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Crustal tilt fields and propagation velocities associated with earthquakes

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Three borehole installation of 15 s horizontal pendulums (of the Lamont lunar type) with capacitance displacement transducers were carried out in 1968–1969 in Central Alaska in Gilmore (GLM near Fairbanks), Patson (PAT) and McKinley (MCK) int he Alaska Range. Data are telemetered over phone lines and v.h.f. radio links and the sensitivity is better than 10^{-9} rad/mm of chart recording.

Tilt steps similar to strain steps have been observed for earthquakes with magnitude from 2 to 8 and distances ranging from 10 to 9000 km. The tilt step propagation velocity from the hypocentre to the station increases from about 1.3 km/s near the epicentral area to 2.6 to 2.8 km/s at 60 to 80 km and to 3.1 km/s at teleseismic distances. Tilt directions, amplitudes and velocities observed at several stations simultaneously for the same earthquake are internally consistent. For local Fairbanks quakes the data from the Alaska long period array (ALPA) also have been used and span a full quadrant from the epicentre. There is an indication that tilt amplitudes depend on the tectonic environment of the station. Examples of tilts from local and regional earthquakes are presented and observations from teleseismisms include the 10 January 1971 ($M = 8.1$) New Guinea, the 9 July 1971 ($M = 7.7$) Chile and the 14 July 1971 ($M = 8.1$) Solomon Island earthquakes.

Introduction

Tilt and strain steps associated with earthquakes have been observed widely. Their amplitudes often exceed those theoretically expected from elastic fields associated with a dislocation at the source. Observations on propagation velocities are sparse and mostly confined to a single path (Wideman & Major 1967; Berg & Pulpan 1971). Tilt (and strain) step amplitudes and velocities are presented for teleseisms travelling through different regions at near S and Rayleigh wave velocities, and for local earthquakes recorded at several stations simultaneously. Observations of some local earthquakes cover a full quadrant and should provide some understanding of near-source dynamics in relation to source and tectonic setting.

To determine tilt amplitudes and velocities, digital records, analogue records or tidal outputs (both to d.c.) were used. For the last two events in table 1, arrival times were read from the records presented in the literature.

For the local Fairbanks earthquakes, Berg & Pulpan (1971) presented a number of offset tidal (d.c.) records and the corresponding pulses on the l.p. outputs for GLM. If the records of local earthquakes from GLM showed tilts, and the pulses propagating through ALPA and COL (velocity transducers) could be superimposed on the calibration pulse form, the output was considered to result from a tilt. Results were similarly obtained for COL (earthquake of 1 May 1971). Poor results are given in brackets in table 1.

Focal point and origin time for local earthquakes have been determined from a local short-period telemeter network. S-P times at LV for the four earthquakes used in the figure ranged from 1.8 to 3.7s.

Results

(*a*) *Distant and regional earthquakes*

Tilt (and strain) amplitudes and propagation velocities are presented in table 1. The velocities determined from digital or Helicorder records should be reliable; those obtained from tidal

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TABLE 1. TILT-STEP AMPLITUDES

date and location	station	tilt amplitude 10^{-3} sec arc		total amplitude 10^{-3} sec arc	total amplitude rad.	est. error %	distance km	magn.	tilt step velocity/km s^{-1} S	tilt step velocity/km s^{-1} surface wave	record type
10 Jan. 1971, New Guinea	PAX	8.6N	32E	32.2	15.6×10^{-8}	5	9550	8.0	6.79	3.17 ± 0.1	digital
	MCK	†	18E	> 18	$> 8.75 \times 10^{-8}$	10	9408	—	—	E3.31	tidal
	GLM	†	⩽ 2E	⩽ 2	$\leqslant 0.9 \times 10^{-8}$	—	9520	—	—	—	
26 Mar. 1971, S. Central Alaska	PAX	2.6S	12.5E	12.7	6.2×10^{-8}	4	380	5.6–5.7	—	2.62 ± 0.1	digital
11 May 1971, Minto	GLM	1.0N	2.7W	2.9	1.4×10^{-8}	—	69	3.6	—	2.63 ± 0.1	helicorder
9 July 1971, Chile	PAX	(2.2)N	< 1.5	< 2.7	$< 1.3 \times 10^{-8}$	—	12431	—	—	—	
	MCK	(2.6)N	13.6E	13.9	6.7×10^{-8}	—	12625	7.5	—	3.62 ± 0.1	tidal
	GLM	2–3N	< 1	< 3	$< 1.4 \times 10^{-8}$	—	12619	—	—	—	—
14 July 1971, Solomon Islands	PAX	17.2N	21.4E	27.4	13.3×10^{-8}	—	9123	—	—	N3.68	tidal
	MCK	> 16N	29.1E	> 33.2	$> 16.1 \times 10^{-8}$	—	9017	7.7	—	E3.63 N3.18	—
	GLM	< 5N	≈ 5E	< 7	$< 3.4 \times 10^{-8}$	—	9153	7.8	—	—	—
5 Sept. 1971, Sakhalin Island	PAX	2.9N	4.4W	5.3	2.6×10^{-8}	25	—	7.1	—	—	—
	MCK	9.1N	12.5E	15.5	7.5×10^{-8}	10	4570	—	—	EN3.32	tidal
	GLM	(< 2)	⩽ 2.3W	< 3	$< 1.4 \times 10^{-8}$	50	—	—	—	—	—
4 Jan. 1972, Taiwan region	HIG	†	14W	14	6.8×10^{-8}	20	8160	—	—	3.74 ± 0.1	helicorder
	GLM	< 1 if any	‡	—	—	—	—	6.8	—	(3.17)	tidal (south)
	PAX	†	‡	—	—	—	—	6.9	—	—	
	MCK	‡	‡	—	—	—	—	—	—	—	—
29 Feb. 1972, Japan Sea	HIG	†	27W	27	13.1×10^{-8}	20	— 6170	7.2 7.1	5.78	3.55 ± 0.1	helicorder
6 Nov. 1971, Amchitka	Cape Sarichef	—	—	—	$< 4 \times 10^{-9}$	strain	1125	—	—	2.80 ± 0.1	Tocher & Brown (1972) chart at 40 mm/min
	—	—	—	—	5×10^{-10}	strain	—	—	(4.1—4.4)	—	doubtful; too short a record
17 Jan. 1968, E. New Guinea	Mt. Nebo (near Brisbane)	17.3S	—	17.3	8.4×10^{-8}	—	1910	5.3	4.6	3.77 ± 0.15	Stacey & Rynn (1970) paper 1 mm/min

† = not available.
‡ no offset = $< 5.10^{-9}$ or 1×10^{-3} sec arc

records are presented as being indicative. Three distinct velocity groupings are apparent: that of 2.6 to 2.8 km/s travelling through parts of the Aleutian arc, South Central Alaska, and in an area north of Fairbanks; that near 3.1 km/s travelling partially through the continental area; and that of 3.5 to 3.8 km/s travelling through the Pacific. All three types of step arrivals seem to be associated with and follow somewhat the maximum amplitudes of the Rayleigh waves. A fourth step arrival follows closely the S wave arrival: it is visible on Stacey & Rynn's (1970) illustration and on digital and Helicorder records. A tilt associated with the P wave arrival might also be present in Stacey & Rynn's record.

Tilt steps at PAX and MCK for the New Guinea and the Solomon Islands earthquakes are nearly identical in direction and amplitude. The stations are 200 km apart, along the Denali fault in the Alaska Range, whereas at GLM, on the northern edge of the Tanana Basin 250 km away, the tilt steps show much smaller amplitudes for similar epicentral distance and azimuth. Both earthquakes also had comparable magnitudes.

The rise time of the tilt steps seems to be small compared to seismometer and circuit time constants. Most of the tilt steps do not seem to recover with time.

(*b*) *Local earthquakes*

Figure 1 shows tilt-step arrival times plotted against focal distance. The earthquake magnitudes ranged from 3.0 upward and depths were 18 to 20 km and 11 km (1 May 1971). A

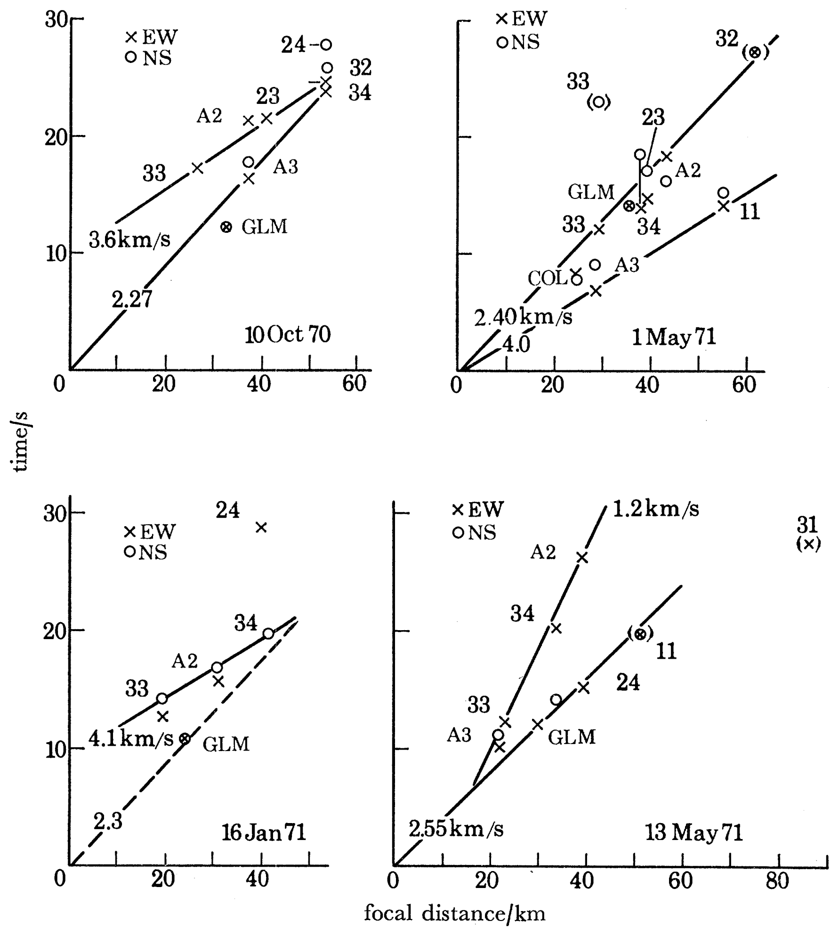

Figure 1. Plots of tilt arrival time against focal distance for four Fairbanks earthquakes. Station identification given by numbers and/or letters.

magnitude 2 earthquake was the smallest, for which a tilt step (of 2×10^{-3} sec arc) has been observed at GLM.

Three groups of velocities are indicated: one of about 4 km/s (which includes the 3.6 km/s (10 October 1970) because of relatively poor time resolution on the computer plots); a second of about 2.3 to 2.5 km/s; and the third of 1.2 km/s. For the earthquake of 1 May 1971, stations 33, A2, and 32 are alined with the epicentre and GLM is only slightly off. If the 2.40 km/s line through the arrivals at those stations is adjusted so as to pass 0 focal distance at a time different from the origin time, a better fit is obtained, resulting in a somewhat lower velocity near 2.2 km/s.

Rise times on the ALPA, GLM and COL output correspond (from visual matching by superposition) to that of a calibration step input.

Discussion

(a) Distant and regional earthquakes

Maue (1954) has investigated the motion of relaxation that occurs when an elastic medium under tension is suddenly cut open from one side. The plane compressional wave corresponding to a step is the strain at the shockfront, and the amplitude is such that the initial tension is compensated. On the other hand, if a solution corresponding to a sinusoidal point force in a semi-infinite medium may be expressed as

$$g\ (\omega, \text{coordinates, elastic and source parameters}) \cdot e^{i\omega t*},$$

$t*$ corresponding to a particular propagation mode, and a step in force is applied at the source at $t = 0$, the resulting solution is given by the Fourier integral over the Fourier transform of the source time function times the solution function $g e^{i\omega t*}$ (Ewing, Jardetzky & Press 1957, p. 61) integrated over ω. Therefore a step in stress (and tilts and strain) is expected at the recording site at times corresponding to the particular propagation modes. The observations of steps travelling at velocities near S and Rayleigh wave velocities appear to confirm this.

The velocities of steps occurring during the Rayleigh wave train seem to correspond closely to the high-frequency portion of the continental Rayleigh waves group velocity (i.e. 3.1 km/s), and for the local earthquakes, also close to the velocities of sedimentary Love and Rayleigh waves (2.0 to 2.5 km/s) (Oliver 1962). The velocities (table 1) across parts of the Pacific correspond to those observed by Wideman & Major (1967) for oceanic paths.

The tilt amplitudes for the teleseismic events often exceed the theoretical expected ones by many times. There also are large amplitude differences among PAX and MCK on the one hand, and GLM on the other, for the New Guinea and the Solomon Islands earthquakes. For a different azimuth (the Chile earthquake), however, amplitudes are much smaller at PAX, and MCK, their relation to those at GLM is different. This supports Stacey & Rynn's (1970) idea that the tilt steps are related to local tectonics – in the Alaska case on a large scale, since the records for MCK and PAX near the Alaska Range are remarkably similar, whereas those at GLM north of the Tanana Basin are different.

(b) Local earthquakes

Theoretical calculations for surface deformation resulting from strike-slip faulting at distances, comparable to source depth, and realistic velocity-depth functions are almost non-existent.

The assumption of almost vertical faults with strike slip motion resulting from a N- to NW-oriented, compressional axis in the area is supported by short-period and tilt investigation

(Berg & Pulpan 1971). The tilt and first motion field of the 10 October 1970 earthquake is consistent with theoretical calculations (Chinnery 1961; Press 1965) for a semi-infinite medium if the line for zero vertical uplift is placed beyond stations BRH and 33. The nodal planes are nearly NS and EW, and the motion is either north on the eastern side of the north–south plane or east on the northern side of the east–west plane, implying a northeasterly compressional axis. Tilt-field directions would not be altered drastically if a realistic velocity-depth function were to be used in the theoretical calculations, and the amplitudes might be closer to observations. R. Sato (personal communication, April 1972) has shown theoretically that the inclusion of a more realistic surface layer drastically alters the surface deformation field.

For focal distances to 40 km, velocities of 2.0 to 2.3 km/s are observed. At greater distances (beyond 70 km), velocities near 2.8 to 3.1 km/s have been observed corresponding to those for the pulses associated with Rayleigh waves over continental paths (see figure 1, 13 May 1971, station 31). A branch with 4 km/s also is present.

A very low propagation velocity (1.2 km/s) was observed between stations 33 and A2, and occasionally for arrivals at a single station (like 24). The lowest velocity observed was 0.9 km/s. Low velocities seem to be associated with the propagation of a plastic pulse in a highly stressed area. On superposing the earthquake-generated stress, the non-linear portion of the stress strain curve is reached and a plastic wave will travel with a velocity V as given by Kolsky (1953):

$$V^2 = (\mathrm{d}\sigma/\mathrm{d}\epsilon)/\rho$$

where σ is the stress, ϵ the strain, and ρ the density. In the linear part of the stress strain curve $\mathrm{d}\sigma/\mathrm{d}\epsilon = E$ or the Young modulus. For $V = 1.2$ km/s and $\rho = 2.7$ g/cm^3, a value of 3.9×10^9 N/m^2 is obtained, twenty times lower than the corresponding E modulus for a material in the Fairbanks area with $V_\mathrm{p} = 5.5$ km/s. As a consequence, a plastic wave will generate a considerably larger deformation than the elastic wave. Similarly, elastic wave triggered plastic deformation associated with teleseisms could account for some of the larger tilts at stations in tectonically active areas.

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