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Radial modes from the great 1994 Bolivian earthquake: No evidence for an isotropic component to the source

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Abstract. We investigate a possible isotropic component in the source of the Bolivian earthquake of 09 June 1994 through a study of the radial modes ${}_pS_0$ (p = 0, 1) excited by the event. Our study departs from previous similar attempts by making use of a time series of sufficient duration (over 116 days) to sample the shape of the spectral line of the fundamental radial mode ${}_0S_0$, and by combining measurements of two radial modes, thereby lifting the trade-off between deviatoric and isotropic sources of excitation. Our result (an isotropic component of 0.5 ± 1.3% of the main double-couple) fails to identify a significant change in volume in the source of this, the largest deep earthquake ever recorded.

Introduction

The question of the possible existence of an isotropic component to the source of deep shocks has bewildered seismologists ever since it was proposed [*Bridgman*, 1945] that these events may find their origin in a phase transformation of upper mantle minerals. Early efforts in the search for such components to the moment tensors of deep earthquakes have been, at best, inconclusive [*Gilbert and Dziewonski*, 1975; *Geller*, 1974; *Okal and Geller*, 1979]. This situation stems principally from the fact that the excitation of classical mantle waves decays with depth significantly faster for isotropic sources than for deviatoric ones. This leads to a singularity in the inversion for the isotropic component, and requires in principle the use of ultra-long-period signals (1 to 2 mHz), generated only by exceptionally large events, and which were not properly recorded before the advent of broadband instruments. *Okal and Geller* [1979] have argued that the claimed implosive precursor to the great 1970 Colombian shock was below the threshold of detection, and could also have been an artifact of laterally heterogeneous structures.

Recently, *Kawakatsu* [1991] used multiply reflected body waves from 19 large deep shocks, and concluded that this dataset could not even help decide in favor of an implosive, rather than explosive, trend for the isotropic component of deep events. This inability to firmly document any such component suggests that, while phase transitions may play a role in the nucleation of deep events, their stress release must proceed mainly through a physical process fundamentally similar to those of shallow shocks, a contention generally supporting the model of transformational faulting in metastable olivine for the origin of deep seismicity [*e.g., Kirby et al.*, 1991].

In this general framework, the 1994 Bolivian deep shock (at 2.8×10^{28} dyn-cm, the largest ever recorded) provides a unique opportunity to explore the ultra-low frequency part of its spectrum, in the quest for a definite answer regarding the existence of an isotropic component to the source of deep earthquakes.

Kikuchi and Kanamori [1994] used both the ratio of the amplitudes of pP and P, and a preliminary estimate of the amplitude of ${}_0S_0$, to search for an isotropic component. Based on body waves, they suggested an implosive component equal to 7% of the main double-couple, but stressed that their results, especially from ${}_0S_0$, would trade-off significantly with the dip of the fault plane.

Among later studies, *Wu et al.* [1995] reported a 4% isotropic component (based on ${}_0S_0$), but detailed neither its sign, nor their method. *Hara et al.* [1995] used a variety of methods to investigate the isotropic component; their normal mode study at 1–2 mHz yielded a nominal *explosive* component (1.7% of M_0), but they cautioned that this small value was not statistically significant, with the sign of the isotropic component depending on the method of analysis.

There are several problems with the use of ${}_0S_0$ in these studies. First, this mode is excited by a combination of isotropic and deviatoric sources (see below), and the amplitude of its excitation cannot, by itself, resolve the isotropic component, a point outlined by *Hara et al.* [1995]. Also, in order to adequately explore the amplitude and shape of the spectral line of a free oscillation, it is necessary to have proper sampling in the frequency domain. In turn, this requires a time series extending at least as long as the product $T_0 \cdot Q_0$ of the period of the mode by its quality factor. For ${}_0S_0$, $T_0 = 1227$ s and $Q_0 \approx 5700$ [*Riedesel et al.*, 1980], which translates into a minimum window of about 7×10^6 s or 82 days. For this reason, previous evaluations of the amplitude of ${}_0S_0$ excited by the Bolivian event, which relied on much shorter time windows (at most 5 days), must be considered preliminary. Here, we use a time window of 116.75 days for the study of ${}_0S_0$.

Theoretical Background and Technique

Radial modes are excited by only two combinations of moment tensor components: M_{rr} on the one hand, and $(M_{\theta\theta} + M_{\phi\phi})$ on the other. For the purpose of the present study, it is more appropriate to isolate the trace of the moment tensor, and to consider the two equivalent

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combinations $M_I = [M_{rr} + M_{\theta\theta} + M_{\phi\phi}]/3$ and $[M_{rr} - (M_{\theta\theta} + M_{\phi\phi})/2]$, which in the notation of *Kanamori and Cipar* [1974] is the product of the scalar moment M_0 by the coefficient $s_R = \cos\delta \sin\delta \sin\lambda$, controlled by the fault dip δ and slip angle λ; it is equivalent to $-3C/2$ in the notation of *Kawakatsu* [1991]. The excitation of the mode is then proportional to $(M_0\, s_R\, K_0 + M_I\, N_0)$, where N_0 and K_0 are excitation coefficients depending only on depth [*Kanamori and Cipar,* 1974; *Okal,* 1978]. It is clear that when seeking to invert the single mode ${}_0S_0$, M_I trades off with s_R, *i.e.,* with the geometry of the fault plane of the main double-couple. This situation is aggravated by the scatter in values of s_R in published solutions (Table 1). In particular, *Kikuchi and Kanamori*'s [1994] solution has essentially zero s_R, which amounts to transferring to M_I all the observed excitation of ${}_0S_0$; thus, it is not surprising that theirs is the model requiring the largest isotropic component.

Here, we study the excitation of both ${}_0S_0$ and ${}_1S_0$, allowing us to determine both M_I and $M_0 s_R$. In particular, the size of M_I relative to the total scalar moment is determined directly *without any assumption on the dip of the fault plane,* a computation which was not possible in previous studies which considered only a *single* radial mode. This is made possible by a remarkably simple property of the two modes, namely that, for deep sources (h = 635 km for the Bolivian shock), the two excitation coefficients are roughly equal for ${}_1S_0$ ($N_0 = -0.118$; $K_0 = -0.101$) and *equal in magnitude but of opposite sign* for ${}_0S_0$ ($N_0 = -0.319$; $K_0 = 0.272$; units are 10^{-31} dyn^{-1}). Hence, the matrix resolving M_I and $M_0\, s_R$ from the amplitudes of the two modes is very well behaved, and the ratio of the modes' amplitudes effectively lifts the trade-off between the two moment components.

We attempted to include ${}_2S_0$ in our study; however its observed phase is irreconcilable (by an amount of π) with those of ${}_0S_0$, ${}_1S_0$, and ${}_3S_0$. A similar problem has prevented *Durek and Ekström* [1995] from using this mode in their study of bulk attenuation based on radial modes; as mentioned by *Park* [1990], ${}_2S_0$ is strongly coupled to the high-Q core mode ${}_7S_2$, as a result of ellipticity, rotation and lateral heterogeneity. As for higher radial overtones ${}_pS_0$, *Park* [1990] has shown that these are more prone to coupling with spheroidal modes than ${}_0S_0$ and ${}_1S_0$; even though we successfully processed ${}_3S_0$, the quality of its spectral stack was clearly inferior to that for p = 0 and 1, and, in the end, we limited our study to the latter two.

Finally, it is important to ascertain that source duration can be neglected in the interpretation of the spectra under study. The absence of a very slow component which could affect ${}_0S_0$ and ${}_1S_0$ is documented by the study of the excitation of the regular (non-radial) spheroidal modes in the range 1–5 mHz [*Ihmlé and Jordan,* 1995]. This and other studies of the Bolivian event show a maximum duration of about 60 s, respectively 1/20 and 1/10 of the eigenperiods considered here.

An additional advantage of working exclusively with radial modes is that, because the motion of the Earth is in phase everywhere, the particular position of an epicenter, as well as the orientation in space of a deviatoric source (for a given $M_0\, s_R$) are irrelevant to the excitation. Thus, as long as the duration of the source can be neglected, and hence the initial phase of the mode is not affected, the radial modes are insensitive to a spatial evolution of the source (propagation of rupture and/or change of focal mechanism), a phenomenon known to otherwise build artifacts into inverted moment tensors [*Kuge and Kawakatsu,* 1990; *Houston,* 1993].

Dataset and Results

We analyzed time series recorded on very-long-period (VHZ) channels of the IRIS network for a window starting at 06:00 GMT, 09 June 1994 and ending at 00:00 on

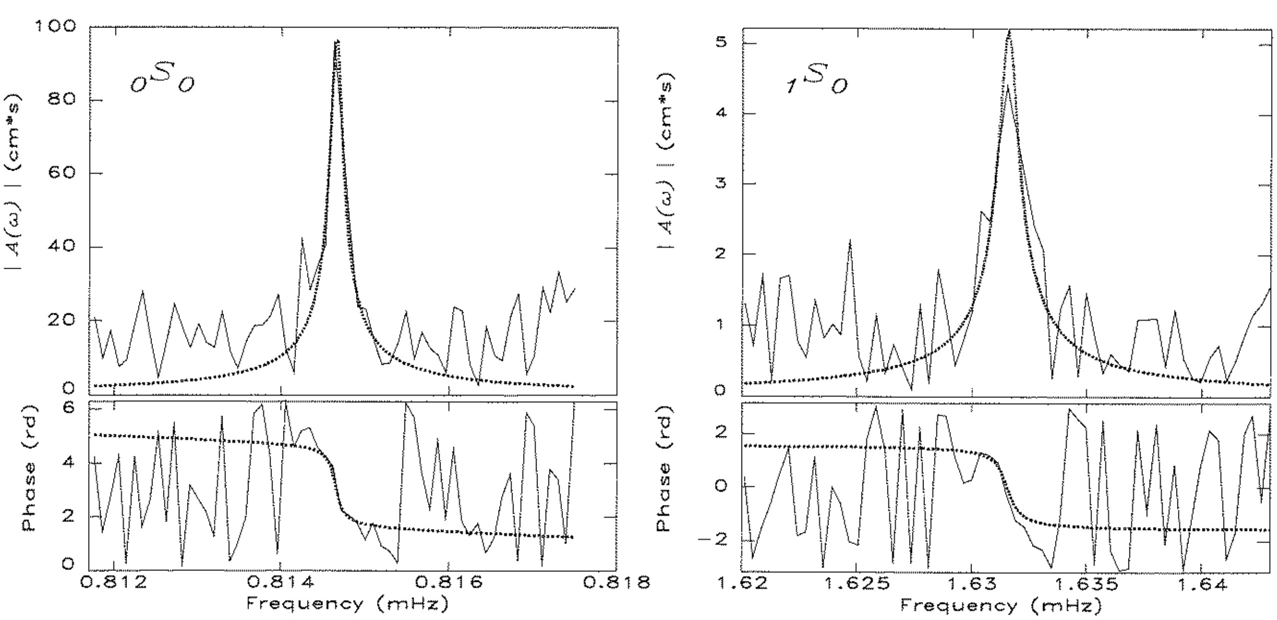

Figure 1. Stacked spectra of ${}_0S_0$ (*Left*) and ${}_1S_0$ (*Right*). The thick dotted lines show the best fits to the spectral amplitudes, and the resulting expected phases in the neighborhood of the resonant frequency. Note the difference in phase between the two modes (π for ${}_0S_0$; 0 for ${}_1S_0$).

04 October 1994. We could not consider longer time series, since the great Kuril earthquake ($M_0=3\times10^{28}$ dyn-cm) resets the mode 13 hours later. Fortunately, no large earthquake took place during the Summer of 1994, which could have significantly affected the decay of the mode, as excited by the Bolivian shock. We explored this problem by summing the contributions to the relevant Fourier integral of all 259 events reported in the CMT catalogue [*Dziewonski et al.*, 1995*a*, *b*, *c*] for the duration of our window. Their total moment amounts to 4×10^{27} dyn-cm (15% of that of the Bolivian shock), but their focal mechanisms and staggered origin times interfere destructively, resulting in spectral contributions of only 4% for ${}_0S_0$ and 0.2% for ${}_1S_0$, relative to the Bolivian event. The length of our window, 116.75 days, translates into 1,008,720 digital points sampled at δt = 10 s, a number close to 2^{20} = 1,048,576, thus allowing efficient analysis by Fast-Fourier Transforms. For ${}_1S_0$, a time window of 2^{18} = 262,144 samples was used, covering approximately one month of data.

Each one of the 36 VHZ records available at IRIS stations was visually inspected in its entire length, and all glitches removed. For a variety of reasons, including long gaps in the data, flagrant non-linearity in the relevant frequency range, or excessive noise levels, only 10 stations were eventually kept for the analysis: AFI, CMB, COR, CTAO, KIP, KIV, MAJO, PAS, RAR, TAU. After removal of each instrument response, the complex spectral lines of ${}_0S_0$ and ${}_1S_0$ were isolated and stacks built of the corresponding spectra at the 10 stations.

For a mode with an initial amplitude a, angular eigenfrequency ω_0 and attenuation $\alpha_0 = \omega_0/2Q_0$, analyzed between times t_1 and $t_1 + T$ after the event, the complex spectrum at angular frequency ω is given for $\omega \approx \omega_0$ by [*Gilbert and Buland*, 1976]:

$$A(\omega) = \frac{a}{2}\, e^{[i(\omega_0-\omega)-\alpha_0]t_1} \cdot \frac{e^{[i(\omega_0-\omega)-\alpha_0]T} - 1}{i(\omega_0-\omega)-\alpha_0}$$

so that the amplitude at resonance is simply

$$|A(\omega_0)| = \frac{|a|}{2} \cdot e^{-\alpha_0 t_1} \cdot \frac{1-e^{-\alpha_0 T}}{\alpha_0}$$

and the phase of $A(\omega_0)$ is either 0 ($a>0$) or π ($a<0$).

We computed a by best-fitting a resonance curve to the amplitude of the complex stack in the neighborhood of ω_0. The latter was allowed to vary slightly about the published value (in practice less than 0.1%), and Q_0 was constrained to 5700 for ${}_0S_0$ [*Riedesel et al.*, 1980] and 2000 for ${}_1S_0$ [*Durek and Ekström*, 1995]. Figure 1 presents the stacked spectra and best fits for both modes.

We verified the robustness of our results through a bootstrapping procedure, by considering all possible subsets of 9 out of 10 stations, and retained as final values of the amplitudes of a weighted (2:1) average between the fit to the whole stack, and the mean values of the bootstrapping experiments. This yields the amplitudes excited by the source: ${}_0a = -0.9\times10^{-4}$ cm for ${}_0S_0$ and ${}_1a = 0.3\times10^{-4}$ cm for ${}_1S_0$. It is difficult to estimate the uncertainty of these numbers, but our tests suggest that they are probably robust within $\pm10\%$. We will consider that they range from -0.8 to -1.0 and from 0.25 to 0.35, respectively, in units of microns (10^{-4} cm). It is immediately clear that the ratio of the spectral amplitudes of the two modes (${}_0a/{}_1a = -3$) approaches that of their deviatoric excitation coefficients K_0 (–2.7). Thus one expects little if any isotropic component.

We then solved for the two independent moment tensor elements contributing to the excitation: $M_0\, s_R = -3.15\times10^{27}$ and $M_I = 0.13\times10^{27}$ dyn-cm. Using the average value $M_0 = 2.8\times10^{28}$ for the scalar moment, we find $s_R = -0.11$, in excellent agreement with most published geometries of the deviatoric moment (Table 1). As for M_I, it amounts to an explosive component of +0.5% of the scalar moment. Given the uncertainty on ${}_0a$ and ${}_1a$, we also computed systematically the value of M_I for a dense grid covering their range of acceptable values. The results, expressed as the 1–σ confidence ellipse around the preferred solution, are shown on Figure 2. In general, they agree with *Hara et al.*'s [1995] conclusion: the isotropic component could vary anywhere between 1.8% (explosive) and -0.8% (implosive) of the main double-couple. By contrast, the deviatoric component, is perfectly robust, with s_R varying only from -0.097 to -0.128. The bottom line is that we fail to identify a statistically significant isotropic component in the source mechanism of the Bolivian earthquake.

Conclusion

By considering both ${}_0S_0$ and ${}_1S_0$ over sufficiently long time windows, we eliminate the trade-offs which affected previous attempts to determine an isotropic component to the source of the Bolivian earthquake. The deviatoric

Table 1. Best double-couples for the Bolivian earthquake

Reference and method	Focal mechanism			s_R	M_0 (10^{28} dyn-cm)
	ϕ	δ	λ		
Kikuchi and Kanamori [1994]; *P* waves	1	13	-4	-0.015	2.2
Kikuchi and Kanamori [1994]; Full wave	351	8	-12	-0.029	2.2
Dziewonski et al. [1995]; Harvard CMT	302	10	-60	-0.148	2.6
Wu et al. [1995]; Time independent inversion	287	8	-74	-0.132	2.7
Lundgren and Giardini [1995]; centroid	311	11	-51	-0.146	2.5
Chen [1995]	298	13	-67	-0.202	2.9
Hara et al. [1995]; *P*, *SH*	322	12	-41	-0.130	1.9
Hara et al. [1995]; Long-Period Body waves	303	9	-59	-0.129	1.3
Hara et al. [1995]; Long-Period Surface waves	260	7	-104	-0.123	2.8
Hara et al. [1995]; Free oscillations	321	12	-41	-0.139	3.1
Estabrook and Bock [1995]	326	12	-35	-0.117	2.6

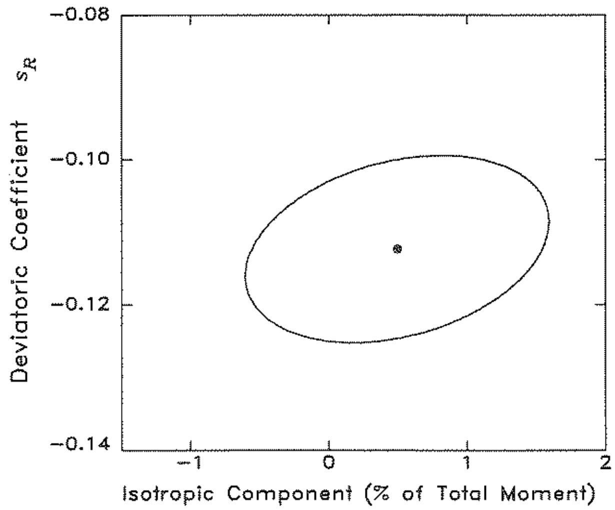

Figure 2. Isotropic component M_I and deviatoric coefficient s_R inverted from the amplitudes of the two radial modes. The figure gives values inverted from the best-fitting amplitudes measured on Figure 1 (central dot), and the 1–σ confidence ellipse inferred from the precision of the measurements (see text).

component $M_0\, s_R$ is in line with most published geometries of the event. No significant isotropic component can be resolved from the spectra of these two radial modes, a conclusion supporting *Hara et al.*'s [1995] results. Thus, the largest earthquake ever recorded at the bottom of a subduction zone (and as such the most promising one in terms of the possible detection of an implosive component to its source) fails to evidence any such process, to a precision of better than 2% of the total moment, despite adequate instrumentation and a methodology specifically targeted for that purpose.

This result is in agreement with the case of the second-largest deep earthquake, the Colombian shock of 1970, for which *Okal and Geller* [1979] showed that the reported implosive component was below the threshold of detectability, given the quality of data available at the time. We then conclude that the two largest deep earthquakes ever recorded fail to exhibit an isotropic component in their source. If the earthquakes find their origin in a change of volume (*e.g.*, in the release of metastability of olivine entrained down the cold subducting slab), then this process must be only a trigger, and as such a negligible contributor to the release of seismic energy. The latter must emanate principally from a different source, as suggested by the model of transformational faulting, in which seismic waves are generated by shear failure developing along thin fault zones in the fine grains of the high-pressure phase [*Kirby et al.*, 1991].

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