Ocean noise triggering of rhythmic long period events at Deception Island volcano

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[1] We report on swarms of repeating long-period (LP) events with remarkably periodic occurrence at Deception Island volcano, Antarctica. The LP events show dominant frequencies near 2 Hz and characteristic inter-event times that range from ~10 s to ~20 s for individual swarms. We observe that LP inter-event times are approximate integer multiples of the dominant periods of the oceanic microseism, indicating a synchronization of LP activity with the phase of ocean noise. We attribute LP periodicity to the coincidence of sustained LP activity in an unstable hydrothermal system and external forcing by ocean noise that introduces periodic pressure variations in volcano fluids. We estimate the volumetric strain change generated by the oceanic microseism at the source location and conclude that strain of order 10^{-7} is sufficient to introduce clear periodicity in the LP sequences, and that periodicity increases with increasing strain. **Citation:** Stich, D., J. Almendros, V. Jiménez, F. Mancilla, and E. Carmona (2011), Ocean noise triggering of rhythmic long period events at Deception Island volcano, *Geophys. Res. Lett.*, *38*, L22307, doi:10.1029/2011GL049671.

1. Introduction

[2] Deception Island is an active volcano located in the South Shetlands archipelago west of the Antarctic Peninsula (Figure 1). Volcanism at Deception is attributed to backarc spreading in the Bransfield Strait [*Martí et al.*, 1996]. Deception Island is a horseshoe-shaped caldera with diameter of ~14 km and flooded inner harbour. The last episode of strombolian and phreatomagmatic eruptions from 1967 to 1970 caused the destruction of the Chilean and British Antarctic bases on the island [*Gonzalez-Ferran*, 1995]. At present, active volcanism is manifested in thermal anomalies and fumarole activity [*Ortiz et al.*, 1992; *Caselli et al.*, 2004], deformation episodes [*Fernandez-Ros et al.*, 2007] and seismic activity of varying intensity, including volcano-tectonic earthquakes, long-period (LP) events, hybrid events and volcanic tremor [*Almendros et al.*, 1997; *Alguacil et al.*, 1999; *Ibáñez et al.*, 2003]. An active seismic tomography experiment was able to image a magma chamber at shallow depth (2–5 km) in the northern part of the inner harbour [*Zandomeneghi et al.*, 2009].

[3] Seismic monitoring of Deception Island volcano has been performed through temporary summer deployments during the operation period of the Spanish base since 1986. Instruments currently include a network of three-component seismic stations and seismic arrays, as well as a permanent station operated by the Instituto Andaluz de Geofísica (IAG). This permanent station (DCP, Figure 1) was installed near the Spanish base (62°59′S, 60°41′W) in 2008 and recorded continuously since then. DCP is equipped with an electrochemical, intermediate period (16s) three-component seismometer (Eentec SP400) and a 24-bit datalogger (Eentec DR4000).

[4] In this study we analyze sequences of highly periodic LP events recorded at station DCP during the austral winter 2009. The generation of LP events is commonly attributed to short-term oscillatory pressure fluctuations and conduit resonance in magmatic or hydrothermal fluid systems [*Chouet*, 1996]. We propose that the periodicity observed in the occurrence times of LP events is the result of dynamic triggering of the LP source process by the effect of oceanic microtremors.

2. Rhythmic LP Events at Deception Island

[5] LP events are conspicuous at Deception Island volcano, generally related to the activation of a shallow hydrothermal system [*Ibáñez et al.*, 2000, 2003]. They very often display similar waveforms, indicating the repeated activation of a non-destructive source process. When LP events appear in clusters, the interevent times show no definite trends [*Almendros et al.*, 1999; *Ibáñez et al.*, 2000].

[6] However, during May–October 2009 we detected highly periodic sequences of LP events characterized by astonishingly regular interevent times. These sequences may last from several minutes up to a few hours. Figure 2 shows an example of the onset of a periodic LP swarm recorded on August 17th, characterized by remarkably constant interevent times showing only minor fluctuations around 18 s. When individual events are missing or below the noise level, the next LP generally occurs after a time that is close to a multiple of 18 s. The LP events have a narrow-band spectra centered at ~2 Hz and quite similar waveforms, and resemble typical LP events recorded at Deception Island during the summer.

[7] Although swarms of LP events with similar waveforms are common [*White et al.*, 1998; *Stephens and Chouet*, 2001; *Petersen et al.*, 2006; *Varley et al.*, 2010], the regular timing described above is quite unusual and has been found in just a few volcanoes. For example, periodic swarms of similar events have been recorded at Mount St. Helens [*Iverson et al.*, 2006; *Moran et al.*, 2008], where they have been named "drumbeats". *Ohminato and Ereditato* [1997] detected regularly-spaced volcanic events at Satsuma-Iwojima volcano, although in a lower frequency band. Periodic phe-

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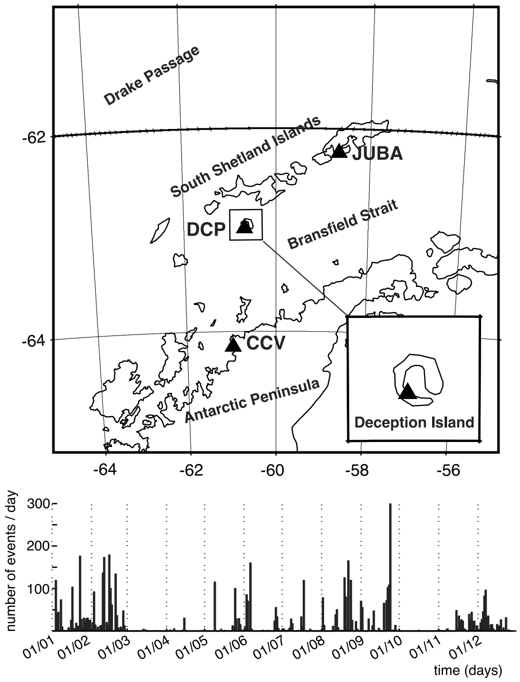

Figure 1. (top) Location map of the South Shetlands with station DCP on Deception Island volcano and regional stations used for comparison (CCV, JUBA). (bottom) Daily number of LP events at station DCP for 2009.

nomena at volcanoes may be also at the origin of seismic signals such as banded tremor [*Gresta et al.*, 1996; *Fujita*, 2008] and harmonic tremor [*Powell and Neuberg*, 2003; *Lesage et al.*, 2006].

[8] The periodic nature of the LP swarms observed at Deception Island requires a source mechanism that repeats itself at constant time intervals. Periodicity in nature often suggests a steady state process, where driving forces are approximately constant in time. Examples could be the stick-slip motion of a magma dome [*Iverson et al.*, 2006] and the steady-flux recharge of a cavity (geyser-like mechanism) [*Ingebritsen and Rojstaczer*, 1996; *Matoza and Chouet*, 2010]. We note, however, that the amplitudes of the periodic LPs at Deception Island vary significantly over a short time scale (factor >5, Figure 2), which makes an association with a steady state internal process less obvious. If we attribute periodicity to constant driving forces, varying amplitudes indicate that the system response is highly variable. We could reconcile these observations by invoking a complex source model, but any such model would have to satisfy the restrictive constraint that temporal variations in the system response should not affect the observed regularity in time. As an alternative explanation, we explore a much simpler hypothesis in which we attribute constant inter-event times to periodic mechanical forcing of an unstable hydrothermal system. We will direct our attention to ocean waves as the required periodic phenomena.

3. LP Periodicity and Ocean Noise

[9] We select six of the most clear and intense episodes of periodic LP activity detected during the 2009 austral winter for an analysis of LP timing (sequences 1–6, Figure 3). We manually pick LP interevent times in one-hour time windows on high-pass-filtered three-component seismograms. We select swarms of short-duration LPs to facilitate the picking of closely spaced events. We use both seismograms and spectrograms to improve the detection threshold. Picking accuracy is ~0.2 s for similar LP events.

[10] Ocean waves couple into Rayleigh waves and produce a strong peak in seismic noise spectra in the microseism range [e.g., *Webb*, 1998]. For the selected sequences,

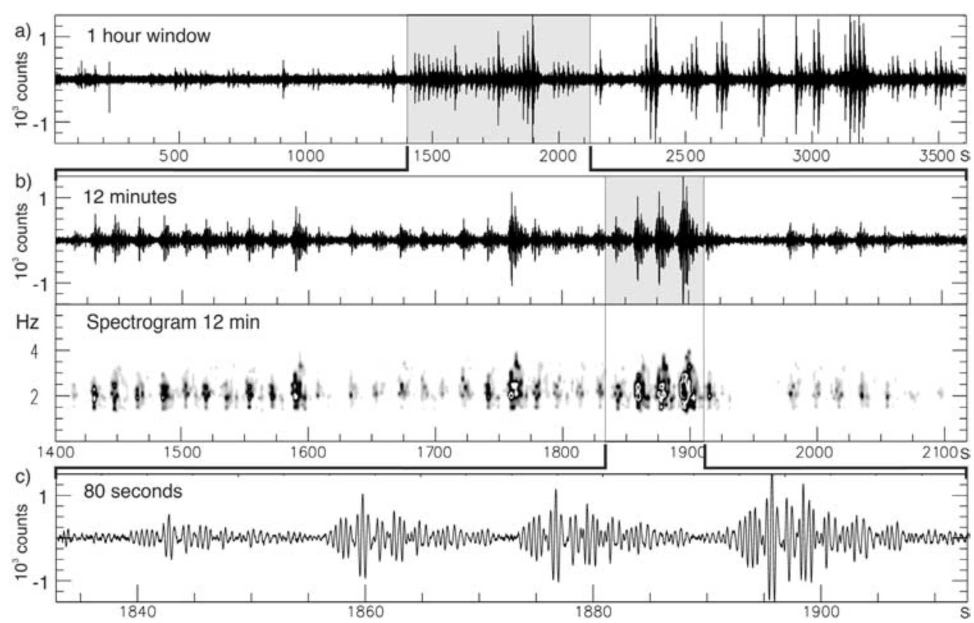

Figure 2. Example of rhythmic LPs at station DCP. (a) One hour of activity (east component) starting at 17/08/2009, 18:00 (time scale in seconds, high pass filter 1.5 Hz). (b) Close-up (12 min) showing periodic, repeating LP events with interevent times around 18 s and frequency of ~2.2 Hz in seismogram and spectrogram. (c) Close-up (100 s) showing waveforms of four consecutive events 16.8 to 19.0 seconds apart.

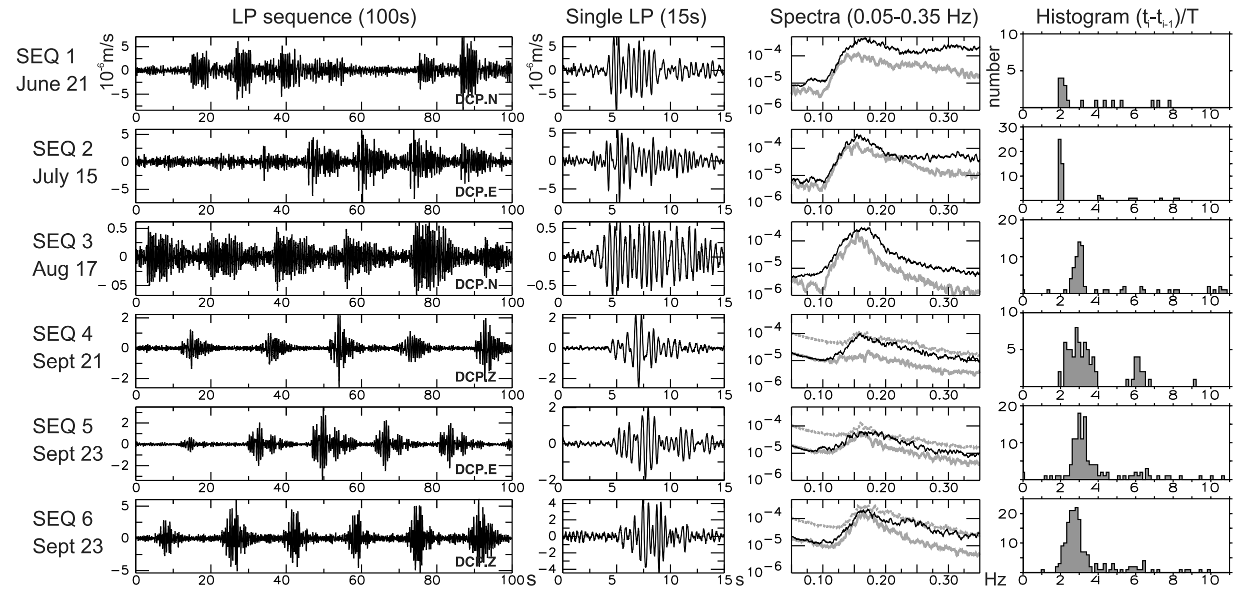

Figure 3. Characteristics of six episodes of rhythmic LPs. First column: Seismogram examples (time scale in s, velocity in 10^{-6} m/s, high pass filter 1.5 Hz, component according to annotation). Second column: Waveforms of one single LP event. Third column: Spectra (0.05–0.35 Hz) of the oceanic microseism at DCP (black line, average of 3 components) and regional stations CCV (grey) and JUBA (dotted). Fourth column: Histograms of normalized interevent time $(t_i - t_{i-1})/T$, where T is the period of the spectral maxima of ocean noise at DCP. Histogram peaks occur at small integer multiples of T.

we observe this peak directly in the unfiltered seismograms as a nearly monochromatic signal. We compute the noise spectra at DCP and find that the maxima occur at periods of ~6 s (6.0, 6.5, 6.2, 6.3, 5.5 and 5.8 s for the sequences 1 to 6). Spectra at permanent stations on the Antarctic Peninsula (CCV, operated by IAG) and King George Island (JUBA, operated by ASAIN), both at ~150 km distance from Deception Island, show similar ocean noise (Figure 3), suggesting a dominant contribution of regional sources like storms in the Drake Passage or southern Atlantic.

[11] We compare the dominant period of the ocean microseisms and the characteristic LP interevent times for the six sequences. After normalizing the interevent times to the periods of the ocean noise maxima, a simple pattern emerges from the histograms: LP interevent times are close to small, integer multiples of the dominant periods of the oceanic microseism. This indicates a synchronization of LP activity with the phase of ocean noise. The dominant recurrence time is two or three times the period of the secondary microseism, and sometimes secondary peaks can be distinguished (sequences 2 & 4), apparently representing multiples where individual events are missing or below the noise level.

[12] We observe fairly clear differences between the LP sequences 1 to 2 and 4 to 6. Sequences 1 and 2 show histogram peaks at twice the period of the oceanic microseism and higher periodicity (i.e., narrower peaks). Sequences 4 to 6 show peaks centered at about three times the microseism period and wider inter-event time distributions, suggesting more variable periodicity. This behavior correlates with the microseism amplitude: for sequences 1 & 2, peak-to-peak displacement amplitudes are ~6 μm and ~4 μm, respectively, while for sequences 4 to 6 the amplitudes are significantly lower (~1–2 μm). Sequence 3 shows intermediate amplitudes (~3 μm) and stability of periodicity. The positive correlation between microseism amplitude and LP periodicity supports the idea of a dynamic triggering mechanism.

4. Discussion

[13] Dynamic triggering by microseismic noise provides a simple explanation for the periodicity we observe in LP sequences at Deception Island. We attribute rhythmic LPs to a coincidence of sufficiently intense and sustained LP activity and favourable microseismic noise conditions; i.e., rather monochromatic ocean noise. Both aspects taken alone are necessary, but not sufficient conditions for periodic LP swarms. In fact we observe that (1) the repetition of similar noise conditions do not result in similar, periodic LP activity at other times, and (2) there are many LP swarms at Deception island that are not periodic. Seasonal variations may have an important role as rhythmic LP sequences were quite common during the winter of 2009, while there are no comparably clear observations from many previous summer campaigns on Deception Island. In particular, the extensive sea ice coverage in the winter 2009 [*Fetterer et al.*, 2002, 2009] efficiently suppresses local sources of microseismic noise, while during summer ocean waves in the inner harbour do contribute to the microseismic spectrum.

[14] To further characterize dynamic triggering, we estimate the strain amplitudes associated with the oceanic microseism. Volumetric strain affects pressure in volcano fluids. We assume harmonic Rayleigh waves in a Poisson half-space [e.g., *West et al.*, 2005; *Hill*, 2008]. For a harmonic wave the volumetric strain change $\Delta V/V$ at depth z can be related to the vertical-component Rayleigh-wave amplitude at the surface, $u_z|_{z=0}$, as:

$$\Delta V/V = -0.456k \cdot u_z|_{z=0} \cdot e^{-0.847kz} \quad (1)$$

where k is the Rayleigh wavenumber (auxiliary material).[1] We assume a P-wave speed of α = 3.0 km/s [*Zandomeneghi et al.*, 2009], corresponding to Rayleigh wave speed c = 0.531α = 1.6 km/s. For a period of 6 s, the Rayleigh wavenumber is k = 0.66 km^{-1}. We first choose a source depth of 200 m, drawing upon previous analyses that suggest that LPs on Deception Island are generally very shallow and associated with the hydrothermal system [*Almendros*, 1999; *Ibáñez et al.*, 2000]. The results are peak-to-peak strain variations of $0.3 \cdot 10^{-6}$ for microseism amplitudes of 1 μm (sequence 5), and $1.6 \cdot 10^{-6}$ for amplitudes of 6 μm (sequence 1). Exploring a range of values (Rayleigh wave speed between 1 and 2 km/s; source depth between 0 and 1 km), amplitudes of $1 \cdot 10^{-6}$ m translate to 0.2 to 0.5 micro strain, showing that strain of order 10^{-7} seems to be sufficient to introduce clear periodicity in the LP sequences. We note that this is the same order of magnitude as transient strain changes that have been observed to trigger non-volcanic tremor [e.g., *Miyazawa and Brodsky*, 2008].

[15] In the rhythmic LP sequences at Deception Island, the external triggering mechanism can be held responsible for the high level of periodicity. However, an intrinsic time scale seems to be preserved in the variety of integer factors between noise period and LP inter-event times. A dominant recurrence time of two or three times the oceanic microseism period indicates that the system needs time to recover after each LP event, before a transient strain instability can trigger the next event. We conclude that the regular LP timing at Deception can be adequately modelled by external periodic dynamic triggering and an intrinsic minimum lag time. Taking into account strain variations due to external forcing adds a new facet to the interpretation of periodic phenomena on volcanoes, and may provide constraints for the physics of LP generation and the state of the volcanic plumbing system.

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