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Observations at Costa Rican Volcano Offer Clues to Causes of Eruptions

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Recent measurements of ground deformation at an active volcano show great promise for elucidating the processes that lead to volcanic eruptions. A long-term effort to continuously monitor ground deformation over a very wide bandwidth using state-of-the-art geodetic, seismic, and acoustic instruments at Arenal Volcano in Costa Rica is producing high-quality recordings of harmonic tremor and explosive events and offers an exciting opportunity to explore possible lunar periodicities in volcanic eruptivity.

While the physical processes of earthquake rupture and subsequent seismic wave generation are fairly well characterized, those related to volcanic eruptions are not yet understood and pose an exciting challenge to Earth scientists. In contrast to earthquakes, which can largely be described from a seismological perspective, volcanoes are complex, multicomponent systems that truly require a multidisciplinary approach to study. The integrated seismic, geodetic, and acoustic investigation of Arenal Volcano is a step toward this goal and will yield rich information about the inner workings of this dangerous class of explosive volcanoes.

Arenal was selected for monitoring because of its high level of activity, which ensures rich geophysical observations, its young age (~3000 years, *Borgia et al.* [1988]), which offers the possibility of observing a transition in the eruptive behavior, and for the importance of studying explosive stratovolcanoes that threaten population centers throughout the world. We have collected two years of continuous seismic and geodetic data at 5 sites distributed around the circumference of the volcano and have made periodic video recordings of eruptions and gas emissions. In addition, we recently deployed a temporary array of co-located seismometers and acoustic microphones.

The geodetic observations collected thus far reveal shortening across a north-south baseline consistent with deflation of a shallow, nonreplenishing magma chamber. Preliminary analysis of both the seismic and acoustic data sets reveals clear examples of harmonic tremor (Figure 1) and suggests that the source of tremor and eruptions at Arenal may be magmatic degassing with bubbles periodically coalescing into large gas slugs that rise and explode beneath the summit.

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Experiment

In May, 1995, two permanent Global Positioning System (GPS) receivers were installed on the north and south flanks of Arenal as part of a program to test the utility of using GPS for monitoring active, potentially explosive volcanoes (Figure 2). The GPS antenna at site LOLA (Los Lagos) is mounted atop a wide concrete pillar cored with steel rods, while AROL's (Arenal Observatory Lodge) antenna is mounted to the roof of a building. Data from LOLA are transmitted to the base site at AROL via a repeater located on a ridge midway between the two sites. Data from both sites are continuously sampled every 30 s and recorded to a computer located at AROL. The resulting data are retrieved manually and shipped to the United States for processing at the University of Miami following *Dixon et al.* [1997]. Future plans call for transferring the data via phone modem directly to the Internet for rapid access.

In November, 1995, we established five seismic observation sites around the circumference of the volcano (Figure 2), two of which were chosen to coincide with the continuous GPS sites, and a third to coincide with the location of a permanent short-period seismometer that is used to monitor seismicity in the Arenal region. Each site is equipped with a three-component (vertical, north, east) broadband seismometer mounted on a concrete pier buried 1–2 m beneath the surface. The seismic data are sampled continuously at 20 Hz by a 24-bit digital datalogger and written to a local hard disk. In addition, each of the five sites is equipped with an electronic bubble-type tiltmeter (AGI-800) sampled continuously at 1 Hz by the datalogger, with tilt axis oriented toward the volcano summit. Each site is powered by 12 V batteries, which are charged by solar panels. GPS clocks provide synchronized timing.

Overview of Geodetic and Seismic Signals

Arenal was thought to be extinct prior to a violent Plinean eruption in July of 1968 that opened three craters on its western flank and killed 87 people. In 1984 Arenal entered its current Strombolian phase of activity, which is characterized by frequent summit explosions and less-frequent block lava flows.

Two years of continuous GPS measurements of the 6 km AROL-LOLA baseline are summarized in Figure 3. Each data point represents a 24-hour average. Gaps in the data are due to malfunctions in the data transmission system or power outages, some of which were caused by lightning strikes. A weighted, least-squares fit through all available data yields a rate of baseline shortening of 7.5±0.4 mm/yr, with a weighted rms (wrms) scatter of 2.9 mm. An error estimate of 2.0 mm/yr is more realistic, however, given that the smaller error estimate assumes only white noise and underestimates error in the presence of time-correlated noise such as spurious monument motion [*Langbein and Johnson*, 1997].

The small wrms scatter of the length time-series is an indication of the good performance of the GPS system at Arenal, and is comparable to that obtained for a similarly oriented baseline at Long Valley Caldera [*Dixon et al.*, 1997]. Individual coordinate velocities relative to a global reference frame are noisier at Arenal than at Long Valley, probably due to the more humid, variable troposphere of the tropical location of Arenal. These effects largely cancel for the short base-

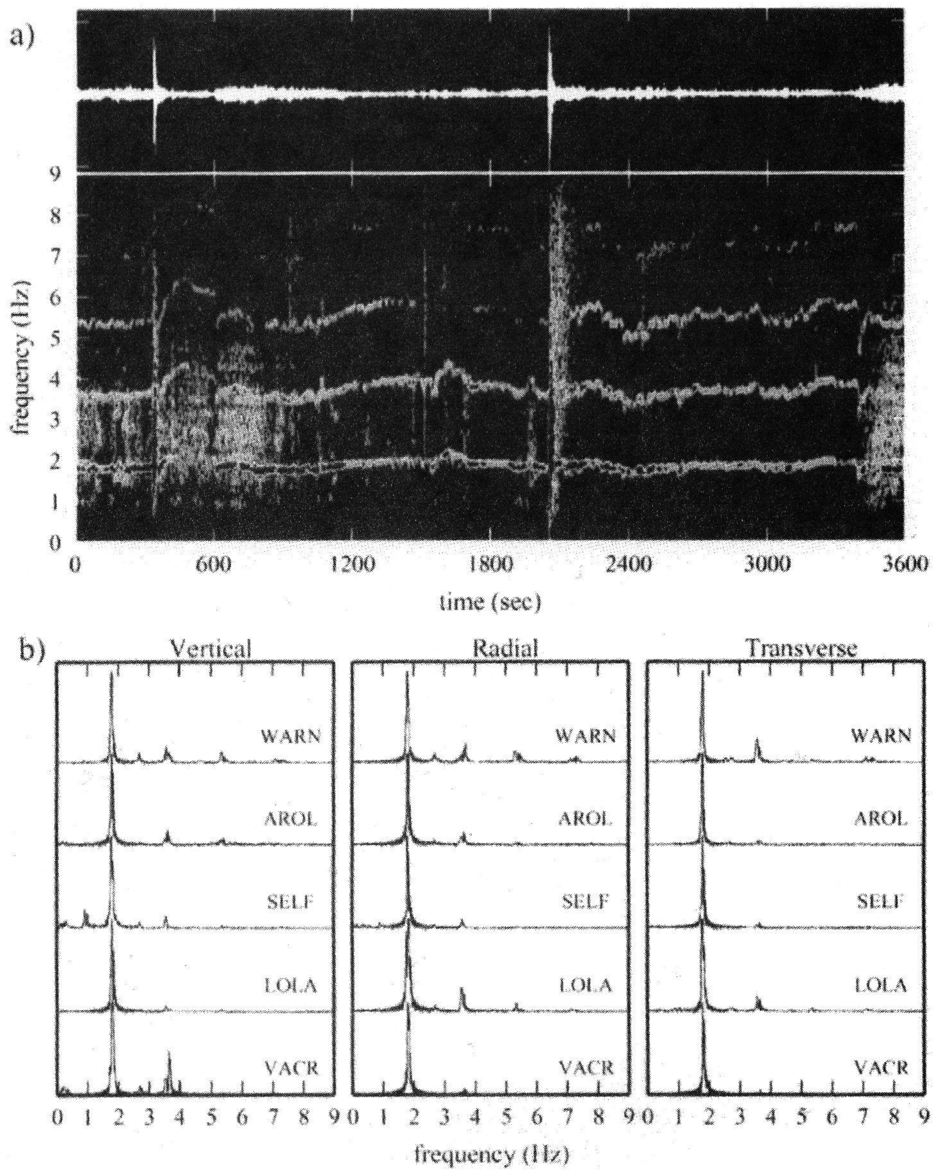

Fig. 1. a) One hour of normalized, vertical component velocity recorded at station WARN (Fig. 2) and the corresponding spectrogram, showing the log of the power spectral density between 0 and 9 Hz , as a function of time. b) Normalized, linear Fourier spectra for a 30 s window of tremor is shown for vertical, radial, and transverse components at each of the five stations. Original color image appears at the back of this volume.

line between AROL and LOLA, and thus have little influence on the length estimate.

The Arenal length data show subsidence consistent with deflation of a crustal magma chamber. If this model is correct it implies that the volcanic reservoir is not in steady-state; that is, it is not being replenished with new material to compensate for the loss of material erupted as lava, ash, and volatiles. To improve spatial resolution of the geodetic deformation, which is needed to quantitatively model the ground deformation and to distinguish between competing models, the continuous GPS sites were augmented with four additional sites that will be observed biannually (Figure 2).

Arenal produces impressive volcanic tremor, a distinctive seismic signal observed at active volcanoes throughout the world [*McNutt*, 1989]. Figure 1a is a plot of 1 hour of the vertical component of ground velocity recorded at station WARN, located approximately 2 km from the summit. Beneath the seismic trace is a contour of the corresponding power spectral density as a function of time. In contrast to seismic signals generated by tectonic earthquakes, volcanic tremor displays a very peaked frequency spectrum with most of the energy concentrated between about 1–2 Hz.

In the case of Arenal, the tremor is termed harmonic since the peaks in the frequency spectrum are integer multiples of a fundamental frequency. During the period shown in Figure 1a, the tremor has a fundamental frequency (first harmonic) near .9 Hz with up to 10 harmonics; the odd harmonics (.9, 2.7 Hz, etc.) are diminished with respect to the even harmonics (1.8, 3.6 Hz, etc.). The resulting fundamental frequency and its overtones are analogous to the frequency spectrum produced by a plucked guitar string.

While volcanic tremor at several global volcanoes has proven to be a good predictor of impending volcanic eruptions, the physical mechanisms for its generation and its relationship to volcanic flow properties are under investigation. Past studies of volcanic tremor have wrestled with the question of whether the narrowband frequency content of the seismic signals is due to the effects of propagation through shallow, absorbent layers (a path effect), or rather to the flow properties of a resonating source (a source effect). While current belief is fairly unanimous that volcanic tremors are generated by active source processes, recent studies [e.g., *Kedar*, 1996; *Chouet*, 1996] highlight the importance of path effects in special circumstances.

Figure 1b shows normalized Fourier spectra plotted on a linear scale for a 30 s slice of tremor recorded on the vertical, radial, and transverse components at all five stations. The high sensitivity of the seismometers combined with the large dynamic range of the digital recorders results in sharp recordings of the relatively faint tremor signals. Harmonic tremor seen at Arenal is clearly not a site effect; there is no variation in the harmonic frequencies at the five sites, nor on the three components of any site.

The harmonic spectral content and the phenomena of "gliding" seen in Figure 1a, whereby the ensemble of spectral peaks shift frequencies as a function of time while maintaining their regular spacing, are very similar to reported tremor features at Langila Volcano, Papua, New Guinea [*Mori et al.*, 1989] and at Mt. Semeru, Indonesia [*Schlindwein et al.*, 1994] and probably reflect changes in the gas concentration in the conduit. We hope that by modeling the observed tremor characteristics (harmonic structure, rapid gliding, and horizontal wavefield polarization) we will gain some insight into the mechanisms of volcanic tremor generation and their relationship to the degassing process.

The Strombolian activity at Arenal is remarkably regular and consists of summit explosions that eject incandescent fragments and propel ash laden columns to heights of .5–2 km approximately every half-hour. The resulting explosion waveforms have emergent onsets, spindle-shaped envelopes, and narrowband frequency content—characteristics that are very similar to so-called long-period events reported for many volcanoes throughout the world [*Chouet*, 1996]. The ab-

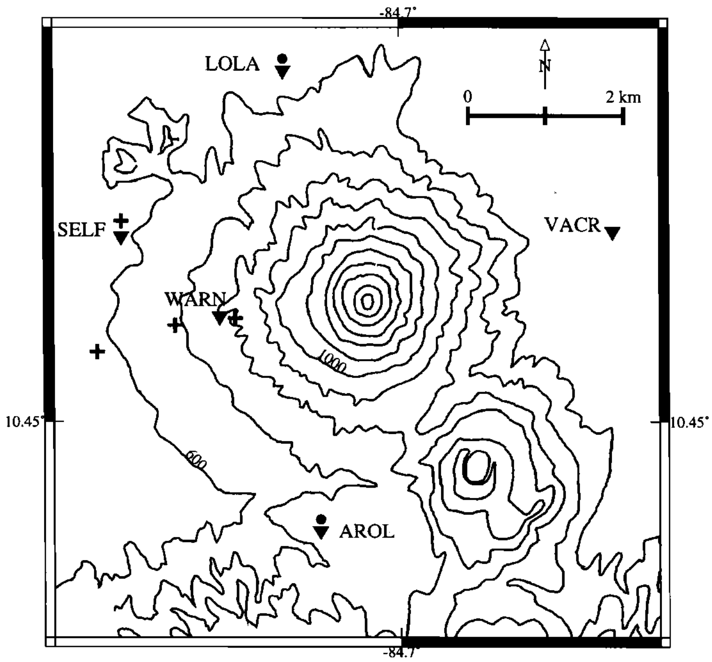

Fig. 2. Map of Arenal Volcano showing topography (100 m contour interval) and observations sites. Circles denote continuous GPS receivers; inverted triangles denote three-component, broadband seismometers; crosses denote additional GPS observation sites.

sence of a high-frequency precursor in the explosion waveforms supports our belief, based on tremor behavior and visual observations of uninterrupted degassing from the summit vent, that Arenal is an open system undergoing continual degassing. While the waveforms and spectra of the different explosion events are nearly identical at a particular station, they vary greatly from station to station, exhibiting significant path and/or site modification. This observation, coupled with the small scatter of inter-station first-arrival times of different explosions, suggests that the explosions originate at fairly shallow depth (<200 m) beneath the summit, from a small source volume that is not changing location appreciably over time.

Particle motions of explosion waveforms are complex and appear to indicate overlapping body and surface waves. However, at least one wave type, a ground-coupled, airborne acoustic wave often heard to accompany the eruptions, is easily identified in the seismograms. This wave travels through the air at the speed of sound (330 m/s) and couples to the slow, superficial layers of the volcano as it moves down its flanks. The resulting seismo-acoustic arrival contains higher frequencies (4–8 Hz) than the pure seismic phases (1–3 Hz) and exhibits Rayleigh wave particle motion. A particular phenomenon observed in the seismic data set is that explosions with impulsive (high signal-to-noise ratio) P onsets usually contain small seismo-acoustic arrivals and vice-versa. This variation in energy partitioning between the seismic and acoustic wavefields could reflect a changing source depth; however, the time separation between the P and acoustic arrivals does not appear to vary. Alternatively the partitioning may be governed by the gas content, the melt flow properties, and the boundary conditions of the conduit, such as the degree of openness of the explosion vent.

A linear array of coincident, three-component short-period seismometers and acoustic microphones spaced 100 m apart was deployed in April 1997 along the western flank of the volcano to the east of WARN (Figure 2). The resulting seismo-acoustic profiles of tremor and explosions will help us identify the seismic wavetypes and will provide valuable insight into the coupling mechanisms between the seismic and acoustic wavefields [*Garcés*, 1997]. In addition, the sharp acoustic phases recorded by the microphones do not propagate through the heterogeneous volcanic edifice and thus offer a very clear view of the degassing processes occurring in the conduit. Preliminary analysis of the acoustic data reveals several episodes of harmonic tremor, with spectral content identical to that contained in the seismic recordings. During these periods, the acoustic recordings consist of regularly repeating impulses. These observations suggest that tremor is generated by repeated explosions of gas during magma degassing. Many of our observations at Arenal are quite similar to those made in a recent study at Stromboli by *Chouet et al.* [1997], and corroborate their proposed model for Strombolian activity consisting of steady degassing with some bubbles becoming trapped at the top of the magma chamber and forming a foam layer that periodically collapses into a large gas slug that rises and explodes upon reaching the surface.

Several studies have sought a correlation of solid Earth tides with volcanic eruption times in an attempt to implicate tidal triggering of volcanic eruptions [e.g., *Mauk and Johnston*, 1973]. Most studies have compared widely spaced eruption dates with finely sampled lunar tidal phases. Long-term, continuous seismic measurements of mean tremor level and explosion amplitudes offer a unique opportunity to examine periodicities in the eruption behavior using high-resolution spectral techniques. Other statistics derived from the long-term observations will provide a very detailed characterization of Arenal's behavior over time. In particular, explosion recurrence intervals, easily derived from the continuous seismic data, have implications for the rate of recharge of the eruption source.

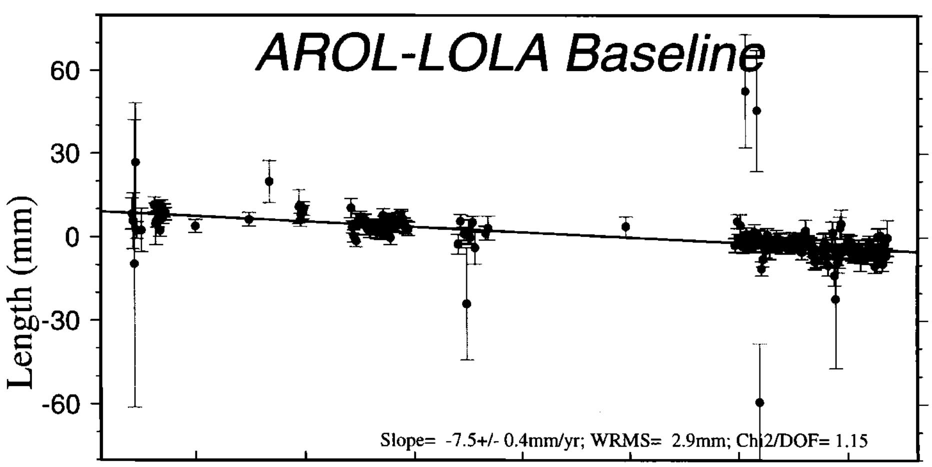

Fig. 3. Summary of two years of continuous GPS measurements of the 6 km AROL-LOLA baseline (see Fig. 2) and a weighted, least-squares line fit to the data.

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Gas Hydrate Drilling Conducted on the European Margin

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Since 1996, the Norwegian government has licensed hydrocarbon exploration in seven deep water areas on the continental slope north of the Norwegian Trough. Data acquired in this region, which is of interest to both scientists and the oil industry, provide an opportunity to improve understanding of the geology and development of the area through Quaternary times. Gas hydrates, slope stability, and geohazards are especially important topics for research near the Norwegian Trough.

Seismic reflection data revealed gas hydrates in the marine sediments. A bottom simulating reflector (BSR) is believed to represent the base of the gas hydrate stability field. Questions remain about whether the seismic expressions of gas hydrates and free gas can be confirmed by drilling, and if so, what the concentration of gas hydrate and free gas is in the pore space of the sediment. Humankind's influence on global climate is likely to initialize chain reactions that are not well understood; therefore, the probability and order of magnitude of future greenhouse gas releases from oceanic gas hydrates need to be determined.

Past and Current Research

The European North Atlantic Margin (ENAM) project, funded by the European Commission since 1996, serves as a bridge between the academic institutes and the oil industry for mapping and interpreting gas hydrates and sediment slides on the Norwegian deep water continental margin. ENAM and the Norwegian oil company consortium Seabed Project exchange knowledge and information gathered by both groups and jointly plan new field activities. The oil companies use state-of-the-art multichannel two- and three-dimensional seismic records to study the distribution of gas hydrates, and they plan to investigate further by drilling (Figure 1). A team from GEOMAR has developed and deployed a High-Frequency Ocean Bottom Hydrophone (HF-OBH) data logger to determine in situ, small-scale changes in compressional wave velocities from near-vertical and wide-angle seismic experiments (Figure 2) in areas that possess gas hydrates and slope instabilities [*Mienert and Posewang*, 1997; *Mienert et al.*, in press].

Over the past 10 years, the Universities of Tromsø, Bergen, Oslo, and Kiel have collaborated to study the Norwegian continental margin. The main focus has been on understanding the composition, distribution, and stability of the thick Quaternary deposits found along this margin, in particular, the composition and formation of the large deep-sea fans. Emphasis has also been placed on mapping the various types of mass movements, both spatially and temporally, to eluci-

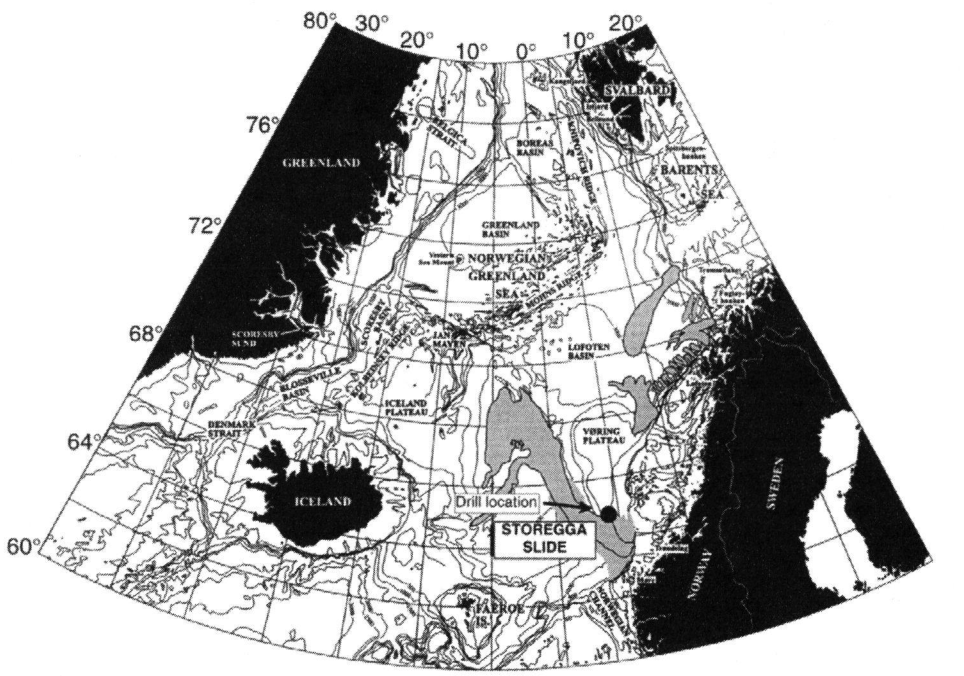

Fig. 1. The Norwegian-Greenland Sea continental margins showing the major slides on the Norwegian margin (in gray) [Vorren et al., *in press] and the location of the drill site north of the Storegga slide.*

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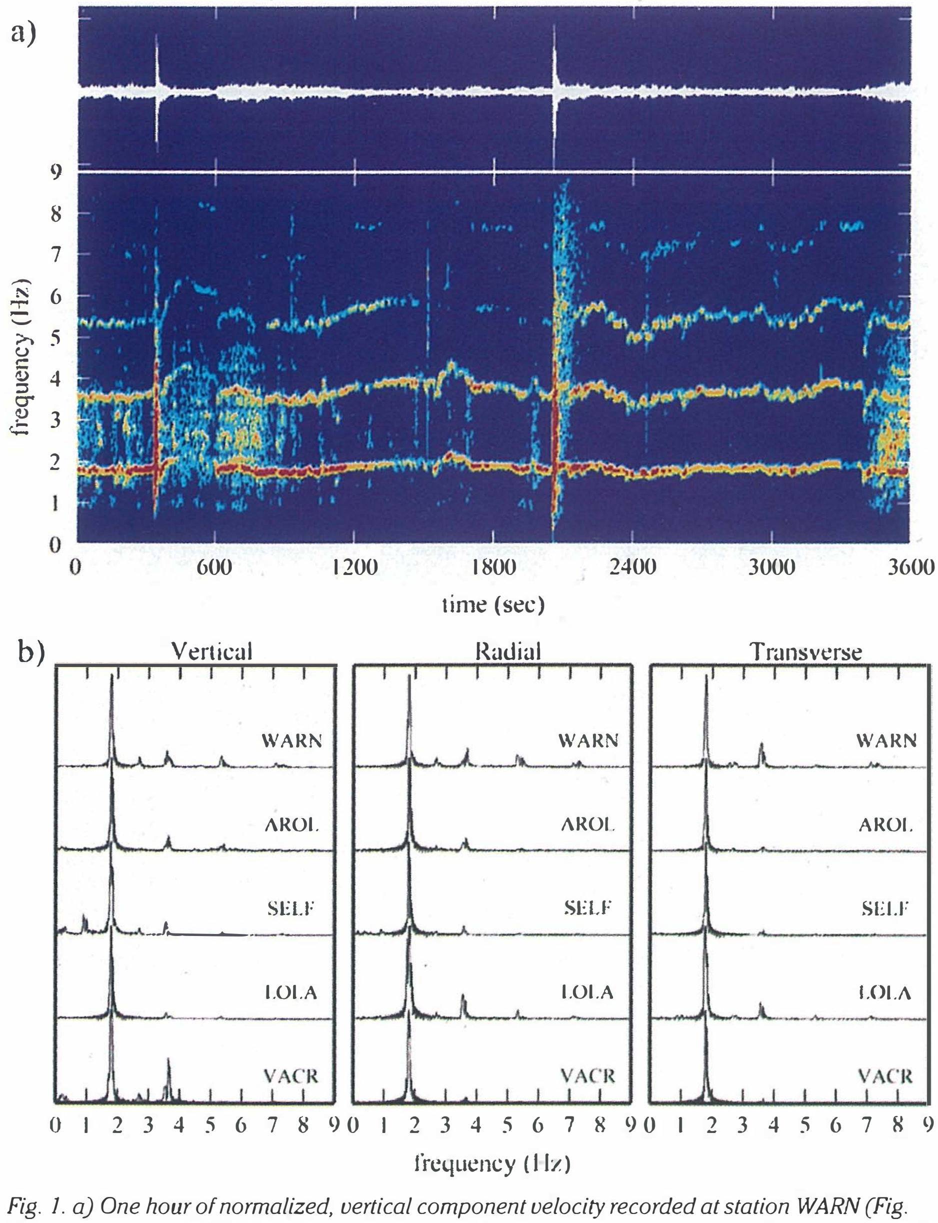

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