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Root zone processes in the phreatomagmatic pipe emplacement model and consequences for the evolution of maar–diatreme volcanoes

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Abstract

The understanding of processes within the root zone of maar–diatreme volcanoes is important for the interpretation of the geology, volcanology and even hazard assessment of these volcanoes. In the phreatomagmatic model of pipe formation, the irregularly shaped root zone is the site of the phreatomagmatic explosions, and thus functions as the "engine" for pipe formation. In this model the root zone grows over a period of time in a series of many single thermohydraulic, i.e. phreatomagmatic, explosions. The explosions initially occur close to the surface and with ongoing explosive activity penetrate towards deeper levels. The ejection of country rock clasts from the root zone results in a mass deficiency in the root zone that causes the overlying tephra and the adjacent country rocks to subside passively in a sinkhole-like fashion into the root zone. Many phreatomagmatic eruptions consequently result in the formation of a cone-shaped diatreme. Thus with ongoing eruptions the cone-shaped diatreme has to grow systematically both in depth and diameter. During its growth, processes in the lower diatreme levels successively destroy the upper levels of the evolving root zone. At the surface, the maar crater in turn reacts to the underlying subsidence processes and also grows both in depth and diameter.

Thermohydraulic explosions, which fragment both magma and the surrounding country rocks, mostly occur within the bottom part of the root zone. Violent explosions in small pipes may clear the overlying diatreme for a short period of time before tephra fall and collapse of the walls of the new crater refill the small initial diatreme. In larger pipes, via expansion of the mixture of highly pressurized water vapor, juvenile gas phases and explosively produced tephra, the confined and expanding eruption cloud has to pierce through the diatreme fill in a feeder conduit in order to erupt. Diatreme-clearing events in large pipes are difficult or impossible to maintain, since the explosive force in the root zone is only in exceptional instances strong enough to lift or entrain the entire diatreme tephra. Knowledge of the genetic relationships between root zones and diatremes is critical to understand pipe growth processes. The combination of such processes can lead to substantial variation in volcanic behavior and thus produce fundamentally different volcano and rock types.

It is the purpose of this paper to outline important features of root zones and suggest their significance for the genesis and evolution of maar–diatreme and related volcanoes.

Keywords: phreatomagmatic; root zone; maar; diatreme; pipe; kimberlite

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1. Introduction

The root zones of maar–diatreme volcanoes (Figs. 1, 2) first became known from the studies of diamondiferous South African kimberlite pipes (Wagner, 1914; Williams, 1932; Wagner, 1971; Hawthorne, 1975; Clement, 1982; Clement and Reid, 1989). It was Clement (1982) who introduced the term "root zone" for the irregular shaped transition zone between a narrow kimberlite feeder dike and the overlying large cone-shaped kimberlite diatreme. This paper is largely based on kimberlite root zones due to the availability of data from diamond mining and exploration drill cores. The root zone processes described in this paper, however, are relevant for all other phreatomagmatic maar–diatreme volcanoes. Since root zones of maar–diatreme volcanoes are rather well known from pipes encased within hard rocks, this investigation will discuss almost exclusively maar–diatreme volcanoes formed in such environments. For maar–diatreme volcanoes formed in soft sediment environments see Lorenz (1985, 1986), Boxer et al. (1989), White (1991, 2000), Lorenz et al. (2002) and Zimanowski and Büttner (2002).

In respect to the formation of maar–diatreme volcanoes, two families of models exist: phreatomagmatic and magmatic models. There is broad consensus that maars and diatremes formed phreatomagmatically (Fisher and Schmincke, 1984; Cas and Wright, 1987; Francis, 1996; Fisher et al., 1997; Schmincke, 2000, 2004). In contrast, a number of researchers consider the vast majority of kimberlite (and carbonatite) maar–diatreme volcanoes to have formed magmatically, i.e. via exsolution and expansion of juvenile volatile phases (Clement, 1982; Mitchell, 1986, 1989; Stoppa, 1996; Kirkley et al., 1998; Stoppa and Principe, 1998; Field and Scott Smith, 1999; Scott-Smith, 1999; Head and Wilson, 2003; Lloyd and Stoppa, 2003; Skinner and Marsh, 2003; Wilson and Head, 2003). Some of these authors accept potential involvement of groundwater in their magmatic model; however, they do not provide any details on the mechanism. Also, none of the above studies gives an estimate of the volatile content of a kimberlite at diatreme emplacement level. To our knowledge, this critical question, the answer to which is a prerequisite for any volatile-driven diatreme-forming emplacement model, has not been investigated in detail in modern scientific studies. In this study we concentrate on the phreatomagmatic model of maar–diatreme formation, which is not strongly sensitive to the magma type involved.

We define a maar–diatreme volcano (Lorenz, 1975) as the entire volcanic edifice from the bottom of the root zone upwards, including the tephra ring (Figs. 1 and 2). We use the term "pipe" in a non-genetic way and only for a diatreme and the underlying root zone, i.e. the subsurface portion of a maar–diatreme volcano.

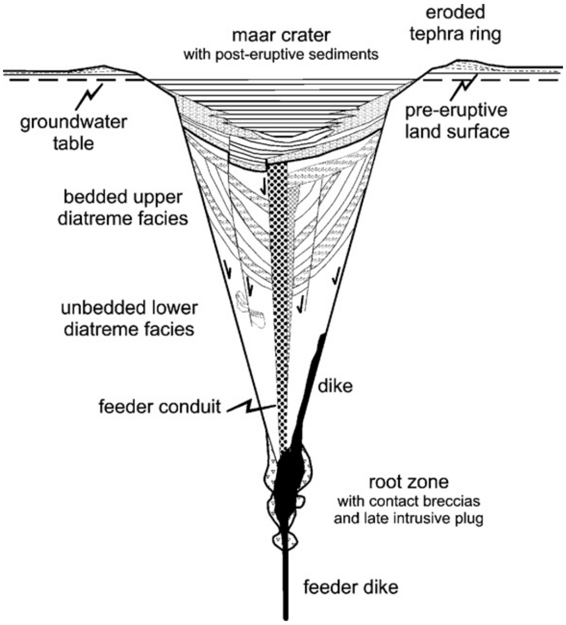

Fig. 1. Schematic diagram of an idealized large kimberlite pipe with its feeder dyke, root zone, overlying diatreme, and maar crater as well as the tephra ring surrounding the maar crater. Note: the feeder dyke is out of scale (too thick). The bedded upper diatreme facies consists of alternating primary thinly bedded tephra and reworked thickly bedded tephra, i.e. lahars. In posteruptive time the maar crater became filled with coarse sediments at its margins and finer grained lacustrine sediments in its center. During syneruptive times subsidence of the diatreme fill caused formation of intra-diatreme faults which due to posteruptive compaction (in most diatremes) and diagenesis became propagated upward (after Lorenz et al., 2003). Horizontal and vertical scales are roughly the same.

Next to the basic and ultrabasic scoria cones, maar–diatreme volcanoes represent the second most common volcano type in subaerial environments (Wohletz and Heiken, 1992; Vespermann and Schmincke, 2000; Schmincke, 2004). Both volcano types are monogenetic, thus short-lived volcanoes and frequently they occur in basic and ultrabasic volcanic fields. Volcanic fields themselves are rather long-lived and may be active for up to several million years (Connor and Conway, 2000; Schmincke, 2000; Walker, 2000; Schmincke, 2004). Many researchers suggest that maar–diatreme volcanoes represent the phreatomagmatic equivalent of the positive landform volcanoes represented by scoria cones (and their associated lava flows), possibly also of small volcanic shields of scutulum type (Walker, 2000). They also represent the equivalent of small acidic to intermediate monogenetic volcanoes such as domes and their