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Analysis of the 2009 earthquake swarm near Sunset Crater volcano, Arizona

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ABSTRACT

A swarm of microearthquakes occurred on October 31, 2009 within 5 km of the Sunset Crater, Arizona, volcano. A detailed study of the swarm was warranted because of its location near a young volcanic construct and its proximity to the population center of Flagstaff, Arizona. The question posed in this study was whether the swarm was the result of tectonic stress release during fault slip, or due to stresses driven by magmatic processes. This question was addressed by analyzing and comparing the physical and seismic characteristics of the swarm to the regional tectonic environment and to the characteristics of tectonic swarms in Arizona and magmatic/volcanic swarms elsewhere. This analysis included swarm duration, frequency of events, b-value, focal depths and epicentral pattern of the swarm. The comparison of the salient features of the 2009 Sunset Crater swarm to both magmatic and tectonic swarms indicates that the Sunset Crater swarm has features similar to magmatic swarms and is a potential magmatic swarm candidate.

1. Introduction

A swarm of earthquakes occurred in a six and a half-hour span on October 31, 2009 approximately 15 km north-northeast of Flagstaff, Arizona and approximately 5 km west of the Sunset Crater volcanic cone (Fig. 1). The cinder cone and volcanic flows are part of a magmatic event that occurred less than 1000 years ago. Northern Arizona is a region of the Earth's crust containing both numerous examples of well mapped surface faults and volcanic features. The question addressed by this study is whether or not the swarm was a phenomenon related to magmatic activity or to tectonic release of strain by faulting.

Seismic monitoring has been ongoing in northern Arizona on a continuous basis since 1973. The seismic monitoring capabilities of the area were improved in 2009 by the addition of several new broadband stations captured from the Transportable Array experiment (Brumbaugh et al., 2010). This fortuitous timing of the occurrence of the swarm after the improved station density allowed for the collection of data from 120 events in the 2009 swarm that would not have been possible the previous year. Because of the anomalous nature of the swarm and the proximity to the densely populated city of Flagstaff, this swarm deserves detailed study.

2. Geologic setting

The San Francisco volcanic field (SFVF) is a cluster of vents and lava flows that cover an area of approximately 5000 km^2 on the southern edge of the Colorado Plateau in northern Arizona (Fig. 2). Magma generation has been dominantly basaltic producing over 600 cinder cones and lava flows across the volcanic field (Tanaka et al., 1986). Rhyolitic and intermediate composition volcanism has produced contemporaneous stratovolcanoes and lava domes, including the 1 to 4 million year old San Francisco Peaks stratovolcano complex (Fig. 2). Volcanism initiated during the late Miocene (~6 mya) in the western portion of the SFVF and has migrated northeastward to where the youngest eruption at Sunset Crater occurred at ~990 years ago (Conway et al., 1997). Vent migration has been interpreted to result from absolute southwestern movement of the North American plate over a fixed hotspot (Tanaka et al., 1986). However the fundamental cause of volcanism in the SFVF is poorly understood. It is because of the Sunset Crater activity as well as other eruptions in the field in the last 100,000 years that the SFVF has been termed likely active by the U. S. Geological Survey (Priest et al., 2001).

The SFVF overlies a ~2 km-thick sequence of Paleozoic and Triassic sedimentary rocks that cover Precambrian basement terranes (Moore and Wolfe, 1976). Both cover and basement rocks are extensively fractured by jointing and faults. The crust beneath the SFVF is 40 km thick and can be subdivided into an upper (0–12 km), mid (13–25 km) and lower crust (26–40 km). Abundant evidence to the north of the SFVF

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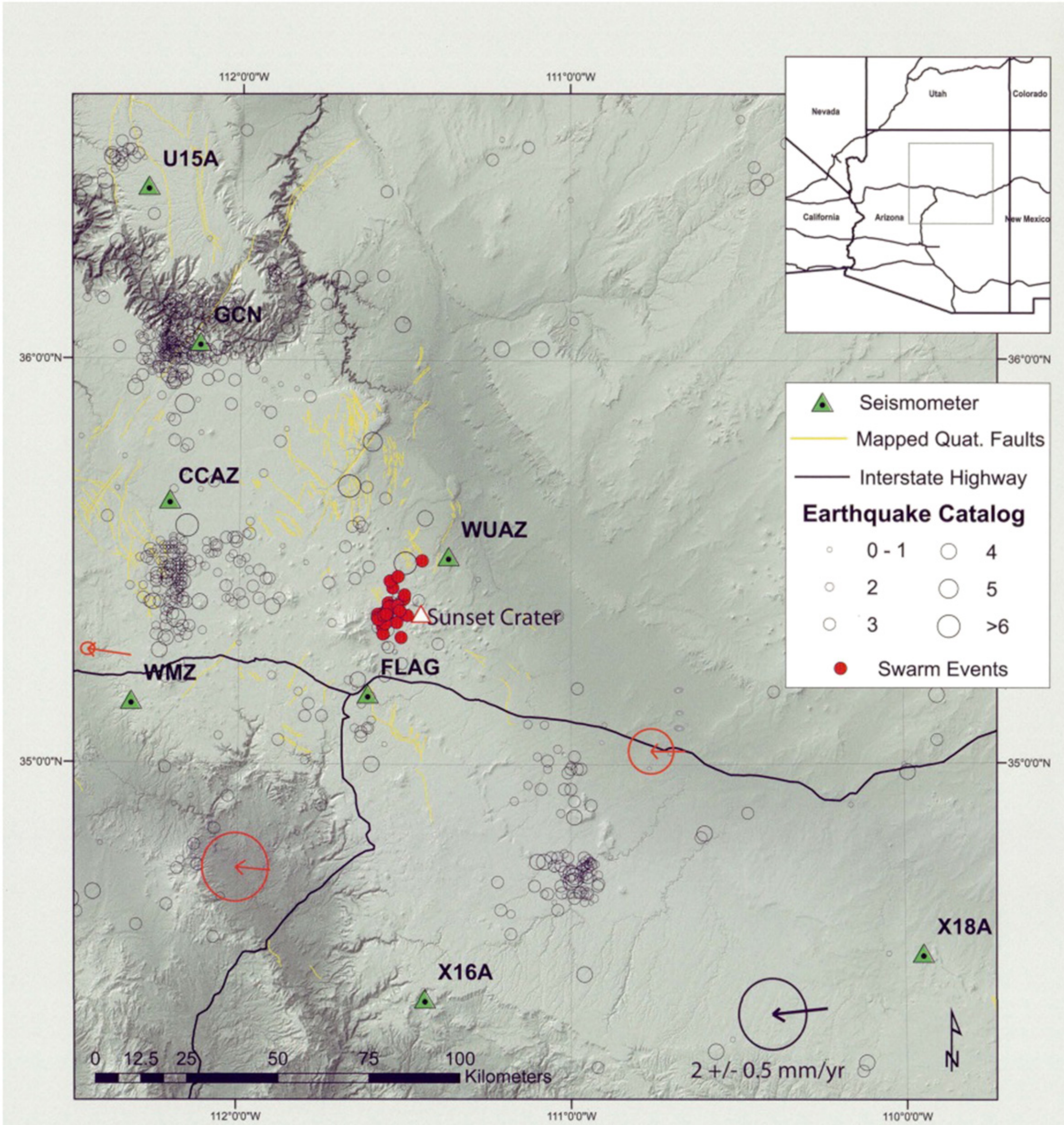

Fig. 1. Index map of northern Arizona showing location of Sunset Crater swarm (dots) and seismic stations (triangles). Sunset Crater indicated by open triangle. Historical magnitudes are Richter scale, while the Sunset Crater swarm magnitudes are duration (M_D). Historical seismicity represented by open circles. Circles with arrows show movement direction and velocity of the region from GPS data.

exists in the Grand Canyon exposures of the multiple reactivation of the crustal faults, often causing them to switch from reverse to normal faulting as the regional stress system changed over time (Brumbaugh, 2005). Shoemaker et al. (1978) recognized that many of the mapped surface faults displayed parallel to sub-parallel trends creating groups of fault systems with well-defined trends. These were named from prominent geographic/geologic features as the northwest-trending Cataract Creek fault system and the northeast-trending Mesa Butte and Bright Angel fault systems (Fig. 3). The SFVF lies at the intersection of the Cataract Creek and Mesa Butte systems, suggesting a locus of volcanism related to a highly fractured crust (Brumbaugh, 2012).

3. Swarm seismicity

Earthquake swarms are characterized by clusters of spatially and temporally-related earthquakes which do not contain a large mainshock event. Typically a swarm may produce many similarly sized events distributed over a span of several hours to months (Kurz et al., 2004; Farrell et al., 2009). The classification system of Mogi (1963) used these characteristics to separate what he termed Type 3 or swarm sequences from two other types of sequences, the Type 1 mainshock-aftershock and the Type 2 foreshock-mainshock-aftershock (Fig. 4).

Earthquake swarms have been detected in many different tectonic settings associated with faulting events. Seismic swarms have, for example, been detected during slow-slip events on subduction zone thrust faults (Shelly et al., 2006), detachment faults in Hawaii (Segall et al., 2006), strike-slip faults in southern California (Roland and McGuire, 2009) and intraplate normal faults (Weins and Petroy, 1990).

Earthquake swarms commonly occur in volcanically active regions as well where a shallow magmatic or hydrothermal system is known to exist (Benoit and McNutt, 1996; Hill et al., 2003; Farrell et al., 2009). Seismic swarms in many cases have been interpreted to occur from stress perturbations caused by magma intrusion and/or fluid flow and by volcano-tectonic interaction with these processes (Aster et al, 1992; Waite and Smith, 2002; Hill et al., 2003; Von Seggern