1 Introduction

1.1 Background

For generations, active volcanoes all over the world have fascinated mankind. The era of scientific observation began with Plinius the Younger's record of the eruption of Vesuvius in 79 A.D. At first, observations were limited to the descriptions of eruptions. Later, investigators broadend the scope of volcano studies to include geological, geochemical, petrological and mineralogical investigations. Despite this long history, very little is known about the physical processes which take place in volcanoes.

These processes occur on broad ranges in scale, both in space and time. Microscopic phenomena, such as the formation of crystals, are as important to understanding volcanoes as the tremendously large Plinian eruptions and pyroclastic flows which can kill thousands of people. Strombolian gas or ash explosions may last only minutes, while the extrusion of an andesitic lava dome can take many months. To describe the processes which occur in volcanoes requires many branches of physics. The fundamentals of rock mechanics, thermodynamics and fluid dynamics are all important. In addition, it is often necessary to consider the dynamics of two- or even three-phase systems, as well as modern methods for parametrizing non-linear processes, when describing volcanic phenomena.

A major obstacle to understanding the physics of volcanic systems is that it is not yet possible to directly measure physical state variables inside the volcano. We must therefore invent simple physical or chemical models for the processes which take place in volcanoes and constrain them using observations made at the surface. Years of seismic measurements have shown that such observations can be gathered by recording and analyzing the many different types of seismic signals produced by active volcanoes which can often be correlated with visible or audible activity [Ripepe and Braun 1993, Hellweg et al, 1994, Wasserman and Scherbaum, 1994, Benoit and McNutt, 1997, Lees et al, 1997]. Recent improvements in instrumentation allow continuous, high dynamic range recording of such volcanic seismic signals. Many other types of observation and measurement, such as tilt, deformation and gravity, contribute important information to understanding volcanoes, but they are not conducive to continuous, immediate and remote observation as is seismology, nor can they capture the same dynamic range of activity.

Some volcanic seismic signals are like those known from earthquake seismology. They must be the result either of extensional or shear fractures, or of explosive point sources similar to those of explosion seismology. Such signals, however, represent only a small portion of the “seismic spectrum” of a volcano. More frequently, the volcanic seismic signals appear to be generated continuously by an unknown source within the volcano. These signals, which often vary in amplitude and frequency content and are present in some form at all active volcanoes, are called “volcanic tremor”.

What is the source of volcanic tremor? The term volcanic tremor describes a continuous sequence of seismic waves traveling through a complex medium, the volcano. Seismic waves can, for example, be generated by the action of a point force on the medium (Aki and Richards, 1980) or by a change in the volume of a source region (Wielandt, 1975). The source of tremor is a physical or chemical process in the volcano which produces seismic waves by acting as a time-dependent point force on the medium, or by causing the volume of the source region to change. A better understanding of volcanic tremor will provide insights into such processes in a volcano.

The analysis of volcanic tremor presents two problems to the seismologist. First, the multitude of volcanic seismic signals often exceeds the “classical” analysis possibilities offered by techniques developed for analysing the wavefield generated by the short excitations due to rock fracture or explosions. Second, the volcano is not a simple medium for wave propagation. Tremor analysis as a means of studying its source is complicated by the passage of the tremor waves through the highly inhomogeneous volcanic edifice. Analysis techniques from other branches of physics, information theory or mathematics offer some help in discovering and defining characteristics of volcanic tremor which may otherwise remain hidden in the seismic data. These characteristics, along with information attained using “classical” seismological methods must then be carefully analysed to determine whether they describe parameters of the tremor source or the path.

Finally, tremor source parameters derived from seismic measurements must be related to the variables of state in a volcano. Even thorough and exhaustive analysis of seismic data cannot replace the direct measurement of such variables. To improve our understanding, we must develop physical or chemical models for processes occurring in volcanoes and compare their predictions with the results of measurements.

1.2 Objectives

The spectrum of volcanic tremor is often characterized by narrowband peaks. In the past, tremor was recorded using single-component, low-gain equipment, leaving many questions about the tremor wavefield open. It was difficult to determine tremor parameters other than the frequency and amplitude or to distinguish between propagation effects and source characteristics. Without such discrimination, it is impossible to use tremor recordings to constrain models of physical or chemical processes in a volcano. Data from several three-component seismometers recorded with high dynamic range allow a more complete analysis of the tremor wavefield. As a result, tremor traits due to the source may be distinguished from those influenced by path and medium. The source-related parameters can then be used, along with source models, to determine the volcano's variables of state.

Although both chemical and physical interactions occur in volcanoes, there is, as yet, little evidence that chemical processes produce seismic signals. The goal of this thesis is, therefore, to develop physical models for the source of volcanic tremor using parameters measured from tremor recordings. The first step must therefore be to determine tremor characteristics which can be used for modelling. This occurs in Chapters 2 and 3. Only then (Chapters 4 and 5) can I propose and develop models for the source and path which use the tremor parameters, while at the same time making predictions about tremor behavior. I describe Lascar Volcano, the seismological measurements and a selection of Lascar's seismic signals (Chapter 2). During the deployment, Lascar generated a unique type of tremor, characterized by a harmonic spectrum with a sharply peaked fundamental and up to thirty integer overtone frequencies. I analyze this tremor to determine parameters which can be used for modelling and discuss the implications of the analysis results for the tremor source (Chapter 3). One aspect of this discussion is the distinction between tremor characteristics which can be attributed to the source and can therefore be used to constrain physical models and those which may be affected by the path. In Chapter 4, I use the fundamental tremor frequency to develop three theoretical models for physical processes in Lascar Volcano which can generate harmonic tremor and compare their predictions with the results of tremor analysis. I follow this with a description of three simple models for the path of seismic waves through the volcano and relate them to the polarization of harmonic tremor (Chapter 5).