Journal of Volcanology and Geothermal Research 200 (2011) 116–128

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Deep long-period earthquakes beneath Washington and Oregon volcanoes

M.L. Nichols [a,*,1], S.D. Malone [a], S.C. Moran [b], W.A. Thelen [b], J.E. Vidale [a]

[a] University of Washington, Johnson Hall 070, Box 351310, Seattle, WA 98195, USA
[b] USGS, 1300 SE Cardinal Ct., Building 10, Suite 100, Vancouver, WA 98683, USA

ARTICLE INFO

Article history:
Received 2 July 2010
Accepted 10 December 2010
Available online 22 December 2010

Keywords:
deep long-period earthquake
volcano seismology
Cascade volcano
eruption forecast
low frequency earthquake
magma ascent

ABSTRACT

Deep long-period (DLP) earthquakes are an enigmatic type of seismicity occurring near or beneath volcanoes. They are commonly associated with the presence of magma, and found in some cases to correlate with eruptive activity. To more thoroughly understand and characterize DLP occurrence near volcanoes in Washington and Oregon, we systematically searched the Pacific Northwest Seismic Network (PNSN) triggered earthquake catalog for DLPs occurring between 1980 (when PNSN began collecting digital data) and October 2009. Through our analysis we identified 60 DLPs beneath six Cascade volcanic centers. No DLPs were associated with volcanic activity, including the 1980–1986 and 2004–2008 eruptions at Mount St. Helens. More than half of the events occurred near Mount Baker, where the background flux of magmatic gases is greatest among Washington and Oregon volcanoes. The six volcanoes with DLPs (counts in parentheses) are Mount Baker (31), Glacier Peak (9), Mount Rainier (9), Mount St. Helens (9), Three Sisters (1), and Crater Lake (1). No DLPs were identified beneath Mount Adams, Mount Hood, Mount Jefferson, or Newberry Volcano, although (except at Hood) that may be due in part to poorer network coverage. In cases where the DLPs do not occur directly beneath the volcanic edifice, the locations coincide with large structural faults that extend into the deep crust. Our observations suggest the occurrence of DLPs in these areas could represent fluid and/or magma transport along pre-existing tectonic structures in the middle crust.

1. Introduction

Many volcanoes within the Cascade volcanic chain are seismically active. While the overwhelming majority of seismicity consists of high-frequency volcano-tectonic (VT) earthquakes, other types of events including deep long-period (DLP) earthquakes (e.g., White, 1996; Power et al., 2004) also have occasionally been identified (Malone and Moran, 1997; Pitt et al., 2002). DLPs have been inferred by other investigators to represent the movement of magma and/or magmatic fluids within the mid-to-lower crust (10–50 km), and are characterized by mostly low-frequency energy (<5 Hz), emergent arrivals and long-duration codas (e.g., White et al., 1996; Power et al., 2004). Earthquakes at these depths are unusual, as such depths are generally thought to lie below the brittle–ductile transition (e.g., Sibson, 1982). The waveform characteristics of DLPs are also different than that of typical VTs. The differences are illustrated in Fig. 1, which shows seismograms and spectrograms from a DLP and a VT with similar locations near Mount Rainier. The DLP is dominated by emergent phase arrivals and low frequencies, mostly below 5 Hz, whereas the VT has more impulsive phases and broader spectral content, with frequencies between 1 and 20 Hz. Although DLPs were once considered to be rare, they are now observed in the background seismicity of many volcanically active regions worldwide, including Hawaii (e.g., Wright and Klein, 2006; Okubo and Wolfe, 2008), Japan (e.g., Nakamichi, 2000; Nakamichi et al., 2003, 2004; Matsubara et al., 2004; Ukawa, 2005), Alaska (e.g., Power et al., 2004), California (Pitt and Hill, 1994; Pitt et al., 2002), and Washington (Malone and Moran, 1997). It is important to note that other forms of deep low-frequency seismicity, specifically deep nonvolcanic tremor composed of low-frequency (LFE) and very low-frequency (VLF) events, have been observed along major plate boundaries including the Japan and Cascadia subduction zones (e.g., Shelly et al., 2006; La Rocca et al., 2009) and the San Andreas Fault (Nadeau and Dolenc, 2005). Like DLPs, these "tectonic" deep low-frequency events occur below the brittle–ductile transition, and exhibit waveforms lacking high-frequency energy and clear impulsive phase arrivals. Although we do not discuss deep nonvolcanic tremor in this paper, it is important to note that these similarities could suggest a relation between their respective source processes.

In addition to being part of background volcanic seismicity, DLPs are especially important because some have correlated with eruptions (White, 1996; Power et al., 2004), various forms of volcanic unrest including increased shallow VT and long-period (LP) seismicity (White, 1996; Nakamichi et al., 2003), and magma intrusion with associated CO_2 emissions (Hill, 2006). Most volcanoes exhibit changes in their background seismicity pattern prior to an eruption, which sometimes include increased DLP activity. The clearest example is Mount Pinatubo, Philippines, where many hundreds of DLPs occurred

* Corresponding author. Tel.: +1 989 274 3240.
E-mail address: maisie15@uw.edu (M.L. Nichols).
[1] Permanent address: 3221 W. Government Way, Seattle, WA 98199, USA.

0377-0273/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jvolgeores.2010.12.005

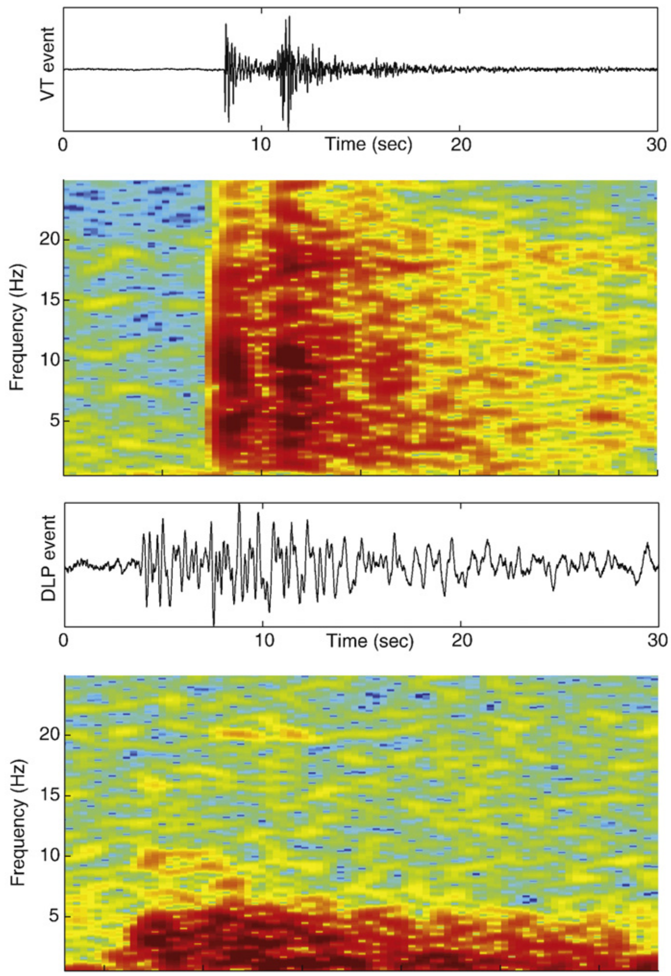

Fig. 1. Seismograms and spectrograms from two events recorded on station FMW near Mt. Rainier illustrate the difference in frequency content between a VT (top—1995/07/14 12:14) and a DLP (bottom—1996/03/05 14:09). The VT contains frequencies between 1 and 20 Hz, and the DLP contains energy mostly below 5 Hz. VT and DLP hypocentral distances are 23.2 km and 23.8 km, respectively. VT and DLP maximum amplitude counts are 1554 and 253, respectively. Spectrogram colors represent amplitude intensity and range from blue (low) to yellow (intermediate) to red (high).

beneath the volcano in the months preceding the major 1991 eruption (White, 1996). Some of these DLPs occurred several hours prior to increased shallow seismicity and steam emissions from the site where a lava dome later emerged. Roughly a week before the climactic eruption, DLP activity diminished with the emergence of the hybrid-andesite dome containing inclusions of basalt that had arrived from the deep crust only days to weeks earlier (Pallister and Hoblitt, 1992). The spatiotemporal development of DLP seismicity and subsequent surface activity, especially the emergence of the dome, suggests a link between the deep and shallow volcanic system. This set of observations is taken as evidence that DLPs represent the injection of deep-seated basaltic fluids into the base of the magma chamber which likely triggered the eruptive sequence at Mount Pinatubo (White, 1996).

DLPs have occurred in association with eruptions at several Alaskan volcanoes (Power et al., 2004). In 1992, Mount Spurr produced three main explosive eruptions on June 27, August 18, and September 16–17. A single DLP occurred nine days prior to the first explosion on June 27, after which the number of DLPs steadily increased, peaked just after the September eruption, and slowly declined until September 1996. Power et al. (2002) suggest that the steady increase in DLP activity after the first eruption represents an increased flux of magma from lower- to mid-crustal levels in response to depressurization of the shallow magmatic system. The 1999 eruption of Shishaldin Volcano was preceded by six DLPs that occurred roughly 10 months prior (Moran et al., 2002; Nye et al., 2002) and were followed ~12 days later by the first shallow LPs. Power et al. (2004) use these temporal relations to suggest a link between magmatic activity within the lower crust, intrusive activity in the upper crust, and eruption at the surface. At Mount Redoubt, an increase in DLP activity was observed three months prior to the onset of the most recent 2009 eruption, suggesting that it may have followed the ascent of magma from the lower crust (Power et al., 2009).

At each of these volcanoes, a relation was inferred between DLPs and eruptive phenomena. Although DLPs do not necessarily signal an eruption, they may be one of the earliest indications of renewed volcanic activity, and therefore the rapid identification of DLPs could improve forecasts of future eruptions at other volcanoes. Malone and Moran (1997) previously reported a total of 11 DLPs beneath three Washington volcanoes, and indicated that additional DLPs may have been recorded, but not identified as such during routine analysis. The motivation for this study was to search for additional DLPs in the Pacific Northwest Seismic Network (PNSN) catalog in order to provide improved constraints on the conditions under which DLPs occur in the Cascades, and to better understand their potential use in forecasting eruptions at Washington and Oregon volcanoes.

In this paper we first provide a brief summary of the seismic network surrounding the volcanoes, and explain our process for systematically identifying DLPs. This is followed by a description of DLP occurrence at each of the six volcanoes where they were observed (Fig. 2). In these sections we include some background information on historical eruptions, magmatic composition, and seismicity for each volcano, followed by a description of DLP locations. Finally, we discuss our observations of DLPs and the relation between these earthquakes and magmatic transport beneath the various volcanic centers.

2. Summary of seismic network

The PNSN automatically detects and locates earthquakes in Washington and Oregon, including those occurring at 10 of the major Cascade volcanoes (Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, Mount Adams, Mount Hood, Mount Jefferson, Three Sisters, Newberry Volcano and Crater Lake). Most instruments surrounding the various volcanic centers are short-period vertical-component stations, with a few short-period three-component seismometers and broadband seismometers near some volcanoes (Moran, 2004). The standard short-period vertical-component instruments are sufficient to detect and locate VT and impulsive LP events. The number and type of instruments at each volcano varies throughout the arc, as do the resulting detection thresholds (Table 1). Only triggered events are reported in the PNSN catalog, and prior to 2001 (when PNSN began archiving continuous data) data containing events that did not meet the network's detection threshold were discarded. Detected events are located using PNSN 1-D layered velocity models. The PNSN triggering algorithm is not well-tuned to capture DLPs due to their emergent and low-frequency nature, and those that trigger may have poor locations resulting from large picking errors. Other non-volcanic sources existing near volcanoes, such as glacier quakes and explosions, can produce similar waveforms to DLPs. For these reasons, the possibility exists for mislocated or misidentified DLPs within the existing PNSN catalog.

3. Methods

DLPs are characterized by their depth (>10 km) and by being enriched in low frequencies compared to VTs. A visual comparison between frequency spectra of previously identified DLPs and VTs from