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Introduction

The time reported Seweryn J. Duda spent in the USA. Our investigations have been continued during his stay at the Seismological Laboratory, California Institute of Technology, Pasadena, California, where he spent most of the time.

On January 6, 1964, Seweryn J. Duda went from the U.S. Air Force Base in Frankfurt/Main to the U.S. Air Force Base in McGuire, N.J., using MATS' travelling facilities. On his way across the United States from New York, N.Y., to Pasadena, Calif., geophysical departments, institutes and observatories at universities and/or geophysical companies were visited by him in the following towns: Palisades, N.Y., Washington D.C., Alexandria, Va., St. Louis, Mo., Dallas, Texas, and Albuquerque, N.M. For details see Nineteenth Monthly Status Report (Report No. 24).

On January 27, 1964, Seweryn J. Duda started his activities at the Seismological Laboratory in Pasadena, Calif., under the guidance of

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Prof. Frank Press and Prof. Hugo Benicff. He has been working full-time on the project the whole time.

In the following we report about our investigations carried out and results obtained there in the following order:

1. Secular strain energy release;
2. Strain energy release in the Prince William Sound aftershocks from March 28, 1964, onwards and in the Kurile Islands aftershocks from October 13, 1963, onwards;
3. Local seismic activity in Arizona, as recorded at the Tonto Forest Seismological Observatory in Payson, Arizona.
4. Meetings and observatories visited.

1. Secular strain energy release

Instrumental seismology exists since about 70 years. Data on the strongest earthquakes were collected fairly complete since 1897. Our aim was to investigate the secular strain energy release in the time interval from 1897 through 1963 in different parts of the world.

Accomplishment:

As sources of the earthquake data we used the following publications:

- B. Gutenberg: Great earthquakes 1896-1903; Trans. Am. Geoph. Union,
Vol. 37, 1956
- B. Gutenberg and C.F. Richter: Seismicity of the Earth; Princeton University
Press, 1954
(for the time 1904-1952)
- C.F. Richter: Seismological Laboratory Bulletin;
(for the time 1953-October 1957)
- C.F. Richter: Provisional Readings at Pasadena;
(for the time November 1957-December 1963)
- C.F. Richter: Elementary Seismology; W.H. Freeman and Company, 1958
(magnitude revisions)

We collected data for a total of 1117 earthquakes. Included are earthquakes with magnitude 7 and above for the years after 1896, their number being complete after 1917. These 1117 earthquakes are responsible for the principal part of strain energy released in seismic waves. Since the energy decreases exponentially with decreasing magnitude of an earthquake, the omission of earthquakes with smaller magnitudes does not result in an essential inaccuracy as long as considerations are made in terms of energies.

The strain energies were calculated from the magnitudes of the shocks, using Bâth's conversion formula (M. Bâth: The energies of seismic body waves and surface waves, "Contributions in Geophysics in Honour of Beno Gutenberg", 1-16, Pergamon Press, London, 1958).

a. Division of the circum-Pacific belt into 8 regions

Obviously most of the seismic energy was released in the circum-Pacific belt. For a more detailed investigation, the belt was subdivided into 8 regions, every region being naturally defined by the clustering of epicenters. The regions diverge somewhat from those defined in Gutenberg and Richter's Seismicity of the Earth for the reason, that the regions had to be large enough in our case to contain a number of earthquakes sufficient for a statistical investigation.

Table 1 shows the regions with their total numbers of earthquakes and the summary strain energy released in each of them in the 67 investigated years. Furthermore, the table shows the number of shocks and energies released in shallow shocks, as well as in intermediate and deep shocks. As shallow were assumed all earthquakes with focal depth $h < 70$ km. The strain energy release per 1° of arc, the arc being defined by the epicenter distribution of the shallow shocks in each region, was calculated. This figure shows (inasmuch a regularity, as the region embracing Japan, Kurile, Kamchatka has the highest strain energy release per 1° of arc, decreasing in both directions around the circum-Pacific belt. Only in the

region including South America the figure increases again.

The b-coefficient in the formula relating the number of earthquakes N in a magnitude class with the magnitude M , $\log N = a - bM$, was determined in 7 of the regions, the earthquakes in the 8th region being too few for the determination. The b-coefficient for both shallow and intermediate shocks, as well as for shallow separately is presented in Table 1. These b-coefficients refer however to regions of different size. Therefore, they had to be related to 1° of arc, which renders all figures referring to the same time interval of 67 years comparable among themselves. This coefficient appears highest in the region covering New Hebrides, Solomon Islands, and East New Guinea. It is smallest in North America.

We compared the b-coefficients for the regions including Kamchatka, Aleutian Islands and Chile respectively, with the values of the b-coefficient obtained for aftershock sequences in Kamchatka 1952 (M. Bath and H. Benioff: The aftershock sequence of the Kamchatka earthquake of November 4, 1952, Bull. Seismol. Soc. Am., 48, 1-15, 1958), Aleutian Islands 1957 (S.J. Duda: Phaenomenologische Untersuchung einer Nachbebenseerie aus dem Gebiet der Aläuten-Inseln, Freiburger Forschungsh., C 132, Geophys., 1-90, 1962), and Chile 1960 (S.J. Duda: Strain release in the circum-Pacific belt: Chile 1960, Journ. Geophys. Res., 68, 5531-5544). The b-coefficients were related to 1° of arc of the aftershock zone and to the time interval of 67 years so as to make them comparable with the b-coefficients from the secular seismicity in these regions. The b-coefficients for aftershock sequences turn out to be greater by about 2 orders of magnitude (1.85 - Kamchatka 1952, 2.78 - Aleutian Islands 1957, 1.26 - Chile 1960) as compared with the values for secular activity (0.0281 - Kamchatka, 0.0221 - Aleutian, 0.0202 - Chile, see Table 1). From a comparison of these figures it does not follow, that geographical differences of the material in the zones are responsible for the regional differences, as frequently inferred.

The significance of both the strain energy per year and the b-coefficients related to 1^0 of arc are under further consideration.

b. Strain energy release in dependence on time

The strain energy release characteristics for shallow, intermediate and deep shocks in every region were constructed, as well as histograms for the yearly strain energy release in every region. The summary histogram for the yearly strain energy release in the entire circum-Pacific belt was obtained. These histograms for shallow, intermediate and deep shocks exhibit as common feature a decrease of the strain energy release per year in the investigated time interval. The least-square solutions for the strain energies released per year in shallow, intermediate and deep shocks are respectively:

$$E(t) = 54.68 - (t - 1896) 0.57$$

for the years $1897 \leq t \leq 1963$;

$$E(t) = 17.80 - (t - 1902) 0.27$$

for the years $1903 \leq t \leq 1963$;

$$E(t) = 1.14 - (t - 1906) 0.01$$

for the years $1907 \leq t \leq 1963$.

$E(t)$ denotes the strain energy released in the year t , expressed in 10^{23} ergs.

This decrease is found also for the earthquakes outside the circum-Pacific belt.

The overall decrease of seismic activity cannot be obtained from an analysis of the number of shocks (with $M \geq 7.0$) per year alone.

As another feature of the histograms for shallow shocks we found a temporary decrease or absence of seismic activity in the years from about 1906 through 1916, the period of quietness varying somewhat in length from region to region. This well pronounced quietness in shallow shocks was compensated by an increase of seismic activity in intermediate but also deep shocks in the years about 1906 until 1916.

From this we draw the conclusions that:

- a) the strain energy release in different depth ranges does not occur independently; and
- b) the increase of intensity of strain release in one depth range (in this case below 70 km) is accompanied by a decrease of the intensity in the adjacent depth range (in this case above 70 km).

Previously, we discovered the mutual dependence of strain energy release in geographically neighbouring regions for the same depth range (S.J. Duda: Strain release in the circum-Pacific belt, as above). Both findings together show that the strain energy release in earthquakes in different regions is dependent on the release in adjacent regions both in the horizontal direction along the belt, and in the direction toward greater hypocentral depths.

c. Auto- and crosscorrelation

The strain energies released per year during 67 years in shallow, intermediate, and deep shocks were subjected to an autocorrelation to find any possible periodicities of strain release in each depth range. The results - although not yet completely evaluated - do not show any clear periodicity in the time range investigated. This is not surprising, as the time interval of 67 years must be considered as extremely small in the geological time scale.

The following combinations of strain energy release per year were also processed:

1. shallow with intermediate for the years 1897-1963;
2. shallow with intermediate for the years 1903-1938;
3. shallow and intermediate with deep for the years 1906-1963.

The crosscorrelation for shallow with intermediate earthquakes yields, that activity in these depth ranges is correlated with a time lag of 28 years. This means that the yearly strain energy release pattern in shallow shocks is repeated, though with smaller absolute values, in intermediate

shocks after 28 years.

The investigation of the secular strain energy release in the circum-Pacific belt is essentially finished and a paper will be prepared after Seweryn J. Duda's return to Uppsala.

2. Strain energy release: Prince William Sound March 28, 1964, and Kurile Islands October 13, 1963, aftershock sequences

On March 28, 1964, an aftershock sequence started in the Prince William Sound region. The magnitude of the main shock was 8.4 (Pasadena). On October 13, 1963, an aftershock sequence started in the Kurile Islands region. The magnitude of the main shock was 8 1/4 (Pasadena). Both aftershock sequences are still going on and are situated relatively close to each other on the circum-Pacific belt. For these reasons they are of special interest and an investigation was started.

Accomplishment:

The USCGS Preliminary Epicenter Determinations were used in both cases. Some distinct features and differences of these aftershock sequences could be found.

The Prince William Sound aftershocks show an epicenter distribution such that the strain energy release was highest towards the horizontal extremities of the aftershock zone. About 50 days after the main shock, the aftershock activity shifted towards the middle of the aftershock zone. The oscillation pattern between the horizontal extremities of the aftershock zone is fairly well developed. The b-coefficient is remarkably small, and amounts to about 0.5. The strain energy release characteristic is very similar to the second branch of the characteristics as found for the Aleutian 1957 and Chile 1960 sequences (M. Bath and S.J. Duda: Earthquake volume, fault plane area, seismic energy strain, deformation and related quantities, Appendix I, Fourth Semi-Annual Technical Report, Report No. 23, 1964). The lack of the first branch, with relatively small

intensity of strain energy release, usually observed in aftershock sequences, is striking.

The Kurile 1963 aftershock sequence exhibits inasmuch a difference to the Prince William Sound sequence, as no concentration of strain energy release towards the horizontal extremities can be observed in the initial stage of the sequence: the intensity is highest in the middle of the aftershock region. This resembles the pattern in the Kamchatka 1952 sequence (M. Bath and H. Benioff: The aftershock sequence of the Kamchatka earthquake of November 4, 1952, as above). After 100 days, an increase of activity at the horizontal extremities of the aftershock region is observed. The succession of shifts of strain energy release is here just opposite to that of the Prince William Sound sequence.

This investigation is planned to be extended.

3. Local seismic activity in Arizona

An investigation is performed of the very local seismic activity in Arizona, USA, on the base of the records of the Tonto Forest Seismological Observatory in Payson, Arizona. The maximum magnification on the instruments is of the order of 2 000 000. This allows to record local earthquakes with very low magnitudes, otherwise undetected. The investigation seems to be important for at least two reasons:

- a) It is so far not clear if the laws governing the strain energy release in large earthquake and sequences, occurring on major tectonic structures, can be transferred to the scale of small shocks, occurring on minor tectonic structures; and
- b) Arizona is a region with formations of volcanic origin. This is in complete difference to the seismic activity in the adjacent and seismologically already better investigated California. A comparison of both regions seems promising.

Accomplishment:

The effort was hitherto concentrated on the collection of data from the seismograms. Local earthquakes ($\Delta \leq 3^\circ$) from September 15 (seismograms available since that date) until December 31, 1963, are read, their location determined and magnitudes calculated. Amplitudes, periods and durations of Pn, Pg, Sn and Sg phases were measured. For the magnitude determination a conversion from the Johnson-Matheson recordings (seismographs of this type being used at TFSO, Payson) to the Wood-Anderson seismographs is needed, so that the original magnitude definition by Richter can be applied.

As a preliminary result it may be stated that the region with highest earthquake activity in Arizona has the geographical coordinates:

$33^\circ \pm 0.5^\circ$ N, $111^\circ \pm 0.5^\circ$ W.

4. Meetings and observatories visited

Seweryn J. Duda took part in the Annual Meeting of the Seismological Society of America in Seattle, Wash., March 27-28, 1964, and in the Annual Meeting of the American Geophysical Union in Washington D.C., April 20-24, 1964.

Besides a study visit of the seismological installations in Pasadena, the seismological observatory in Ely, Nevada, and the strain-seismometer observatory in Isabella, Calif., both belonging to the Seismological Laboratory in Pasadena, were visited by S.J. Duda.

Markus Bâth

Markus Bâth
Project Scientist

Table 1.

Region	Total number of shocks	E 10^{23} ergs	Shallow shocks		Intermediate and deep shocks		Length of arc	Shallow shocks E 10^{23} ergs/ 1°	b-coeff. shallow and interme- diate	b-coeff. shallow	b-coeff. per 10^0 of arc shallow	Magnitude of largest shallow shock
			number	E 10^{23} ergs	number	E 10^{23} ergs						
1. South America	117	423.94	55	359.11	62	64.82	45° 58° (x)	7.85 6.19 (x)	0.971	0.910	0.0202 0.0157 (x)	8.6
2. North America	90	318.26	75	300.62	15	17.64	76°	3.96	1.380	1.325	0.0174	8.3
3. Aleutian Alaska	59	195.59	45	171.74	14	23.84	33°	5.20	0.792	0.730	0.0221	8.7
4. Japan, Kurile, Kamchatka	160	690.72	107	550.23	53	140.49	36°	15.28	1.006	1.012	0.0281	8.9
5. New Guinea, Banda, Celebes, Moluccas, Philippines	169	568.07	125	395.10	44	172.98	59°	6.70	1.185	1.282	0.0217	8.6
6. New Hebrides, Solomon Islands, New Guinea	172	255.66	105	175.37	67	80.29	40°	4.38	1.563	1.421	0.0355	8.3
7. New Zealand, Tonga, Kermadec	95	236.66	44	178.52	51	58.14	54°	3.31	1.103	1.097	0.0203	8.4
8. Caroline, Mariana Islands	29	75.35	12	11.66	17	63.68	23.5°	0.50				7.2
Total	891	2764.25 100%	568	2142.37 77.5%	323	621.88 22.5%						

(x) if including the very few shocks south of $41^\circ S$