 1/2
238		Nov. 15	5 1/2	289		May 23	6.0
239		Nov. 23	6.4	290		May 28	5 1/2
240	1932,	March 9	5 1/2	291		June 24	5 1/2
241		Apr. 27	5 1/2	292		July 13	5 3/4
242		May 14	5 1/2	293		July 23	5 1/2
243		June 29	5 1/2	294		Sept. 1	5 1/2
244		Sept. 26	6.9	295		Dec. 13	6.0
245		Sept. 26	6.1	296	1942,	June 16	5.6
246		Sept. 29	6 1/4	297		Aug. 27	5 1/2
247		Sept. 30	5 1/2	298		Sept. 1	5.8
248		Oct. 23	5 1/2	299		Oct. 28	6.0
249		Nov. 1	5 1/2	300		Oct. 28	6.0
250	1933,	Jan. 5	5 1/2	301	1943,	July 23	5 3/4
251		March 14	5.6	302	1944,	March 14	5.9
252		Apr. 28	5 1/2	303		June 25	6.0
253		May 8	6.1	304		July 30	5.6

Table 1 (cont.)

No	Date		Magnitude adopted	No	Date		Magnitude adopted
305	1944,	Oct. 6	7.2	356		Aug. 12	6.2
306		Oct. 7	5 1/2	357		Aug. 12	5 1/2
307	1945,	Sept. 2	6 1/2	358		Aug. 12	6.0
308	1946,	Apr. 12	5 1/2	359		Aug. 12	5.5
309		Apr. 16	5.5	360		Aug. 13	5 1/2
310	1947,	March 21	5 1/2	361		Sept. 5	5.8
311		Apr. 12	5.7	362		Sept. 14	5.7
312		June 1	5 1/2	363		Oct. 10	5 1/2
313		July 21	5.5	364		Oct. 21	5.7
314		Aug. 30	6.3	365		Oct. 21	6.5
315		Oct. 6	7.0	366		Nov. 28	5 1/2
316		Nov. 29	5 1/2	367		Dec. 28	5 1/2
317		Dec. 9	5.5	368	1954,	Jan. 2	5 1/2
318	1948,	March 29	5 1/2	369		March 8	5 1/2
319		March 29	5.9	370		Apr. 17	5 1/2
320		Apr. 22	6.4	371		Apr. 30	7.0
321		May 26	5.5	372		May 1	5 1/2
322		June 30	6.4	373	1954,	May 3	5 1/2
323		Oct. 10	5.8	374		May 4	5.7
324		Oct. 18	5.5	375		May 4	5.6
325	1949,	Jan. 4	5.7	376		May 25	5.7
326		June 17	6.7	377		July 18	5 1/2
327		July 23	6.8	378		Aug. 3	6.0
328	1950,	Sept. 23	5 3/4	379		Dec. 23	5.9
329	1951,	Apr. 5	6.1	380	1955,	Jan. 3	5.8
330		Aug. 24	5.5	381		March 28	5 3/4
331		Aug. 31	5 3/4	382		Apr. 13	6.0
332		Aug. 31	5.6	383		Apr. 19	6 1/4
333		Oct. 1	5 1/2	384		Apr. 21	6.0
334	1952,	March 19	5 3/4	385		June 2	5 1/2
335		Oct. 5	5 3/4	386		July 9	5 1/2
336		Oct. 10	5 1/2	387		July 16	6.8
337		Oct. 13	5 1/2	388	1956,	Jan. 6	5.7
338		Dec. 31	5 3/4	389		May 15	5.6
339	1952,	Dec. 31	5 3/4	390		May 15	5.8
340	1953,	Jan. 7	5.5	391		May 18	5.8
341		Febr. 7	6.0	392		July 9	7 1/2
342		March 18	7.2	393		July 9	6 3/4
343		March 18	5.6	394		July 9	5.7
344		May 2	5 1/2	395		July 9	5.6
345		June 3	5 3/4	396		July 9	5 1/2
346		June 13	5 1/2	397		July 9	5.5
347		June 18	5 1/2	398		July 10	5 3/4
348		July 22	5 1/2	399		July 10	5 3/4
349		Aug. 9	6.5	400		July 22	5.5
350		Aug. 11	6.8	401		July 30	5.6
351		Aug. 11	5 1/2	402		July 30	6.0
352		Aug. 11	5 1/2	403		July 30	5.6
353		Aug. 12	5 1/2	404		Aug. 16	5.5
354		Aug. 12	7.2	405		Sept. 6	5.7
355		Aug. 12	5.6	406		Sept. 16	5 1/2

Table I (cont.)

No	Date			Magnitude adopted	No	Date			Magnitude adopted
407	1956,	Nov.	2	5 $^3/_4$	431	1958,	June	5	5 $^1/_2$
408		Nov.	20	5 $^1/_2$	432		July	15	5 $^1/_2$
409	1957,	Jan.	23	5 $^1/_2$	433		July	17	5 $^3/_4$
410		Febr.	19	6.0	434		Aug.	27	6.5
411		March	8	6 $^1/_2$	435		Sept.	2	5 $^1/_2$
412		March	8	6 $^3/_4$	436		Sept.	4	5 $^1/_2$
413		March	8	5.6	437	1959,	Apr.	25	6 $^1/_4$
414		March	8	6.0	438		Apr.	25	5.6
415		March	28	5.7	439		May	14	6 $^1/_2$
416		Apr.	26	6.2	440		June	10	5 $^3/_4$
417		May	21	5.7	441		Aug.	16	5 $^1/_2$
418		May	29	5.5	442		Aug.	17	6.0
419		Oct.	5	5 $^1/_2$	443		Sept.	1	6 $^1/_4$
420		Oct.	30	5.7	444		Oct.	5	5 $^1/_2$
421		Oct.	30	5 $^3/_4$	445		Oct.	7	5 $^3/_4$
422		Nov.	26	5.7	446		Nov.	15	7.0
423		Nov.	26	5.6	447		Nov.	19	5 $^1/_2$
424		Nov.	27	5.9	448		Dec.	1	5 $^3/_4$
425	1958,	Jan.	2	5.8	449	1960,	Febr.	23	5 $^1/_2$
426		Jan.	16	5.7	450		March	12	5.6
427		March	15	5.6	451		May	26	6 $^1/_2$
428		Apr.	3	5 $^3/_4$	452		July	13	5 $^1/_2$
429		May	3	5 $^1/_2$	453	1961,	Oct.	2	5 $^1/_2$
430		May	9	5 $^3/_4$	454	1962,	Jan.	26	6 $^1/_4$

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 $M = 7^1/_2$.

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

$$\log E^{1/2} = 5.9 + 0.75\ M\ ,$$

and

$$S \approx \Sigma E^{1/2}\ ,$$

where E is the seismic wave energy, M the earthquake magnitude and S the strain release in units 10^{11} $(\text{ergs})^{1/2}$, 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 $\geqslant 5^1/_2$ with focal depth $\geqslant$ 40 km occurred in the area of Greece during the period 1843-1962.

No	Date	Magnitude adopted	No	Date	Magnitude adopted
1	1846, March 28	8.1	38	1935, Febr. 25	$6\ ^3/_4$
2	1856, Oct. 12	8.6	39	March 18	$6\ ^1/_4$
3	1862, June 21	6.8	40	1936, Apr. 28	$5\ ^3/_4$
4	1863, Apr. 22	8.5	41	Aug. 8	$5\ ^3/_4$
5	1867, Febr. 4	7.9	42	1937, Dec. 16	$6\ ^1/_2$
6	Sept. 20	7.6	43	1938, Jan. 16	$5\ ^1/_2$
7	1869, Apr. 18	6.9	44	June 3	$5\ ^3/_4$
8	1886, Aug. 27	8.4	45	Sept. 18	$6\ ^1/_2$
9	1887, July 17	7.7	46	1939, Sept. 20	$6\ ^1/_2$
10	1897, May 28	7.6	47	1942, May 9	$5\ ^3/_4$
11	1903, Aug. 11	8.3	48	May 21	$5\ ^1/_2$
12	1904, Aug. 11	8.0	49	June 21	$6\ ^1/_4$
13	1908, May 17	$6\ ^3/_4$	50	1943, Jan. 7	$5\ ^1/_2$
14	1910, Febr. 18	7 0	51	Febr. 14	6 0
15	Aug. 21	$6\ ^1/_2$	52	June 27	$5\ ^3/_4$
16	1911, Apr. 4	7.0	53	Oct. 16	$6\ ^1/_4$
17	1912, Jan. 24	$6\ ^3/_4$	54	1944, Jan. 5	5.7
18	1913, Sept. 30	$5\ ^3/_4$	55	May 27	$6\ ^1/_4$
19	1918, July 16	$6\ ^1/_2$	56	Aug. 9	$5\ ^1/_2$
20	1922, Aug. 13	$6\ ^3/_4$	57	1946, Apr. 5	6.0
21	Nov. 11	5.7	58	1947, June 4	6 0
22	1923, Aug. 1	6.7	59	July 7	$5\ ^1/_2$
23	1925, July 6	$6\ ^1/_2$	60	1948, Febr. 9	7.1
24	1926, June 26	8.3	61	July 24	$6\ ^1/_2$
25	July 5	$5\ ^1/_2$	62	Sept. 11	6.5
26	Aug. 30	7.0	63	1952, Dec. 17	$6\ ^3/_4$
27	Sept. 19	$6\ ^1/_4$	64	1953, Febr. 14	$5\ ^3/_4$
28	1927, July 1	6.9	65	June 23	$5\ ^3/_4$
29	1929, March 27	$5\ ^3/_4$	66	1957, Apr. 24	7 0
30	Nov. 11	5.7	67	Apr. 25	$7\ ^1/_4$
31	1930, Febr. 14	$6\ ^3/_4$	68	1958, June 30	$6\ ^1/_2$
32	March 6	$5\ ^3/_4$	69	May 27	5.6
33	March 6	6.0	70	Nov. 15	$5\ ^3/_4$
34	1931, June 30	$5\ ^1/_2$	71	1960, Nov. 4	5.8
35	1932, Aug. 15	$5\ ^1/_2$	72	Nov. 11	5.7
36	1933, Apr. 23	$6\ ^3/_4$	73	1961, May 23	$6\ ^1/_2$
37	1934, Nov. 9	$6\ ^3/_4$	74	Nov. 28	$5\ ^1/_2$

Discussion.

Assuming with Båth and Duda (1964) that " *the main difference between large and small earthquakes is not to be found in the strain but* *in the total volumes 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 (Båth 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 soliqueous mantle* ", and even more that " *when computational procedures are further refined, it may turn out that all earthquakes are basically mantle raptures, 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.

The research reported in this document has been sponsored by the «Air Force Office of Scientific Research» under contract AF 61(052)–803 through the « European Office of Aerospace Research (OAR) », « United States Air Force », as part of the Advanced Research Projects Agency's Project *Vela Uniform*.

The author would like to express his sincere thanks to Dr. B. C. Papazachos for reading critically the manuscript of this paper.

REFERENCES

BÅTH M. and DUDA S. J., *Earthquake Volume, Fault Plane Area, Seismic Energy, Strain, Deformation and Related quantities*, " Annali di Geofisica ", **17**, 353-368, (1964).

BÅTH M. and DUDA S. J., *Strain Release in Relation to Focal Depth*, " Geofisica Pura e Applicata ", **56**, 93-100, (1963/III).

BENIOFF F., *Earthquakes and Rock Creep*, Part I: *Creep Characteristics of Rocks and the Origin of Aftershocks*, " Bull. Seism. Soc. Amer. ", **41**, 31-62, (1951a).

BENIOFF H., *Global Strain Accumulation and Release as Revealed by Great Earthquakes*, " Bull. Geol. Soc. Am. ", **62**, 331-338, (1951b).

BLOT C., *Deep Origin of Shallow Earthquakes and Volcanic Eruptions*. Abstract submitted to the IUGG General Assembly in Berkeley, 19-31, August 1963.

DON LEET L. and FLORENCE J. LEET, *The Earth's Mantle*, " Bull. Seism. Soc. Am. ", **55**, 3, 619-625, (1965).

GALANOPOULOS A., *The Seismic Efficiency of Greece*, " Prakt. of Athens Academy " **31**, 368-375, (1956).

KARNIK V., *Seismicity of Europe*. Progress Report IV prepared for the conference of the European Seismological Commission in September 1964. Mimeographed, 1-22 (Tokio, 1964).

PRESS F., *Displacements, Strains, and Tilts at Teleseismic Distances*. " Jour. Geoph. Res. ", **70**, 10, 2395-2412, (1965).

UTSU T. and SEKI A., *Relation between the Area of the Aftershock Region and the Energy of the Main Shock*, " Jour. Seism. Soc. Japan ", Ser. II, **7**, 233-240, (1955).