208

Physics of the Earth and Planetary Interiors, 26 (1981) 208–216
Elsevier Scientific Publishing Company, Amsterdam – Printed in The Netherlands

A negative search for an ultra-slow component to the source of the Yunnan earthquakes of May 29, 1976

Emile A. Okal and Lisa M. Stewart

Department of Geology and Geophysics, Yale University, P.O. Box 6666, New Haven, CT 06511 (U.S.A.)

(Received August, 1980; revised and accepted January 17, 1981)

Okal, E.A. and Stewart, L.M., 1981. A negative search for an ultra-slow component to the source of the Yunnan earthquakes of May 29, 1976. Phys. Earth Planet. Inter., 26: 208–216.

Following Nagamune's suggestion of a giant, but very slow, component to the source of the Yunnan earthquakes of May 29, 1976, a systematic study of the ultra-low frequency content of a number of tiltmeter, strainmeter, and IDA records of the events is conducted. First, Nagamune's hypothesis is quantified, and it is found that it would require a moment in the range 10^{29}–10^{30} dyn-cm. Such a large moment would have important consequences for our understanding of stress release in the plates, but is incompatible with the extent of the aftershock zone, and with observations on other instruments: specifically, only one IDA record shows a time-domain oscillation which may be related to the proposed source. In the Fourier domain, however, a spectral analysis fails to identify any of the Earth's modes in any of the available records, including the one originally used by Nagamune. It must therefore be concluded that the apparent signal present in a few records is due to noise—probably of instrumental origin—rather than to an ultra-low-frequency component of the seismic source.

1. Introduction

Over the past 15 years, the systematic study of the mechanism of large earthquakes in inter-plate areas has led scientists to the conclusion that they correctly describe the geometry of the relative motions of the plates. Quantitatively, however, it has been observed (Kanamori, 1977a) that in some instances a substantial fraction of this motion may remain unaccounted for by an energy balance of the related seismicity. Kanamori went on to suggest that the remainder of the plate motion be taken up by creep and/or extremely long-period components of the seismic source, which may escape detection through classical seismological methods. Specifically, he proposed that the 1952 Kamchatka earthquake was accompanied by a huge slow deformation, with a rise time on the order of half an hour or longer, exciting ${}_0S_2$ in a disproportionate way (Kanamori, 1976). Similarly, Kanamori and Cipar (1975) and Kanamori and Anderson (1975) have argued for a slow precursor to the 1960 Chilean event, with a time constant on the order of 15–20 min.

More recently, Nagamune (1977) used a tiltmeter record at Aso, Japan, of the otherwise moderate earthquakes of May 29, 1976 in Yunnan (China), to conclude that a giant seismic source with a time constant of 20 min. or more was necessary to account for a residual tilt of 10^{-7} rad amplitude, and for a series of one- to two-thousand second oscillations present on the record several hours after the events [see Fig. 2 of Nagamune (1977)]. If it could be confirmed, the existence of such a source would shed an entirely new light on the size of tectonic mechanisms involved in this area of China, and the whole concept of a narrow, linear plate boundary might be affected. The purpose of the present paper is, therefore, to critically discuss Nagamune's hypothesis, and to test its interferences against a larger dataset, including records obtained from the IDA network. We conclude that no giant slow seismic source accompanied these events, and that the observed signals must have had a different origin, possibly signal-generated noise.

2. The Yunnan events: a classical study

Two major seismic events were reported in the Yunnan province of China (see Fig. 1) on May 29, 1976, with the following epicentral characteristics (ISC unless otherwise noted). Event I: 24.51°N, 98.95°E; origin time 12:23:18.4 GMT; $m_b = 5.9$; $M_s = 6.9$ (NEIS), 7.3 (Beijing). Event II: 24.54°N, 98.60°E; origin time 14:00:19.4; $m_b = 5.7$, $M_s = 7.0$ (NEIS), 7.4 (Beijing). The depth of both earthquakes was given as very shallow ($\leqslant 10$ km) by the ISC and NEIS, while Beijing gives focal depths of 24 km for event I and 21 km for event II. The

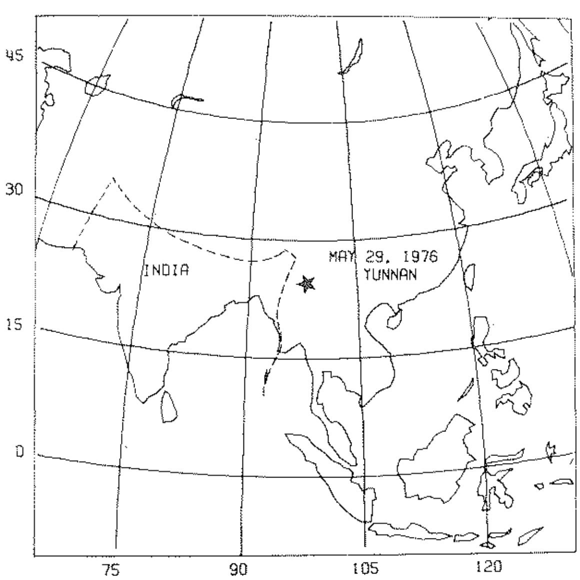

Fig. 1. Map of Southern Asia, showing the epicentral area of the Yunnan events of May 29, 1976 (star). The broken line identifies the continental portion of the Indian plate boundary. Its eastern part constitutes the Mandalay fault, located about 300 km west of the epicenters.

location of these events some 300 km east of the Mandalay fault makes them intraplate events, possibly related to the deformation incurred by China as a secondary effect of the Himalayan collision (Tapponnier and Molnar, 1977). The focal mechanism of the first event was investigated by Nagamune (1977) on the basis of station bulletin reports. He proposed a right-lateral strike-slip along a fault striking NNE–SSW. His solution (strike = 20°, dip = 86°, rake = −14°) is very close to a mechanism published by the Chinese State Seismological Bureau. The latter agency also proposed a different focal mechanism for the second event (strike = 259°; dip = 67°; rake = 130°); in this respect, it is interesting to note that the mechanisms proposed for the two events share a common compressional axis (azimuth 325 ± 4°, plunge 7 ± 5°), which suggests that they were stress-controlled, rather than displacement-controlled. This would be in agreement with the absence of a well-developed fault system in the area (comparable, say, to the Red River fault to the East), as evidenced by Landsat mosaics of the region [see fig. 8 of Tapponnier and Molnar (1977)]. The only prominent feature on these photographs is a small northeast trending scarp about 75 km southeast of the epicenter.

We conducted an independent first-motion study of event I, using a number of long-period records at a set of high-gain WWSSN stations (see Table I and Fig. 2), which were in agreement with the proposed mechanism, but were insufficient to constrain it. This was not possible for event II, since its long-period body waves are perturbed by the coda of surface waves from event I. G_1 and R_1 surface waves from event I were equalized, using Kanamori's [1970] technique, again confirming the focal mechanism, and suggesting a moment of $(5 \pm 2) \times 10^{25}$ dyn-cm, or $M_w = 6.4$ (Kanamori, 1977b). The interference of event II's surface waves with higher-order passages from event I prohibits a similar study of event II; however, the general pattern of the record does indicate that the two focal mechanisms must be different, without providing any definite constraint on the second mechanism. In the absence of a reliable focal mechanism for the second event, only an order of magnitude of its moment can be obtained. The compari-

TABLE I

Seismic stations used in the present study

Code station		Distance (deg.)	Azimuth (deg.)	P-wave first arrival	Surface waves used
WWSSN stations					
AAM	Ann Arbor, Michigan	113.2	2.0	down (Pdiff)	
TUC	Tucson, Arizona	116.6	27.8	down (Pdiff)	R
MAT	Matsushiro, Japan	35.7	61.1	up	
MUN	Mundaring, Western Australia	58.8	162.7	emergent	G,R
KOD	Kodaikanal, India	24.9	238.7	up	
NAI	Nairobi, Kenya	65.4	256.5	up	
SHI	Shiraz, Iran	41.3	287.6	emergent	
IST	Istanbul, Turkey	59.4	304.5	down	
STU	Stuttgart, Germany	71.6	315.9	down	R
KEV	Kevo, Finland	60.8	337.8	down	
GDH	Godhaab, Greenland	84.2	350.5	down	
COL	College, Alaska	77.2	23.6		G
KIP	Kipapa, Hawaii	92.4	65.1		G,R
PMG	Port Moresby, Papua–New Guinea	58.0	119.6		G
SPA	South Pole	114.5	180.0		R
IDA stations					
UR	Sutherland, South Africa	93.6	236.2		
NNA	Ñaña, Peru	166.8	341.6		
HAL	Halifax, Nova Scotia	109.1	346.9		

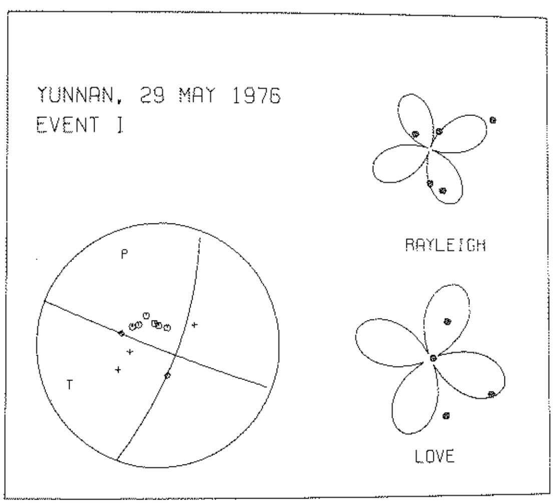

Fig. 2. Focal mechanism of the first Yunnan event of May 29, 1976. Left: P-wave first motions plotted on a stereographic projection of the lower focal hemisphere. Open circles: dilatations. Crosses: compressions. Diamonds: emergent arrivals. P and T are projections of the compressional and tensional axes, respectively. The fault planes have been drawn following Nagamune's solution. Right: Love- and Rayleigh-wave radiation patterns for direct surface waves, using Nagamune's solution and a moment of 5×10^{25} dyn-cm. Individual dots are amplitudes of equalized records.

son of a number of clean phases (e.g. G_2 at MAT, prominent period = 120 s; R_2 at SUR(IDA), prominent period = 180 s), with synthetics built for a variety of source geometries yields $M_0 = (4-15)\times10^{25}$ dyn-cm, or $M_w = 6.3-6.7$.

These events were also recently studied by Upadhyay and Duda (1980), through an investigation of corner frequencies of P and S waves. They give somewhat lower moment estimates of $(1.4-2.0)\times10^{25}$ dyn-cm for event I and $(0.8-2.2)\times10^{25}$ dyn-cm for event II. Since their study involves primarily higher frequencies ($\nu \geqslant 0.1$ Hz), the agreement must be considered acceptable.

In conclusion, a study of the two Yunnan events at classical seismic periods ($T \leqslant 300$ s) fails to show any anomalous behavior in their mechanism. No significant discrepancies are found between magnitude values computed around 20, 100, or 180 s, and we conclude that the events in question do not correspond to a slow release of energy similar to that observed on a number of fracture zones and elsewhere (Kanamori and Stewart, 1976, 1979). However, our results do not, at this stage, exclude the possibility of a much slower source, such as the one claimed by Nagamune.

3. Nagamune's hypothesis: a quantitative assessment

In his 1977 paper, Nagamune proposed that the strong zero-frequency tilt and the later oscillations observed on the Aso tiltmeter were due to an ultra-long period component of the seismic source. Observations of residual tilt following much larger earthquakes have been reported at teleseismic distances, notably by Nishimura (1953), Tomaschek (1955) and Bonchkovski (1962). This prompted Press (1965) to investigate the matter quantitatively, using a model involving a dislocation in a half-space. He concluded that the theoretical amplitude of the residual tilts (proportional to the seismic moment of the source), computed for a number of earthquakes with well-documented rupture parameters, were considerably smaller than the values claimed observed at any given station. In the present case, and using Press' model, Nagamune estimated that a magnitude $M_s = 6.9$ event would create only a tilt of 10^{-9} rad, as opposed to the 2×10^{-7} rad observed on the Aso tiltmeter. Conversely, the latter would require a seismic moment of a few times 10^{28} dyn-cm, depending on the exact geometry of the long-period source.

The quantitative interpretation of the oscillations observed between 15:00 and 17:00 GMT on the Aso tiltmeter is even more difficult. Nagamune interprets them as the Love waves G_5 and G_6 from the first event. It is however debatable whether the concept of travelling waves can be used at the ultra-long periods involved, for which the normal mode angular orders are very low ($l = 5$ at 1000 s). Furthermore, Nagamune fails to explain the absence of the wavetrains $G_1 - G_4$. Nevertheless, we compared the Aso tilt record with synthetics obtained by mode summation for a source having the geometry of the first event and a rise time varying from 800 to 1200 s. Sources with faster rise times were not considered since they would excite energy preferentially at higher frequencies, absent from the Aso record. Although it was not possible to achieve a satisfactory match of the waveshapes of the synthetic and observed traces, we concluded that a tilt oscillation on the order of 10^{-7} rad at this stage in the record would require a source moment of 4×10^{29} dyn-cm for a rise time of 800 s, and 2×10^{30} dyn-cm for a rise time of 1200 s. Since the geometry of any slow precursor may be different from that of the earthquake source at higher frequencies, these figures are only estimates of the moments required by Nagamune's interpretation; however, they suggest very large seismic sources, which, if they could be confirmed, would have far-reaching consequences. Having obtained a quantitative estimate of the sources in question, we can now examine closely a number of predictable effects.

A figure of 2×10^{30} dyn-cm would make this event as large as the 1960 Chilean earthquake, and even the smallest estimate of a few times 10^{28} (necessary to account for the residual tilt) would make it comparable to the well-documented and extensively-studied 1977 Indonesian earthquake. In this context, the amount of tectonic deformation involved in the slow source would be enormous. Nagamune suggested an area of faulting of 45000 km^2, which he probably derived from scaling laws (Geller, 1976), using a moment of about 10^{29} dyn-cm and a stress drop of 30 bar (although the applicability of scaling laws to slow sources is unwarranted since most slow earthquakes feature low stress drops [e.g., Kanamori and Stewart (1979)], and inferred a displacement along the fault of several meters. Although the correlation of the area of aftershocks with the surface of faulting may not hold for extremely slow sources, whose mechanism of rupture may be smoother than that of the standard earthquake, a study of 19 aftershocks with $m_b \geqslant 4.0$ in the 22 days following the mainshocks yielded a more probable upper bound of 4000 km^2 for the area of rupture, and displacements ranging from 10 to 500 m, using a relatively high rigidity of 5×10^{11} dyn cm^{-2}, and the previously discussed moment values of 2×10^{28} and 10^{30} dyn-cm. On the basis of their corner frequency studies at shorter periods, Upadhyay and Duda (1980) have proposed even smaller areas of rupture, which, compared to the above moment values, would yield even larger displacements. Such truly gigantic displacements would have produced substantial geodetic effects, none of which have been reported. Furthermore, they would represent a major deformation of this portion of the Chinese plate which, if recurrent with time, would be observed as a major feature on Landsat photos, comparable to the big strike-slip systems in China. No such system is identifiable in that part of Yunnan.

Displacements on the order of tens of meters would be comparable to, if not larger than, the fault slips involved during major earthquakes on the nearby plate boundaries, e.g. Assam, 1950, for which Ben-Menahem et al. (1974) have proposed a slip of 35 m. This would suggest that a substantial portion of the plate motion process takes place in Yunnan, thus violating the agreement reported by Fitch (1970) between earthquake slip along the Himalayan front and the Mandalay fault, and plate motion rates, as obtained by Le Pichon (1968).

Finally, and this will be the crucial test of Nagamune's hypothesis, if a slow seismic source in the range $2 \times 10^{28} - 10^{30}$ dyn-cm was indeed present in the mechanism of the Yunnan events, it should have excited seismic waves observable on instruments designed to record low-frequency energy, such as the accelerometers of the IDA network (Agnew et al., 1976). The investigation of records from this network is the subject of the next section.

4. IDA records of the Yunnan events

Three stations operating IDA gravimeters recorded signals from the May 29, 1976 Yunnan events: Sutherland (SUR), Halifax (HAL) and Ñaña (NNA). At SUR, an unusual, long-period oscillation is clearly observed following the record of the second event (see Fig. 3). Its period is approximately 45–50 min. NNA and HAL rec-

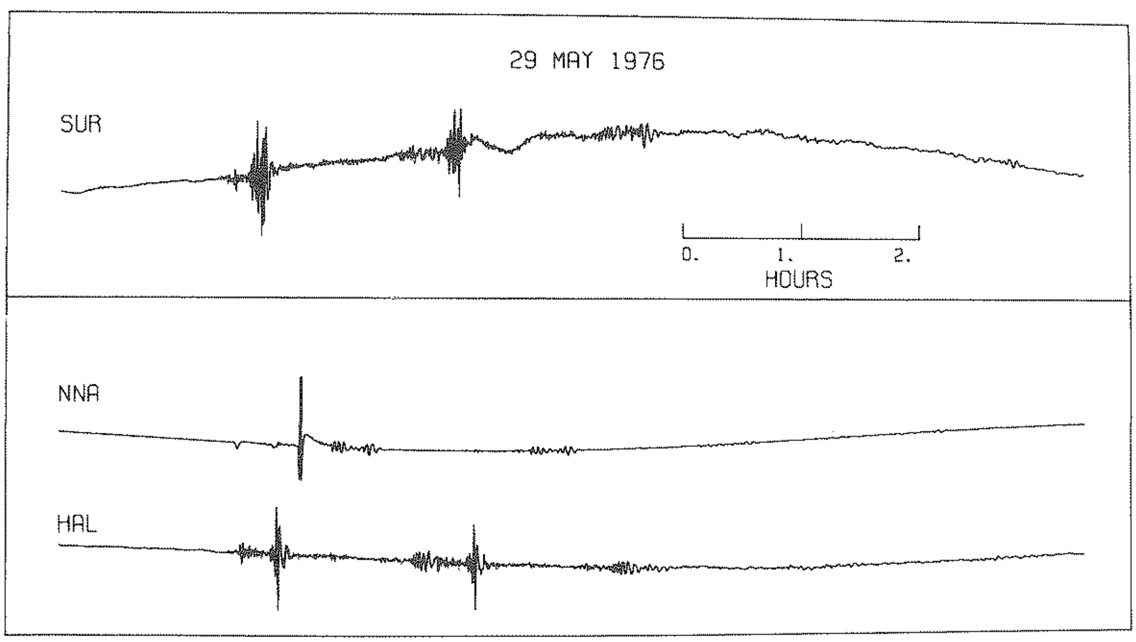

Fig. 3. Top: Record of the Yunnan events at the Sutherland (SUR) IDA station. Record starts at 11:30 GMT, ends at 20:00 GMT. Peak-to-peak amplitude is 248 IDA counts. Note the ultra-long period oscillation around 15:10 GMT, following surface waves from the second event. Bottom: Records of the Yunnan events at NNA and HAL. Note that while NNA goes off-scale right after the first event, and shows some non-linearity immediately following, no oscillation comparable to the one at SUR is observed at either NNA or HAL. Peak-to-peak amplitudes are 4095 IDA counts at NNA, 180 at HAL.

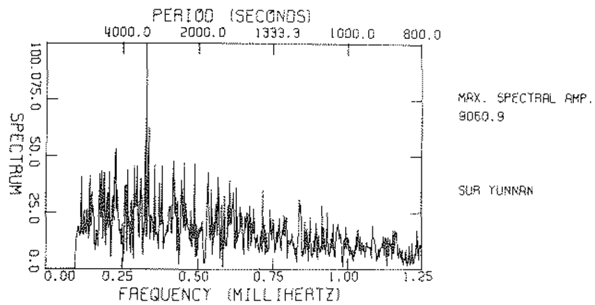

Fig. 4. Frequency-domain amplitude spectrum of a 327 680-s segment of the SUR record. Note the single peak isolated above noise level, at 3048 s. Units at left are arbitrary; maximum amplitude is given for comparison with other spectra.

ords show no similar feature. Our purpose in this section is to investigate whether this oscillation can be due to the kind of slow seismic source described in Section 3.

The release of low-frequency seismic energy is most efficiently described in terms of the excitation of the Earth's low-order normal modes. Therefore, the presence or absence of spectral peaks at the modal frequencies in the records will be a crucial clue as to the reality of the alleged giant slow seismic source.

A 327680-s window of the SUR record was thus Fourier-analyzed in the period range 800–10000 s. The resulting spectrum, shown in Fig. 4, is characterized by a single peak, isolated above noise level, with a period of 3048 s. This value does not correspond to the period of any spheroidal mode of the Earth, the closest one being the singlet ${}_0S_2^{+2}$, split from the ${}_0S_2$ multiplet, and whose period is 3141 s. Our frequency resolution ($\delta f = 3.05 \times 10^{-6}$ Hz) does make the difference significant. Furthermore, any source localized within a few hundred km in space can be considered a point source for the excitation of ${}_0S_2$, and should therefore excite singlets symmetrically (Stein and Geller, 1977). No energy is present in the SUR record at the period of ${}_0S_2^{-2}$ (3333 s), and so the isolated peak in the SUR record *cannot* be an Earth mode, and we conclude that no modes are present in the spectrum of the SUR record. The NNA and HAL records were subjected to the same analysis, which failed to exhibit any peak of significant amplitude above the noise level (see Fig. 5). Since we can rule out that all three stations fall in nodes of the radiation pattern of the source due to their repartition in azimuth, we conclude that the source of the Yunnan events did not excite the Earth's modes over the noise level. In order to assess the quantitative significance of these results, we ran a comparison of the spectra of the SUR records of the Yunnan events and of the 1977 Indonesian earthquake (see Fig. 6). The Indonesian event has been given a moment of 4×10^{28} dyn-cm (H. Kanamori, personal communication, 1979). In order to use a clean portion of the Indonesian record, and to emphasize the radial mode ${}_0S_0$, whose local amplitude is insensitive to receiver geometry, we used in both cases time windows starting two days after the events. From Fig. 6 it is clear that the spectral amplitude of this mode is at least eight times smaller for Yunnan than for Indonesia. It could be argued that pure strike-slip or motion on a vertical fault would not excite ${}_0S_0$; however, a small dip in the fault would contribute some excitation. Allowing for the uncertainty in the focal mechanism, we estimate that 1.5×10^{28} dyn-cm is a conservative upper bound on the moment of the Yunnan events at the corresponding period (1230 s), substantiated by the absence of energy at the nearby frequency of ${}_0S_5$. A similar estimate, based on spectral amplitudes at the period of ${}_0S_4$ (which is less sensitive to the geometry of the source, and has a maximum of amplitude at a distance of 90°, close to the epicentral distances at SUR for both cases) would be: M_0 (1600 s) $\leqslant 3 \times 10^{28}$ dyn-cm. An estimate based on ${}_0S_7$ is M_0 (800 s) $\leqslant 5 \times 10^{28}$ dyn-cm. From these results, we strongly believe that the observed oscillations on the Aso and SUR records cannot be due to a slow component of the seismic source. In order to produce the amplitude observed at Aso, we need $M_0 = 4 \times 10^{29}$ dyn-cm with a rise time of 800 s, $M_0 = 2 \times 10^{30}$ dyn-cm with a rise time of 1200 s, or still higher values for even slower sources; however, a spectral mode analysis puts upper bounds 10 to 100 times lower on the moment of the source at these periods.

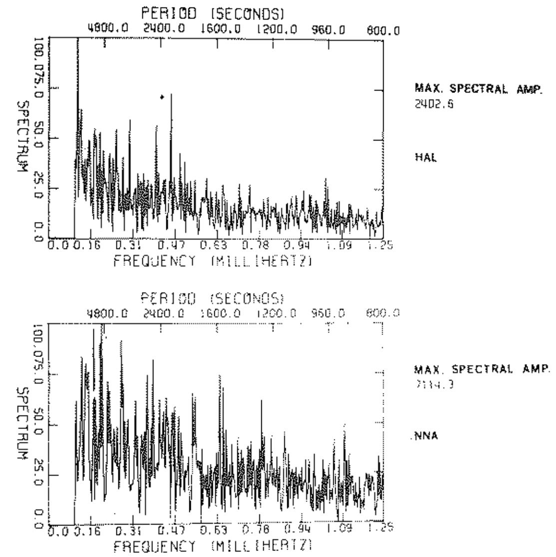

Fig. 5. As Fig. 4, for NNA and HAL. In the case of NNA, the analyzed window includes the non-linearity following the first event. Note, however, that no spectral peak is clearly present above the noise level either for NNA or HAL.

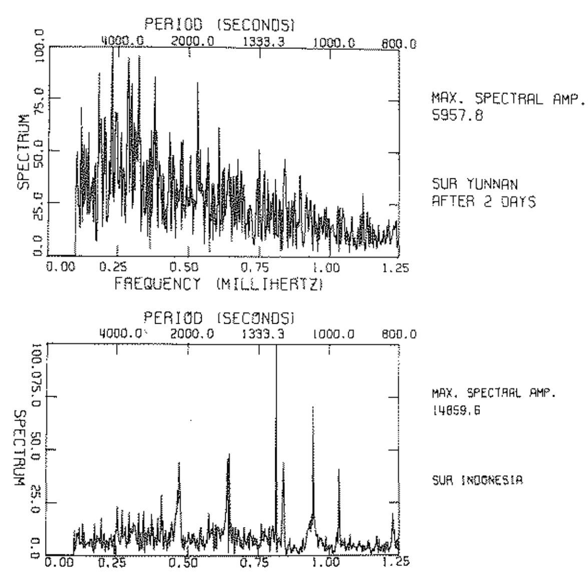

Fig. 6. Comparison of the spectra of the SUR records of the Yunnan events (top) and the 1977 Indonesian event (bottom). The analyzed window starts in both cases two days after the event. Note the absence of spectral peaks in the Yunnan spectrum.

5. Discussion

In order to explore the nature of the oscillation on the Aso record, we similarly Fourier-analyzed a 17-h window of the east–west Aso tilt record (obtained from Dr. T. Nagamune). The amplitude spectrum is seen in Fig. 7a. No energy is present above the noise level at the modal frequencies for either spheroidal or toroidal modes. A relatively poor spectral resolution can be expected, since only 17 h of record are used; however, a comparison can be made with a spectrum obtained from a synthetic seismogram corresponding to a 10^{29} dyn-cm source, with the geometry of the first event and a rise time of 1000 s, shown in Fig. 7b. The

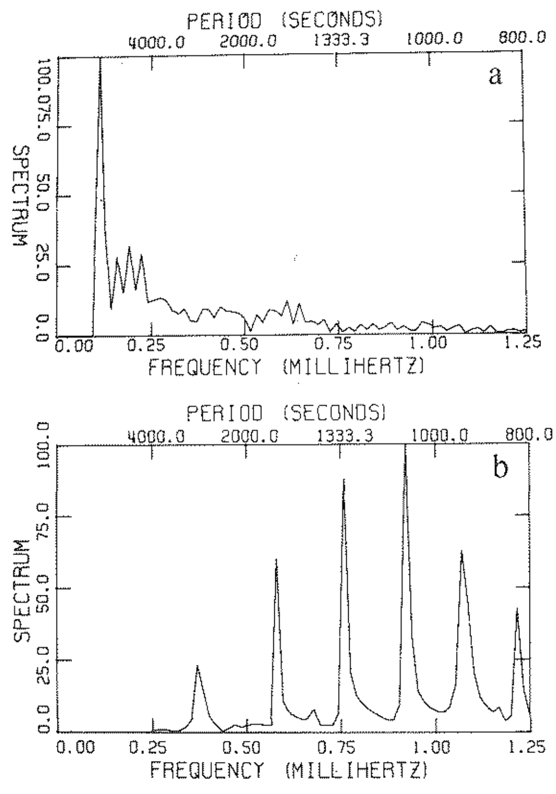

Fig. 7. Top: As Fig. 4, for the tiltmeter record used by Nagamune. A 17-h section of record, starting at 12:30 GMT is used. Note the absence of spectral peaks above noise level. Bottom: Spectrum of a synthetic tiltmeter record, computed in Event I's fault geometry, for a rise-time of 1000 s, and lasting 17 h. This figure proves that the Earth's modes can be resolved even with such a relatively short time window.

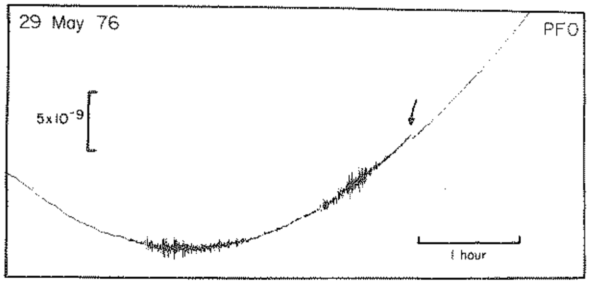

Fig. 8. Strainmeter record of the Yunnan events at Piñon Flats, California. Record starts at 11:50 GMT. Note the absence of any long-period oscillation comparable to those on the Aso or SUR records. The small glitch in the record around 15:40 (arrow) is most probably due to instrument resetting.

purpose of this figure is simply to show that modes (or groups of modes) are adequately isolated even with such a relatively short window. Thus, we must come to the conclusion that none of the Earth's normal modes emerge from the noise level in the Aso tilt record. In this respect, this record exhibits a major difference with the record of the 1952 Kamachatka event at Pasadena, in whose spectrum Kanamori (1976) was able to precisely identify a large number of modes as spectral peaks. Given the absence of modal peaks in the Fourier spectrum of the Aso tilt record, we believe it is not possible to prove the existence of a slow seismic source from an analysis of its time series.

We further investigated a digital strainmeter record, obtained at Piñon Flats, California (see Fig. 8). Although a small glitch is present around 15:40 GMT, it is most probably due to instrumental resetting (D.C. Agnew, pers. comm., 1980). No signal is present over the noise level of about 10^{-9} strain units. Since the tilt and strain in an Earth mode with low angular order should be on the same order of magnitude, we estimate that the source proposed by Nagamune should create a strain 100 times larger than the noise level. Additional records obtained on various instruments failed to provide evidence for any anomalous oscillation; their quantitative interpretation is, however, more difficult because of long-period instrumental instability (strainmeters) or poor gain at ultra-low frequencies (standard gravimeters).

In conclusion, in view of all the above results, we reject Nagamune's suggestion; we believe that there is no evidence for a large, slow component to the source mechanism of the 1976 Yunnan earthquakes, and propose that the oscillations observed on the Aso tiltmeter and the IDA instrument at SUR have a non-seismic origin. The IDA station at SUR has indeed had a history of oscillations similar to the one observed in Fig. 3 (D.C. Agnew, personal communication, 1980), whose origin is presently unclear and may be related to atmospheric conditions, as discussed by Warburton and Goodkind (1977). It may also represent genuine instrumental instability. As for the station at Aso, located on Kyushyu, Japan, in the vicinity of the large Yatsushiro Bay, we investigated the possibility that the observed oscillation may represent a tilt generated by a seiche in the bay. However, a crude model of the forces loading the Earth which could create a tilt of 2×10^{-7} rad at a distance of 75 km yields a value of at least several meters for the variation of sea level producing the required pressure on the bottom of the bay. Clearly, this hypothesis must be discounted. The oscillation observed on the tilt record is therefore most likely of instrumental origin. Its occurrence right after the second event suggests that it may be due to signal-generated noise.

6. Conclusion

Having critically evaluated Nagamune's suggestion of an ultra-slow component to the mechanism of the Yunnan events, we found no evidence for such a source. These events do not exhibit the extremely slow deformations which have been detected along certain plate boundaries. In this respect, the present results reaffirm the concept of relatively rigid plates, with the majority of motion being taken up at their boundaries. Our failure to detect even one Earth mode in the spectra of the Yunnan events rules out the use of their records as evidence for a large slow seismic source. We suggest that instrumental noise is responsible for the observation of anomalous oscillations on a variety of instruments.

Acknowledgments

We are grateful to Professor H. Kanamori for many discussions and for providing us with a variety of records. Through conversations with Dr. D.C. Agnew, we benefited greatly from his invaluable experience with the IDA network. Dr. G. Purcaru sent us a copy of the Bulletin of the State Seismological Bureau (Beijing). This research was supported by the National Science Foundation, under grant EAR79-03907.

References

Agnew, D.C., J. Berger, R.P. Buland, W. Farell and F. Gilbert, 1976. International deployment of accelerometers: a network for very-long period seismology. ES, Trans. Am. Geophys. Union, 57: 180–188.

Ben-Menahem, A., Aboodi, E. and Schild, R., 1974. The source of the great Assam earthquake: an interplate wedge motion. Phys. Earth Planet. Inter., 9: 265–289.

Bonchkovski, V.F., 1962. Deformation of the Earth's surface accompanying certain disastrous earthquakes. Izv. Akad. Nauk SSSR, Fiz. Zemli., 2: 190–193 (English transl.).

Fitch, T.J., 1970. Earthquake mechanisms in the Himalayan, Burmese and Andaman regions, and continental tectonics in Central Asia, J. Geophys. Res., 75: 2699–2709.

Geller, R.J., 1976. Scaling relations for earthquakes source parameters and magnitudes. Bull. Seismol. Soc. Am., 66: 1501–1523.

Kanamori, H., 1970. Synthesis of long-period surface waves and its applications for earthquake source studies—Kurile Islands earthquake of 13 October 1963. J. Geophys. Res., 75: 5011–5027.

Kanamori, H., 1976. Re-examination of the Earth's free oscillations excited by the Kamchatka earthquake of November 4, 1952. Phys. Earth Planet. Inter., 11: 216–226.

Kanamori, H., 1977a. Seismic and aseismic slip along subduction zones and their tectonic implications. In: Island Arcs, Deep Sea Trenches and Back-Arc Basins. Maurice Ewing Ser., Am. Geophys. Union, 1: 163–174.

Kanamori, H., 1977b. The energy release in great earthquakes. J. Geophys. Res., 82: 2981–2987.

Kanamori, H. and Anderson, D.L., 1975. Amplitude of the Earth's free oscillations and long period characteristics of the earthquake source. J. Geophys. Res., 80: 1075–1078.

Kanamori, H. and Cipar, J.J., 1975. Focal process of the great Chilean Earthquake of May 22, 1960. Phys. Earth Planet. Inter., 9: 128–136.

Kanamori, H. and Stewart, G.S., 1976. Mode of the strain release along the Gibbs Fracture Zone, Mid-Atlantic Ridge. Phys. Earth Planet. Inter., 11: 312–332.

Kanamori, H. and Stewart, G.S., 1979. A slow earthquake. Phys. Earth Planet. Inter., 18: 167–175.

Le Pichon, X., 1968. Sea-floor spreading and continental drift. J. Geophys. Res., 73: 3661–3681.

Nagamune, T., 1977. Time characteristics of crustal deformation of the Yunnan earthquake of May 29, 1976 as inferred from tilt recording. J. Phys. Earth., 25: 209–218.

Nishimura, E., 1953. On some destructive earthquakes observed with a tiltmeter at a great distance. Bull. Disaster Prev. Res. Inst. Kyoto Univ., 6: 1–16.

Press, F., 1965. Displacements, strains and tilts at teleseismic distances. J. Geophys. Res., 70: 2395–2412.

Stein, S. and Geller, R.J., 1977. Amplitude of the Earth's split normal modes. J. Phys. Earth, 25: 117–142.

Tapponnier, P. and Molnar, P., 1977. Active faulting and tectonics in China. J. Geophys. Res., 82: 2905–2930.

Tomaschek, R., 1955. Earth tilts in the British Isles connected with far-distant earthquakes. Nature (London), 176: 24–26.

Upadhyay, S.K. and Duda, S.J., 1980. Source parameters of earthquakes from the Himalayan region. J. Geophys., 48: 67–79.

Warburton, R.J. and Goodkind, J.M., 1977. The influence of barometric pressure variations on gravity. Geophys. J. R. Astron. Soc., 48: 281–292.