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The impact of a volcanic edifice on intrusive and eruptive activity

Alberto Roman [*], Claude Jaupart

Institut de Physique du Globe de Paris, Université Sorbonne Paris Cité, Université Paris Diderot, CNRS UMR 7154, 1 rue Jussieu, 75238 Paris cedex 05, France

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ABSTRACT

In a volcanic area, the orientation and composition of dikes record the development of the magmatic system that feeds intrusive and eruptive activity. At Spanish Peaks, Colorado, curved dike trajectories issuing from a single focal area have been attributed to horizontal propagation from a pressurized central reservoir in a deviatoric tectonic stress field. These dikes, however, are nowhere in contact with the central intrusion, are younger than it by about 1 My and are not filled with the same magma. They were emplaced at shallow depths (≈ 1 km), where the local stress field is very sensitive to surface loads. Here, we show that their trajectories can be set by the load of a volcanic edifice in a tectonic stress field. The orientation and distribution of the Spanish Peaks dikes have changed in the course of two million years as magmas were evolving chemically. Early dikes that were parallel to each other and filled with primitive melts document ascent in the regional tectonic stress field. They were replaced by curved dikes carrying evolved melts, which record the influence of a sizable volcanic edifice. Beneath this edifice, the induced compression prevented dense primitive magmas from erupting in the focal area and diverted intermediate magmas sideways. The growth of this large volcanic cone was probably responsible for the formation of a magma reservoir. The mechanisms that have shaped the Spanish Peaks dike swarm may control the spatial distribution and migration of eruptive centers in many active volcanic areas.

1. Introduction

Active volcanic areas such as the Cascade arc, Western North America, are dotted with a large number of cones and vents, some of which eventually grow into large shields and stratovolcanoes (Hildreth, 2007). How eruptive activity becomes focused on a few sites and how magma reservoirs form in such settings are key issues that have received little attention. A related question is the degree of connection between neighboring eruption centers. In some cases, there is clear evidence for lateral magma transport, as at Mount Katmai, Alaska, for example (Hildreth and Fierstein, 2000; Eichelberger and Izbekov, 2000). However, at which stage and under which conditions such horizontal connections get established has not been ascertained.

The present work began by an analysis of the Spanish Peaks dike swarm, Colorado, which has motivated several studies because of its striking exposures of curved dike trajectories emanating from a focal area (Fig. 1). Of even greater interest is the fact that intrusion conditions have changed with time. Early dikes carried primitive magmas and did not radiate from a common focus, in marked contrast to later ones which were fed by evolved magmas (Fig. 1). This link between changes of emplacement characteristics and magma composition provides a powerful hint on the mechanisms that shape volcanic plumbing systems.

Curved dike trajectories have been observed in many areas, including Silver Mountain, Colorado (Penn and Lindsey, 2009), North Sister, Oregon Cascades (Schmidt and Grunder, 2009) as well as Ship Rock, New Mexico (Delaney and Pollard, 1981). They have been attributed to magma propagation from a pressurized reservoir in a regional tectonic stress field. In this model, the reservoir generates radial dikes in a central region. With increasing distance from source, the reservoir influence decreases and dikes respond by deviating from their initial trajectories towards the direction of maximum regional compressive stress (Odé, 1957; Muller and Pollard, 1977; Koenig and Pollard, 1998; Mériaux and Lister, 2002). This attractive model, however, runs into severe difficulties when assessed against the characteristics of the Spanish Peaks swarm (Fig. 1). The Spanish Peaks dikes cannot be traced to the central intrusion/stock that is supposed to have acted as their reservoir. In fact, they are younger and of different compositions than this stock (Penn and Lindsey, 2009) (Fig. 1). They radiate in all directions from a focal area, and we show in Appendix A that this is at odds with the behaviour of a reservoir in a tectonic stress field.

The model of a pressurized central reservoir appears to be consistent with neither observations nor physical considerations, and

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[*] Corresponding author.

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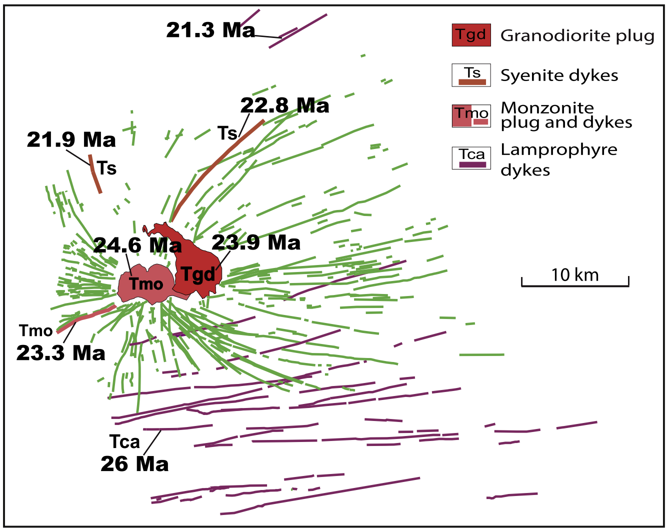

Fig. 1. Geological map of Spanish Peaks intrusions and dikes with ages (modified from Penn and Lindsey, 2009). For the sake of clarity, the compositions of dikes and intrusions have been simplified and grouped into four main categories. Early parallel dikes (in purple) are filled with primitive minette/camptonite (lamprophyre) rocks, the radial dike swarm (in green and orange for those that have been dated) is made of evolved syenites and monzonites, and late dikes located to the North revert to minette compositions. The most evolved rocks with up to 73% SiO_2 contents are the granodiorites of East Spanish Peaks (in dark red) (Jahn et al., 1979).

we have looked for an alternative one. Dike trajectories that bend at some distance from a magmatic focus call for the influence of two different stress components, one that dominates in the focal area and another that takes over in the far-field. Here, we propose that the central stress component is generated by a volcanic edifice. For example, a 2500-m high volcanic cone, close to the typical dimensions of central volcanoes in the Cascades, induces stresses that are as large as 60 MPa in its substrate, which exceeds the critical reservoir overpressure prior to eruption (Rubin, 1995). These stress perturbations decrease with depth over a characteristic distance that is about twice the edifice radius, which is in a 5–15 km range for mature volcanic constructions. At Spanish Peaks, the current erosion level corresponds to a paleodepth of only 1 km (Smith, 1975), which was clearly in the zone of influence of a surface load. The edifice radius also sets the horizontal distance at which the loading effect vanishes. One therefore expects that dikes align themselves with the tectonic stress at distances in a 5–15 km range, as observed.

The impact of volcanic edifices on dike propagation has already drawn the attention of a few authors. Fiske and Jackson (1972) have documented the influence of topography on dike emplacement. Others have shown that a volcanic cone acts to attract fluid-filled fractures towards the axial area and to stop them at a depth which depends on its size and on magma buoyancy (Dahm, 2000; Pinel and Jaupart, 2000; Muller et al., 2001; Acocella and Neri, 2009; Maccaferri et al., 2011). We build on these studies and use information from exposed dike swarms to elucidate some of the physical controls on the spatial distribution of dikes and time changes of magma composition. We show that, in a zone of tectonic extension, principal stress trajectories below a volcanic edifice resemble those of Spanish Peaks. We evaluate under which conditions and over what depth range an edifice can affect dike propagation. Observations from Summer Coon, another exhumed magmatic system of Oligocene–Miocene age in Colorado (Lipman, 1968), help us illustrate the impact of magma buoyancy on dike propagation beneath an edifice. Insights from these examples are used to discuss the behaviour of the Three Sisters volcanic cluster, Oregon.

Table 1
Densities of the main magma types at Spanish Peaks, from data in Jahn et al. (1979). Liquidus temperatures have been set to likely values for dry magmas.

Magma[†] (Igneous rock)	Density [$kg\,m^{-3}$]	Temperature [°C]
Alkali basalt (lamprophyre/minette)	2560–2630	1100
Trachy-andesite (syenodiorites)	2430	1000
Rhyolite (granite)	2300	900

[†] Magma types that correspond to the solidified plutonic rocks.

2. The dike swarms of Spanish Peaks and Summer Coon

2.1. Spanish Peaks: changes of intrusion pattern and magma composition

The tectonic setting of magmatic activity at Spanish Peaks has been debated. The presence of thrust faults in the Sangre del Cristo Range to the West led early workers to invoke a state of regional compression (Odé, 1957; Muller and Pollard, 1977). These faults, however, date from the Laramide orogeny which ended about 40 Ma ago (Keller and Baldridge, 1999). Magmatic activity occurred later in an extension regime marked by the propagation of the Rio Grande rift (Lipman et al., 1972; Christiansen and Lipman, 1972). The N–S direction of the rift seems to be inconsistent with the ≈ E–W orientation of the dikes (Fig. 1). The tectonics of the Rio Grande and adjacent areas are complicated, however, with a stress field that is far from uniform spatially (Thompson and Zoback, 1979; Aldrich and Laughlin, 1984). On a West to East traverse across the Rio Grande into the Southern Great Plains, the least principal horizontal stress rotates by nearly 90° from an EW direction to an N–S to NNE–SSW direction (Aldrich et al., 1986). In the Spanish Peaks area, the latter direction has been predominant since at least 28 My, which is consistent with the preferential dike alignment. The sharp change of extension direction that occurs east of the Rio Grande has been attributed to different causes, including structural discontinuities (faults) and an inherited geological fabric (Aldrich et al., 1986).

The compositions of the Spanish Peaks magmas have changed with time (Jahn et al., 1979; Penn and Lindsey, 2009) (Fig. 1). Similar magma series have been documented elsewhere (McDonald et al., 1986), which shows that they result from a reproducible set of petrogenetic processes. These magmas are largely co-genetic with only small amounts of contamination from crustal rocks (McDonald et al., 1986; McGregor et al., 2011). The earliest dikes (about 26.6 Ma) brought primitive camptonite/lamprophyre magmas to the surface. They are straight and nearly parallel to one another. The West Spanish Peaks central stock was formed at 24.6 Ma, followed by East Spanish Peaks 0.7 My later. These stocks are composites of smaller intrusions of evolved silicic magmas, showing that, by those times, a reservoir where primitive magmas could undergo fractionation had formed. The radial dikes came afterwards and were emplaced over a time interval of 1 My starting at about 23.3 Ma. The latest dikes (about 21.3 Ma) were fed by primitive magmas, indicating that the deep source of melt remained active in the area through the whole time sequence.

We have calculated the densities of the main Spanish Peaks magmas using standard silicate melt models. We have assumed that the compositions of intrusive rocks are identical to those of the magmas that generated them. This is valid for dikes which cool rapidly but may be an oversimplification for the central intrusive complexes. We have not allowed for significant amounts of volatiles for lack of information. A systematic and large density decrease occurs from primitive to evolved magmas (Table 1). With water present, this trend would likely be enhanced because volatile contents usually increase with increasing degree of differentiation and because water acts to decrease density.