Evidence of explosive seafloor volcanic activity from the Walvis Ridge, South Atlantic Ocean

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[1] Hydrophones moored in the North Atlantic Ocean recorded a sequence of explosive, volcano-acoustic signals originated at the Walvis Ridge in the South Atlantic Ocean. 365 explosive signals were detected from the Walvis Ridge beginning 24 November 2001 continuing through March 2002. The largest swarm began on 19 December at 2329 GMT, and lasted 1.25 hrs producing 32 locatable events. Swarm locations are centered on the northern flank of an unnamed seamount (−32.96°S; −5.22°W), northwest of Wüst Seamount. These signals are interpreted as volcanogenic explosions due to similarities with acoustic signals recorded from a confirmed submarine eruption in the Caribbean in 2001 (Kick'em Jenny volcano). The observations presented suggest recent magmatic activity along the Walvis Ridge may be unrelated to the Tristan da Cunha mantle plume. Furthermore, these events lend support for an extensional fracture-zone model resulting in the recurrence of volcanic activity along older segments of large-scale sea floor lineaments. **Citation:** Haxel, J. H., and R. P. Dziak (2005), Evidence of explosive seafloor volcanic activity from the Walvis Ridge, South Atlantic Ocean, *Geophys. Res. Lett.*, *32*, L13609, doi:10.1029/2005GL023205.

1. Introduction

[2] The Walvis Ridge is a ~3400 km long submarine ridge that trends northeast at an oblique angle from the Mid-Atlantic Ridge (MAR) to beneath the continental crust of Africa (Figure 1). The Walvis Ridge is currently thought to be either a hotspot derived seamount chain [*Morgan*, 1971], or a fracture zone with an extensional component that results in volcanism [*Fairhead and Wilson*, 2005].

[3] An array of six autonomous underwater hydrophones (AUH) have been deployed since February 1999 along the flanks of the northern MAR from 15N to 35N (Figure 1) [*Smith et al.*, 2003]. The hydrophones record the acoustic Tertiary (*T*-) waves of seafloor earthquakes that propagate through the ocean sound channel. Using *T*-waves to detect seafloor earthquakes provides a more complete catalog of M > 3.0 earthquakes from throughout the Atlantic Ocean basin [*Dziak et al.*, 2004a], a significant improvement over the M ~ 4.5 detection limit of land-based seismic networks. This study presents evidence of explosive seafloor volcanic activity recorded on the north Atlantic hydrophones that originated along the middle section of the Walvis Ridge (Figure 1). The most intense period of seismic activity occurred from November 2001 through March 2002 and was not observed by any other global seismic monitoring system. Present day detection of low-level seismicity associated with active magmatism along a massive seafloor lineament is a significant discovery. This magmatic activity suggests segments of intraplate ridges may be re-activated millions of years following their initial emplacement by a mantle plume or other processes [*Kumar*, 1979; *O'Connor and Duncan*, 1990; *Fairhead and Wilson*, 2005].

2. Tectonic Setting

[4] Plate tectonic theory accompanied by the technology to produce high-resolution bathymetric maps has spurred various models for the emplacement and evolution of the Walvis Ridge. The most popular of these models involves the influence of hotspot volcanism as the initial generation mechanism for the Walvis Ridge [*Morgan*, 1971]. In the hotspot model, the evolution of this NE/SW trending seafloor lineament is attributed to plate motion over a fixed mantle plume (Tristan da Cunha hotspot) near the MAR axis. The trace of seamounts and volcanic islands comprising the Walvis Ridge thus provide a record of past plate motion over the hotspot during the opening of the Atlantic Ocean [*O'Connor and le Roex*, 1992; *Wilson*, 1992; *Gallagher and Hawkesworth*, 1994; *O'Connor et al.*, 1999].

[5] Smaller scale topographic features within the Walvis Ridge lineament are better aligned with South Atlantic fracture zones than the absolute plate motion of Africa. The presence and structure of these smaller scale features along the Walvis Ridge can be explained by another model based on deformational processes related to the tectono-magmatic evolution of the African plate [*Fairhead and Wilson*, 2005]. In this model, dextral shear and extension are brought on by the release of intra-oceanic plate stresses along zones of existing crustal weakness (fracture zones). It is along these deformation zones that decompression melting of the mantle may occur producing short volcanic lineaments that in composite form the Walvis Ridge. In this way, episodic volcanic events may occur along these existing lineaments each time intra-plate stress is relieved during a deformation event.

[6] A combination of these models is the most probable mechanism for the generation and continued evolution of this seafloor lineament with the bulk of the Walvis Ridge emplaced millions of years ago as the African plate drifted over the fixed Tristan da Cunha hotspot plume. The evolution of the Ridge has likely continued with subsequent volcanic episodes related to intra-plate stress

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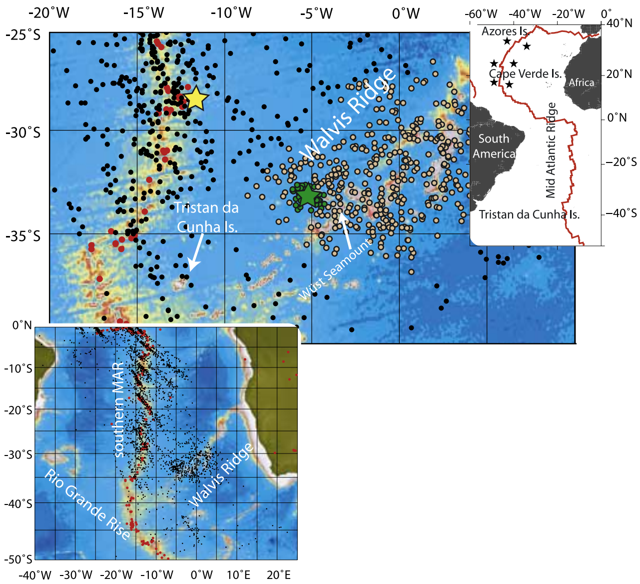

Figure 1. Bathymetry and earthquake locations in the South Atlantic Ocean during the period from February 1999 through December 2002. Hydro-acoustic epicenters are shown as black dots and NEIC epicenters as red dots. Events associated with Walvis Ridge activity are colored tan and green. The average location of the largest Walvis Ridge swarm (40 green events) is shown as a green star. The epicenter of a typical earthquake produced *T*-wave signal from the southern MAR as discussed in the text is shown as a yellow star. The location of each instrument in the AUH array are shown as stars in the top right map.

relief deformation events along the accompanying fracture zone.

3. Hydroacoustic Records of Walvis Explosion Activity

[7] Between February 1999 and November 2001, 22 hydro-acoustic events from the Walvis Ridge in the south Atlantic were detected and located on the North Atlantic hydrophones (Figure 2a). However, beginning on 24 November 2001, a total of 11 explosion-style signals were detected from the Walvis on the north Atlantic array with a mean location of −33.18°S/−4.36°W (Figure 2b). This initial burst of activity was followed by sporadic activity of between 1–7 events/day over the next 24 days. Then on 19 December at 2329Z a larger, more intense sequence began producing 40 locatable events over the next 15 hours (shown as green circles Figure 1). This main sequence of signals had an average location of −32.96°S/−5.22°W, which is on the northern flank of an unnamed seamount located northwest of the Walvis Ridge axis (Figure 1). Overall, the peak Walvis activity occurred during November 2001 to March 2002 and produced 365 locatable events. Event rate reduced dramatically following this large pulse of activity, with only 39 total events occurring through December 2002, and all occurred along the central Walvis Ridge lineament (Figure 2).

[8] The acoustic energy associated with these events exhibits a unique spectral character differing from typical earthquake produced *T*-wave signal packets observed along the Mid-Atlantic Ridge at similar latitudes (Figure 3). The Walvis Ridge signals are readily distinguished by a sharp onset, long-duration (from 10 min to 1 hr), and consistently broad-band energy across the recorded spectrum (2–50 Hz) in contrast to typical MAR earthquakes that have a short coda (2–5 minutes) and tapered spectral structure. In addition the Walvis acoustic events are very similar to signals recorded by this hydrophone array from a documented explosion and seafloor eruption sequence in 2001 at Kick'em Jenny Volcano located in the Lesser Antilles Volcanic Arc [*Venzke et al.*, 2002] (Figure 3). Signals from both sequences exhibited sharp-onset, long-duration (>10 min) acoustic energy with multiple broadband (3–40 Hz) peaks in the signal packet as well as some harmonic banding at the low-frequency end (3–20 Hz). Coherence squared values from cross-spectral magnitude analysis of these 3, 10 minute signal packets quantifies the similarities and dissimilarities between them. The peak of the coherence squared between the Walvis Ridge and Kick'em Jenny signals is 0.273 and occurs at 15 Hz, between Kick'em Jenny and the *T*-wave earthquake signal is 0.270 occurring at 17 Hz, and between the Walvis Ridge and *T*-wave earthquake is 0.235 occurring at 24 Hz. Each of these squared coherence values is significant above the 95% confidence interval 0.054. These values provide

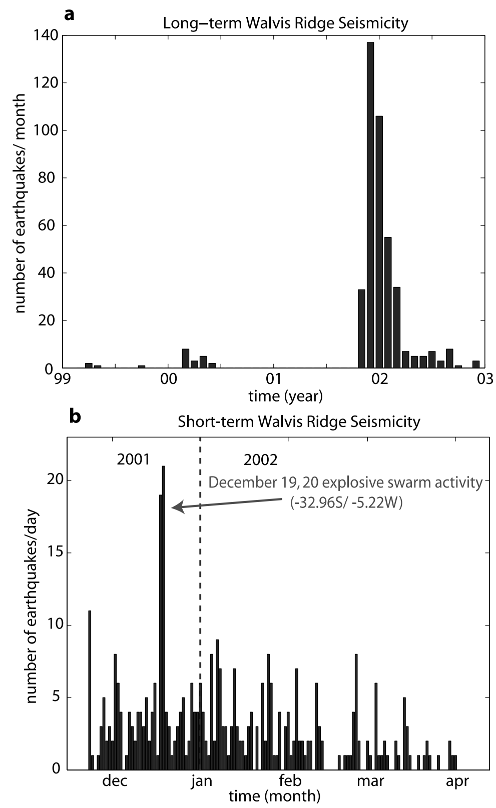

Figure 2. Histograms showing (a) the number of hydro-acoustic events from the Walvis Ridge per month over the entire AUH record illustrating the anomalous character of the heightened activity from late 2001 through spring 2002, and (b) the number of hydroacoustic events per day during the most active periods from 15 November 2001 through 15 April 2002.

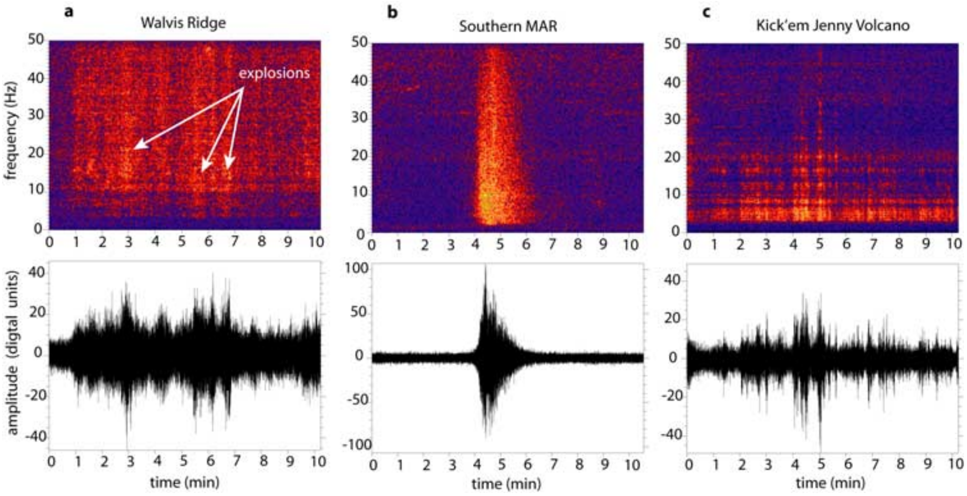

Figure 3. 10 minutes of hydro-acoustic spectrograms and time series data from the North Atlantic AUH array. (a) The onset of a swarm of explosive acoustic signals recorded 19 December 2001 from the seamount marked by the green star northwest of the Walvis Ridge in Figure 1. (b) A typical *T*-wave signal from a 4.7mb earthquake (NEIC) on February 5, 2002, centered along the Southern MAR at the yellow star in Figure 1. (c) Acoustic record of explosive signals from the Kick'em Jenny volcanic eruption December 5, 2001.

quantifiable support relating the Walvis Ridge signals to the known volcanogenic signals generated by the Kick'em Jenny eruption. In contrast, from cross-spectral analysis, the Walvis Ridge and *T*-wave earthquake signals are the least correlated. The similarity of the Walvis Ridge signals with those recorded from the Kick'em Jenny eruption as well as other volcanogenic acoustic signals described by *Talandier and Okal* [2001], suggest the Walvis Ridge has recently undergone an eruptive episode.

[9] Individual events were easily distinguished and peak arrival times were selected at the center of the peak in the spectral energy for each explosion (Figure 3). Explosion source locations were estimated using peak arrival times at each of the six hydrophones. Then a non-linear regression algorithm was used to minimize the difference between observed and predicted travel time (using standard ocean sound-speed models) to derive the latitude, longitude, and origin time of the event [*Fox et al.*, 2001]. Since the Walvis Ridge source locations are well outside ($\sim$5,500 km) the hydrophone array, location errors are much larger than for sources located within the array which are on the order of $\pm$2 km in latitude and longitude at the 68% confidence interval [*Smith et al.*, 2003]. Typically acoustic sources located several aperture lengths outside the hydrophone array are normally distributed along an ellipsoid in the error surface. Taking the mean location of the 40 event swarm distribution (Figure 1, green star) reduces large discrepancies in location giving a better estimate of the signal's origin. Unfortunately, none of the Walvis signals were apparently recorded by T-phase stations on Tristan da Cunha Island (R. Stewart, Comprehensive Nuclear Test Ban Treaty Organization, personal communication, 2004) which may have aided in constraining event locations. This is likely due to inherent differences between sound channel hydrophones (the AUH array) and the CTBTO *T*-phase stations which are actually land based seismometers that record *T*-phases converted at the coastline. Acoustic energy may also be attenuated or blocked entirely due to the geometry involved in the propagation from the Walvis Ridge to the Tristan da Cunha station.

[10] An acoustic magnitude, or source level (SL), is calculated for each explosion by removing the effects of acoustic attenuation along the propagation path from source to receiver [*Dziak et al.*, 2004a] and the hydrophone instrument response [*Dziak*, 2001]. Source levels are measured in decibels relative to micro-Pascals (pressure) at 1m. The equivalent seismic magnitudes of the Walvis events can be estimated using an empirical source level to body-wave magnitude (m_b) relationship developed for the north Atlantic hydrophone array of SL = $18.95m_b + 151.91$ [*Dziak et al.*, 2004a]. The Walvis Ridge events range from 2.7–4.7 m_b, with a mean of 3.3 m_b. Since none of the Walvis events were recorded on land-based seismic networks, this implies a >4.7 m_b earthquake detection threshold for this part of the south Atlantic Ocean.

4. Discussion

[11] The discovery of active volcanic processes along the normally low seismicity Walvis Ridge is an important step in understanding the geophysical processes controlling the formation of large seafloor lineaments. It would seem unlikely that this recent magmatic activity was hotspot related because of the large distance ($\sim$780 km) of the explosions' source at the Walvis Ridge from the Tristan da Cunha hotspot. We therefore interpret this recent volcanic episode as support of the extensional fracture zone formation model of *Fairhead and Wilson* [2005]. A combination of both models may, however, be possible. In this scenario, the Tristan da Cunha hotspot plume is much larger and more diffuse than previously thought and thus provides a magma source that is more easily entrained along the fracture zone as plate motion moves it eastward from the MAR.

[12] Documentation of explosive acoustic signals related to underwater volcanic activity in the Atlantic and other ocean basins [*Dziak et al.*, 2004b] is an important step in

understanding the time/space relationships and recurrence intervals of seafloor volcanism as well as providing insight on the dynamics of intra-oceanic plate stresses and deformation processes. Hydro-acoustic methods often provide the only means with which to detect volcanism in deep, remote ocean areas, and now the Walvis Ridge has been shown as another apparently active magmatic region. Detection of otherwise unobserved volcanic activity throughout the oceans is critical to understanding the contribution of seafloor volcanism to the global pace of volcanic activity.

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