Bulletin of the Seismological Society of America, Vol. 72, No. 6, pp. 2181–2200, December 1982

TIDAL TRIGGERING OF EARTHQUAKES

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ABSTRACT

Analysis of the tidal stress tensor at the time of moderate to large earthquakes fails to confirm an earlier hypothesis that the origin times of shallow dip-slip earthquakes correlate with solid-earth tidal shear stress. Furthermore, no correlation is seen for either tidal shear stress or tidal normal-to-the-fault compressive stress with shallow strike-slip earthquakes or with deep earthquakes.

INTRODUCTION

In an earlier study (Heaton, 1975), I reported on the results of an investigation that suggested a correlation between the origin times of moderate to large shallow dip-slip earthquakes and tidal shear stress as resolved into a coordinate frame defined by the slip vectors of individual earthquakes. In that investigation, I computed the solid earth tidal shear stress for 107 earthquakes for which the focal mechanisms were known. Although no significant tidal correlation was found for the entire data set, which contained earthquakes of all depths and mechanisms, a fairly striking correlation was seen for those 34 earthquakes that were classified as shallow dip-slip earthquakes. Because of that result, I concluded that there is good reason to believe that larger shallow dip-slip earthquakes are tidally triggered. In order to test the validity of that hypothesis, in this study I calculate tidal stress histories for 222 earthquakes that were not considered in the previous study. Of these, 68 are classified as shallow dip-slip. If the previous hypothesis is to be considered physically meaningful, then a similar correlation between tidal shear stress history and the origin times of earthquakes should be seen for this new data set. The purpose of this study, then, is to confirm or reject the hypothesis that the origin times of shallow dip-slip earthquakes correlate with tidal shear stress.

As geophysical problems go, the problem solved in this paper is very well posed. That is, there are very few subjective judgments which must be made. Both the way in which the data are chosen and the method of statistical analysis are defined by the earlier study. Having well-defined rules is essential if statistics are to have meaning. Furthermore, the statistics are invalid if results are examined before deciding whether to play the game. This is a common problem with many earthquake prediction statistical studies and one which I seem to have poorly understood in my earlier study (Heaton, 1975). However, it seems clear that professional casinos would not allow their patrons to make this same mistake.

EARTHQUAKES AND TIDES

In this study, a very simple earthquake tidal triggering mechanism for earthquakes is tested. That is, do earthquakes occur preferentially at times when solid earth tides increase the shear stress on faults? In order to answer this question, the solid body tidal stress is computed as a function of time and then rotated into the coordinate frame which is defined by the earthquake fault plane and the slip vector. In this way, the tidal shear stress that can be considered to be sympathetic to failure can be plotted as a function of time. The coordinate frame that is used in this study is illustrated in Figure 1. The procedure used for calculating the solid earth tidal stress is described by Heaton (1975) and identical computer codes are used in both these studies. In addition to calculating the shear stress, the normal-to-the-fault compressive tidal stress, and the hydrostatic stress $(\tau_{11} + \tau_{22} + \tau_{33})/3$ are also computed for each earthquake. The fault plane and slip vector of each earthquake are defined from published source studies. Due to the symmetry of the stress tensor, either of the two complementary fault planes and slip vectors that are obtained from focal-mechanism studies can be used to specify the coordinate frame into which the tidal stress tensor is rotated.

The effects of oceanic tides on crustal stress are ignored in this study. This is not to imply that oceanic tides are unimportant. On the contrary, oceanic tidal stress can cause significant pertubations in the phase and amplitude of crustal tidal stress and in some instances may dominate over the solid earth tidal stress (Beaumont and Berger, 1975). Unfortunately, computation of tidal stress due to oceanic loading is quite difficult and beyond the scope of this study. Because of the statistical nature of this problem, one may argue that inclusion of the contribution of oceanic tides is

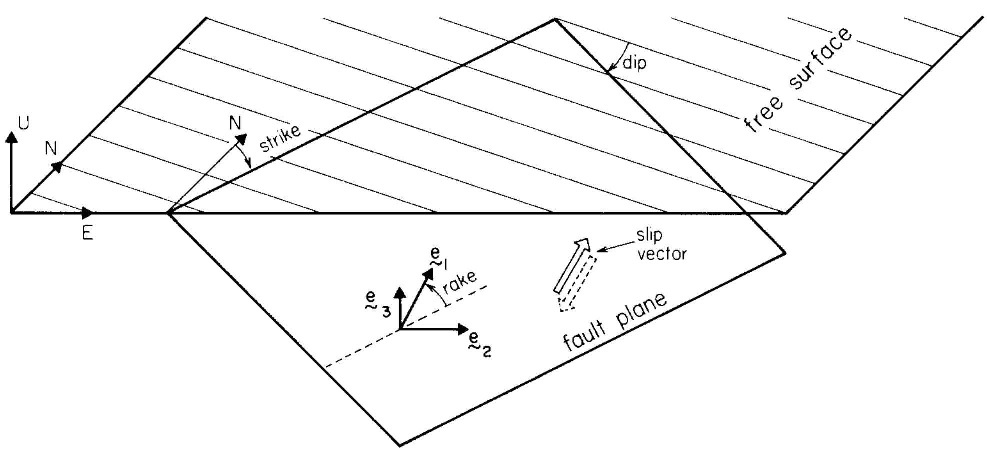


FIG. 1. Coordinate system used in this report. Fault strike is defined as clockwise from north. Dip is positive for a fault striking north and dipping east. Rake is 0° for left-lateral and positive 90° for thrust. e_1 is alined parallel to the slip vector and e_3 is perpendicular to the fault.

not crucial for this test of tidal triggering. Nevertheless, it is clear that modeling the contribution of oceanic loading is desirable.

CHOICE OF DATA SET

The purpose of this study is to determine whether the origin times of earthquakes depend upon tidal stress. Thus, it seems clear that only earthquakes whose origin time is independent of other obvious factors should be chosen. Therefore, an attempt was made to include only earthquakes that were main shocks and that were not preceded by obvious large foreshock activity. Furthermore, the fault plane and slip vector for each earthquake should be known and well constrained. These parameters were obtained from either observed surface rupture or seismically determined fault-plane solutions. Because of the free-surface boundary condition, τ_{31} (the shear stress sympathetic to failure) for dip-slip earthquakes on vertical faults is always nearly zero. The polarity of the computed tidal shear stress for dip-slip earthquakes on nearly vertical faults is thus sensitive to minor errors in the fault-plane solution. Therefore, earthquakes with dip-slip motion on near-vertical faults are excluded. Earthquakes that appear to meet the specifications listed above were rather randomly chosen from a variety of sources. The earthquakes were then classified according to focal depth and mechanism. They are listed in chronological order in Tables 1 to 3. Entries with an asterisk represent earthquakes that were considered in my earlier study (Heaton, 1975). Earthquakes with slip angles of less than 30° from horizontal are classified as strike-slip and earthquakes with depths greater than 30 km are considered as deep. However, since a focal depth of 33 km is often used as a default value in published catalogs, some of the earthquakes that are called deep may have actually been significantly shallower. To protect against systematic error due to my own predjudices (i.e., a desire to repeat my previous results), the decisions were made about earthquake parameters before any tides were computed and the decisions were final.

Data Analysis

The data analysis in this study is identical to that in my earlier study (Heaton, 1975). Tidal stresses are plotted as a function of time for each earthquake. A phase is then assigned using a linear scale (with time) from 0° to 360°, where 0° and 360° are defined by the times of tidal stress maxima immediately before and after the earthquake, respectively (see Figure 2). These phases are then plotted on rose diagrams. If earthquake origin times and tidal stress are independent, then the phases will appear uniformly distributed about the rose diagram. Clustering of the phases on one side of a rose diagram indicates a possible relationship between tides and earthquakes. The statistical significance of clustering is evaluated by a clever and simple method developed by Rayleigh (1919). Consider a random walk in two dimensions (see Figure 3). Let each earthquake phase ζ_i represent a unit step in the ζ_i direction. If the magnitude of the vector sum of m unit two-dimensional vectors $(1, \zeta_i)$ is denoted by R, then the probability P_R that a random set of m phases will produce a vector sum whose magnitude exceeds R is approximately equal to $\exp(-R^2/m)$. This approximation is sufficient when m is larger than 10. Thus, the smaller is P_R, the greater becomes our confidence in tidal triggering.

Results

The results of this study are summarized in Tables 1 to 3 and Figures 4 and 5. Phases of the hydrostatic stress, normal-to-the-fault compressive stress, and shear stress are given for each earthquake. Zero degrees phase denotes either maximum tensile or maximum shear stress. Figure 5, a and b, shows no apparent correlation between earthquake origin times and tidal shear stress or normal-to-the-fault compressive stress for the entire data set (328 earthquakes). The same conclusion is reached when only those earthquakes deeper than 30 km are considered (Figure 5, c and d). If the data set is restricted to shallow (depth < 30 km) strike-slip (slip vector $< 30°$ from horizontal) earthquakes, then no apparent correlation can be seen for either shear stress or normal-to-the-fault compressive stress (Figure 5, a and b). All of the above results are compatible with my earlier study (Heaton, 1975). In that earlier study, however, there was a rather striking correlation between the origin times and tidal shear stress seen for shallow dip-slip earthquakes (34 events). An additional 68 shallow dip-slip earthquakes are investigated in this study. The phases of the tidal shear stress for those new earthquakes are shown in Figure 5c; no correlation can be seen. The phases of the tidal shear stress for shallow dip-slip earthquakes, and the combined data set are shown in Figure 5d; once again, the correlation is not statistically significant. Therefore, I conclude that the previously

TABLE 1
EARTHQUAKES DEEPER THAN 30 KM

Date	Time	Comments	Reference (year)	Magnitude	Depth	Longitude	Latitude	Strike	Dip	Rake	Hydro.	Shear	Normal
8/1/1940	15:8	* Shakotan	Fukao and Furumoto (1975)	7.0	33	139.5	44.4	0.0	46.0	90.0	52.0	282.0	40.0
11/6/1958	22:58	So. Kuriles	Fukao and Furumoto (1979)	8.2	32	148.6	315.0	30.0	90.0	10.0	143.0	332.0	44.4
3/7/1962	11:1	Marianas	Katsumata and Sykes (1969)	6.6	683	145.2	19.1	139.0	46.0	−90.0	243.0	232.0	259.0
2/13/1963	8:50	Taiwan	Katsumata and Sykes (1972)	7.4	67	122.1	24.3	79.0	61.0	90.0	59.0	240.0	64.0
7/9/1963	5:45	* Mediterranean	McKenzie (1972)	5.5	33	8.2	43.4	2.0	40.0	80.0	148.0	40.0	138.0
8/29/1963	8:53	Central Asia	Tapponier and Molnar (1979)	6.7	51	74.2	39.6	90.0	30.0	90.0	158.0	318.0	166.0
9/17/1963	5:54	* Peru-Chile	Isacks and Molnar (1971)	6.8	76	−78.2	−10.6	175.0	35.0	−75.0	28.0	33.0	27.0
9/18/1963	16:58	* Mediterranean	McKenzie (1972)	5.2	33	29.2	40.9	276.0	70.0	−100.0	194.0	183.0	189.0
9/24/1963	16:30	* Peru-Chile	Isacks and Molnar (1971)	6.5	60	−78.3	−10..7	130.0	10.0	−90.0	216.0	237.0	234.0
10/17/1963	0:48	* North Atlantic	Chandra (1971)	6.3	35	−37.4	7.6	355.0	85.0	5.0	313.0	265.0	313.0
1/14/1964	15:58	* Solomons	Isacks and Molnar (1971)	5.6	169	150.8	−5.2	55.0	80.0	90.0	63.0	257.0	53.0
1/15/1964	21:36	Japan	Katsumata and Sykes (1972)	6.4	80	141.1	29.2	81.0	59.0	113.0	193.0	0.0	196.0
3/6/1964	18:57	Solomons	Johnson and Molnar (1972)	5.8	74	154.4	−6.1	132.0	45.0	90.0	328.0	149.0	322.0
4/30/1964	16:3	New Ireland	Johnson and Molnar (1972)	5.2	78	153.2	−4.6	105.0	56.0	90.0	182.0	184.0	184.0
6/15/1964	0:5	No. Sumatra	Fitch (1970)	5.5	67	96.8	5.3	103.0	31.0	90.0	85.0	272.0	82.0
7/9/1964	16:39	* New Hebrides	Isacks and Molnar (1971)	7.5	121	167.6	−15.5	175.0	53.0	90.0	110.0	277.0	123.0
7/7/1964	2:34	Greece	Sengupta and Toksöz (1977)	5.4	151	23.9	38.1	150.0	72.0	138.0	280.0	80.0	277.0
8/13/1964	0:31	* Solomons	Isacks and Molnar (1971)	6.5	392	154.3	−5.5	135.0	30.0	−100.0	225.0	253.0	253.0
10/11/1964	11:21	No. Celebes	Fitch (1970)	6.3	45	121.8	−0.6	143.0	59.0	−52.0	120.0	115.0	122.0
11/1/1964	12:26	No. Halmahera	Fitch (1970)	6.3	89	128.1	3.1	218.0	51.0	146.0	307.0	133.0	312.0
11/2/1964	6:50	* Peru-Chile	Isacks and Molnar (1971)	6.8	91	−76.9	−4.1	150.0	30.0	−90.0	78.0	88.0	95.0
11/17/1964	8:15	New Britain	Johnson and Molnar (1972)	6.7	45	150.7	−55.7	86.0	56.0	90.0	228.0	45.0	228.0
11/23/1964	16:41	* Peru-Chile	Isacks and Molnar (1971)	5.5	650	−71.3	−7.9	155.0	45.0	−85.0	85.0	85.0	111.0
12/7/1964	8:58	New Britain	Johnson and Molnar (1972)	5.8	54	151.3	−5.4	48.0	64.0	104.0	155.0	333.0	154.0
12/9/1964	13:35	* Chile	Stauder (1973)	5.9	586	−63.2	−27.5	170.0	80.0	−120.0	176.0	85.0	199.0
1/10/1965	13:36	New Hebrides	Johnson and Molnar (1972)	6.5	32	166.6	−13.5	155.0	34.0	119.0	217.0	34.0	213.0
2/8/1965	15:46	Kamchatka	Cormier (1975)	5.6	40	165.7	55.1	177.0	57.0	−32.0	173.0	227.0	120.0
2/25/1965	4:51	New Britain	Johnson and Molnar (1972)	5.9	35	152.0	−5.5	83.0	60.0	92.0	203.0	19.0	200.0
3/3/1965	15:14	New Britain	Johnson and Molnar (1972)	6.0	44	151.9	−5.5	88.0	60.0	62.0	34.0	218.0	34.0
3/5/1965	14:32	* Peru-Chile	Isacks and Molnar (1971)	5.6	573	−63.3	−27.0	170.0	70.0	−110.0	275.0	198.0	302.0
3/14/1965	15:53	Hindu-Kush	Chatelain *et al.* (1980)	6.6	205	70.6	36.4	122.0	60.0	75.0	300.0	100.0	294.0
3/18/1965	6:22	Tonga	Chung (1979)	6.0	219	−175.9	−19.9	199.0	87.0	16.0	184.0	317.0	178.0
3/21/1965	11:8	Molucca Sea	Fitch (1970)	6.2	51	125.1	−0.2	104.0	52.0	−113.0	159.0	159.0	159.0
3/28/1965	13:22	Kamchatka	Cormier (1975)	5.9	33	162.1	55.1	55.0	50.0	76.0	76.0	260.0	98.0

4/29/1965	15:28	* NW U.S.	Isacks and Molnar (1971)	6.5	59	−122.3	47.4	350.0	70.0	−75.0	247.0	226.0	230.0
6/12/1965	18:50	* Peru-Chile	Isacks and Molnar (1971)	5.8	102	−69.3	−20.5	150.0	7.0	−90.0	86.0	134.0	103.0
8/5/1965	0:7	New Britain	Johnson and Molnar (1972)	6.2	47	151.7	−5.3	44.0	50.0	103.0	111.0	292.0	100.0
8/12/1965	12:57	New Britain	Johnson and Molnar (1972)	5.9	41	152.2	−5.3	70.0	68.0	90.0	326.0	148.0	330.0
9/12/65	13:12	Tonga	Chung (1979)	5.7	649	−178.1	−18.1	132.0	62.0	−39.0	18.0	347.0	39.0
11/3/1965	1:39	* Peru-Chile	Isacks and Molnar (1971)	6.2	593	−71.4	−9.1	170.0	50.0	−90.0	13.0	5.0	43.0
11/13/1965	4:33	Central Asia	Tapponier and Molnar (1979)	6.4	55	87.7	43.9	269.0	52.0	104.0	248.0	25.0	244.0
11/18/1965	20:0	Tonga	Chung (1979)	6.2	424	−177.8	−12.8	237.0	90.0	120.0	300.0	357.0	300.0
12/8/1965	18:5	Tonga	Chung (1979)	6.0	156	177.5	−37.1	118.0	30.0	56.0	178.0	48.0	193.0
12/10/1965	21:53	Santa Cruz	Johnson and Molnar (1972)	5.8	52	166.2	−11.4	163.0	50.0	90.0	228.0	60.0	232.0
12/28/1965	20:32	Bonin Region	Katsumata and Sykes (1969)	5.9	36	142.2	27.6	16.0	66.0	106.0	66.0	242.0	69.0
1/28/1966	4:36	Tonga	Chung (1979)	3.8	545	177.0	−17.6	69.0	60.0	215.0	24.0	51.0	19.0
2/5/1966	15:12	China	Tapponier and Molnar (1977)	6.0	35	103.2	26.2	78.0	85.0	173.0	300.0	234.0	301.0
3/7/1966	21:29	China	Tapponier and Molnar (1977)	6.0	33	115.0	37.3	114.0	90.0	0.0	137.0	176.0	131.0
3/17/1966	15:50	Tonga	Chung (1979)	6.2	630	−179.2	−21.1	34.0	70.0	275.0	178.0	218.0	145.0
4/23/1966	0:9	No. Celebes	Fitch (1970)	6.0	45	122.4	−0.9	113.0	40.0	−90.0	218.0	220.0	220.0
5/1/1966	16:22	* Peru-Chile	Isacks and Molnar (1971)	5.8	154	−74.3	−8.4	15.0	70.0	−115.0	31.0	49.0	27.0
5/21/1966	18:45	* Sumatra	Chandra (1971)	6.3	173	101.5	−1.0	160.0	70.0	120.0	22.0	184.0	23.0
6/6/1966	7:46	* Afghanistan	Chandra (1971)	6.5	225	71.1	36.3	270.0	40.0	82.0	320.0	145.0	312.0
6/13/1966	18:8	* New Hebrides	Isacks and Molnar (1971)	6.0	259	167.1	−12.2	190.0	45.0	55.0	257.0	52.0	277.0
6/27/1966	10:41	* Nepal	Chandra (1971)	6.5	37	80.9	29.7	315.0	25.0	85.0	228.0	357.0	205.0
7/21/1966	18:30	Tonga	Chung (1979)	5.8	590	−178.6	−17.8	56.0	66.0	195.0	130.0	164.0	114.0
8/5/1966	4:33	* Solomons	Isacks and Molnar (1971)	5.5	52	162.6	−11.1	130.0	45.0	100.0	41.0	225.0	50.0
8/14/1966	14:34	Molucca Sea	Fitch (1970)	6.1	51	123.1	−0.2	21.0	70.0	87.0	356.0	183.0	0.0
8/17/1966	19:54	Banda Sea	Sengupta and Toksöz (1977)	5.5	553	125.1	−5.0	166.0	64.0	90.0	104.0	234.0	124.0
9/12/1966	11:29	New Hebrides	Johnson and Molnar (1972)	5.9	49	170.6	−23.1	30.0	44.0	−144.0	2.0	2.0	358.0
10/17/1966	21:42	* Peru	Abe (1972)	7.5	38	−78.6	−10.7	330.0	12.0	90.0	70.0	240.0	54.0
11/12/1966	18:45	New Hebrides	Johnson and Molnar (1972)	5.2	40	167.3	−15.6	160.0	48.0	103.0	176.0	8.0	182.0
12/1/1966	4:56	* New Hebrides	Isacks and Molnar (1971)	6.0	132	167.1	−14.0	165.0	45.0	95.0	69.0	242.0	82.0
12/14/1966	21:7	* Solomons	Isacks and Molnar (1971)	5.7	80	144.1	−4.9	310.0	60.0	90.0	148.0	341.0	150.0
12/20/1966	12:26	* Peru-Chile	Isacks and Molnar (1971)	5.7	586	−63.2	−26.2	160.0	70.0	−75.0	32.0	334.0	54.0
12/21/1966	8:52	* New Hebrides	Isacks and Molnar (1971)	5.8	249	169.7	−20.0	15.0	65.0	−40.0	25.0	82.0	9.0
12/23/1966	15:50	E. New Guinea	Johnson and Molnar (1972)	6.1	43	148.0	−7.1	63.0	30.0	70.0	133.0	310.0	126.0
12/31/1966	18:23	Santa Cruz	Johnson and Molnar (1972)	5.5	33	166.5	−11.8	42.0	42.0	69.0	82.0	267.0	75.0
1/2/1967	19:59	Santa Cruz	Johnson and Molnar (1972)	5.3	33	166.4	−12.3	168.0	64.0	90.0	64.0	265.0	68.0
1/5/1967	0:14	Central Asia	Tapponier and Molnar (1979)	6.0	35	102.9	48.2	12.0	87.0	−177.0	157.0	43.0	162.0
1/13/1967	13:48	Solomons	Johnson and Molnar (1972)	5.7	325	161.4	−10.6	178.0	66.0	90.0	325.0	108.0	342.0
1/17/1967	1:8	* Peru-Chile	Isacks and Molnar (1971)	5.5	590	−63.3	−27.4	155.0	65.0	−115.0	147.0	100.0	178.0

TABLE 1—*Continued*

Date	Time	Comments	Reference (year)	Magnitude	Depth	Longitude	Latitude	Strike	Dip	Rake	Hydro.	Shear	Normal
1/19/1967	12:38	* New Hebrides	Isacks and Molnar (1971)	5.5	156	166.4	−11.8	0.0	60.0	100.0	162.0	10.0	152.0
1/23/1967	1:50	Hindu-Kush	Chatelain *et al.* (1980)	5.7	281	71.6	36.7	122.0	26.0	53.0	257.0	20.0	253.0
2/15/1967	16:11	* Peru-Chile	Isacks and Molnar (1971)	6.2	597	−71.3	−9.0	170.0	45.0	−90.0	244.0	243.0	278.0
3/4/1967	17:58	* Mediterranean	McKenzie (1972)	6.8	33	24.6	39.2	98.0	54.0	105.0	353.0	182.0	348.0
3/11/1967	8:33	Santa Cruz	Johnson and Molnar (1972)	6.0	49	166.2	−10.7	69.0	66.0	−109.0	224.0	227.0	222.0
3/27/1967	8:58	China	Tapponier and Molnar (1977)	5.5	59	116.6	38.6	202.0	80.0	177.0	123.0	163.0	137.0
3/31/1967	20:5	* New Hebrides	Isacks and Molnar (1971)	5.3	132	167.5	−15.4	165.0	45.0	90.0	100.0	161.0	51.0
4/5/1967	2:34	Marianas	Kasumata and Sykes (1969)	5.7	50	147.4	20.0	139.0	57.0	−113.0	72.0	57.0	66.0
4/12/1967	4:51	No. Sumatra	Fitch (1970)	6.1	55	96.5	5.3	102.0	30.0	90.0	308.0	130.0	312.0
5/11/1967	15:5	* Chile	Stauder (1973)	6.1	115	−68.5	−20.3	330.0	70.0	−100.0	287.0	215.0	298.0
8/12/1967	9:39	Tonga	Chung (1979)	6.5	134	−177.5	−24.7	38.0	27.0	44.0	187.0	266.0	71.0
8/13/1967	20:6	* Honshu	Isacks and Molnar (1971)	6.0	357	135.0	35.3	225.0	70.0	−115.0	320.0	287.0	314.0
8/19/1967	15:28	Philippines	Fitch (1970)	5.6	58	126.0	10.4	25.0	56.0	120.0	360.0	133.0	178.0
8/26/1967	0:36	W. Caroline	Katsumata and Sykes (1969)	6.1	53	140.8	12.2	69.0	40.0	−83.0	207.0	210.0	209.0
9/4/1967	3:51	Tonga	Chung (1979)	6.2	231	−179.4	−31.4	119.0	16.0	50.0	119.0	358.0	135.0
9/18/1967	15:33	E. New Guinea	Johnson and Molnar (1972)	5.5	39	146.6	−5.9	130.0	50.0	105.0	39.0	218.0	43.0
9/28/1967	4:56	New Britain	Johnson and Molnar (1972)	5.8	44	153.4	−6.6	142.0	58.0	−84.0	197.0	200.0	204.0
10/4/1967	17:21	New Ireland	Johnson and Molnar (1972)	6.3	52	153.9	−5.7	125.0	40.0	90.0	95.0	279.0	100.0
10/9/1967	13:27	New Ireland	Johnson and Molnar (1972)	4.9	41	154.0	−5.7	130.0	70.0	90.0	232.0	48.0	253.0
10/25/1967	0:59	Taiwan	Katsumata and Sykes (1969)	6.0	70	122.2	24.4	34.0	44.0	133.0	151.0	213.0	71.0
11/12/1967	10:36	Tonga	Chen and Forsyth (1978)	5.6	42	−172.0	−17.2	215.0	63.0	120.0	50.0	221.0	46.0
11/19/1967	17:29	New Hebrides	Johnson and Molnar (1972)	5.2	33	170.9	−22.6	101.0	74.0	90.0	108.0	303.0	111.0
12/25/1967	1:23	New Ireland	Johnson and Molnar (1972)	7.0	64	153.7	−5.3	112.0	46.0	90.0	134.0	322.0	140.0
12/25/1967	10:41	* Peru-Chile	Isacks and Molnar (1971)	3.8	135	−68.3	−21.2	160.0	25.0	−85.0	310.0	316.0	322.0
12/27/1967	9:17	* Peru-Chile	Isacks and Molnar (1971)	6.4	135	−68.3	−21.2	160.0	25.0	−85.0	220.0	233.0	237.0
12/27/1967	16:22	Tonga	Johnson and Molnar (1972)	5.8	33	−174.8	−22.3	189.0	76.0	−42.0	210.0	272.0	213.0
1/7/1968	9:56	* Solomons	Isacks and Molnar (1971)	5.1	118	153.9	−5.1	145.0	45.0	80.0	81.0	262.0	94.0
1/20/1968	21:21	Tonga	Chung (1979)	6.0	349	−179.5	−29.9	3.0	57.0	277.0	189.0	219.0	157.0
3/11/1968	8:26	Tonga	Chung (1979)	6.2	112	−173.9	−16.2	125.0	67.0	251.0	313.0	328.0	330.0
4/20/1968	12:25	Samoa Region	Johnson and Molnar (1972)	5.7	33	172.6	−15.7	98.0	26.0	−90.0	98.0	102.0	102.0
5/15/1968	15:0	Kermadec	Johnson and Molnar (1972)	5.1	33	179.0	−29.7	0.0	80.0	180.0	31.0	127.0	27.0
5/28/1968	9:6	Kermadec	Johnson and Molnar (1972)	5.5	45	178.3	−30.7	14.0	60.0	90.0	253.0	96.0	243.0
5/28/1968	13:27	New Guinea	Fitch (1972)	6.1	65	139.3	−2.9	119.0	40.0	94.0	301.0	124.0	304.0
7/25/1968	7:23	Kermadec	Johnson and Molnar (1972)	6.4	60	178.3	−30.7	12.0	30.0	90.0	219.0	58.0	199.0
8/1/1968	0:14	So. of Fiji	Richter (1979)	5.6	123	−177.5	−26.6	3.0	53.0	42.0	243.0	59.0	231.0

8/23/1968	22:36	* Chile	Stauder (1973)	5.8	537	−63.5	−22.0	185.0	30.0	−80.0	190.0	230.0	230.0
9/26/1968	14:37	Tonga	Chung (1979)	6.0	251	−176.7	−20.9	61.0	60.0	−104.0	31.0	23.0	15.0
9/26/1968	18:2	Kermadec	Johnson and Molnar (1972)	6.5	33	178.1	−30.5	6.0	70.0	113.0	27.0	48.0	40.0
11/16/1968	7:45	Fiji Region	Johnson and Molnar (1972)	5.6	66	175.8	−16.6	0.0	54.0	163.0	301.0	136.0	296.0
1/6/1969	15:39	Santa Cruz	Johnson and Molnar (1972)	6.2	32	164.4	−10.5	28.0	86.0	180.0	28.0	354.0	20.0
1/19/1969	7:2	* Hokkaido	Chandra (1971)	6.5	204	143.2	45.0	150.0	88.0	43.0	115.0	103.0	48.0
1/19/1969	18:50	New Hebrides	Chung (1979)	6.4	107	167.2	−14.9	174.0	52.0	180.0	147.0	23.0	160.0
1/29/1969	17:44	Tonga	Johnson and Molnar (1972)	5.6	33	−171.5	−17.2	2.0	18.0	90.0	251.0	80.0	241.0
2/3/1969	21:41	* Talaud	Chandra (1971)	6.5	33	127.4	4.9	120.0	60.0	60.0	162.0	340.0	163.0
2/11/1069	22:6	Banda Sea	Cardwell and Isacks (1978)	6.0	447	126.7	−6.8	145.0	75.0	−90.0	288.0	222.0	289.0
2/11/1969	22:8	Central Asia	Tapponier and Molnar (1979)	5.8	33	79.2	41.3	62.0	58.0	49.0	100.0	339.0	216.0
3/5/1969	19:33	Hindu-Kush	Chatelain *et al.* (1980)	5.9	208	70.7	36.4	115.0	65.0	90.0	348.0	146.0	329.0
4/13/1969	14:54	East Russia	Sengupta and Toksöz (1977)	5.6	564	131.1	42.0	54.0	54.0	−168.0	96.0	125.0	111.0
4/13/1969	23:33	Banda Sea	Cardwell and Isacks (1978)	5.8	163	129.9	−6.1	94.0	54.0	90.0	285.0	104.0	283.0
4/16/1969	1:22	New Ireland	Johnson and Molnar (1972)	5.7	39	150.9	−3.5	35.0	85.0	174.0	356.0	344.0	352.0
5/1/1969	19:5	Tonga	Chung (1979)	6.1	204	−174.6	−16.7	85.0	64.0	240.0	232.0	247.0	228.0
6/29/1969	10:34	Kermadec	Johnson and Molnar (1972)	5.6	43	178.2	−30.5	0.0	70.0	90.0	322.0	156.0	318.0
8/8/1969	6:30	Hindu-Kush	Chatelain *et al.* (1980)	5.8	196	70.9	36.4	106.0	38.0	90.0	60.0	230.0	56.0
8/8/1969	20:44	Banda Sea	Cardwell and Isacks (1978)	5.9	185	129.7	−6.1	134.0	50.0	146.0	229.0	44.0	243.0
9/14/1969	14:46	Central Asia	Tapponier and Molnar (1979)	5.1	33	74.9	39.6	50.0	60.0	67.0	195.0	32.0	205.0
9/29/1969	16:20	Banda Sea	Cardwell and Isacks (1978)	5.7	139	128.8	−7.3	136.0	52.0	71.0	333.0	147.0	346.0
11/22/1969	23:9	Kamchatka	Cormier (1975)	7.3	33	163.6	57.8	38..0	73.0	88.0	321.0	170.0	170.0
12/10/1969	19:53	New Hebrides	Pascal *et al.* (1978)	5.5	32	166.8	−14.9	133.0	40.0	−80.0	182.0	0.0	89.0
12/23/1969	13:22	Kamchatka	Cormier (1975)	5.4	33	163.1	57.1	57.0	64.0	58.0	9.0	196.0	27.0
1/4/1970	17:0	China	Tapponier and Molnar (1977)	5.9	31	102.5	24.1	121.0	85.0	180.0	58.0	279.0	59.0
1/8/1970	17:12	So. of Kermadec	Richter (1979)	6.1	179	−178.6	−34.7	11.0	57.0	116.0	143.0	35.0	107.0
1/10/1970	12:7	Philippines	Fitch (1972)	6.1	73	126.7	6.8	28.0	48.0	116.0	205.0	33.0	200.0
1/30/1970	8:28	New Hebrides	Pascal *et al.* (1978)	5.7	177	167.5	−14.6	168.0	52.0	120.0	93.0	277.0	114.0
2/17/1970	5:46	Philippines	Fitch (1972)	5.9	72	125.9	9.8	138.0	40.0	−97.0	125.0	119.0	126.0
3/29/1970	10:8	New Hebrides	Pascal *et al.* (1978)	6.0	234	168.6	−17.1	86.0	46.0	152.0	180.0	348.0	199.0
3/30/1970	16:46	Philippines	Fitch (1972)	5.9	76	126.6	6.7	10.0	36.0	122.0	175.0	329.0	163.0
5/15/1970	17:13	Central Asia	Tapponier and Molnar (1979)	5.9	33	91.3	50.2	149.0	50.0	142.0	93.0	231.0	77.0
5/31/1970	20:23	* Peru	Abe (1972)	7.8	43	−78.2	−9.2	160.0	37.0	−90.0	151.0	156.0	162.0
6/11/1970	6:2	* Chile	Stauder (1973)	6.0	112	−68.5	−24.5	170.0	25.0	−80.0	235.0	274.0	278.0
6/19/1970	10:56	* Chile	Stauder (1973)	6.3	52	−70.5	−22.2	355.0	70.0	−90.0	188.0	200.0	188.0
7/31/1970	17:8	* Columbia	Mendiguren (1973)	7.1	651	−72.6	−1.5	340.0	30.0	−80.0	32.0	13.0	1.0
8/28/1970	10:6	So. of Kermadec	Richter (1979)	5.6	90	−179.8	−33.8	24.0	78.0	180.0	357.0	337.0	347.0
8/30/1970	17:46	Sea of Okhotsk	Sengupta and Toksöz (1977)	6.6	625	151.1	52.4	40.0	50.0	−90.0	131.0	194.0	241.0

TABLE 1—*Continued*

Date	Time	Comments	Reference (year)	Magnitude	Depth	Longitude	Latitude	Strike	Dip	Rake	Hydro.	Shear	Normal
9/1/1970	5:11	Marianes	Chapple and Forsyth (1979)	6.4	40	147.6	-17.7	355.0	65.0	−60.0	86.0	85.0	86.0
9/3/1970	9:32	New Hebrides	Pascal *et al.* (1978)	5.5	35	167.8	−16.9	90.0	81.0	150.0	229.0	2.0	229.0
2/1/1971	3:12	Solomons	Lay and Kanamori (1980)	7.1	53	155.6	−7.8	345.0	45.0	62.0	317.0	132.0	312.0
7/8/1971	19:6	Banda Sea	Cardwell and Isacks (1978)	6.1	101	129.7	−7.0	10.0	69.0	107.0	107.0	298.0	101.0
8/14/1971	0:15	New Hebrides	Chung (1979)	5.5	124	167.2	−14.8	284.0	89.0	44.0	175.0	312.0	170.0
10/27/1971	17:58	New Hebrides	Pascal *et al.* (1978)	6.3	45	167.2	−15.6	165.0	44.0	68.0	277.0	97.0	283.0
1/16/1972	12:43	Hindu-Kush	Chatelain *et al.* (1980)	5.6	120	69.9	35.7	76.0	63.0	90.0	159.0	11.0	166.0
1/20/1972	11:36	Hindu-Kush	Chatelain *et al.* (1980)	6.0	214	70.7	36.4	118.0	60.0	53.0	222.0	44.0	
3/7/1972	7:45	Kermadec	Richter (1979)	6.1	192	−178.3	−28.2	15.0	49.0	−28.0	126.0	163.0	112.0
3/28/1972	13:58	Kermadec	Richter (1979)	5.6	337	−178.8	−30.7	33.0	62.0	−33.0	80.0	239.0	54.0
4/4/1972	22:43	Banda Sea	Cardwell and Isacks (1978)	6.6	387	125.6	−7.5	114.0	50.0	−74.0	116.0	103.0	132.0
5/4/1972	7:48	New Hebrides	Chung (1979)	6.1	45	167.5	−15.9	36.0	48.0	126.0	108.0	312.0	94.0
5/22/1972	20:45	No. of N.Z.	Richter (1979)	6.1	227	−175.2	−17.7	306.0	54.0	−105.0	180.0	22.0	10.0
5/28/1972	1:55	Banda Sea	Cardwell and Isacks (1978)	6.3	45	117.0	−11.1	45.0	54.0	−133.0	293.0	290.0	283.0
8/7/1972	9:24	Tonga	Chapple and Forsyth (1979)	6.0	45	−172.1	−16.7	170.0	60.0	90.0	327.0	151.0	332.0
9/5/1972	5:23	Banda Sea	Cardwell and Isacks (1978)	5.8	108	129.7	−7.0	136.0	36.0	59.0	97.0	291.0	109.0
9/24/1972	20:9	Banda Sea	Cardwell and Isacks (1978)	6.0	33	131.5	−6.2	75.0	84.0	−174.0	124.0	145.0	124.0
11/2/1972	19:35	New Hebrides	Pascal *et al.* (1978)	6.0	37	168..8	−20.1	160.0	56.0	90.0	266.0	91.0	268.0
11/27/1972	15:17	Banda Sea	Cardwell and Isacks (1978)	6.0	419	126.6	−5.3	84.0	64.0	−26.0	167.0	121.0	159.0
1/30/1973	21:1	Colima, Mexico	Reyes *et al.* (1979)	7.5	35	−103.0	18.4	25.0	30.0	90.0	123.0	325.0	128.0
4/26/1973	20:26	Hawaii	Butler (1979)	6.2	42	−155.1	19.9	351.0	81.0	152.0	56.0	250.0	48.0
6/14/1972	11:2	Banda Sea	Cardwell and Isacks (1978)	5.8	639	120.3	−7.3	62.0	60.0	−78.0	235.0	238.0	220.0
6/17/1973	3:55	* Japan	Shimazaki (1975)	7.4	49	145.8	43.0	230.0	27.0	100.0	26.0	216.0	48.0
7/21/1973	4:19	Tonga	Chung (1979)	6.1	373	−179.2	−24.8	24.0	85.0	−80.0	32.0	131.0	14.0
10/17/1973	3:16	Hindu-Kush	Chatelain *et al.* (1980)	5.4	211	71.1	36.4	72.0	60.0	83.0	160.0	327.0	171.0
11/30/1973	8:9	New Hebrides	Chung (1979)	6.0	124	167.4	−15.2	16.0	9.0	93.0	117.0	154.0	103.0
12/29/1973	0:19	New Hebrides	Chung (1979)	6.2	47	166.9	−15.1	176.0	51.0	133.0	271.0	102.0	276.0
6/4/1974	4:14	Tonga	Chung (1979)	6.3	256	−175.0	−15.9	16.0	85.0	−90.0	150.0	220.0	142.0
1/17/1975	9:30	Tonga	Richter (1979)	5.8	153	−174.6	−17.9	18.0	58.0	63.0	215.0	33.0	200.0
2/22/1975	22:4	Tonga	Chung (1979)	6.6	333	−178.9	−25.0	5.0	80.0	−72.0	179.0	77.0	356.0
3/3/1975	9:48	Hindu-Kush	Chatelain *et al.* (1980)	5.3	187	70.9	36.4	67.0	30.0	90.0	322.0	153.0	306.0
1/24/1976	21:48	Kermadec	Richter (1979)	5.8	78	−177.6	−23.6	5.0	66.0	140.0	81.0	296.0	77.0
2/3/1976	12:27	Tonga	Chung (1979)	6.0	477	179.7	−25.1	189.0	76.0	92.0	321.0	69.0	326.0
3/4/1977	19:21	Romania	Hartzell (1979)	6.1	100	26.7	45.8	220.0	70.0	99.0	290.0	136.0	317.0
9/16/1978	15:36	Tabas-e-Golshan	Berberian *et al.* (1979)	7.7	42	57.3	33.1	332.0	31.0	70.0	224.0	27.0	206.0

noted correlation between tidal shear stress and the origin times of shallow dip-slip earthquakes is not reproducible.

Discussion

Is there a simple relationship between solid earth tidal shear stress and the origin times of shallow dip-slip earthquakes as I suggested in my previous study? This is the primary question addressed in this paper, and the answer clearly seems to be no. This conclusion raises two other questions for which the answers are more

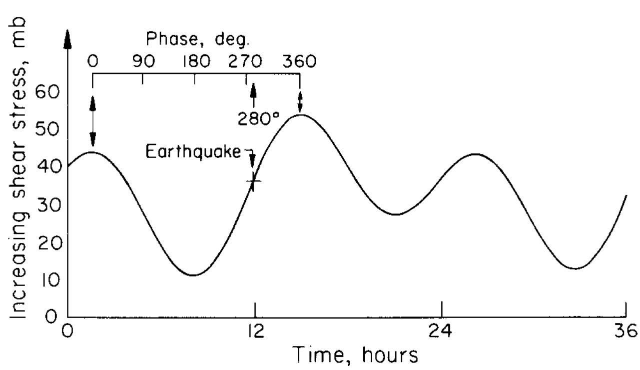
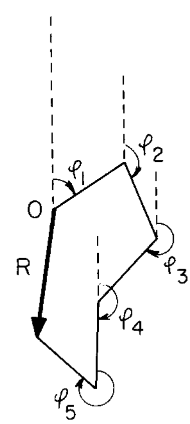


FIG. 2. Example of how earthquakes are assigned a phase relative to tidal stress time history.



$$R = \sqrt{\left(\sum_{i=1}^{m} \sin \varphi_i\right)^2 + \left(\sum_{i=1}^{m} \cos \varphi_i\right)^2}$$

$$P_R \approx \exp\left(-\frac{R^2}{m}\right)$$

FIG. 3. Geometric interpretation of P_R, the probability that a random walk consisting of m unit steps will traverse a distance of R or greater.

ambiguous. The first is: how did my previous study manage to be so misleading? The second is: are the origin times of earthquakes ever affected by tidal stresses?

With regard to the first question, I believe that I made two mistakes, both of which I hope that this paper remedies. The first mistake, if it can be called that, was a lack of followthrough. That is, after calculating tidal phases for all earthquakes, I noticed that a pattern was present if the data set was grouped in a particular manner. Although this grouping formed the basis for a hypothesis, it did not constitute proof of its reality. The second mistake is related to the first. In my earlier

TABLE 2
SHALLOW STRIKE-SLIP EARTHQUAKES

Date	Time	Comments	Reference (year)	Magnitude	Depth	Longitude	Latitude	Strike	Dip	Rake	Hydro.	Shear	Normal
6/10/1836	15:30	* Hayward	Louderback (1947)	7.0	10	−123.0	38.0	145.0	90.0	180.0	291.0	90.0	282.0
1/9/1857	15:30	* Ft. Tejon	Lawson (1908)	8.0	10	−117.5	34.5	145.0	90.0	180.0	260.0	76.0	235.0
9/9/1865	20:30	* San Andreas	Lawson (1908)	7.0	10	−123.0	38.0	145.0	90.0	180.0	322.0	119.0	304.0
10/21/1868	15:47	* Hayward	Lawson (1908)	7.0	10	−123.0	38.0	145.0	90.0	180.0	138.0	312.0	120.0
4/18/1906	13:12	* San Francisco	Lawson (1908)	8.0	10	−123.0	38.0	145.0	90.0	180.0	321.0	36.0	208.0
3/7/1927	9:27	* Tango	Kanamori (1973)	7.9	8	134.3	35.3	155.0	90.0	0.0	128.0	96.0	117.0
12/21/1932	6:10	* Nevada	Richter (1958)	7.3	10	−118.0	34.0	159.0	90.0	180.0	101.0	254.0	95.0
3/11/1933	1:54	* Long Beach	Richter (1958)	6.3	8	−118.0	33.6	140.0	90.0	180.0	199.0	2.0	185.0
12/26/1939	23:57	* Anatolian Fault	Ambraseys *et al.* (1968)	8.0	10	39.7	39.7	115.0	90.0	180.0	69.0	296.0	61.0
5/19/1940	4:37	* Imperial Valley	Richter (1958)	7.0	8	−115.5	32.7	150.0	90.0	180.0	310.0	107.0	294.0
9/10/1943	8:37	* Tottori	Kanamori (1973)	7.4	20	134.0	36.0	80.0	90.0	180.0	228.0	168.0	233.0
12/20/1943	14:3	* Anatolian Fault	Ambraseys *et al.* (1968)	7.3	10	36.6	50.7	115.0	90.0	180.0	269.0	142.0	260.0
2/1/1944	3:22	* Anatolian Fault	Ambraseys *et al.* (1968)	7.3	10	33.0	41.0	80.0	90.0	180.0	47.0	277.0	38.0
4/10/1947	15:58	* Mannix	Richter (1958)	6.5	8	−116.0	35.0	150.0	90.0	180.0	165.0	299.0	148.0
6/28/1948	7:13	* Fukui	Kanamori (1973)	7.3	10	136.0	36.0	165.0	90.0	0.0	8.0	291.0	8.0
12/5/1948	23:43	* D. Hot Springs	Richter *et al.* (1958)	6.5	8	−116.4	33.9	306.0	60.0	165.0	356.0	196.0	330.0
12/26/1951	16:30	China	Tapponier and Molnar (1977)	0.0	0	95.4	40.0	340.0	76.0	−168.0	360.0	200.0	360.0
9/7/1953	19:6	* Anatolian Fault	Ambraseys *et al.* (1968)	7.4	10	27.5	40.0	70.0	90.0	180.0	278.0	227.0	286.0
5/26/1957	6:33	* Anatolian Fault	Ambraseys *et al.* (1968)	7.1	10	31.2	40.6	90.0	90.0	180.0	312.0	232.0	315.0
3/26/1963	21:34	Wakasa Bay	Abe and Katsuyuki (1974)	6.9	4	135.8	35.8	54.0	68.0	158.0	174.0	122.0	186.0
4/19/1963	7:35	China	Tapponier and Molnar (1977)	6.9	0	96.4	35.5	188.0	69.0	169.0	130.0	221.0	128.0
10/23/1964	1:56	Atlantic Ocean	Liu and Kanamori (1980)	6.4	23	−56.0	19.8	296.0	66.0	158.0	276.0	105.0	271.0
3/9/1965	17:57	* Mediterranean	McKenzie (1972)	5.7	18	24.0	39.4	40.0	90.0	180.0	47.0	130.0	47.0
3/22/1966	8:11	China	Tapponier and Molnar (1977)	6.0	3	115.0	37.5	110.0	90.0	0.0	109.0	160.0	105.0

6/28/1966	4:26	* Parkfield	Brown *et al.* (1967)	6.0	9	−121.0	37.0	147.0	90.0	180.0	349.0	134.0	315.0
7/19/1966	1:4	Kamchatka	Cormier (1975)	5.4	20	164.8	56.2	29.0	81.0	−4.0	347.0	199.0	181.0
8/7/1966	17:36	El Golfo	Ebel *et al.* (1978)	6.3	8	−114.4	31.7	140.0	85.0	183.0	196.0	15.0	186.0
8/19/1966	12:22	* Anatolian Fault	Ambraseys *et al.* (1968)	6.8	10	41.6	39.2	115.0	90.0	180.0	44.0	260.0	36.0
7/22/1967	16:52	* Anatolian Fault	Ambraseys *et al.* (1968)	7.1	10	30.8	40.7	90.0	90.0	180.0	186.0	108.0	186.0
7/30/1967	0:0	Caracas	Rial (1978)	6.7	13	−67.3	10.6	350.0	87.0	0.0	53.0	245.0	50.0
8/13/1967	16:54	New Britain	Johnson and Molnar (1972)	5.0	29	152.5	−4.4	114.0	88.0	0.0	237.0	202.0	243.0
12/10/1967	22:51	Koyna	Langston (1976)	6.4	5	73.7	17.3	196.0	67.0	−29.0	222.0	181.0	228.0
4/9/1968	2:29	* Borrego Mtn.	Allen and Nordquist (1972)	6.5	11	−116.0	33.0	132.0	83.0	175.0	269.0	89.0	260.0
8/31/1968	10:48	* Khorasan	Atshar (1968)	7.2	12	58.7	34.0	90.0	90.0	0.0	118.0	12.0	118.0
3/9/1969	13:47	W. New Guinea	Johnson and Molnar (1972)	5.5	14	135.5	−4.1	136.0	84.0	180.0	242.0	62.0	242.0
9/9/1969	5:15	* Gifu	Mikumo (1973)	6.5	5	137.0	30.0	150.0	90.0	0.0	108.0	86.0	99.0
10/2/1969	4:56	* Santa Rosa	Cloud *et al.* (1970)	5.9	10	−122.6	38.5	160.0	90.0	180.0	244.0	149.0	243.0
7/30/1972	21:45	Alaska	Perez and Jacod (1980)	7.3	29	135.9	56.8	344.0	73.0	−173.0	124.0	250.0	13.0
12/23/1972	6:29	* Nicaragua	Algermissen *et al.* (1974)	6.0	5	−86.3	12.1	135.0	90.0	0.0	326.0	326.0	329.0
2/6/1973	10:37	China	Tapponier and Molnar (1977)	7.4	7	100.6	31.4	36.0	84.0	−174.0	113.0	132.0	125.0
3/17/1973	8:30	* Phillipines	Morante and Allen (1973)	7.0	10	122.8	13.4	140.0	90.0	0.0	167.0	161.0	163.0
8/6/1973	23:29	* Anacapa	Ellsworth *et al.* (1973)	4.7	15	−119.0	34.0	90.0	70.0	20.0	125.0	21.0	271.0
3/6/1974	19:29	Banda Sea	Cardwell and Isacks (1978)	6.3	26	129.0	−6.6	136.0	90.0	−172.0	148.0	329.0	151.0
7/4/1974	19:30	Central Asia	Tapponier and Molnar (1979)	5.9	16	94.0	45.1	78.0	90.0	0.0	48.0	166.0	60.0
2/4/1975	11:36	Haicheng	Cipar (1979)	7.4	12	122.6	40.6	288.0	78.0	342.0	1.0	12.0	1.0
2/4/1976	9:1	Guatemala	Kanamori and Stewart (1978)	7.5	8	89.3	15.3	66.0	90.0	0.0	18.0	75.0	23.0
7/27/1976	19:42	Tangshan	Butler *et al.* (1979)	7.7	16	118.0	39.6	220.0	80.0	−175.0	95.0	106.0	119.0
1/14/1978	3:24	Izu-Oshima	Shimazaki and Somersville (1979)	6.8	4	139.2	34.8	270.0	85.0	188.0	267.0	194.0	272.0

TABLE 3
SHALLOW DIP-SLIP EARTHQUAKES

Date	Time	Comments	Reference (year)	Magnitude	Depth	Longitude	Latitude	Strike	Dip	Rake	Hydro.	Shear	Normal
3/26/1872	10:30	* Owens Valley	Richter (1958)	8.0	8	−117.5	34.0	350.0	50.0	−110.0	70.0	75.0	66.0
10/3/1915	6:53	* Nevada	Richter (1958)	7.6	8	−117.5	40.5	0.0	54.0	−90.0	40.0	226.0	225.0
9/1/1923	2:58	* Kanto	Kanamori (1973)	8.2	30	140.0	35.0	290.0	34.0	135.0	284.0	98.0	272.0
3/2/1933	17:31	* Sanriku	Kanamori (1971a)	8.5	20	144.4	39.3	180.0	45.0	−90.0	25.0	166.0	166.0
1/30/1934	18:16	* Nevada	Richter (1958)	6.5	8	−118.5	38.0	295.0	73.0	−90.0	311.0	296.0	296.0
12/7/1944	4:35	* Tonankai	Kanamori (1973)	8.0	25	136.0	34.0	215.0	15.0	90.0	220.0	48.0	235.0
1/12/1945	18:38	Mikawa	Ando (1974)	7.1	6	137.1	34.8	180.0	45.0	116.0	140.0	285.0	141.0
3/15/1946	13:49	* Walker Pass	Richter (1958)	6.3	8	−118.1	35.7	50.0	62.0	55.0	208.0	28.0	221.0
12/20/1946	19:19	* Nankaido	Kanamori (1973)	8.2	25	136.0	34.0	215.0	15.0	90.0	177.0	355.0	195.0
7/21/1952	12:25	* Kern County	Gutenberg (1955)	7.7	10	−119.0	35.0	50.0	62.0	55.0	141.0	344.0	156.0
7/6/1954	11:13	* Nevada	Richter (1958)	6.6	8	−118.5	38.0	170.0	60.0	−90.0	324.0	307.0	310.0
8/24/1954	5:51	* Nevada	Richter (1958)	6.8	8	−118.3	38.0	170.0	60.0	−90.0	352.0	318.0	318.0
12/16/1954	11:7	* Nevada	Richter (1958)	7.1	8	−118.3	39.5	170.0	60.0	−90.0	325.0	331.0	331.0
8/18/1959	6:37	* Montana	Witkind (1959)	7.1	10	−111.0	44.9	100.0	54.0	−90.0	343.0	334.0	334.0
2/13/1963	18:13	Solomons	Johnson and Molnar (1972)	6.8	30	160.7	−9.9	146.0	74.0	90.0	59.0	240.0	64.0
9/4/1963	13:32	Battin Island	Liu and Kanamori (1980)	5.9	7	−73.0	71.3	98.0	66.0	−103.0	248.0	212.0	236.0
1/22/1964	23:59	New Hebrides	Johnson and Molnar (1972)	6.3	24	165.9	−13.7	166.0	60.0	−90.0	120.0	116.0	124.0
3/28/1964	3:36	* Alaska	Stauder and Bollinger (1966)	8.5	20	−147.4	61.1	63.0	10.0	90.0	169.0	17.0	189.0
4/23/1964	3:32	New Guinea	Fitch (1970)	6.4	0	133.9	−5.4	192.0	68.0	−69.0	64.0	64.0	64.0
5/7/1964	7:58	* Oga	Fukao and Furumoto (1975)	6.9	22	139.0	40.4	210.0	40.0	90.0	238.0	86.0	262.0
6/16/1964	4:1	* Niigata	Kanamori (1973)	7.4	20	139.0	39.0	195.0	65.0	90.0	232.0	188.0	320.0
7/4/1964	10:49	Marianes	Katsumata and Sykes (1969)	6.0	10	144.6	11.7	54.0	53.0	−90.0	13.0	21.0	21.0
10/6/1964	14:31	* Mediterranean	McKenzie (1972)	6.0	10	24.0	39.4	122.0	36.0	−90.0	108.0	98.0	98.0
1/9/1965	13:32	Philippines	Fitch (1969)	6.1	5	126.3	11.9	4.0	47.0	−55.0	170.0	165.0	167.0
1/24/1965	0:11	Ceram Sea	Fitch (1970)	6.6	6	126.0	−2.4	101.0	55.0	60.0	105.0	291.0	108.0
3/30/1965	2:37	* Rat Island	Abe (1972a)	7.5	20	177.9	50.3	100.0	60.0	−90.0	111.0	102.0	107.0
4/16/1965	23:22	Alaska Intraplate	Liu and Kanamori (1980)	5.8	12	−160.1	64.7	305.0	66.0	−85.0	363.0	335.0	331.0
4/26/1965	9:47	Molucca Sea	Fitch (1970)	5.7	21	126.6	−1.7	158.0	61.0	−90.0	269.0	269.0	272.0
5/20/1965	0:40	New Hebrides	Johnson and Molnar (1972)	5.6	16	167.4	−14.7	124.0	62.0	46.0	274.0	85.0	285.0
7/6/1965	3:18	* Mediterranean	McKenzie (1972)	5.9	20	22.4	38.4	87.0	76.0	−90.0	291.0	295.0	298.0
7/25/1965	13:33	* Japan	Shimazaki (1972)	5.9	16	146.6	41.3	225.0	45.0	−105.0	32.0	65.0	73.0
10/7/1965	3:36	South China Sea	Wang *et al.* (1979)	5.6	5	114.5	12.5	240.0	50.0	100.0	26.0	210.0	27.0
11/12/1965	17:14	Japan	Katsumata and Sykes (1969)	5.3	21	140.4	30.6	10.0	44.0	−76.0	17.0	13.0	14.0

2/5/1966	2:2	* Mediterranean	McKenzie (1972)	5.6	22	21.7	39.1	134.0	46.0	−55.0	112.0	103.0	100.0
2/22/1966	5:2	New Britain	Johnson and Molnar (1972)	6.1	28	151.5	−5.4	64.0	60.0	90.0	68.0	247.0	67.0
9/18/1966	20:43	* Iran	Nowroozi (1972)	6.2	16	54.3	27.8	135.0	45.0	90.0	297.0	118.0	291.0
9/28/1966	14:0	China	Tapponier and Molnar (1977)	6.1	27	100.1	27.5	290.0	45.0	−114.0	274.0	262.0	265.0
10/27/1966	14:21	Marianes	Katsumata and Sykes (1969)	6.0	28	145.9	22.1	139.0	25.0	−90.0	25.0	25.0	25.0
1/18/1967	5:34	Central Asia	Tapponier and Molnar (1979)	6.0	9	120.9	56.7	26.0	65.0	−146.0	247.0	291.0	258.0
1/20/1967	1:57	Central Asia	Tapponier and Molnar (1979)	6.4	22	103.0	48.1	0.0	50.0	122.0	197.0	36.0	192.0
2/17/1967	10:10	Tonga	Johnson and Molnar (1972)	6.1	19	−175.2	−23.7	34.0	34.0	−99.0	171.0	162.0	160.0
4/10/1967	4:59	Solomons	Johnson and Molnar (1972)	5.5	30	155.7	−7.4	141.0	60.0	97.0	98.0	280.0	101.0
5/1/1967	7:9	* Mediterranean	McKenzie (1972)	5.6	15	21.3	39.7	356.0	52.0	−70.0	219.0	225.0	223.0
8/30/1967	4:22	China	Tapponier and Molnar (1977)	6.1	3	100.3	31.6	29.0	39.0	−105.0	72.0	84.0	82.0
9/20/1967	9:39	Auckland Reg.	Johnson and Molnar (1972)	6.1	30	163.4	−49.8	11.0	18.0	90.0	233.0	11.0	201.0
5/16/1968	0:4	* Tokachi-Oki	Kanamori (1971b)	8.0	15	143.2	40.8	156.0	20.0	35.0	226.0	90.0	291.0
5/23/1968	17:24	* New Zealand	Johnson and Molnar (1972)	6.1	12	171.9	−41.7	10.0	50.0	66.0	205.0	331.0	191.0
7/28/1968	21:12	Kamchatka	Cormier (1975)	5.4	14	166.7	55.4	60.0	34.0	42.0	193.0	34.0	220.0
7/29/1968	23:52	New Guinea	Fitch (1972)	6.1	11	133.4	−0.2	82.0	52.0	54.0	189.0	9.0	189.0
8/3/1968	4:54	Ryukyu	Fitch (1972)	6.8	20	128.4	25.6	24.0	68.0	−115.0	153.0	75.0	73.0
8/10/1968	2:7	Molucca Passage	Fitch (1972)	6.3	30	126.2	1.4	8.0	46.0	102.0	289.0	110.0	286.0
8/14/1968	22:14	No. Celebes	Fitch (1972)	6.0	23	119.7	0.1	90.0	72.0	−80.0	70.0	68.0	70.0
8/28/1968	20:42	Philippines	Fitch (1972)	5.7	15	122.0	15.5	150.0	40.0	78.0	68.0	248.0	68.0
10/14/1968	2:14	* Meckering	Gordon (1971)	6.9	5	117.0	−31.8	0.0	45.0	105.0	119.0	60.0	248.0
11/9/1968	17:1	So. Illinois	Herrmann (1979)	5.5	19	−88.5	38.0	0.0	45.0	−100.0	263.0	127.0	125.0
11/9/1968	20:30	Molucca Passage	Fitch (1972)	5.5	30	126.8	2.4	168.0	50.0	90.0	69.0	248.0	75.0
1/20/1969	14:20	Kamchatka	Cormier (1975)	6.1	23	166.0	54.9	56.0	66.0	104.0	3.0	207.0	16.0
1/25/1969	5:19	Molucca Passage	Fitch (1972)	5.9	24	126.0	0.8	27.0	34.0	90.0	256.0	79.0	249.0
1/26/1969	15:5	Kamchatka	Cormier (1975)	5.5	16	162.9	55.8	66.0	48.0	69.0	95.0	316.0	100.0
1/27/1969	13:15	W. Caroline	Fitch (1972)	5.5	5	137.7	8.7	44.0	60.0	132.0	71.0	241.0	66.0
2/28/1969	2:41	* Portugal	Fukao (1973)	7.9	22	−10.6	36.0	85.0	40.0	100.0	122.0	284.0	117.0
3/20/1969	16:18	Philippines	Fitch (1972)	6.1	10	127.2	8.6	199.0	68.0	−57.0	349.0	341.0	351.0
8/5/1969	2:13	Molucca Passage	Fitch (1972)	6.1	30	126.1	1.2	135.0	50.0	90.0	164.0	334.0	165.0
12/31/1969	19:1	Ryukyu	Fitch (1972)	5.9	30	129.1	28.5	76.0	46.0	−75.0	320.0	326.0	321.0
2/4/1970	5:8	Mid-America	Chapple and Forsyth (1979)	6.5	21	−99.5	15.5	3.0	70.0	−50.0	352.0	361.0	352.0
3/4/1970	3:30	So. of Marianas	Fitch (1972)	6.2	30	143.7	12.1	182.0	56.0	−66.0	87.0	76.0	90.0
3/19/1970	23:33	Aleutian	Chapple and Forsyth (1979)	6.2	20	173.8	51.3	0.0	50.0	−40.0	9.0	296.0	326.0
3/24/1970	10:35	Australia	Liu and Kanamori (1980)	6.2	12	126.6	−21.9	305.0	56.0	112.0	194.0	20.0	198.0
3/28/1970	21:2	* Gediz	Tazdemioglu (1971)	7.0	10	29.5	39.0	350.0	60.0	−80.0	112.0	110.0	110.0
4/7/1970	5:34	Philippines	Fitch (1972)	6.4	30	121.7	15.8	18.0	60.0	122.0	36.0	211.0	36.0

TABLE 3—*Continued*

Date	Time	Comments	Reference (year)	Magnitude	Depth	Longitude	Latitude	Strike	Dip	Rake	Hydro.	Shear	Normal
6/5/1970	4:53	Central Asia	Tapponier and Molnar (1979)	6.0	20	78.8	42.5	90.0	30.0	90.0	287.0	118.0	287.0
9/12/1970	14:30	* Lytle Creek	Newton (Pers. comm.)	5.4	10	−118.0	34.0	313.0	56.0	54.0	244.0	74.0	231.0
2/9/1971	14:3	* San Fernando	Whitcomb *et al.* (1973)	6.5	10	−118.5	34.0	296.0	52.0	60.0	196.0	339.0	187.0
3/23/1971	9:52	Central Asia	Tapponier and Molnar (1979)	5.7	10	79.3	41.4	65.0	55.0	109.0	144.0	11.0	159.0
5/10/1971	14:51	Central Asia	Tapponier and Molnar (1979)	5.6	14	71.4	42.8	74.0	35.0	90.0	228.0	31.0	237.0
6/15/1971	7:39	Central Asia	Tapponier and Molnar (1979)	5.6	17	79.4	41.5	74.0	55.0	90.0	252.0	99.0	264.0
8/20/1971	21:36	Mid-America	Chapple and Forsyth (1979)	5.6	19	−92.4	13.4	93.0	45.0	60.0	105.0	278.0	102.0
9/5/1971	18:35	* Sakhalin	Fukao and Furumoto (1973)	7.1	22	141.2	46.5	184.0	52.0	90.0	111.0	302.0	121.0
9/30/1971	21:24	Atlantic Ocean	Liu and Kanamori (1980)	6.0	13	−4.7	−0.4	72.0	60.0	60.0	332.0	152.0	332.0
10/26/1971	13:30	Central Asia	Tapponier and Molnar (1979)	5.5	15	72.4	41.9	90.0	50.0	90.0	275.0	106.0	282.0
4/9/1972	4:10	Central Asia	Tapponier and Molnar (1979)	5.8	21	84.6	42.2	130.0	55.0	135.0	355.0	190.0	340.0
9/16/1972	9:14	Mid-America	Chapple and Forsyth (1979)	5.7	0	−96.2	15.2	95.0	40.0	−110.0	240.0	235.0	237.0
9/27/1972	9:1	Tonga	Chen and Forsyth (1978)	6.0	6	−172.2	−16.5	207.0	65.0	−43.0	224.0	244.0	217.0
2/21/1973	14:30	* Pt. Mugu	Ellsworth *et al.* (1973)	5.8	18	−119.0	34.0	241.0	40.0	56.0	134.0	322.0	145.0
7/1/1973	13:33	Alaska	Perez and Jacob (1980)	6.7	15	137.4	57.9	121.0	66.0	90.0	297.0	76.0	258.0
7/14/1973	4:51	Tibet	Singh and Gupta (1979)	6.9	22	86.4	35.2	177.0	51.0	81.0	339.0	166.0	339.0
12/28/1973	13:41	New Hebrides	Chung (1979)	6.4	26	166.5	−14.5	354.0	33.0	70.0	317.0	134.0	312.0
1/31/1974	23:30	Solomons	Lay and Kanamori (1980)	7.0	16	155.9	−7.5	309.0	28.0	90.0	103.0	276.0	95.0
5/11/1974	6:14	Marianes	Chapple and Forsyth (1979)	5.9	0	147.3	19.7	130.0	65.0	−80.0	32.0	31.0	31.0
7/2/1974	23:26	Kermadec	Chapple and Forsyth (1979)	7.2	0	−175.9	−29.1	195.0	70.0	70.0	14.0	186.0	1.0
8/25/1974	1:18	Izu Bonin	Chapple and Forsyth (1979)	5.6	6	142.3	32.1	175.0	50.0	−115.0	149.0	61.0	65.0
9/7/1974	20:43	Java	Chapple and Forsyth (1979)	6.5	0	108.4	−9.8	268.0	45.0	−135.0	34.0	41.0	31.0
6/30/1975	18:54	Yellowsone	Pitt *et al.* (1979)	6.0	8	110.5	44.5	315.0	45.0	−80.0	236.0	232.0	230.0
7/20/1975	14:38	Solomons	Lay and Kanamori (1980)	7.9	16	155.1	−6.6	306.0	36.0	90.0	73.0	251.0	70.0
11/29/1975	14:47	Hawaii	Ando (1979)	7.1	10	−155.0	19.3	70.0	20.0	−90.0	198.0	200.0	200.0
5/6/1976	20:22	Fruili	Cagnetti and Pasquale (1979)	6.3	8	13.3	46.3	76.0	75.0	80.0	68.0	277.0	108.0
5/17/1976	2:58	Gazli	Hartzell (1980)	7.0	15	63.4	40.3	40.0	54.0	78.0	153.0	20.0	175.0
8/16/1976	16:11	Mindanao	Cohn and Stewart (1979)	8.0	25	123.4	6.3	327.0	22.0	68.0	253.0	74.0	248.0
8/19/1977	6:8	Java	Stewart (1980)	7.8	0	118.4	−11.1	270.0	45.0	−74.0	351.0	351.0	351.0
2/28/1979	21:27	St. Elias	Lahr *et al.* (1980)	7.7	15	−141.6	60.6	285.0	12.0	116.0	317.0	139.0	308.0

study, I employed the same statistical analysis as that used in this study. Although this analysis is simple and straightforward, I believe that it was incorrect to apply it to the case where the test for significance was conducted after a pattern in the data was recognized. For example, one can often devise a system for winning games of chance simply by observing patterns in the play. Although the system may appear

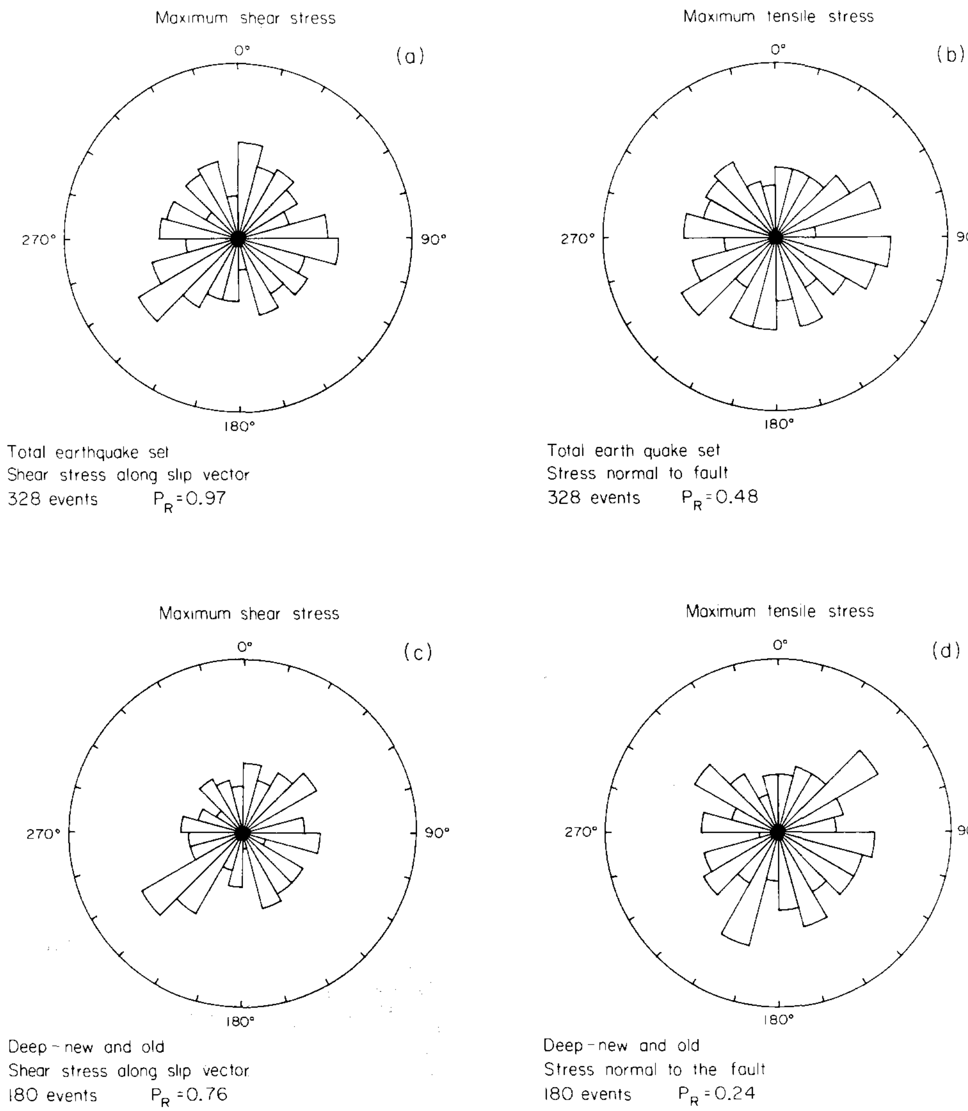


FIG. 4. Tidal phases of earthquakes. (a) Phases of tidal shear stress for entire data set. (b) Phases of tidal normal-to-the-fault compressive stress for entire data set. (c) Phases of tidal shear stress for all earthquakes deeper than 30 km. (d) Phases of tidal normal-to-the-fault compressive stress for all earthquakes deeper than 30 km.

to be foolproof (i.e., statistically significant), use of the system with one's own money may result in unpleasant consequences (e.g., writing this paper). Actually this problem seems to be very common in tidal triggering studies as well as in earthquake prediction studies. We see a pattern and then ask what the probability is that this pattern would arise in a random group of numbers. It has become painfully clear that we are far better at "predicting" earthquakes after their occurrence than before. Unless the question is well posed and strictly defined before any data are examined, statistical analysis of those data is likely to produce misleading results.

Unfortunately, this study does not provide a definite answer to the question of

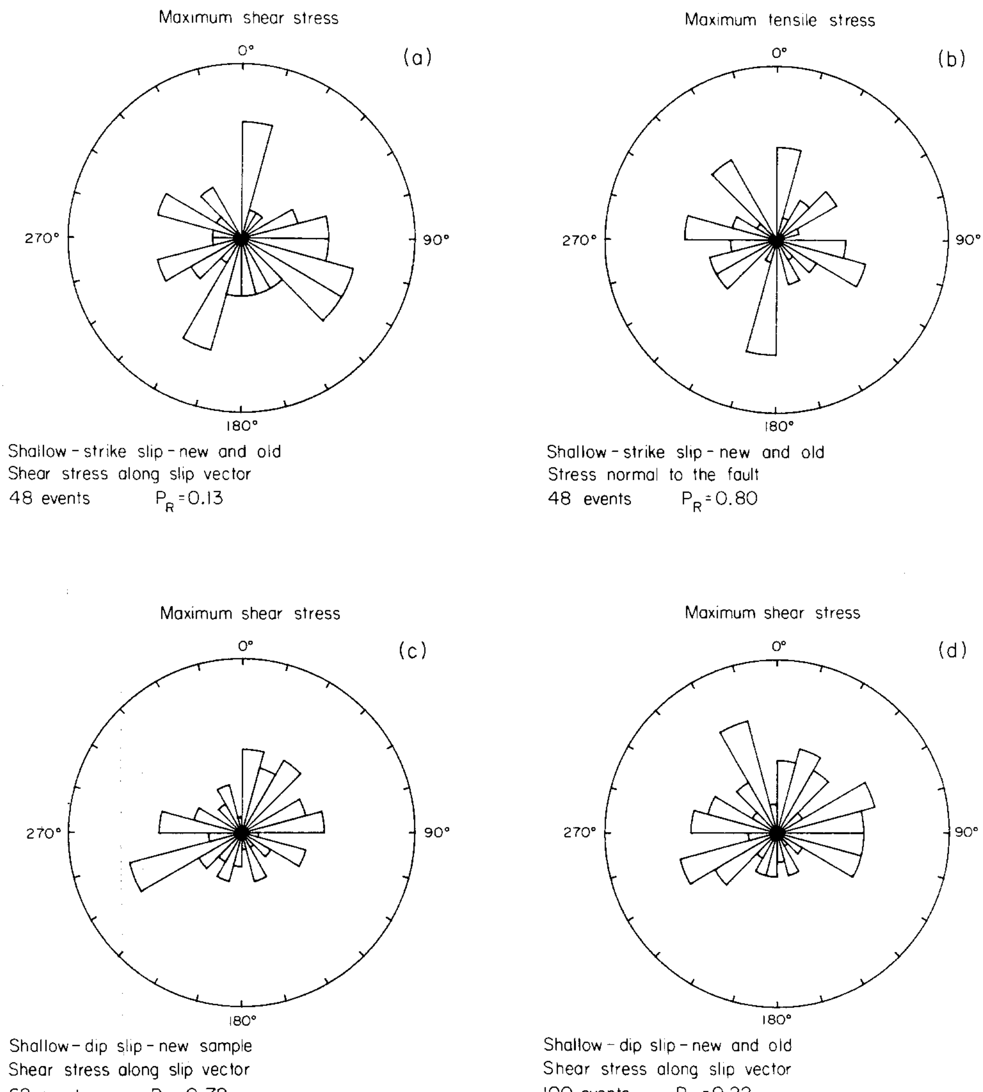


FIG. 5. Tidal phases of earthquakes. (a) Phases of tidal shear stress for all shallow strike-slip earthquakes. (b) Phases of tidal normal-to-the-fault compressive stress for all shallow strike-slip earthquakes. (c) Phases of tidal shear stress for shallow dip-slip earthquakes not included in the previous study (Heaton, 1975). (d) Phases of tidal shear stress for all shallow dip-slip earthquakes.

whether or not earthquake origin times are affected by tidal stresses. It merely shows that a simple correlation between origin times and simple calculations of solid earth tidal stresses is not seen for this data set. Some of the more convincing evidence for tidal triggering comes from investigations of earthquake swarms (Sauk, 1975; Klein, 1976a, b). In these studies, tidal periodicities are reported for swarms in several localities. Although periodicities are seen, the phase relationship for these correlations seems to change from one sequence to another. Klein (1976a) suggests that one mechanism for this phase shift may be the diffusion of pore fluids caused by tidal stresses. If this mechanism is important, details of fluid diffusion in fault zones must be understood before the times at which tidal stresses are most likely to trigger individual earthquakes can be calculated. Unfortunately, this type of analysis does not seem possible for the type of data sample considered in this study. Without such analysis, though, it does not seem possible to exclude tidal triggering for earthquakes of the type used in this study. Furthermore, studies of foreshock occurrence for large earthquakes by Jones and Molnar (1979) and by von Seggern *et al.* (1981) both show that somewhat higher levels of foreshock activity have occurred about 12 hr prior to the large main shocks. One speculation is that this may be a manifestation of tidal triggering.

In conclusion, analysis of the tidal stress tensor for 222 earthquakes with known focal mechanisms fails to support my previous hypothesis (Heaton, 1975) that the origin times of shallow dip-slip earthquakes correlate with tidal shear stress. The application of statistical analysis to test for the statistical significance of patterns that are recognized after the data are inspected can often lead to misleading results.

Acknowledgments

I thank Marcia McNutt, Bruce Julian, and Fred Klein for critically reviewing the manuscript. I also thank Karen Richter Canto and Gary M. Gutierrez for their work in computing and compiling the tidal phases of the earthquakes used in this study.

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Manuscript received 17 May 1982