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Review

Analytical models of magma chamber stability: An abridged critical review of key concepts

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ABSTRACT

Key aspects that need to be taken into consideration when attempting to establish an elastic model of magma chamber stability, and the various forms in which those parameters have been introduced in analytical models of magma chamber stability are examined in critical form. These aspects include the geometry of the chamber, the relative distance and geometry of an outer boundary, the nature of the surface forces that act on each of those two physical boundaries, the role played by a body force (related to the gravitational attraction) and the fact that such force acts on any imaginary surface within the body of interest, as well as some assumptions concerning the description of the lithostatic stress and the criteria used to determine the conditions of tensile failure of the rock. The examination made here reveals that very often the analytical models include one or more sources of internal inconsistencies that are rooted on the disregard of conditions used by the original elastic models. After reviewing key aspects of elastic models the reader is expected to acquire the tools required to fully appreciate the advantages and limitations of specific chamber models, and to decide which of those models is better suited to solve the particular problem at hand.

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1. Introduction

Although analytical models commonly involve several simplifications and idealizations to be solved, their importance resides in that they offer benchmarks that can be used to calibrate the more sophisticated treatments (commonly numerical) that are required to solve more realistic situations. For this reason, it is of paramount importance to be sure that analytical models accurately capture the essence of the problem to be solved, avoiding any inconsistencies with the real world through the introduction of the simplifying assumptions. Unfortunately, there are numerous sources of uncertainty that can be incorporated into analytical models aiming to describe the mechanical stability of magma chamber, rendering those models not entirely self consistent. For example, there are various uncertainties associated with the delineation of the physical boundaries, shape, size and fluid content of real magma chambers. Although clearly important, these uncertainties are almost unavoidable, and can be eliminated as technological advances allow us to obtain more precise measurements of specific parameters within, and in the vicinity of real magma chambers.

Nevertheless, there are other sources of uncertainty that might have a more profound impact on the outcome of specific models aiming to describe the mechanical stability of magma chambers. These additional sources of uncertainty are related to conceptual problems originating in the form in which the fundamental theory is used to define the mechanical state of real materials, and in the form in which such theory is incorporated into particular models aiming to characterize even the more idealized of magma chambers. This type of uncertainty is very often difficult to identify, and consequently, it is equally difficult to deal with it, becoming almost impossible to eliminate it from subsequent versions of a model. For this reason, uncertainties associated to conceptual issues might become an inherent part of analytical models, and these uncertainties might bias our interpretation of the real world, very often in unforeseen forms. Evidently, it is important to make efforts to avoid as much as possible the assimilation of this type of uncertainties in analytical models of magma chambers, even if this requires revisiting from time to time the most basic aspects of current models and the reexamination of the basic concepts surrounding them.

From a pragmatic point of view, the number of alternative approaches and associated equations aiming to quantify the conditions of magma chamber stability already available on the literature (a general overview, and a list of relevant references, can be found on the recent reviews by Gudmundsson, 2006, and Grosfils, 2007), has resulted in the creation of some problems that are related to the question of singling out the "best" model that needs to be adopted when a particular volcano is under examination. Somewhat paradoxically, selecting the best possible model (whether analytical or numerical) may not be an easy task precisely because there is a variety of treatments that have been employed to solve the same fundamental question, and such variety sometimes makes the correct appreciation of key aspects related to the general problem difficult. Actually, the risk of losing sight of the key aspects relevant to the general problem becomes more marked when attention is focused on numerical models, not only because the equations solved in any of these models are deeply rooted in the same basic assumptions that are used in analytical counterparts, but also because numerical models introduce sources of uncertainty related to the accuracy of the calculations and the method used for computation (e.g., finite differences, finite elements or finite volume). Consequently, some of the most common general assumptions underlying many numerical models tend to be not explicitly stated, or are very easily overlooked because most attention is focused on the computational aspects of the problem, making it difficult to distinguish the general from the particular issues.

Actually, even if attention is restricted to purely analytical models, it is not uncommon to find that a specific equation has been used to describe a physical scenario other than that for which it had been established. Nevertheless, this source of internal inconsistency becomes soon obliterated by the avalanche of subsequent works reporting more complex calculations that stem from the original work where the uncertainty was first introduced, and therefore, the source of error soon becomes an integral part of the analytical and numerical models that followed the original one. For this reason, in order to unravel many of the intricacies that have developed over the years on the subject of the mechanical stability of magma chambers, it does not suffice to provide a detailed review of previous works, with an extensive reference list, following the structure of a traditional review paper in which the assumptions made by previous studies is discussed only lightly, and sometimes in a rather uncritical form. Actually, in order to capture the sources of internal inconsistencies found in the published models, offering the reader a set of tools required to identify the underlying assumptions of each analytical model published to date, whether explicitly or implicitly stated on the original paper, some modifications have to be introduced in the structure of the traditional review paper.

Since the aim of this work is not to provide an updated inventory of models that have dealt with the subject of mechanical stability of magma chambers over the years, but rather it aims to provide a better understanding of key aspects embedded in those models, it has been necessary to modify the traditional approach followed by review papers in several important aspects: (1) Attention has been focused on the review of the various parameters that might be incorporated into a specific model of chamber stability, and on the form in which those parameters might influence the outcome of any model, rather than reviewing specific models one at a time, or grouped by any other criteria. (2) Likewise, instead of aiming to provide a summary of previous models commenting the pros and cons of specific models in a one to one basis (or by groups), effort was invested in providing a series of guidelines that might allow the reader to decide which of the previous models is more suitable for his/her specific needs. (3) Expanded sections presenting basic concepts are presented, rather than summarizing the basic concepts to encapsulate the main results of previous works. (4) Reference to the oldest works from where the relevant equations can be traced was privileged over the most recent references, although this was done taking into consideration some aspects of accessibility to the original works where the equations were first derived. This is important because many of the basic concepts behind the fundamental equations used in elasticity were formulated by scientists working in these problems as early as the first half of the XIXth century, and the original works may not be widely available for a large proportion of present-day volcanologists. Actually, even if the original works were widely available, due to differences in language and perhaps even style of presentation, it is probable that such works would remain almost unintelligible for many present-day workers. For this reason, the assertion made in the sense of privileging the oldest possible works should not be taken in the literal sense of making reference to the original works where the equations were first established, but rather it should be interpreted to indicate that reference was made to old works provided that these are relatively accessible, are still available on many libraries within the collections of earth science books (rather than in the history of science sections), were written with a relatively modern style and in English language, and have been directly quoted by at least one paper published in a journal with explicitly identified volcanic interests. (5) The scope of the review was restricted to analytical models, leaving aside examination of any numerical approach.

Although these modifications (and in particular the last two) might seem to be contrary to the scope of a review paper, they turn out to be advantageous for several reasons. First, it is noted that with this approach it is easier to avoid the general confusion that can ensue through the repetition of omissions in the statement of assumptions, and the related errors of application of specific equations