Origin of Microseisms in Equatorial and Southern Africa from Analysis of Broadband Arrays

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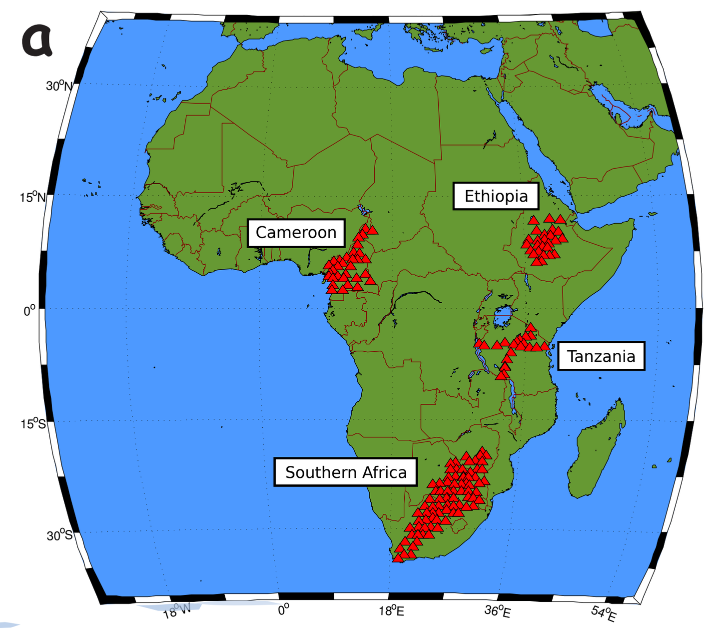
Abstract

Using broadband array noise correlation and frequency-wavenumber analysis, we find evidence for 3 distinct origins of microseisms in the 30-200mHz band: an unusual source of Rayleigh waves at 35-40mHz located in the Bight of Bonny, several abyssal locations with enhanced P-wave production at 100-200mHz, and coastal Rayleigh wave sources that vary in bandwidth. Data analyzed were vertical component recordings sampled at 1Hz from the Cameroon, Southern Africa, Tanzania, and Ethiopia PASSCAL experiments. The Bonny microseism is characterized by 2 well-defined peaks at 36 & 38mHz and is found to have a location on the continental shelf in the northern portion of the Bight of Bonny. Our preliminary analysis finds that the microseism is well represented as a point source with a frequency-dependent location and horizontal slowness. Additional peaks near 61mHz and 69mHz are associated with increased Rayleigh waves sourced from the Bight of Bonny but are below the frequency range expected for a doubled frequency microseism (70-80mHz). Strong P-wave energy is found to originate from abyssal regions west of Retkjanes Ridge near Greenland and in 4 distinct locations in the Southern Ocean. We propose that the locations represent optimal sea floor bathymetry for efficient conversion of nonlinearly interfering ocean waves to seismic P waves. Maputo bay and Sofala bay in Mozambique, the Zanzibar channel east of Tanzania, and several bays in the Mediterranian and North Atlantic are the dominant sources of microseismic Rayleigh waves above 35-40mHz. All noise sources identified in our study have a seasonal signature with peak noise generation in the winter months of each location implying their energy is derived from extratropical cyclones.

Arrays

Location of broadband stations in this study (red triangles). There are 32 stations located in Cameroon (operational during 2005-2007), 28 in Ethiopia (2000-2002), 21 in Tanzania (1994-1995), and 82 in Southern Africa (1997-1999).

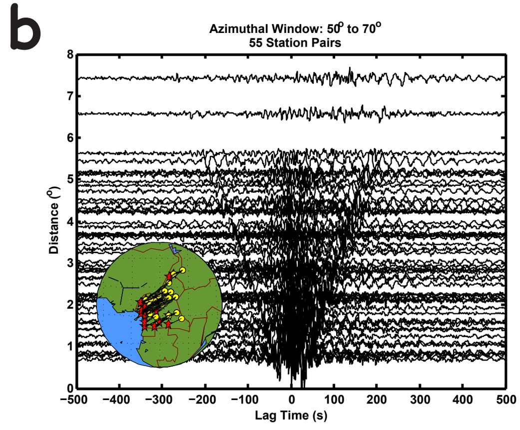
a



Noise Correlation

(b) Record section of 2-year noise correlation functions from station pairs in the Cameroon array with interstation azimuth of 50-70 degrees. Map inset displays station pairs connected by black lines where the red stars and yellow circles denote the source and receiver stations respectively. Arrivals in positive (causal) time correspond to noise that passed through the source station before the receiver station, while a negative (acausal) time indicates the noise arrived at the receiver first. The 'V' pattern of arrivals are the Rayleigh waves from the partially recovered Green's function of the Earth between each station pair. The poor SNR is due to the strong assymetry of the noise distribution. (c) Same but for 140-160 degrees. The inner 'V' of arrivals are not part of the Green's function: they are teleseismic P-waves from specific abyssal locations.

b



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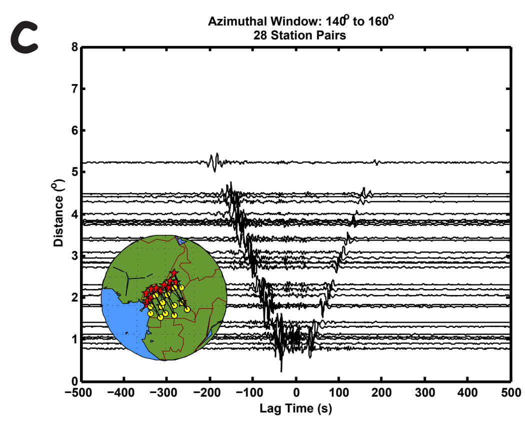
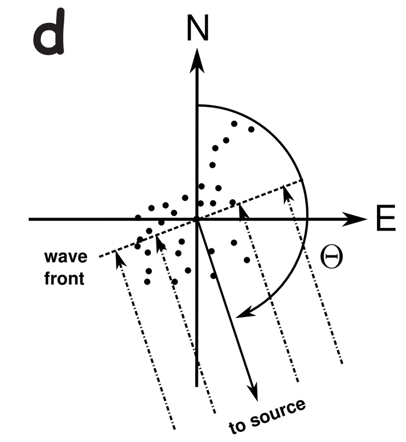


Plane Wave FK Transform

Each point in a frequency-slowness power spectra corresponds to a plane wave moving through the array with a specific frequency, back azimuth and horizontal slowness (1/velocity). See Rost & Thomas 2002 for algorithmic details. The diagram (figure d) below corresponds to the peak value in the example power spectra to its right (figure e) showing a planar wavefront passing through the Cameroon array (black dots in the diagram) with a back azimuth of θ.

d



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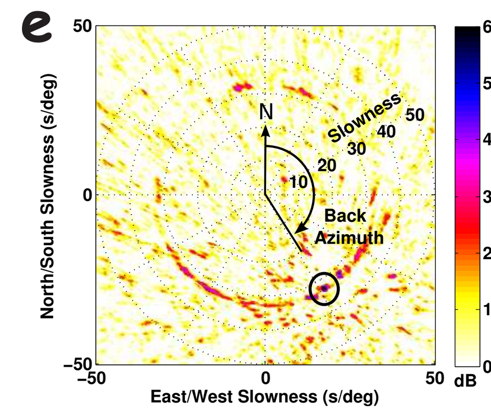

Point Source FK Transform

(f) Sketch illustrating an expanding wavefront passing through an array. The differences in radial distance between every pair of stations and a source provides the phase adjustments necessary to calculate the power spectra as a function of source position. The plane wave FK transform is the far-field approximation of the point source FK transform. (g) Example Array Response Function (ARF) for the Southern Africa array with a synthetic Rayleigh wave point source located in Maputo Bay. An ARF provides insight into how well a source can be resolved by the array in ideal conditions (isotropic velocity, single source). The poor resolution of the source location (manifested as aliasing in space) is due to the limited sampling of the wavefield by the array.

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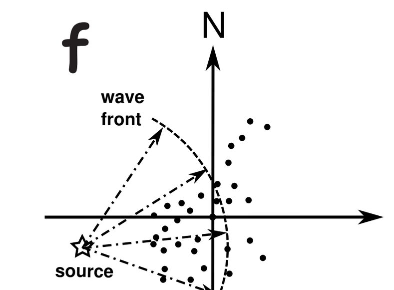

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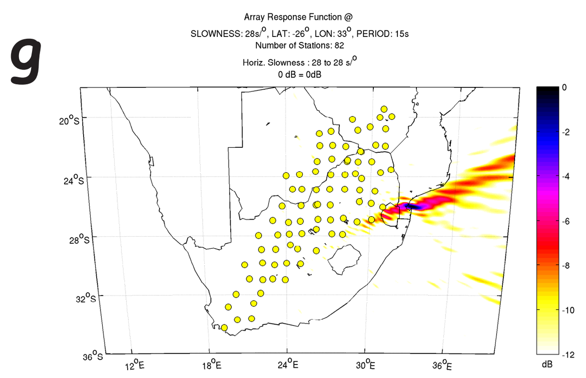

Primary Microseisms

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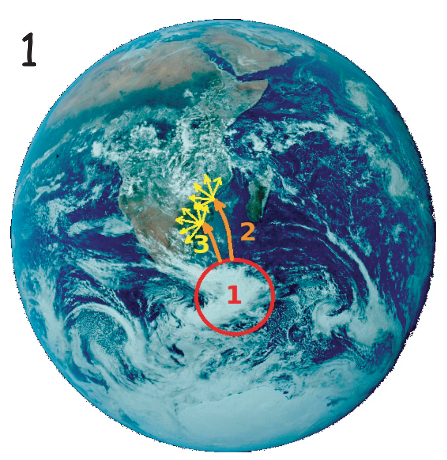

Primary microseisms are strongest between 10s & 20s periods (0.05-0.1Hz). They are generated by the interaction of swells from extratropical cyclones with continental shelves (<100m ocean depth).

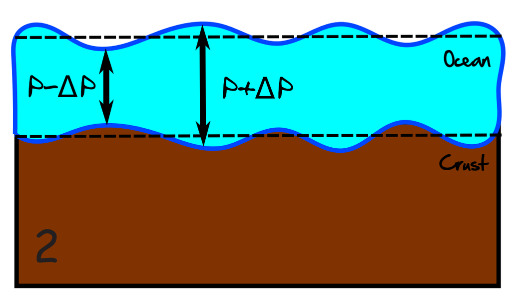

Figure 1 (left) (Earth from Apollo 17). The generation of primary microseisms: (1) winds from extratropical cyclones create waves in the open ocean, (2) the waves propagate away from the cyclones as gravity waves (swell), & (3) the swells interact with the continental shelves generating Rayleigh waves via pressure fluctuations (Figure 2 to the right based on Kundu & Cohen 2004).

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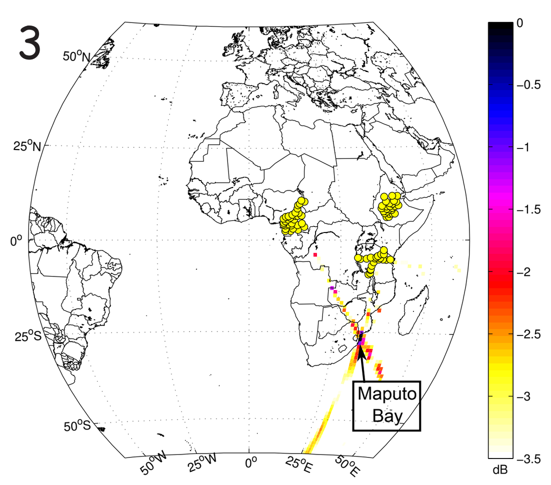


Figure 3 (above). A strong advantage of the point source FK transform over traditional FK analysis is the ease of combining arrays to locate sources of seismic energy. Here we combined the Cameroon, Tanzania, & Ethiopia arrays to locate the dominant source of Rayleigh wave microseisms in Equatorial Africa at 10-15s: Maputo Bay of Mozambique. We assume that the source spanned the 13yr time span of the deployments. Arrays were given equal total weight in the calculation. The power spectra was sampled at 1deg increments in lat/lon and averaged across 0.1s/deg increments in horizontal slowness between 32-34s/deg.

Figure 4 (right). Locating Rayleigh wave microseisms recorded by the Southern Africa array for 2 years at 10-15s periods. The peak in the power spectra corresponds to the innermost coast of Sofala Bay of Mozambique. The FK power spectra was sampled at 1deg increments and averaged over 32-34 s/deg in slowness at 0.1 s/deg increments. dBs are relative to the peak value. Microseisms originating in the direction of the Western Cape province of South Africa are likely secondary microseisms as their bandwidth extends to 5s periods.

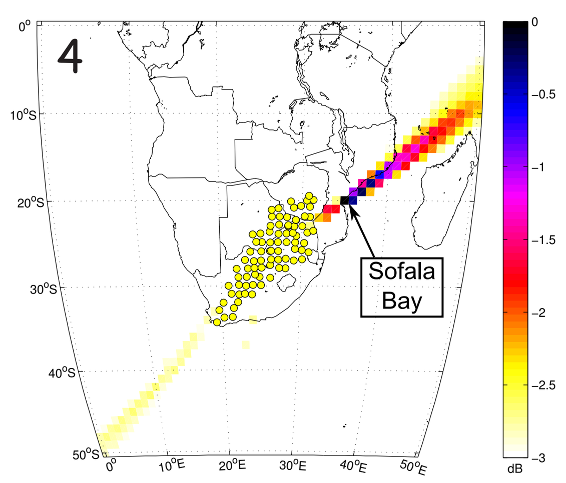
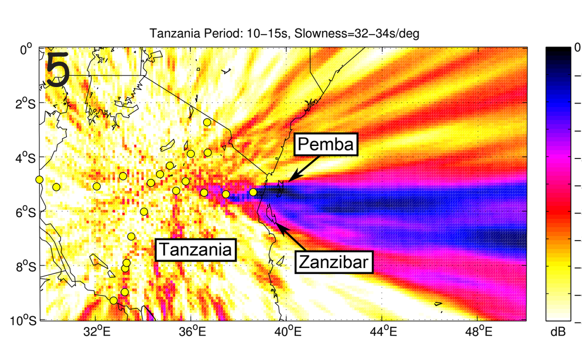
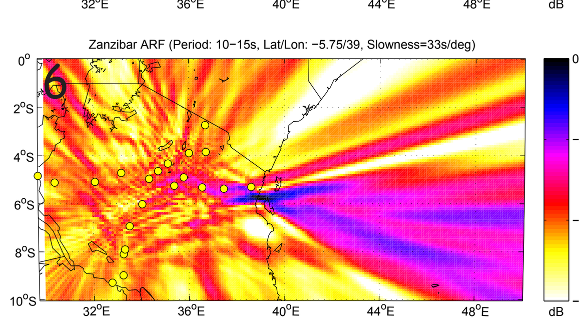


Figure 5 (top right). Point source FK power spectra of Rayleigh wave microseisms at 10-15s periods recorded by the Tanzania array. Power spectra is sampled at 0.2deg increments in lat/lon. The peak in the spectra is near the coast of Tanzania, Zanzibar, and Pemba. Figure 6 (bottom right) is the array response function (ARF) for a point source at -5.75deg South and 39deg East. Shifting the point source by more than 0.5deg dramatically affects the response function and substatially reduces the correlation with Figure 5. Slowness for both spectras was sampled at 0.1s/deg between 32-34s/deg. The ARF was sampled in frequency at 0.25Hz increments.





Figures 7-9 (below). Rayleigh wave microseismic sources farther than ~2 array apertures from a particular array have poor distance resolution. For such cases it is useful to combine multiple arrays to triangulate a source (see Figure 3 above), but this is not always appropriate. Figures 7 & 8 show Rayleigh wave microseismic power spectra (and suggested origins) for the Cameroon & Ethiopia arrays at 10-15s. Combining the two spectra suggests that the microseisms originate in the North Atlantic rather than in the Mediterranean Sea.

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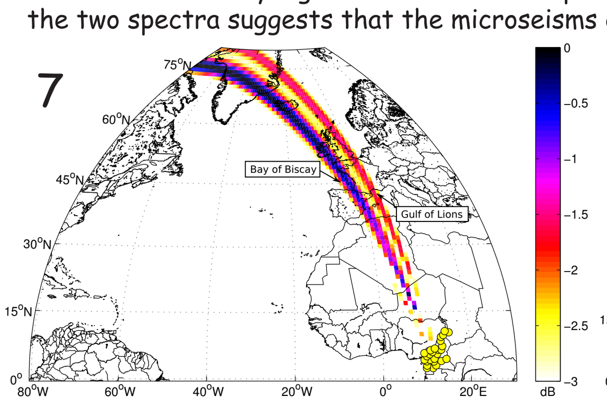

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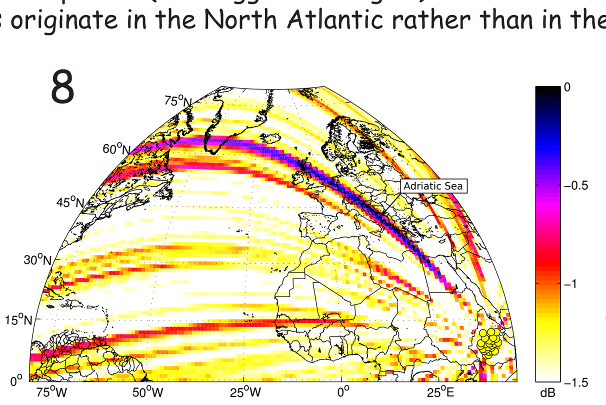

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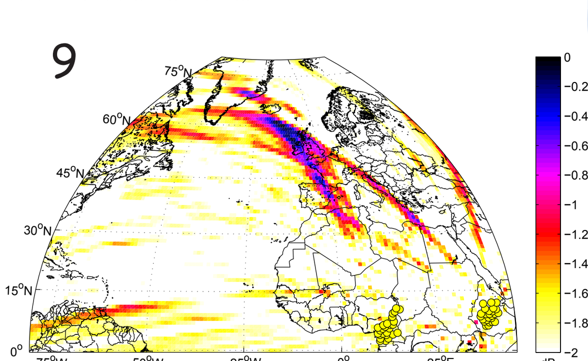

P-wave Microseisms

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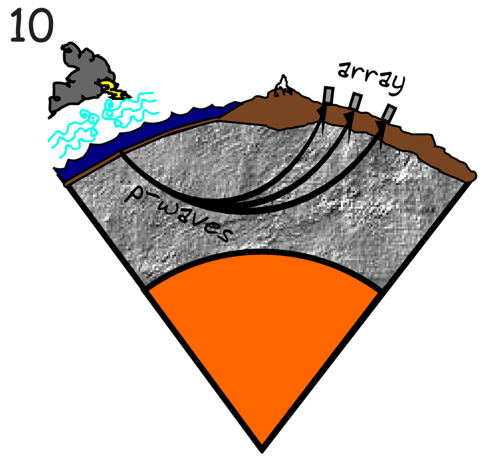
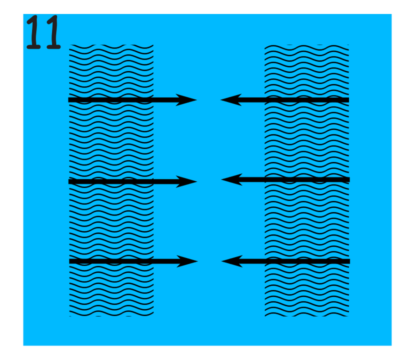


Teleseismic P-wave microseisms are observed at 5-10s periods by all of the arrays in our study. They are generated by the nonlinear interaction of opposing sea waves (Figure 11 - right) in the open ocean (Longuet-Higgins 1950). Those waves in the open ocean are typically generated by strong storms such as hurricanes, typhoons and cyclones (Figure 10). By recording the P-wave arrivals with an entire array of seismometers, we find the slowness of the P-wave and infer the distance using a standard travel time curve such as AK135 (Kennett et al 1995).



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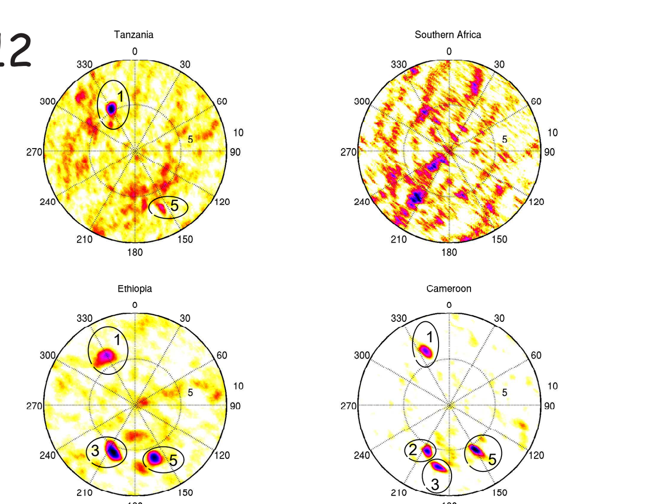

Figure 12 (left). Plane wave FK power spectra averaged over the entire deployment (1-2 years) of each array for the 6-8s period band. The radial axis is horizontal slowness (maximum of 10s/deg) and the azimuth gives the direction from which the plane wave originates. The spectra are normalized by the maximum value in the spectra and clipped below -3dB. Cameroon & Ethiopia arrays recorded microseisms in the range of teleseismic P-wave slowness from multiple directions. These peaks are manifested in the noise correlation functions of these arrays (see Figure C above). The Southern Africa array did not have reliable peaks due to aliasing from surface wave microseisms. Prominent peaks have been numbered according to P-wave source location (see Figure 13 below).

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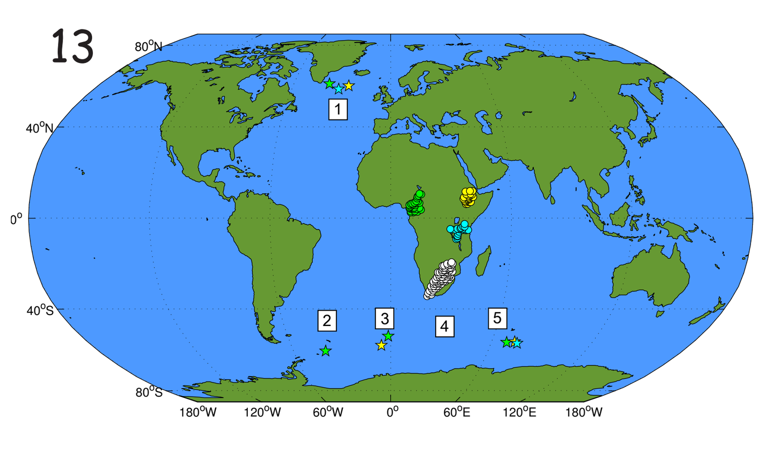

Figure 13 (left). P-wave microseism source locations (stars) corresponding to the peaks in power spectra from Figure 12. The locations are found using the backazimuth and slowness for the peak, where the slowness is converted to distance by comparing to the AK135 P-wave travel time curve. Arrays (circles) and P-wave source locations (stars) are color coded. Three of the four P-wave source locations (1 - North Atlantic, 3 - Bouvet island, 5 - Kerguelen) are confirmed by multiple arrays.

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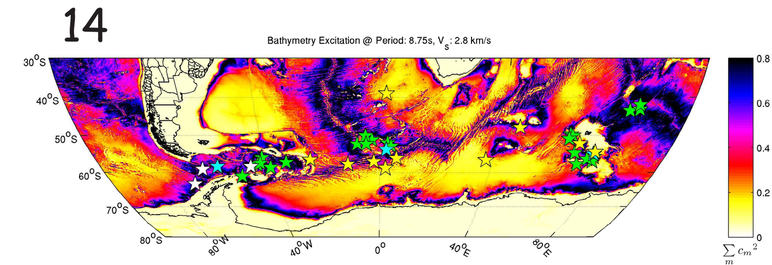

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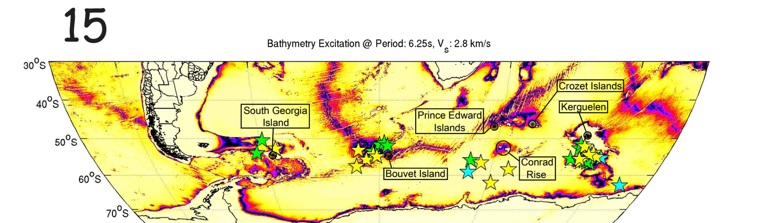
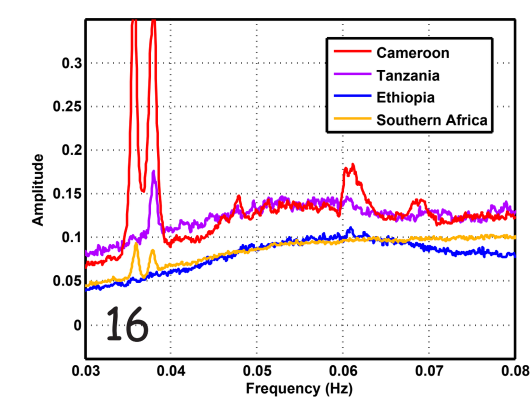
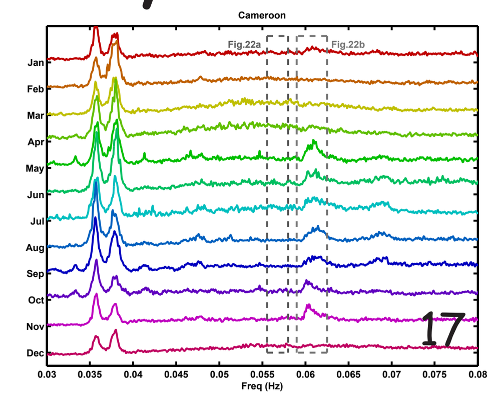
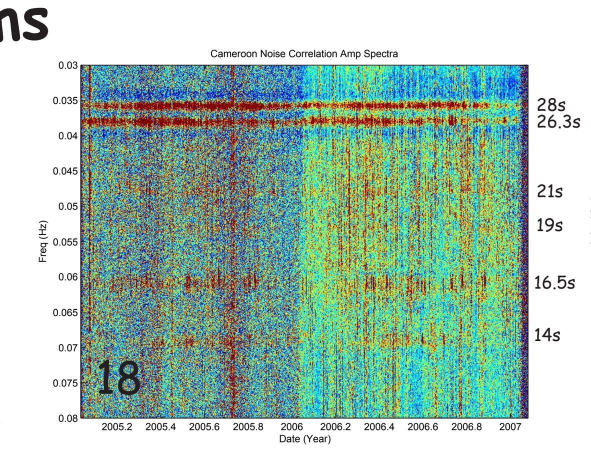


Figures 14 & 15 (left). P-wave microseism source locations (stars) found on a month-by-month basis for the African arrays (color coding matches that of Figure 13) at 7.5-10s (Figure 14 - top left) and 5-7.5s (Figure 15 - bottom left). The locations are overlayed on top of the bathymetrically-influenced wave-wave interaction excitation at the corresponding frequency band. The locations show a strong correlation to the locations with high wave-wave interaction coefficients except for a cluster southwest of the Conrad Rise in the 5-7.5s period range. Furthermore, the locations disperse in unison with the spatial spreading of high wave-wave interaction coefficients with longer periods. This demonstrates the ability of Longuet-Higgins 1950 wave-wave interaction theory to explain the behavior of P-wave microseisms generated in abyssal regions.

Bonny Microseisms







Figures 16 (above left), 17 (above center), & 18 (above right). Figure 16 displays the noise correlation amplitude spectra averaged for the entire deployment for each array. We find spectral peaks at 26s & 28s recorded by the Cameroon, Tanzania, and Southern Africa. The Cameroon array recorded 3 additional peaks at 21s, 17s, & 14s that have a seasonal character as shown in Figures 17 (Cameroon monthly spectra) and 18 (Cameroon daily spectra) in which stronger signals are observed during the Southern hemisphere winter. A possible mechanism to produce such peaks is by seiche waves in a constricted body of water.

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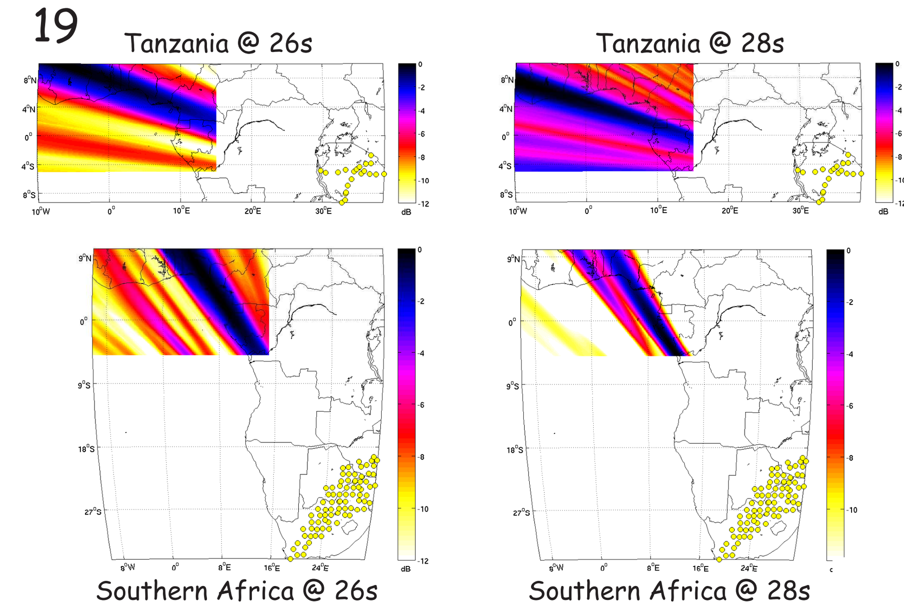

Figure 19 (left). Geographic power spectra of the Tanzania and Southern Africa arrays (spanning the entire deployment time) indicate that 26s & 28s microseism peaks originate in the Bight of Bonny, which extends from the Niger Delta to Gabon. Spectra are sampled at 0.2deg increments and have a bandwidth of +/- 0.05s at 28s & 26.3s. Horizontal slowness was sampled at 0.1s/deg increments between 29-31s/deg. The Ethiopia array did not record anomalous microseisms at 26s & 28s periods (see Figure 16 above).

Figure 21 (above). Map of Bonny microseism point source FK power spectra peak track. The track is shown in white with positions at specific periods marked. There are separate segments for the 28s and 26.3s peaks. The orange line is the 350ft ocean depth contour that roughly corresponds to the edge of the continental shelf. The grey line gives a suggested track between 25s & 28s.

Figure 20 (right). Point source FK power spectra of the Cameroon array (a) 26s & (c) 28s microseism peaks indicate that the array is able to precisely locate their origin within the Bight of Bonny. (c) & (d) are corresponding ARFs for a point source in the Bight of Bonny (see Figure 21 to the left for the ARF input locations). Note the strong correlation of aliasing features.

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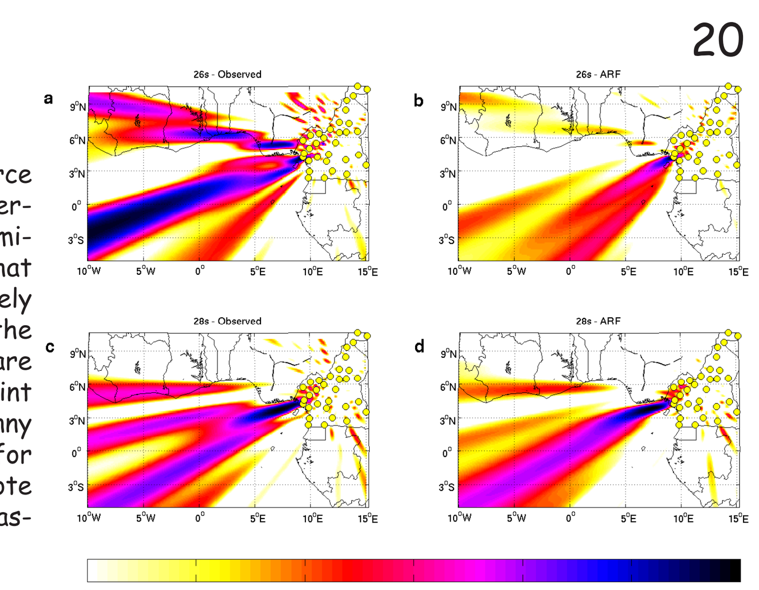

Figure 22 (right). Plane-wave FK spectra for the Cameroon array at (a) 17s-18s & (b) 16s-17s. Frequency bands are shown in Figure 17 (above). Increased power is observed at 16s-17s periods from the direction of the Bight of Bonny (circled). This is evidence that the shorter period spectral peaks share a similar origin with the readily observable 28s & 26s microseism peaks.

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