Twin enigmatic microseismic sources in the Gulf of Guinea observed on intercontinental seismic stations

Article *in* Geophysical Journal International · July 2013

DOI: 10.1093/gji/ggt076

3 authors:

Yingjie Xia
Saint Louis University
8 PUBLICATIONS **75** CITATIONS
SEE PROFILE

Sidao Ni
Institute of Geodesy and Geophysics
303 PUBLICATIONS **5,400** CITATIONS
SEE PROFILE

Xiangfang Zeng
CAS Innovation Academy for Precision Measurement Science and Technology
83 PUBLICATIONS **1,382** CITATIONS
SEE PROFILE

Geophysical Journal International

Geophys. J. Int. (2013) doi: 10.1093/gji/ggt076

Geophysical Journal International Advance Access published April 4, 2013

EXPRESS LETTER

Twin enigmatic microseismic sources in the Gulf of Guinea observed on intercontinental seismic stations

Yingjie Xia,[1,2] Sidao Ni[1] and Xiangfang Zeng[3]

[1]*State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy and Geophysics, Wuhan* 430077*, China. E-mail: sdni@whigg.ac.cn*
[2]*Mengcheng National Geophysical Observatory, University of Science and Technology of China, Hefei* 230026*, China*
[3]*CAS Key Laboratory of Computational Geodynamics, University of Chinese Academy Sciences, Beijing* 100049*, China*

Accepted 2013 February 20. Received 2013 February 20; in original form 2012 December 10

SUMMARY

Based on studies of continuous waveform data recorded on broad-band seismograph stations in Africa, Europe and North America, we report evidences for two temporally persistent and spatially localized monochromatic vibrating sources (around 0.036 and 0.038 Hz, respectively) in the Gulf of Guinea, instead of just one source (0.038 Hz or 26 s) found 50 yr ago. The location of the 0.036 Hz source is close to the Sao Tome Volcano, therefore it may be related to volcano processes. However, the 0.038 Hz source cannot be explained with known mechanisms, such as tectonic or oceanic processes. The most likely mechanism is volcano processes, but there is no reported active volcano in source region. Such repetitive vibration sources may provide valuable tools for detecting temporal variation of crustal structure of the Earth.

Key words: Time series analysis; Interferometry; Volcano seismology; Atlantic Ocean.

1 INTRODUCTION

The Earth is a dynamic planet in continuous vibration as manifested by innumerable wiggles and spikes on the seismograms recorded by seismometers over the world. Almost all the excitation mechanisms of the vibrations have been linked to known dynamic processes. For example, the occasional event-like signals on seismograms are excited by slip-related processes, such as earthquakes, landslides, glacier motion, non-volcanic tremor or volume-change involved processes, such as volcanic activity (magmatic or phreatic eruption, volcanic tremors) (Linde 1996; Ekström *et al.* 2003; McNutt 2005; Rubinstein *et al.* 2008; Peacock 2009; Song *et al.* 2009; Peng & Gomberg 2010). These event-like signals provide the fundamental information for studies of source parameters and have led to in-depth understanding of fault dynamics or dyke formation processes. More importantly for global geodynamic studies, these events excite both surface waves propagating along the surface of the Earth and body waves traversing through interior of the Earth, which enable us to obtain high-resolution image of the entire Earth. In contrast, the much more prevalent uneventful waveforms are usually regarded as background noises (also known as ambient seismic noise), and are generated from persistent and ubiquitous oceanic waves or atmospheric pressure loading (Longuet-Higgins 1950; Hasselmann 1963; Tanimoto & Artru-Lambin 2007; Landès *et al.* 2010; Zhang *et al.* 2010). These continuous waveform data not only provide tools for studying weather events and climate changes (Grevemeyer *et al.* 2000; Gerstoft *et al.* 2006), but also have been demonstrated to achieve unprecedented high-resolution models of crust and uppermost mantle of the Earth with the method of ambient noise tomography (Campillo & Paul 2003; Shapiro *et al.* 2005; Bensen *et al.* 2008).

Furthermore, there are temporally persistent microseismic signals on seismograms that are found to be localized (persistent and localized source, or PL source in abbreviation), such as the Kyushu Island source and the 0.038 Hz source in the Gulf of Guinea (Oliver 1962; Oliver 1963; Zeng & Ni 2011). The signal from the Kyushu Island source is narrowbanded with energy in the band of 0.07–0.12 Hz, and it is proposed to be generated with phreatic processes in the Aso Volcano. The 0.038 Hz microseismic signal was first reported about 50 yr ago, but only after 1980s it was believed to be continuously generated (Holcomb 1980; Bernard & Martel 1990; Holcomb 1998). Recent studies demonstrate that it is excited by one source in the Gulf of Guinea and affects ambient noise tomography (Shapiro *et al.* 2006). However, its amplitude is not constant. Occasionally, the signal becomes so strong that it can be observed on quiet stations almost globally. Such energy burst typically lasts hours, and is as strong as an *M*5 earthquake for the frequency band of 0.037–0.039 Hz (Fig. S1). Its persistent excitation, monochromatic spectra and very strong energy have not yet been accounted for with known models for its excitation mechanism. For example, oceanic processes would lead to broad-band instead of monochromatic energy, and although volcanic processes may generate harmonic signals, no active volcanoes are found to be energetic enough to excite globally observable monochromatic ground motions.

As PL sources may present severe contamination to ambient noise surface wave tomography (Zheng *et al.* 2011). In this paper, we present evidences for two instead of one PL sources in the Gulf of Guinea, based on analysis of spectrograms and noise

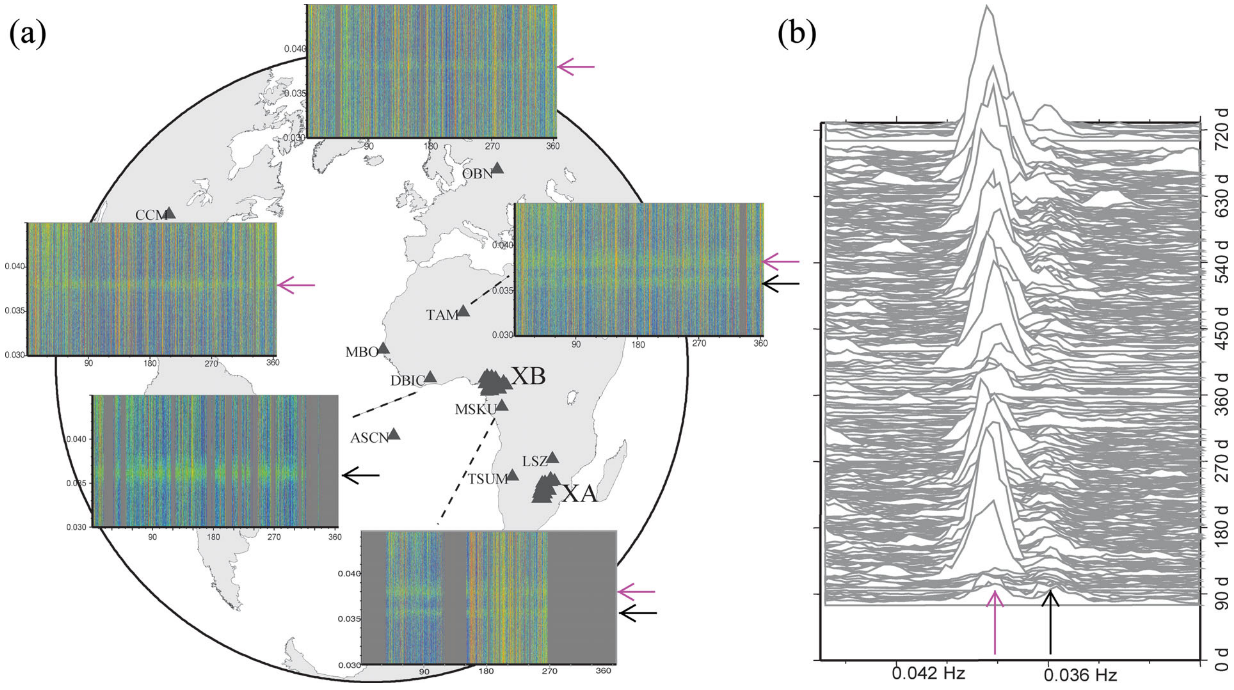

Figure 1. (a) Broad-band seismograph stations (triangle, station CM03 is in temporal array XB) and spectrograms at five stations for year 1999. The 0.038 Hz microseism (indicated with pink arrow) and 0.036 Hz microseism (black arrow) are continuous, demonstrating their persistent nature. (b) Temporal variation of spectral amplitude at TAM in years 1997 and 1998.

correlation functions (NCFs). And we propose that volcano processes are probably responsible for the physical excitation mechanism of PL sources.

2 DATA AND ANALYSIS

2.1 Observation of the 0.038 Hz peak and discovery of a new spectral peak near 0.036 Hz

To resolve their excitation mechanisms, we analyse broad-band seismic records from permanent stations and temporary arrays in Africa, Europe and North America (Fig. 1). Vertical component of seismograms at African stations, CCM (in the United States) and OBN (in Europe) are downloaded from Incorporated Research Institutions for Seismology (IRIS) data management centre and we focus on studying of the long-term behaviours of the 0.038 Hz microseism. 1-yr seismograms are split into segments, and each segment is 4096 s long. Segments are overlapped with 800 s for computing of spectrograms. Only the vertical components are studied as the horizontal components are noisier at long period. 1-yr spectrograms of five permanent stations—CCM, DBIC, MSKU, OBN and TAM are displayed for the frequency range of 0.03–0.045 Hz (Fig. 1a). The 0.038 Hz spectral peak (indicated by pink arrows) is observed continuously on distant stations as far as in North America (CCM) and Europe (OBN). Unexpectedly, at stations close to the Gulf of Guinea (such as TAM and MSKU), another continuous spectral peak is observed at frequency of about 0.036 Hz (black arrows). Though the 0.036 Hz peak is not observed on raw spectrograms of distant stations, it shows up when the waveforms data on these stations are correlated with close stations such as on the NCFs of CM03-TAM and CCM-DBIC (Figs 2 and S2). Therefore, the absence of 0.036 Hz peak on raw spectrogram of distant stations is due to its weaker energy as compared to the 0.038 Hz peak. However, the 0.038 Hz signal is weak at some stations (DBIC and stations in the XB array; Fig. 1), and only the 0.036 Hz peak is observed, suggesting that the two spectral peaks are generated with different radiation patterns of independent sources.

To elucidate the relations between the two spectral peaks, we compare temporal variation of their amplitudes. Following Holocomb's algorithm (Holcomb 1998), we choose quiet power spectral density segments at station TAM for 2 yr (1997–1998). As displayed in Fig. 1(b), the temporal variation pattern of spectral amplitudes clearly shows that the 0.036 Hz signal is much weaker, consistent with its absence on raw spectrograms at distant stations. The two spectral peaks also show different temporal patterns, suggestive of excitation from independent sources.

2.2 Location of 0.036 and 0.038 Hz microseismic sources

Localized microseismic peaks are easier to be observed on NCF between a pair of seismic stations. When the source is far away from the great circle linking two stations, signal due to the localized source shows up earlier than the fundamental Rayleigh waves (Shapiro *et al.* 2006). To compute NCF for each station-pair, earthquake signals are suppressed with the running absolute average method (Bensen *et al.* 2007). Daily cross-correlations between station pairs are computed and then stacked to enhance signal-to-noise ratio of NCFs. NCFs are computed in three bands: (1) Band1: 0.02–0.05 Hz. (2) Band2: 0.02–0.05 Hz, but with a band-stop filter (0.037–0.039 Hz, fourth-order Butterworth filter) to suppress the 0.038 Hz energy. (3) Band3: 0.02–0.05 Hz, but with a band-stop filter (0.035–0.037 Hz, fourth-order Butterworth filter) to suppress the 0.036 Hz energy. The arrival times for the 0.036 and the 0.038 Hz microseism are substantially different on NCF for station pair of CM03 and TAM, arguing that the spectral lines are generated by sources at different locations.

We employ the grid-search algorithm to locate the two sources (Shapiro *et al.* 2006; Zeng & Ni 2011). Six permanent stations

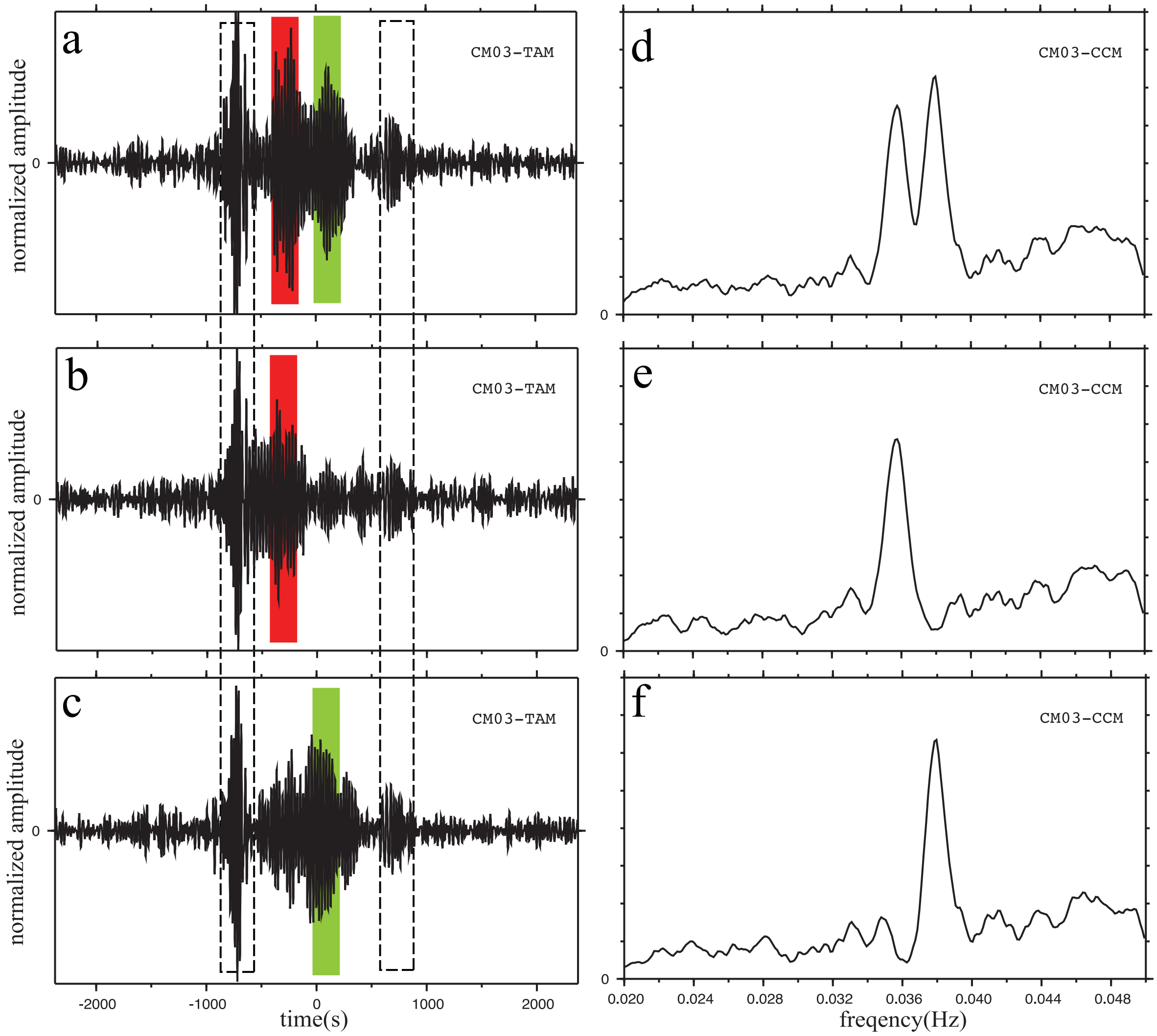

Figure 2. NCFs between TAM and CM03 for Band1 (a), Band2 (b) and Band3 (c) (see text for definition of Band1,2 and 3). The energy packet associated with the 0.036 Hz microseism is indicated with red box, and the 0.038 Hz with green box. The Rayleigh wave signal from the ambient seismic noise is indicated with grey boxes. (d,e and f) Spectra of the NCFs in panels (a, b and c), respectively.

(TAM, DBIC, MSKU, ASCN, TSUM and LSZ) surrounding the Gulf of Guinea and the temporal array XB are chosen to locate the microseismic sources. NCFs of these station pairs are computed by suppressing 0.036 and 0.038 Hz signals separately and only NCFs with strong arrivals are kept. We assume that surface wave velocity is homogeneous in the north African region. Traveltime delays between station pairs and candidate sources can be expressed by

$$\tau_{(u,x,y)} = \frac{d_{i(x,y)}}{u} - \frac{d_{j(x,y)}}{u},$$

where (x,y) is candidate sources location, d_i, d_j are distances between stations i, j and candidate sources, τ is traveltime difference of stations i, j and u is surface wave velocity.

NCFs were then stacked with time delay according to traveltime difference between station pairs

$$E = \sum_n \int_{-39s}^{39s} CC^2_{ij(\tau)} \mathrm{d}\tau,$$

where E is the stacked energy, CC_{ij} is the NCF between the ith and jth stations and τ is delay time. Candidate source locations are searched with spatial grid of every 0.25° in latitude and longitude. The location with maximum energy is thought to be the optimal location of the microseismic source.

Propagation velocity is assumed to be 3.4, 3.6 and 3.8 km s^{-1} to test the stability of our locations (Figs 3 and S3). We also resolve the propagation velocity with array analysis. NCFs are computed between TAM and XA subarray in the Band2 and Band3, respectively. With frequency–wavenumber (*F–K*) method (Rost & Thomas 2002), we determine the propagation velocity and propagation azimuth of the twin microseism peaks. The beamforming results show that the propagation velocity is around 3.8 km s^{-1} for both microseism peaks, and their backazimuths point to the Gulf of Guinea (Fig. S4)

Candidate locations are searched with spatial grid of every 0.25° in latitude and longitude. Different propagation velocities give similar location results (Fig. S3). With the apparent velocity of 3.8 km s^{-1}, both sources are found to be situated in the Gulf of Guinea, with the 0.038 Hz source near (4.50°N, 4.25°E), and the 0.036 Hz source is near (−0.50°N, 7.5°E) (Fig. 3). The large separation (a few hundred kilometres) between the two sources argues that they are independent sources. The 0.036 Hz source is close

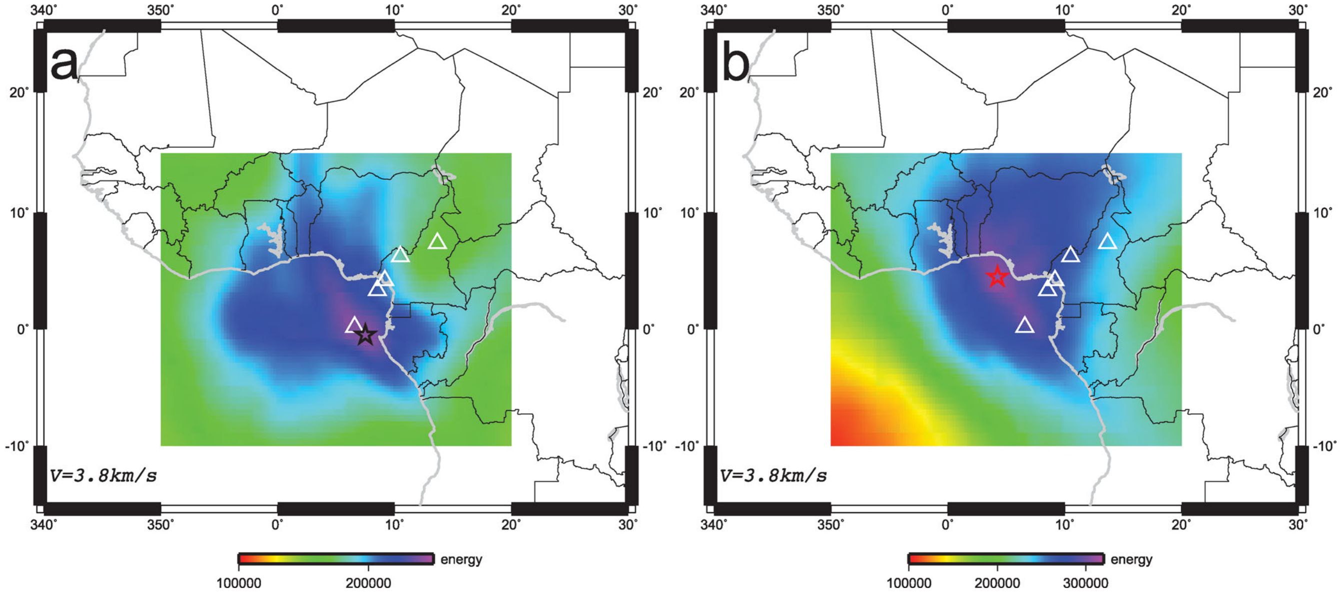

Figure 3. Location of the 0.036 Hz (a) and 0.038 Hz (b) microseismic sources. Black and pink stars indicate each source, respectively. Triangles are volcanoes in the Cameroon Volcano Line.

to the Sao Tome Volcano in the Cameroon Volcanic Lines (CVL) at location of (0.20°N, 6.58°E) and monochromatic spectra is also similar to the very long period (VLP) volcanic tremor. The 0.036 Hz source could be associated with processes in volcanoes like in the case of the Aso Volcano (Zeng & Ni 2011).

3 DISCUSSION

The two sources are probably not related to plate tectonic features, such as major seismogenic faults. There are a few Atlantic fracture zones (such as the Chain Fracture Zone) crossing the Gulf of Guinea and the Ifewara-Zungeru Fault is proposed to be linked with the facture system (Akpan & Yakubu 2010). However, the Gulf of Guinea is far from plate boundaries, and seismicity is low. Earthquake catalogue from National Earthquake Information Center of US Geological Survey (NEIC/USGS) for the period of 1973–2012 does not show a seismically active fault close to the 0.038 Hz source (Fig. S5a). Probably, there are no major active faults capable of accumulating sufficient energy for the continuous excitation of the 0.038 Hz signals observable on intercontinental scale.

Interaction between ocean waves and solid Earth might neither be viable for exciting the two distinct spectral peaks because oceanic wave energy is very weak beyond period of 20 s (Longuet-Higgins 1950; Young 1999). The absence of the stronger 0.038 Hz peak at local stations (only 0.036 Hz peak appears at DBIC and some stations in XB array) suggests that they both are generated with different radiation patterns, contradicting the oceanic excitation mechanism which entails of isotropic pattern for a pressure load on the ocean floor (Longuet-Higgins 1950; Fukao *et al.* 2010). Moreover, both spectral peaks do not show obvious seasonal variations, thus not likely related to oceanic processes (Fig. 1b). The monochromatic nature of the spectral peaks is also against excitation of dispersive signals from oceanic waves (Holcomb 1998). The hypothesis of resonance of oceanic waves due to special bathymetry feature would be difficult to explain for two monochromatic sources situated at different locations. Also energy of oceanic waves near frequency of 0.038 Hz is too weak to generate globally observable signals. For example, the Katrina hurricane did not cause microseismic energy around frequency 0.038 Hz as strong as the 0.038 Hz microseism (Fig. S1b).

Volcanic processes (including magmatic or phreatic processes in volcanoes, or fluidization processes in mud volcanoes) are the most likely mechanism in the Earth known to be capable of continuously inputting energy and persistently generating monochromatic ground motions (McNutt 2005). The long-period volcanic tremors typically feature dominant frequency higher than 1 Hz, and VLP tremors are also reported for some volcanoes with period of 3–100 s or longer. Aso Volcano in Japan is the only reported source persistently generating VLP tremors, at least since 1930s when seismological observation began (Kawakatsu *et al.* 2000; Zeng & Ni 2011), though episodic VLP tremors are reported for some volcanoes (McNutt 2005). Because the 0.036 Hz source is closed to the Sao Tome Volcano, it could be associated with processes in volcanoes. Extinct volcanoes have been found beneath thick sediments of Niger Delta from seismic reflection studies (Davies *et al.* 2005), but no active volcanoes have been reported near the 0.038 Hz source (Fig. S5b). There might be unidentified source with volcanic process near the 0.038 Hz source. Otherwise, there would be no known processes for sufficient power driving its continuous monochromatic excitation.

4 CONCLUSION

In summary, we report two independent localized persistent microseism sources in the Gulf of Guinea. The 0.036 Hz microseisms could be related to processes in a volcano. The 0.038 Hz microseisms cannot be explained with known mechanisms yet, except there is unidentified volcano source in the Gulf of Guinea. The twin persistent microseisms, especially the 0.038 Hz microseisms produce strong precursors in NCFs, and can be used to detect temporal variation of lower crust given the deep penetrating power of long-period surface waves. Moreover, active volcanoes have been found on some extraterrestrial bodies (such as Europa, Io and probably Venus). Therefore, similar persistent and localized microseisms could be generated by volcano-related processes on these extraterrestrial bodies. If so, seismographs can be deployed on them to investigate their internal structures and even to monitor their temporal variation.

These persistent and localized microseismic sources may present severe contamination of ambient noise tomography (Zheng *et al.* 2011), thus identification of such sources in other regions are needed to avoid artefacts in noise tomopgraphy. To eventually decipher the enigmatic processes generating the twin microseisms, seismometers should be installed near Sao Tome and on the ocean bottom near the 0.038 Hz source.

ACKNOWLEDGEMENTS

Waveform data are provided by IRIS DMC. Volcano data are downloaded from the global volcano catalogue by Smithsonian. Supported by CAS programme KZCX2-EW-121, NSFC 40674027, 41204044, China Postdoctoral Science Foundation 2012M520431.

REFERENCES

Akpan, O.U. & Yakubu, T.A., 2010. A review of earthquake occurrences and observations in Nigeria, *Earthq. Sci.,* **23**(3), 289–294.

Bensen, G.D., Ritzowoller, M.H., Barmin, M.P., Levshin, A.L., Lin, F., Moschetti, M.P., Shapiro, N.M. & Yang, Y., 2007. Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, *Geophys. J. Int.,* **169,** 1239–1260.

Bensen, G.D., Ritzwoller, M.H. & Shapiro, N.M., 2008. Broadband ambient noise surface wave tomography across the United States, *J. geophys. Res.,* **113**(B5), B05306, doi:10.1029/2007JB005248.

Bernard, P. & Martel, L., 1990. A possible origin of 26 s microseisms, *Phys. Earth planet. Inter.,* **63,** 229–231.

Campillo, M. & Paul, A., 2003. Long-range correlations in the diffuse seismic coda, *Science,* **99,** 547–549.

Davies, R.J., MacLeod, C.J., Morgan, R. & Briggs, S.E., 2005. Termination of a fossil continent–ocean fracture zone imaged with three-dimensional seismic data: the Chain Fracture Zone, eastern Equatorial Atlantic, *Geology,* **33**(8), 641–644.

Ekström, G., Nettles, M. & Abers, G.A., 2003. Glacial earthquakes, *Science,* **302,** 622–624.

Fukao, Y., Nishida, K. & Kobayashi, N., 2010. Seafloor topography, ocean infragravity waves, and background Love and Rayleigh waves, *J. geophys. Res.,* **115,** B04302, doi:10.1029/2009JB006678.

Gerstoft, P.M., Fehle, C. & Sabra, K.G., 2006. When Katrina hit California, *Geophys. Res. Lett.,* **33,** L17308, doi:10.1029/2006GL027270.

Grevemeyer, I., Herber, R. & Essen, H.-H., 2000. Microseismological evidence for a changing wave climate in the northeast Atlantic Ocean, *Nature,* **408,** 348–353.

Hasselmann, K., 1963. A statistical analysis of the generation of microseisms, *Rev. Geophys.,* **1,** 177–210.

Holcomb, L.G., 1980. Microseisms: a 26 sec spectral line in long-period Earth motion, *Bull. Seismol. 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.

Kawakatsu, H. *et al.*, 2000. Aso94: Aso seismic observation with broadband instruments, *J. Volc. Geotherm. Res.,* **101,** 129–154.

Landès, M., Hubans, F., Shapiro, N.M., Paul, A. & Campillo, M., 2010. Origin of deep ocean microseisms by using teleseismic body waves, *J. geophys. Res.,* **115,** B05302, doi:10.1029/2009JB006918.

Linde, A.T., 1996. A slow earthquake sequence on the San Andreas Fault, *Nature,* **383,** 65–68.

Longuet-Higgins, M.S., 1950. A theory on the origin of microseism, *Philos. Trans. R. Soc. Lond. A,* **243**(857), 1–35.

McNutt, S.R., 2005. Volcanic seismology, *Annu. Rev. Earth planet. Sci.,* **32,** 461–491.

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.

Peacock, S.M., 2009. Thermal and metamorphic environment of subduction-zone episodic tremor and slip, *J. geophys. Res.,* **114,** B00A07, doi:10.1029/2008JB005978.

Peng, Z.G. & Gomberg, J., 2010. An integrated perspective of the continuum between earthquakes and slow-slip phenomena, *Nature Geosci.,* **3,** 599–607.

Rost, S. & Thomas, C., 2002. Array seismology: methods and applications, *Rev. Geophys.,* **40**(3), 1008, doi:10.1029/2000RG000100.

Rubinstein, J.L., Rocca, M.L., Vidale, J.E., Creager, K.C. & Wech, A.G., 2008. Tidal modulation of nonvolcanic tremor, *Science,* **319,** 186–189.

Shapiro, N.M., Campillo, M., Stehly, L. & Ritzwoller, M.H., 2005. High resolution surface-wave tomography from ambient seismic noise, *Science,* **307**(5715), 1615–1618.

Shapiro, N.M., Ritzwoller, M.H. & Bensen, G.D., 2006. Source location of the 26 sec microseism from cross-correlations of ambient seismic noise, *Geophys. Res. Lett.,* **33,** L18310, doi:10.1029/2006GL027010.

Song, T.A., Helmberger, D.V., Brudzinski, M.R., Clayton, R.W., Davis, P., Pérez-Campos, X. & Singh, S.K., 2009. Subducting slab ultra-slow velocity layer coincident with silent earthquakes in southern Mexico, *Science,* **324,** 502–506.

Tanimoto, T. & Artru-Lambin, J., 2007. Interaction of solid Earth, atmosphere, and ionosphere, *Treatise Geophys.,* **4,** 21–444.

Young, I.R., 1999. Seasonal variability of the global ocean wind and climate, *Int. J. Climatol.,* **19,** 931–950.

Zeng, X.F. & Ni, S.D., 2011. Correction to "A persistent localized microseismic source near the Kyushu Island, Japan", *Geophy. Res. Lett.,* **38,** L16320, doi:10.1029/2011GL048822.

Zhang, J., Gerstoft, P. & Bromirski, P.D., 2010. Pelagic and coastal sources of P-wave microseisms: generation under tropical cyclones, *Geophys. Res. Lett.,* **37,** L15301, doi:10.1029/2010GL044288.

Zheng, Y., Shen, W., Zhou, L., Yang, Y., Xie, Z. & Ritzwoller, M.H., 2011. Crust and uppermost mantle beneath the North China Craton, northeastern China, and the Sea of Japan from ambient noise tomography, *J. geophys. Res.,* **116,** B12312, doi:10.1029/2011JB008637.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Comparison of signal strength from three different energy sources.

Figure S2. (a) 1-yr NCF between CCM and DBIC in 1998 and (b) Spectra of the NCF.

Figure S3. Location of the 0.036 Hz (black star) and 0.038 Hz (pink star) microseismic sources.

Figure S4. *FK* analysis for NCFs of the 0.036 Hz (a) and 0.038 Hz (b) source, showing propagation velocity of 3.8 km s^{-1} and with backazimuth pointing to the Gulf of Guinea.

Figure S5. (a) M4.5+ seismicity (circles) around the Gulf of Guinea since 1973. (http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggt076/-/DC1)