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4. *The Mechanism of Some Deep and Intermediate Earthquakes in the Region of Japan.**

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Abstract

The result of the investigation of the patterns of *S* waves recorded at large distances from the foci of 7 intermediate and deep earthquakes, which occurred in and near Japan, confirms the validity of the double couple hypothesis of earthquake mechanism for these shocks. The study of the *S* waves of 39 additional shocks of the region recorded at De Bilt gives support to the hypothesis. The amplitude ratios of the *P* and *S* waves of these earthquakes seem to indicate that the radii of the focal spheres of earthquakes of magnitudes $6^1/_2$ to 7.8 are of the order of 10 to 50 km.

1. Introduction

Some Japanese seismologists have studied *S* waves of many deep and intermediate earthquakes which occurred in and near Japan. Their results which were recapitulated e.g. by Honda in 1957, 1960 and 1962 show more or less clearly that the source mechanisms of these earthquakes can be explained by the double couple hypothesis. In most of these studies the observation data have been confined to those obtained at the stations in Japan. In the present investigation, the author intends to see whether, or how closely, the *S* waves of some strong Japanese earthquakes, as recorded at epicentral distances between 27° and 96°, are in accordance with those recorded at the rather nearby Japanese stations. In addition, we will study the *S* waves, recorded at De Bilt, of some other earthquakes of the region, and we will try to infer the order of magnitude of the focal spheres by use of the ratios of the amplitudes of the *P* and *S* waves.

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2. Source Mechanism

Seven intermediate and deep earthquakes which occurred in and near Japan and whose S waves were recorded clearly at De Bilt are selected (Table 1). The nodal planes of P waves for some of these shocks have already been obtained by other investigators. For the other shocks the solutions are obtained by the author by use of P and PKP data from ISS, BCIS and CMO bulletins. These data are supplemented with our readings of seismograms at the stations given in Table 2.

The azimuth A_z of station to epicenter, the epicentral distance Δ, and the polarization angle γ of the initial motion of the S waves (Fig. 8) are given in Table 3. The angle i_s which the seismic ray of S waves makes with the downward vertical at the focus is taken from the charts given by Ritsema (1958). The directions of the first motion of S waves are plotted in the diagrams in which the nodal planes for P waves for these shocks are also shown (Figs. 1~7). The diagrams show the lower focal hemisphere by use of the Wulff projection. Some P and PKP data are also given in the figures.

In the case of the 1934 shock, two possible solutions are presented, one of which shows a single couple mechanism and the other a double couple mechanism, as we cannot obtain a unique solution for the shock. In the case of the 1961 shock, the two nodal planes of P waves seem

Table 1.

Date	Time h	Time m	Time s	Latitude	Longitude	Depth
1934, June 13	01	51	01	44°.2 N	147°.4 E	0.01 R
1951, July 11(1)	18	21	54	28°.1	139°.9	0.07
1954, May 14(2)	22	39	25	36°.0	137°.4	0.03
1956, Feb. 18(3)	07	34	19	29°.9	138°.5	0.07
1957, Jan. 3(4)	12	48	27	44°	130°	0.09
1960, Oct. 8	05	53	01	40°.0	129°.7	0.09
1961, Jan. 16	07	20	19	36°	141°	0.01

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SAVARENSKI, E. F., *et al.*, *Izv. Akad. Nauk SSSR*, **5** (1960), 633.

Table 2. Seismogram readings of longitudinal waves.

Station	June 13 1934	July 11 1951	May 14 1954	Feb. 18 1956	Jan. 3 1957	Oct. 8 1960	Jan. 16 1961
BRK	D	C, dC	D, (dC)	C, dC	C, cD	C	C
BOM	C, (DC)	D?	C	D	D, (dC)	D, cD	C, (cD)
CHR			−, dC	D, (dC?)	C, (DC)		
DBN	C	D, dC	D, dC	D	D, cD	D, cD	C, dC, (DC)
FLO			D, DC		C, dC, CD	C, CD	C
HYD		D	C, CD	D	D, cD	D, cD	C, CD
IRK		D	D				C
KAB						D	
KHE							C, (DC)
KIR		D, dC	D, (dC)	C, dC, (DC)	D, cD, (CD)	D, cD	C, dC
KYA						D	C
MOS			D		D, cD, (CD), dCD		C, CD?, cDC
PMG						C, dC	D
PUL		D, dC	D, dC		(C)	D, cD	C, CD
RAB				C			D
RES		C, dC	D, (dC)	C, dC	cD?	C, cD	C
RIV	D	D, cD, DC	C, dC	D, cD	C, (cD)	C, (cD)	D?
ROM		D, dC			D		C, (DC)
ROX						C, (cD)	
SCO	D	D, dC	(C), cD	C, dC, (DC)	D, cD	D, (dC)	(D?)
SCP			(C?), (CD?)	−, cD, DC?	C, dC	(D)	
SEM						D, (dC)	C
SIM				D, dC	D, cD		C
STU	C	D, dC?	D, dC, (CD)	D, dC		D, cD	C, dC
SVE		D, (cD)	D	C, dC		D, cD	
TIK					D		
VIC						C	C

USCGS abbreviation for stations: BRK Berkeley, BOM Bombay, CHR Christchurch, DBN De Bilt, FLO Florissant, HYD Hyderabad, IRK Irkutsk, KAB Kabansk, KHE Kheys, KIR Kiruna, KYA Kyakhta, MOS Moscow, PMG Port Moresby, PUL Pulkovo, RAB Rabaul, RES Resolute Bay, RIV Riverview, ROM Rome, ROX Roxburgh, SCO Scoresby Sund, SCP State College, SEM Semipalatinsk, SIM Simferopol, STU Stuttgart, SVE Sverdlovsk, TIK Tiksi, VIC Victoria.

D or C: Dilatational or compressional P wave.

dC or DC: pP or PP wave leaving the focus as a dilatation and emerging at the station as a compression.

cD or CD: pP or PP wave leaving the focus as a compression and emerging at the station as a dilatation.

Table 3. The observed S wave polarization.

Station	1934, June 13			1951, July 11			1954, May 14			1956, Feb. 18			1957, Jan. 3			1960, Oct. 8			1961, Jan. 16		
	Az	Δ	γ_1	Az	Δ	γ_1	Az	Δ	γ_1	Az	Δ	γ_1	Az	Δ	γ_1	Az	Δ	γ_1	Az	Δ	γ_1
BRK	61	65	308-288	53	79	349	no S wave			52	78	344	51	74	114	50	77	79	55	73	265
BOM	274	66	56							276	60	96	261	54	252						
CHR							155	86	62	156	80	295	150	96	271						
DBN	338	78	358	333	91	78	333	83	278	334	88	6	328	73	113	329	76	150			
FLO							36	92	359				30	89	76	30	93	91	38	90	70
HYD				273	57	28	267	55	294							258	49	220	269	58	103
IRK				323	36	68	315	29	359										S not clear		
KAB																no S wave					
KHE																			348	54	220
KIR				340	74	62	338	66	308	340	72	23	335	56	111	336	60	123	340	67	277
KYA																			S small		
MOS							322	66	328				318	56	128				323	68	272
PMG																158	52	211-253	173	46	83-119
PUL				331	75	75	328	67	317				324	57	336	325	60	137	330	69	279
RAB																			no S		
RES				14	72	63	14	65	316							12	61	95	14	63	278
RIV	176	78	88	169	62	336	168	71	40	170	65	326	162	80	269	162	77	243	172	70	131
ROM										no S wave			318	77	114				no S		
ROX																154	92	296			
SCO	357	65	146	354	80	72	353	72	119	354	78	22	350	64	91	350	68	113	354	73	285
SEM																305	35	56	S very small		
SIM										316	78	64	308	64	140				317	76	297
STU	334	80	351	329	91	74	328	83	278	330	88	13				325	76	141	330	85	184
SVE				322	61	82				322	58	27									
TIK													359	27	114	359	31	71			
VIC				43	74	352										42	70	105			

Az: Azimuth of station to epicenter (N through E).
Δ: Epicentral distance.
γ_1: Polarization angle of S with respect to epicenter direction.
[$\gamma=\alpha-\beta$, where α is the epicenter azimuth (N through E), and β the initial motion direction of S (N through E) at the station.]

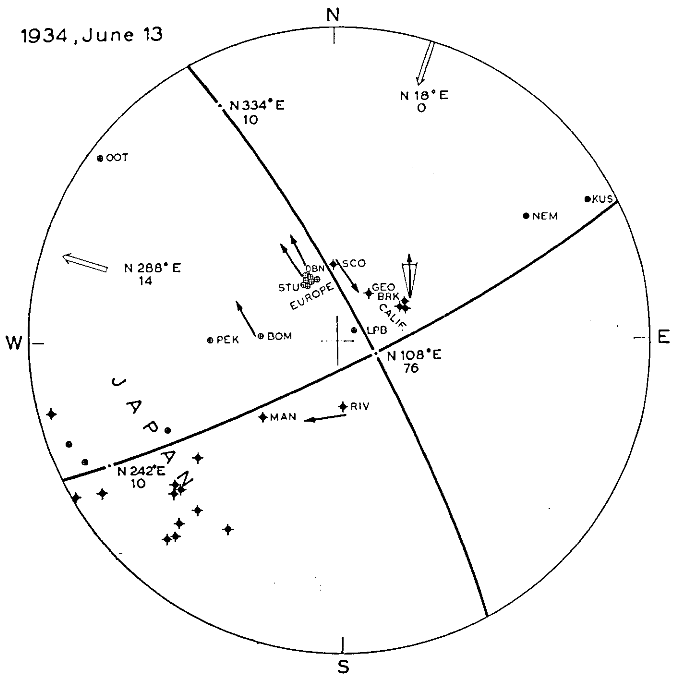


Fig. 1a. Single couple solution; RIV S and BRK S are inconsistent.

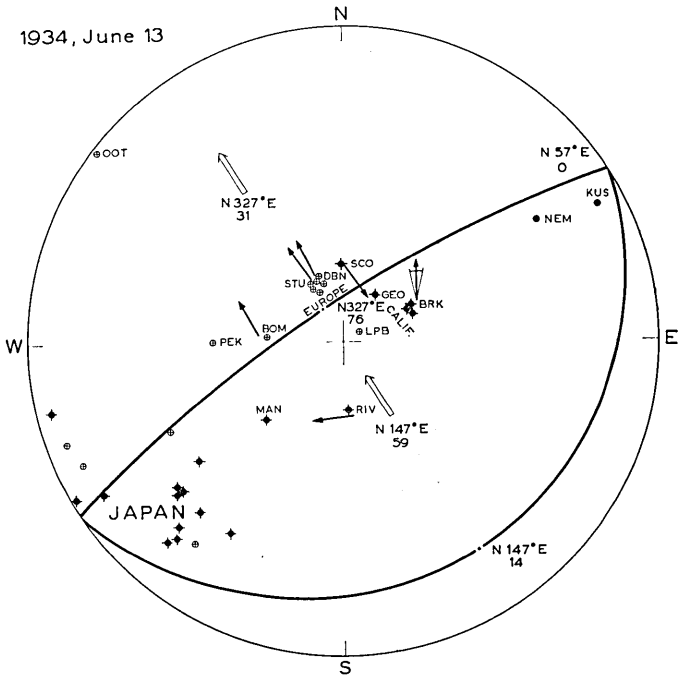


Fig. 1b. Double couple solution; SCO P and S, and LPB PKP are inconsistent.

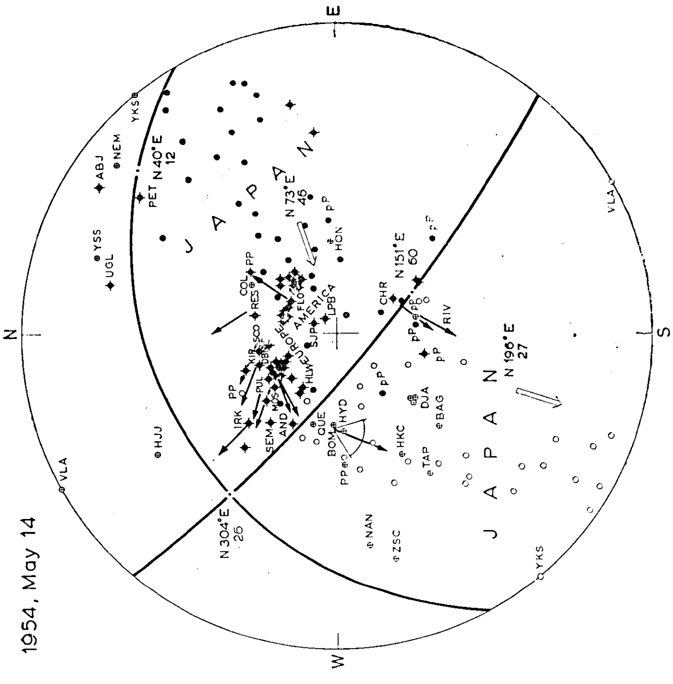


Fig. 3. Double couple source; FLO S is inconsistent.

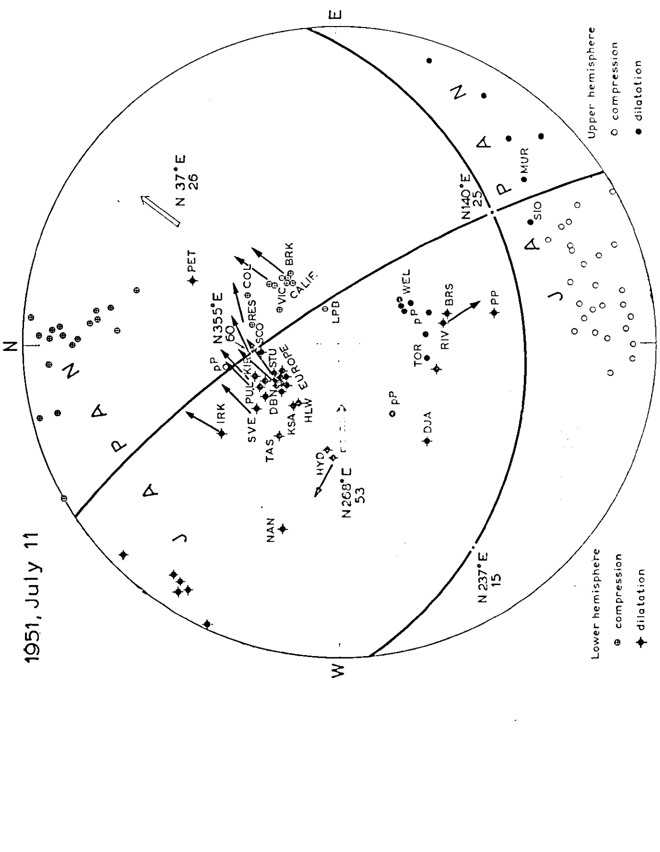


Fig. 2. Double couple source.

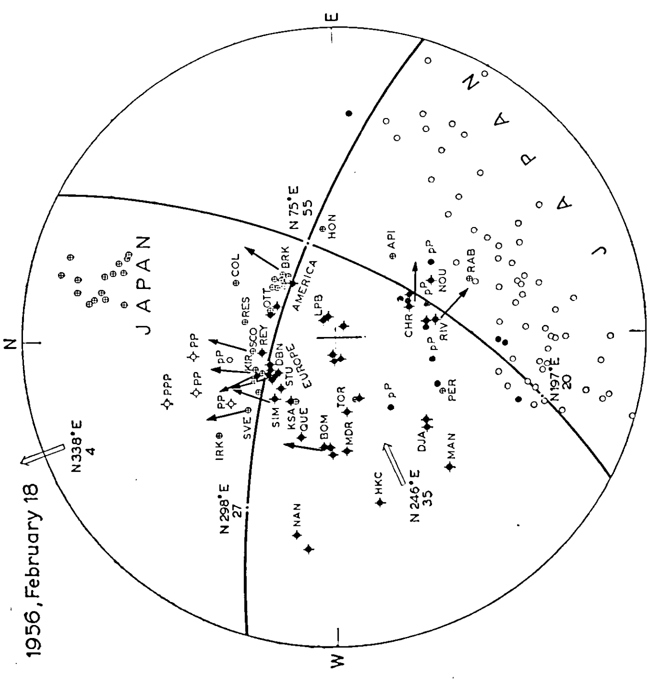


Fig. 4. Double couple source.

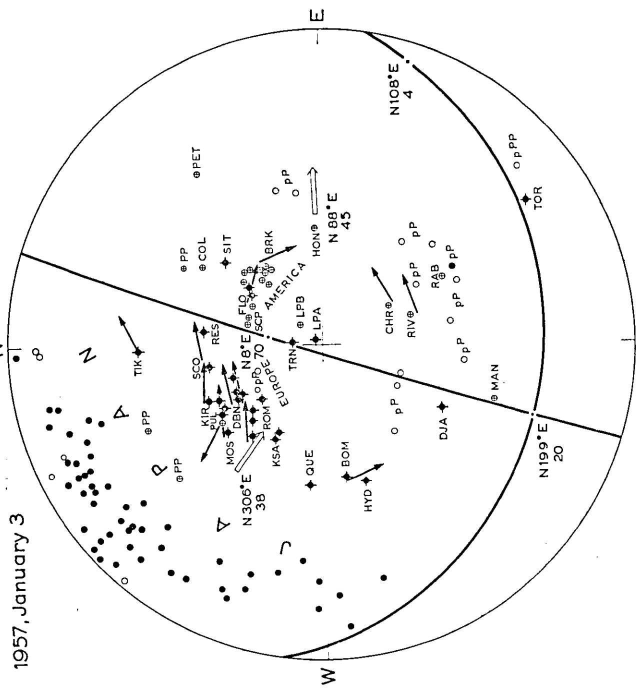


Fig. 5. Double couple source; PUL S is inconsistent.

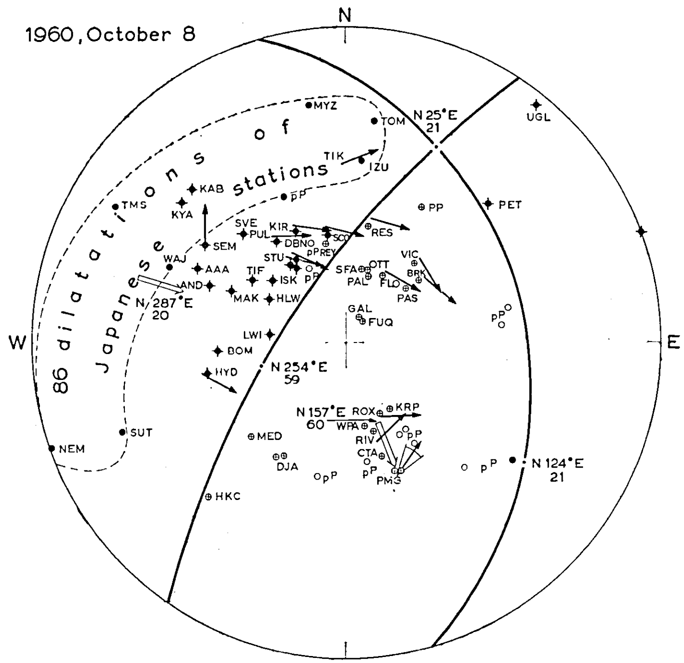


Fig. 6. Double couple source; SEM, RIV, PMG *S* are inconsistent.

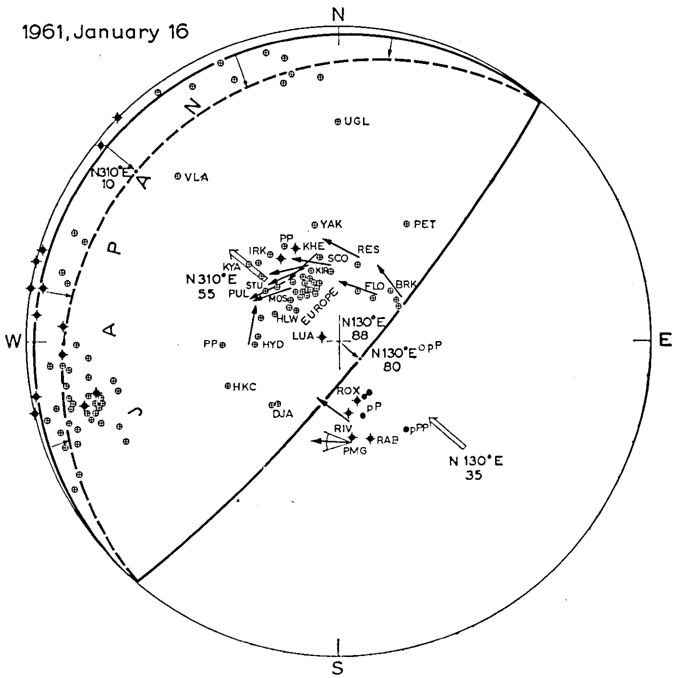


Fig. 7. Double couple source.

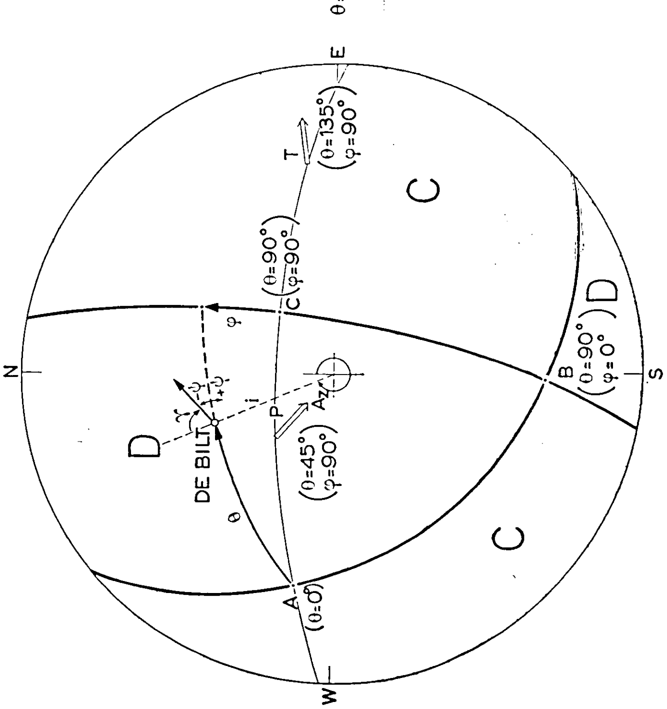
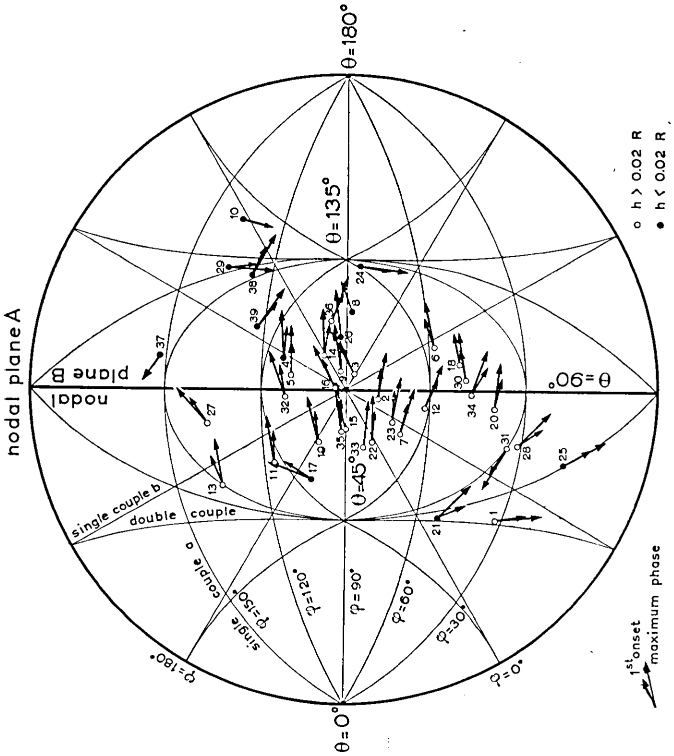


Fig. 8. The angles θ, φ, ψ, Az, i and γ.



Fi.g 9. The S wave polarization of Japanese intermediate and deep earthquakes recorded at De Bilt. The numbers refer to the earthquakes of Table 4. Theoretical polarization directions for the double couple and for the two possible single couple point sources are indicated by continuous thin lines.

Table 4. The polarization of the S waves of earthquakes of Japan area as recorded at De Bilt.

No.	Date	Time	Epicenter N	Epicenter E	Depth	θ	φ	ψ_1	ψ_m
1	1931 Feb. 20	05h 34m	44½°	136°	0.05R	54	32	+ 63	+ 64
2	1932 Sept. 23	14 23	44½	139	0.05	87	78	+ 8	+ 5
3	Nov. 13	04 48	43½	137½	0.045	96	87	− 26	− 27
4	1933 July 20	23 14	38½	145	0.01	101	113	+ 3	− 3
5	Sept. 2	16 42	30½	139½	0.055	95	110	0	− 2
6	Dec. 4	19 34	46½	144½	0.05	105	58	− 15	− 9
7	1935 May 31	08 19	38½	134	0.065	74	70	+ 12	+ 12
8	Oct. 2	09 28	31	130½	0.01	118	88	—	− 19
9	1937 May 28	19 57	24	142½	0.065	97	92	− 5	− 8
10	July 26	19 56	38	142	Shal	140	138	—	+ 80
11	1939 April 21	04 30	47½	140	0.08	66	117	+ 2	− 3
12	1941 July 6	00 35	32	140½	0.015	84	61	+ 21	+ 19
13	1942 March 5	19 48	44½	141½	0.03	61	136	− 11	+ 1
14	April 20	08 40	33	138	0.05	103	98	+ 7	− 3
15	1943 Nov. 17	14 57	33	138	0.05	76	90	− 14	− 12
16	1947 Feb. 18	13 30	33	137	0.06	91	94	− 25	− 27
17	1949 May 3	05 57	48½	153½	0.01	59	104	− 55	− 66
18	1950 Feb. 28	10 21	46	144	0.04	98	50	− 9	—
19	May 17	11 47	39½	130½	0.08	71	100	− 7	− 12
20	July 13	04 04	28	139½	0.08	85	39	+ 9	+ 5
21	1951 March 5	20 12	28	128½	0.02	50	52	+ 32	+ 51
22	May 4	11 53	44½	142	0.03	71	80	+ 2	+ 1
23	July 11	18 22	28	140	0.07	79	73	+ 2	+ 8
24	Aug. 24	14 22	46½	150½	0.025	133	84	+102	+101
25	1952 March 13	13 58	28½	127½	0.04	72	18	+ 48	+ 48
26	April 28	10 54	42	143	0.005	109	92	− 8	− 8
27	May 28	07 59	35½	136	0.05	80	138	− 32	− 36
28	Oct. 26	08 41	34½	137½	0.04	75	31	+ 47	+ 35
29	1953 Dec. 1	05 09	29	128½	0.03	127	137	+ 67	+ 75
30	Dec. 20	00 21	39½	137	0.05	93	48	− 11	− 9
31	1954 May 14	22 39	36	137½	0.03	74	34	−155	−156
32	Nov. 19	05 56	41	132	0.075	88	112	− 12	− 21
33	1955 May 14	06 14	28	140	0.07	70	83	—	+ 5
34	1956 Feb. 18	07 34	30	138½	0.07	89	46	+ 20	+ 30
35	1957 Jan. 3	12 48	44	130	0.09	75	92	0	− 7
36	Sept. 28	00 28	31	138	0.07	115	96	+ 21	+ 20
37	1958 Nov. 6	22 58	44½	148½	0.01	99	152	−150	—
38	Nov. 12	20 23	44½	148½	0.01	127	128	+ 16	+ 15
39	1959 April 26	20 41	25	122½	0.02	112	123	+ 30	+ 32

not to be exactly orthogonal. The source mechanisms of these seven earthquakes, except possibly the 1934 shock, seem to be represented by the double couple hypothesis.

In order to obtain more data on S waves, 39 Japanese shocks are selected of which the positions of the nodal planes are known (Ritsema, 1964) and the S waves are recorded clearly at De Bilt, the epicentral distances being between 75° and 95° (Table 4). The polarization angles γ_1 and γ_m of the motion of the first onset and of the maximum phase respectively, are obtained for these earthquakes. Differences between γ_1 and γ_m are mostly small. The position of De Bilt relative to the nodal planes is expressed by the angles θ and φ (Fig. 8). The angle between the motion direction of the first onset or the maximum phase of S waves and the great circle passing through the station and the pole ($\theta=0$) of the diagram is denoted by ψ_1 or ψ_m (Fig. 8). Now all S data of these 39 shocks are illustrated in a single diagram (Fig. 9), in which, after suitably rotating the focal sphere of each of these shocks, one of the nodal planes for P waves is taken to lie vertically and the other one horizontally, for the sake of convenience. The motion directions of S waves which are expected theoretically from the assumption of the single couple or the double couple hypothesis are represented by continuous thin lines.

For most shocks the position of De Bilt relative to the nodal planes is not favorable for discrimination between the two types of source mechanisms by means of the motion directions of S waves. However, the double couple hypothesis seems to be a more suitable source mechanism than the single couple hypothesis for about 12 shocks, whereas the single couple hypothesis seeems to be better than the double couple hypothesis only for 2 or 3 shocks. Thus, generally speaking, the pattern of S wave data obtained at De Bilt does not contradict Honda's conclusion that the source mechanisms of the earthquakes of this region are explained by the double couple hypothesis.

3. Amplitude Ratio of P and S Waves and the Radius of Focal Sphere

The amplitudes (A_p and A_s) of P and S waves of Japanese intermediate and deep earthquakes were measured from the records of Galitzin seismographs at De Bilt (Table 5), as far as possible. Because of the similarity of the rays of the waves of all these shocks, the observed amplitudes are readily comparable with each other.

Table 5. The radius of the focal sphere (a) estimated from the amplitude ratio of P and S waves.

No.	Date	Depth (R)	Magnitude	A_s/A_p (1st)	A_s/A_p (max)	θ	φ	$\frac{A_s/A_p}{f(\theta,\varphi)}$ (1st)	$\frac{A_s/A_p}{f(\theta,\varphi)}$ (max)	Radius a (km) (1st)	Radius a (km) (max)
1	1931 Feb. 20	0.05	7.4	3.8	4.9	54	32	0.70	0.90	21	21
2	1932 Sept. 23	0.05	6.9	15.0	17.7	87	78	0.30	0.36	30	29
3	Nov. 13	0.045	7.0	11.9	10.8	96	87	0.49	0.44	25	26
5	1933 Sept. 2	0.055	$6\frac{3}{4}$	10.4	12.1	95	110	0.34	0.39	17	16
7	1935 May 31	0.065	$6\frac{1}{2}$	3.2	4.7	74	70	0.38	0.56	20	17
8	Oct. 2	0.01	7.0	—	1.0	118	88	—	0.28	—	23
10	1937 July 26	0.00	7.1	—	1.5	140	138	—	0.33	—	29
11	1939 April 21	0.08	7.0	5.5	7.7	66	117	1.12	1.57	small	
14	1942 April 20	0.05	$6\frac{1}{2}$	6.3	7.0	103	98	0.59	0.66	16	16
16	1947 Feb. 18	0.06	$6\frac{3}{4}$	11.4	17.0	91	94	0.08	0.114	34	26
17	1949 May 3	0.01	7	1.1	1.4	59	104	0.39	0.49	16	15
18	1950 Feb. 28	0.04	7.8	4.0	4.5	98	50	0.22	0.25	52	49
21	1951 March 5	0.02	6.9	1.1	1.0	50	52	0.39	0.36	45	42
23	July 11	0.07	7	9.6	16.0	79	73	0.74	1.24	23	small
27	1952 May 28	0.05	$6\frac{3}{4}$-7	2.5	3.4	80	138	0.17	0.24	35	29
29	1953 Dec. 1	0.03	—	1.6	1.2	127	137	0.42	0.32	33	25
31	1954 May 14	0.03	7	1.3	1.8	74	34	0.14	0.19	37	31
32	Nov. 19	0.075	$6\frac{1}{2}$	14.8	20.3	88	112	0.20	0.27	20	18
34	1956 Feb. 18	0.07	$7\frac{1}{4}$-$7\frac{1}{2}$	27.7	28.5	89	46	0.19	0.19	20	20
35	1957 Jan. 3	0.09	7	9.1	10.5	75	92	1.00	1.16	small	
38	1958 Nov. 12	0.01	6.9	7.4	3.6	127	128	2.50	1.22	small	
39	1959 April 26	0.02	$7\frac{1}{2}$	8.4	5.2	112	123	1.48	0.92	small	

For the measuring of the amplitude of the first onset the magnification curves for Galitzin seismographs, which are valid for the first onset of a suddenly beginning sinusoidal motion of the ground, are used. The maximum amplitude is obtained by use of the normal magnification curves for a continuous sinusoidal motion of the ground. Differences between the two values are mostly small. It is to be noted here that the periods of S waves are generally 1.2 to 1.8 times longer than those of P waves.

Honda showed that the radiation pattern of P and S waves for a radial force $F \sin 2\theta \sin\varphi \exp(i\omega t)$, F being a constant and ω the circular frequency, acting on the surface of a spherical cavity of radius a in an infinite elastic solid, is equivalent to that for the double couple force system. The ratio of the amplitude of S waves to that of P waves at large distances from the source, is expressed by

$$A_s/A_p = R \cdot f(\theta, \varphi) \ ,$$
$$f(\theta, \varphi) = 5.20\sqrt{\cos^2 2\theta \sin^2 \varphi + \cos^2 \theta \cos^2 \varphi} \Big/ |\sin 2\theta \sin \varphi| \ .$$

The curve which shows the relation between R and $2\pi a/l_p$, l_p being the wavelength of P waves, has been given by Honda et al. (1937, 1962). If we assume that we can apply these theoretical relations to our observations, we are able to assign a certain value to the radius a of the hypothetical focal sphere for each of the shocks of Table 5, whose source mechanisms are represented by the double couple model. The radii of the focal spheres estimated in this way are given in Table 5, although it is to be remarked that a much simplified model on the source mechanism is used here.

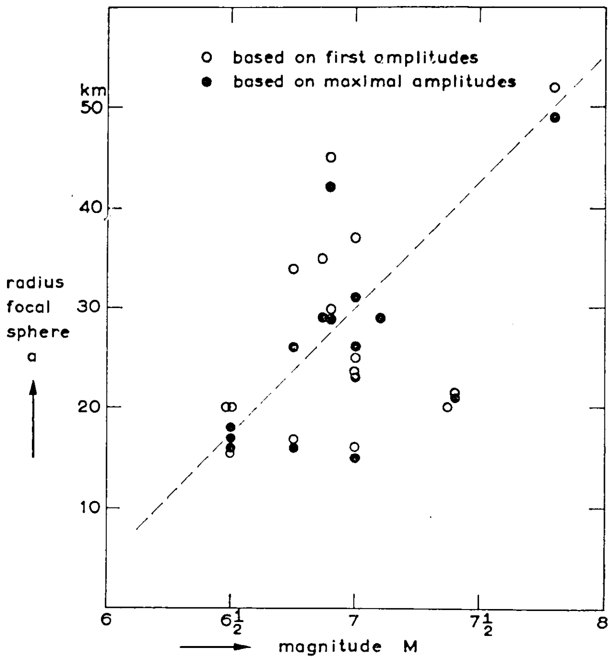


Fig. 10. The radius of the focal sphere and the magnitude of the earthquake.

The relations between the values of a and the magnitudes of the shocks given by Pasadena are illustrated in Fig 10. Although the points in the figure are scattered, one can still find a tendency for larger earthquakes to correspond to larger values of a, just as may be expected. Thus the radii of the focal spheres of the Japanese intermediate and deep earthquakes of magnitudes $6^1/_2$ to 7.8 seem to be about 10 to 50 km. These values of a are not in contradiction with the values of the lengths of faults or volumes of focal regions of some earthquakes which were estimated by Kasahara (1957), Tsuboi (1956), Keylis-Borok (1959) and Berckhemer (1962) by use of some methods other than the present one.

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4. 日本附近の稍深発および深発地震のメカニズム

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日本附近に起こつた 7 個の稍深発および深発地震について，遠距離の地点における S 波の運動の向きの分布を調べて，これらの地震のメカニズムが double couple の仮説によつて説明できることを示した．また De Bilt において記録された同地域の 39 個の地震の S 波を調べて同じ仮説が成り立つことがわかつた．マグニチュードが $6^1/_2$ から 7.8 の範囲内にあるこれらの地震の P 波と S 波の振幅の比から，メカニズムのモデルとして用いた震源球の半径は 10 km から 50 km 位であると推定される．
