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Source location of the 26 sec microseism from cross-correlations of ambient seismic noise

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Very strong, narrow band Rayleigh wave arrivals peaking near 26 sec are observed in cross-correlations of long time sequences of ambient noise records on US, European, and African stations with apparent arrival times that are typically smaller than expected for propagation along the great-circle linking the stations. Use of these apparent travel times to locate the narrow band arrivals shows that the waves originate off the west African coast in the Gulf of Guinea and propagate with an average speed of about 3.5 km/s; i.e., close to the expected group speed of Rayleigh waves at this period. Using data from different months demonstrate that the source location is temporally stable with amplitudes that maximize during the southern hemisphere winter. A microseism with similar features but with a slightly broader spectral peak is observed at stations in East Asia and in the western Pacific, and apparently originates in the North Fiji Basin. The nearly antipodal location of the two source regions leads to the hypothesis that the 26 sec signals are excited by a single source located in the Gulf of Guinea. The Pacific inter-station cross-correlations are probably for major-arc propagation. The physical cause or causes of the microseisms originating in the Gulf of Guinea and the North Fiji Basin remain(s) unclear. We believe the most likely cause to be long period oceanic (infragravity) waves that interact with the continental shelf, perhaps reflect from it, and constructively interfere in a narrow frequency band in the deep ocean.

1. Introduction

In recent years, there has been increasing interest in ambient seismic noise, the continuous oscillation of the solid earth produced by oceanic and atmospheric forcing. Ambient noise provides a useful resource for the study of the interaction between the solid earth, the oceans, and the atmosphere [e.g., *Kedar and Webb*, 2005] as well as deterministic information about the Earth's crust and upper mantle which can be extracted from correlations of long noise sequences observed at pairs of seismic stations [e.g., *Shapiro and Campillo*, 2004; *Shapiro et al.*, 2005; *Sabra et al.*, 2005a, b; *Roux et al.*, 2005]. This fact derives from fundamental properties of random seismic wavefields [e.g., *Weaver and Lobkis*, 2001; *Derode et al.*, 2003; *Campillo and Paul*, 2003].

A simple model of ambient seismic noise is a wavefield produced by sources that are randomly but inhomogeneously distributed over the Earth's surface that emit mostly surface waves. In this case, surface waves generated near the great-circle connecting a pair of receivers interfere constructively on cross-correlations. The resulting time-series displays strong arrivals at positive and negative correlation lag times, referred to as causal and acausal arrivals, respectively. The arrivals correspond to near great-circle propagation of surface waves from one station to the other. In the case of a spatially homogeneous source distribution, cross-correlations will be nearly symmetric in time. The often observed asymmetry of the cross-correlations is caused by the spatially inhomogeneous distribution of noise sources [*Stehly et al.*, 2006]. In most cases, this inhomogeneity affects only the amplitude of the causal and acausal parts of the cross-correlations and not their travel times. However, this model breaks down when temporally persistent and spatially localized noise sources are located off the great-circle linking the stations. Such sources produce signals with apparent travel times that are smaller than expected for waves propagating along the inter-station great-circle. These arrivals, therefore, can corrupt travel-time measurements and tomography based on the cross-correlations of ambient noise. It is important, therefore, to identify strong spatially localized and temporally persistent noise sources and, if possible, to understand their origin to minimize possible errors in dispersion measurements based on ambient seismic noise.

The most prominent example discovered so far of such a localized noise source is the narrow band spectral peak centered on 26 sec period in the seismic background noise observed in seismograms during calm local conditions (Figure 1). Based on polarization analysis, earlier studies identified that this signal is composed of Rayleigh waves originating in the equatorial Atlantic near the African coast [*Oliver*, 1962, 1963; *Holcomb*, 1980; *Bernard and Martel*, 1990; *Holcomb*, 1998]. *Holcomb* [1998] showed that peak amplitudes are strongly seasonal, maximizing during the southern hemisphere winter, which suggests an atmospheric or an oceanic origin of this narrow band microseism. However, the physical cause of this 26 sec microseism remains unclear.

In this paper, we analyze the origin of the 26 sec signal based on cross-correlations of seismic noise records between different stations. Inversion of apparent travel times measured from these cross-correlations shows that the narrow band 26 sec arrivals are waves originating off the west African coast in the Gulf of Guinea and propagate with an average speed close to 3.5 km/s; i.e., close to the expected group speed of Rayleigh waves at this period. Inversions using data from different months demonstrate that the source location is temporally stable with amplitudes maximizing during the southern hemisphere winter. A microseism with similar features but with a slightly broader spectral peak is observed at stations in East Asia and in the western Pacific, and apparently originates in the North Fiji Basin.

2. The 26 sec microseism observed in North America, Europe, and Africa

A narrow band spectral peak centered on 26 sec period can be observed in records of seismic noise at North American and European stations during periods without earthquakes (Figure 1). This signal is seen much more clearly on inter-station cross-correlations where it results in strong, nearly monochromatic arrivals with apparent arrival times that are often smaller than expected for propagation along the great-circle between the stations (Figure 2). The cross-correlations are computed from records of seismic noise that have been bandpassed between 0.02 and 0.05 Hz and then one-bit normalized [e.g., *Campillo and Paul*, 2003; *Shapiro and Campillo*, 2004]. One-bit normalization (the retention of only the sign of the waveform) is a non-linear operation that amplifies weak periodic signals hidden in the noise by a mechanism similar to stochastic resonance [e.g., *Gammaitoni et al.*, 1998].

Examples of the 26 sec arrivals in cross-correlations shown in Figure 2 demonstrate that the amplitudes of these signals are strongly seasonal, maximizing during the southern hemisphere winter, but their apparent inter-station travel times remain nearly constant in time. This suggests a localized source. Analysis of the apparent inter-station arrival times shows that the 26 sec signal arrives approximately from the east for the North American stations and approximately from the south for the European stations. A more precise location of the source of the 26 sec microseism has been obtained with a grid-search procedure. We computed cross-correlations of noise records bandpassed between 0.02 and 0.05 Hz for numerous station pairs in North America, Europe, Africa, and South America. The 26 sec signal was not observed on South American stations, so they will not be considered further here. After bandpassing the cross-correlations between 0.03 and 0.045 Hz, we estimated apparent inter-station arrival times by taking the maximum of the envelopes of the waveforms. Finally, we computed the following misfit function M on a 1-degree geographical grid and with a 0.1 km/s step in group speed:

$$M(U,x,y) = \frac{1}{N}\sum_{ij}\left|\left(\frac{d_i(x,y)}{U} - \frac{d_j(x,y)}{U}\right) - t_{ij}\right| \quad (1)$$

where (x,y) is the hypothetical source position, i and j are station indexes, N is the total number of station pairs, $d_i(x,y)$ is the distance between station i and the source position, U is the tested group speed, and t_{ij} is the measured apparent arrival time between stations i and j. We obtained best misfits with an average speed U approximately equal to 3.5 km/s; i.e., close to the average group speed of Rayleigh waves at 26 sec period. Locations estimated in this way from summer (August) and winter (February) months of 2004 are shown in Figures 3a and 3b, respectively. They demonstrate that the source of the 26 sec microseism observed at North American, European, and African stations is located in the Gulf of Guinea, off the west coast of Africa. The source region is better constrained during February because more stations in West Africa and on Ascension Island were available during this time.

3. The 26 sec microseism observed in East Asia, Australia, and the Western Pacific

A signal similar to the 26 sec microseism seen in the Atlantic region is observed on cross-correlations between stations located in East Asia, Australia, and the Western Pacific (Figure 4). Similar to the signal observed around the Atlantic, inter-station travel times are systematically smaller than expected from great-circle propagation and also are stable in time, indicating a spatially localized temporally persistent source. There are, however, significant differences between the cross-correlations observed in the Atlantic and Pacific theatres. Cross-correlation amplitudes between Asian, Pacific, and Australian stations do not exhibit clear seasonal variations. Moreover, the spectral amplitudes of the Pacific signals are weaker and their band-width broader (Figure 4) than for the microseism observed around the Atlantic. Similar characterization was reported by *Holcomb* [1998]. The grid search algorithm locates the source of the 'Pacific' microseism in the North Fiji Basin (Figure 5).

4. Discussion

The source locations of the 26 sec microseisms are observed in Atlantic and Pacific to be in nearly antipodal regions. The relatively weaker amplitudes and spectral broadening of the signals observed at Pacific stations indicate that these stations are more distant from the source. This suggests that the 26 sec microseism may be excited by a single source located in the Gulf of Guinea so that in the Pacific we are observing Rayleigh waves propagating along major-arcs. For many Asian, Pacific, and Australian stations, the propagation along minor-arcs from the Gulf of Guinea may be less efficient because these paths must cross large continental areas where the 26 sec Rayleigh wave is strongly attenuated. The only observation that apparently contradicts the single source hypotheses is the absence of the seasonal amplitude variability observed between Pacific station-pairs. However, these cross-correlations are computed on on-bit normalized time series in which the source strength is relative to the background noise level. The difference in seasonal variability, therefore, may be due to seasonal difference s in background noise levels in the Atlantic and Pacifc areas and not different source behaviors.

Similar to results of *Holcomb* [1998], we have observed the 26 sec microseism nearly everywhere except in South America. This may suggest that a strong directivity exists in the radiation of this microseism located in the Gulf of Guinea. The physical cause or causes of the 26 sec microseism remain unclear. We believe the most likely mechanism to be long period oceanic waves that interact with the continental shelf, perhaps reflecting from it, and constructively interfering in a narrow frequency band in the deep ocean.

The 26 sec microseism must be accounted for in surface-wave travel-time measurements from cross-correlations of ambient seismic noise. Otherwise, the large amplitude arrivals produced by this microseism will result in erroneous dispersion measurements near 26 sec period. Therefore, to minimize such errors, a band-reject filter centered around 26 seconds should be applied systematically to the ambient noise series before computing cross-correlations.

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References

Bernard, P. and L. Martel (1990), A possible origin of 26 s microseisms, *Phys. Earth Planet. Int.*, *63*, 229-231.

Butler, R. T. Lay, K. Creager, P. Earl, K. Fischer, J. Gaherty, G. Laske, B. Leith, J. Park, M. Ritzwoller, J. Tromp, and L. Wen, The global seismic network surpasses its design goal, Eos., 85(23), 8 June 2004.

Campillo M. and A. Paul (2003), Long-range correlations in the diffuse seismic coda, *Science*, *299*, 547-549.

Derode, A., E. Larose, M. Tanter, J. de Rosny, A. Tourin, M. Campillo, and M. Fink (2003), Recovering the Green's function from field-field correlations in an open scattering medium (L), *J. Acoust. Soc. Am.*, *113*, 2973-2976.

Gammaitoni, L., P. Hängii, P. Jung, and F. Marchesoni (1998), Stochastic resonance, *Re. Mod. Phys.*, *70*, 223-287.

Holcomb, L.G. (1980), Microseisms: a 26 sec spectral line in long-period Earth motion, *Bull. Seism. Soc. Am.*, *70*, 1055-1070.

Holcomb, L.G. (1998), Spectral structure in the Earth's microseismic background between 20 and 40 seconds, *Bull. Seism. Soc. Am.*, *88*, 744-757.

Kedar, S. and F.H. Webb (2005), The Ocean's Seismic Hum, *Science*, *307*, 682-683.

Oliver, J. (1962), A worldwide storm of microseisms with period of about 27 seconds, *Bull. Seism. Soc. Am.*, *52*, 507-517.

Oliver, J. (1963), Additional evidence relating to "a worldwide storm of microseisms with periods of about 27 seconds", *Bull. Seism. Soc. Am.*, *53*, 681-685.

Roux, P., K.G. Sabra, P. Gerstoft, W.A. Kuperman, and M.C. Fehler (2005), P-waves from cross correlation of seismic noise, *Geophys. Res. Lett.*, *32*, L19303, doi:10.1029/2005GL023803.

Sabra,K.G., P. Gerstoft, P. Roux, W.A. Kuperman, and M.C. Fehler (2005a), Extracting time-domain Green's function estimates from ambient seismic noise, *Geophys. Res. Lett.*, *32*, doi:10.1029/2004GL021862.

Sabra, K.G., P. Gerstoft, P. Roux, W.A. Kuperman, and M.C. Fehler (2005b), Surface wave tomography from microseisms in Southern California, *Geophys. Res. Lett.*, *32*, L14311, doi:10.1029/2005GL023155.

Shapiro, N.M. and M. Campillo (2004), Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise, *Geophys. Res. Lett.*, *31*, L07614, doi:10.1029/2004GL019491.

Shapiro, N.M., M. Campillo, L. Stehly, and M.H. Ritzwoller (2005), High resolution surface wave tomography from ambient seismic noise, *Science*, *307*, 1615-1618.

Stehly, L., M. Campillo, and N.M. Shapiro (2006), A Study of the seismic noise from its long range correlation properties, *J. Geophys. Res.*, *submitted*.

Tanimoto, T. (2005), The oceanic excitation hypothesis for the continuos oscillations of the Earth, *Geophys. J. Int.*, *160*, 276-288.

Weaver, R.L. and O.I. Lobkis (2001), On the emergence of the Green's function in the correlations of a diffuse filed, *J. Acoust. Soc. Am.*, *110*, 3011-3017.

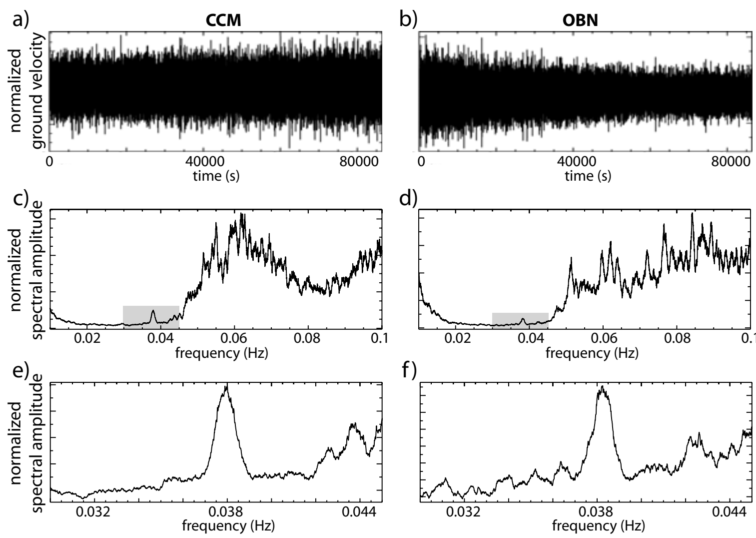

Figure 1. Examples of observation of the 26 sec (0.38 Hz) microseism from analysis of day-long records of seismic noise at stations CCM and OBN during August 22, 2004. Station locations are shown in Figure 3a. (a)-(b) Seismograms. (c)-(d) Amplitudes of the Fourier spectra. (e)-(f) Spectra zoomed around the 26 sec peak (indicated with gray boxes in (c) and (d)).

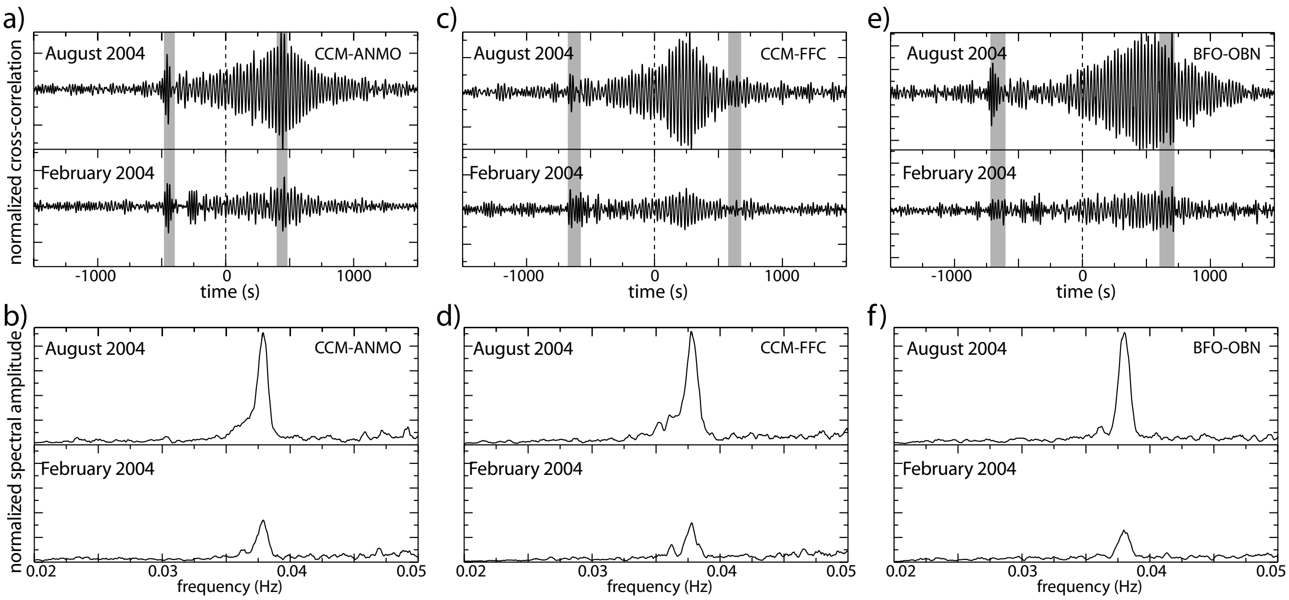

Figure 2. Examples of observation of the 26 sec (0.38 Hz) microseism in cross-correlations of records of seismic noise between pairs of North American and European stations during August and February of 2004. Station locations are shown in Figure 3a. (a), (c), and (e) show cross-correlations computed from one-month records bandpassed between 0.02 and 0.05 Hz. Results from August and February of 2004 are shown in upper and lower frames, respectively. Gray bands indicate time intervals corresponding to group velocities between 3 and 3.5 km/s. (b), (d), and (f) show corresponding amplitudes of Fourier spectra. (a)-(b) Cross-correlations between stations CCM and ANMO. (c)-(d) Cross-correlations between stations CCM and FFC. (e)-(f) Cross-correlations between stations BFO and OBN.

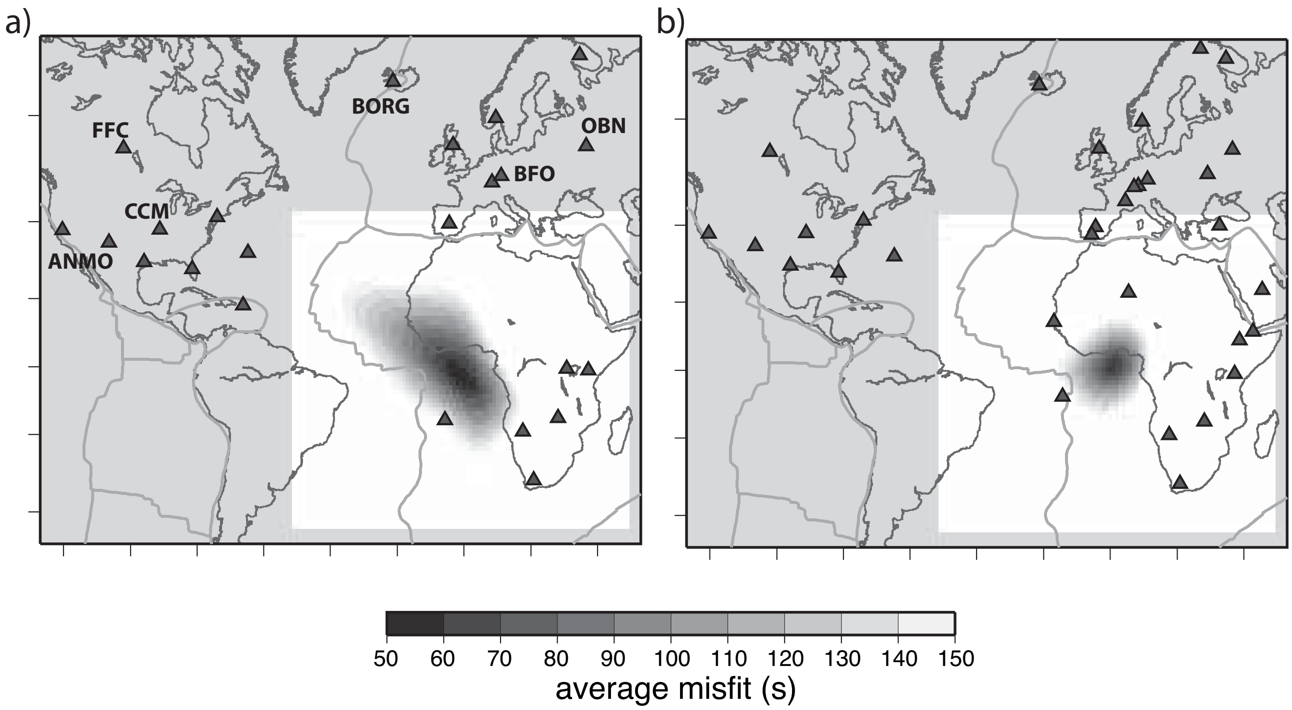

Figure 3. Results of the grid-search location of the source of the 26 sec microseism seen by North American, European, and African stations. (a) Results from 48 cross-correlations computed during August 2004. (b) Results from 71 cross-correlations computed during February 2004. Triangles show stations used to compute inter-station cross-correlations used for location. White rectangle shows the region where the grid-search was conducted. Gray lines show the plate boundaries.

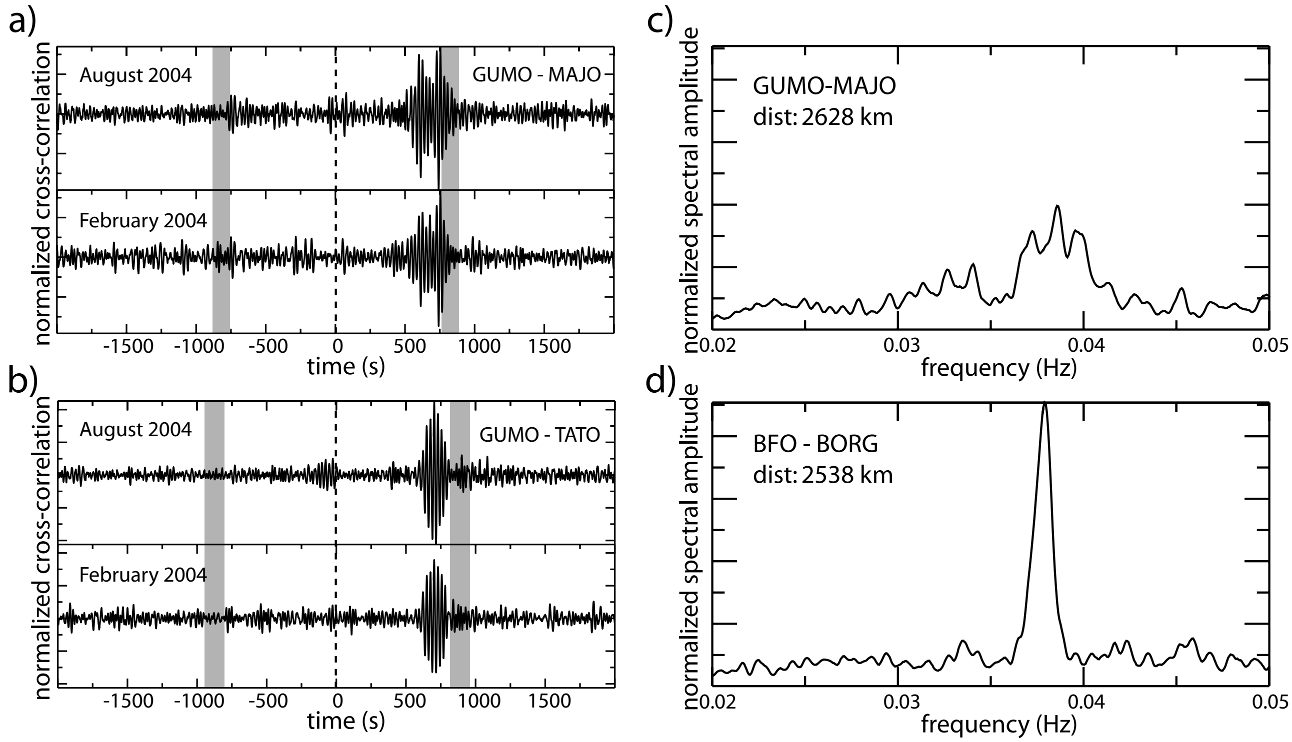

Figure 4. Examples of observation of the 26 sec (0.38 Hz) microseism in cross-correlations of records of seismic noise between pairs of Asian and Pacific stations during August and February of 2004. (a) Cross-correlations computed from one-month records bandpassed between 0.02 and 0.05 Hz between stations GUMO and MAJO. (b) Cross-correlations computed from one-month records bandpassed between 0.02 and 0.05 Hz between stations GUMO and TATO. Results from August and February of 2004 are shown in upper and lower frames, respectively. Gray bands indicate time intervals corresponding to group velocities between 3 and 3.5 km/s. (c) Amplitude of the Fourier spectrum computed from cross-correlation between GUMO and MAJO during August 2004. (c) Amplitude of the Fourier spectrum computed from cross-correlation between BFO and BORG during August 2004. Station locations are shown in Figures 3a and 5a.

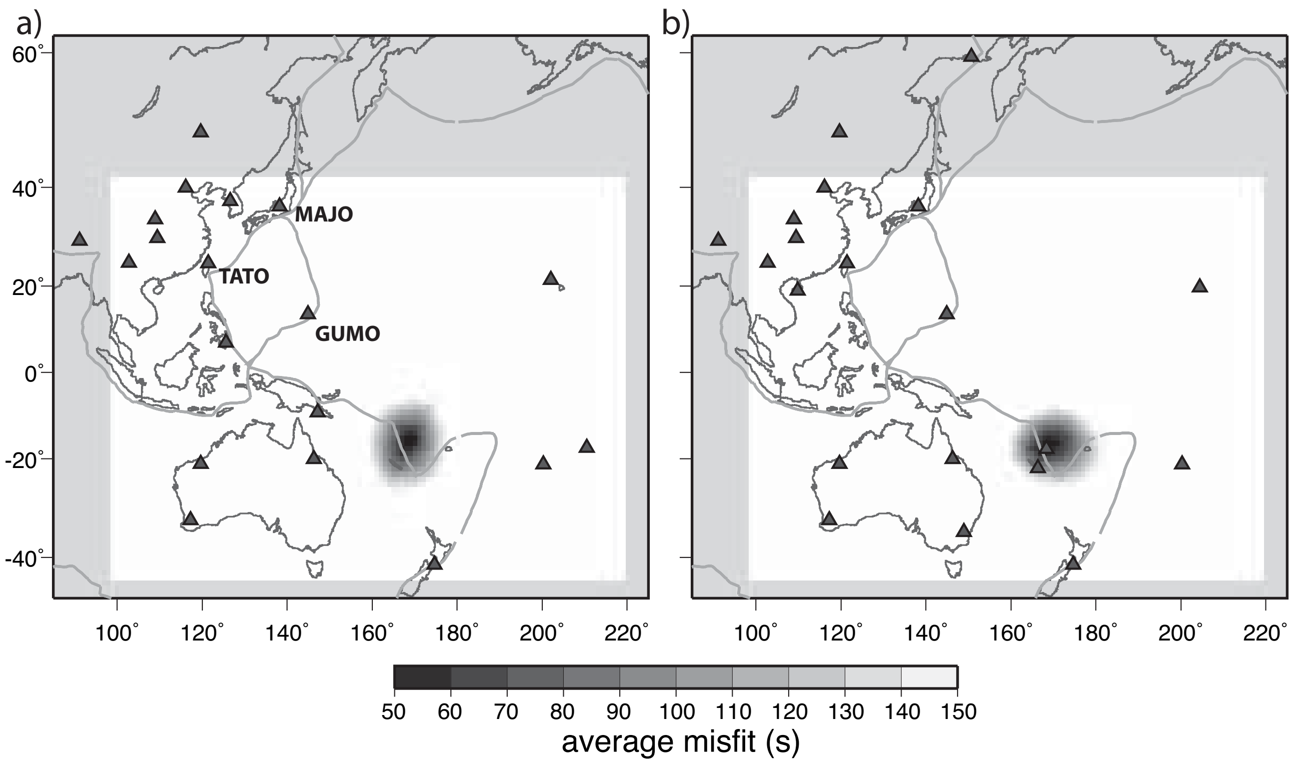

Figure 5. Results of the grid-search location of the source of the 26 sec microseism seen by East-Asian, Pacific, and Australian stations. (a) Results from 33 cross-correlations computed during August 2004. (b) Results from 46 cross-correlations computed during February 2004. Triangles show stations used to compute inter-station cross-correlations used for location. White rectangle shows the region where the grid-search was conducted. Gray lines show the plate boundaries.