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Evaluation of the evolving stress field of the Yellowstone volcanic plateau, 1988 to 2010, from earthquake first-motion inversions

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ABSTRACT

Although the last rhyolite eruption occurred around 70 ka ago, the silicic Yellowstone volcanic field is still considered active due to high hydrothermal and seismic activity and possible recent magma intrusions. Geodetic measurements document complex deformation patterns in crustal strain and seismic activity likewise reveal spatial and temporal variations in the stress field. We use earthquake data recorded between 1988 and 2010 to investigate these variations and their possible causes in more detail. Earthquake relocations and a set of 369 well-constrained, double-couple, focal mechanism solutions were computed. Events were grouped according to location and time to investigate trends in faulting. The majority of the events have normal-faulting solutions, subordinate strike-slip kinematics, and very rarely, reverse motions. The dominant direction of extension throughout the 0.64 Ma Yellowstone caldera is nearly ENE, consistent with the perpendicular direction of alignments of volcanic vents within the caldera, but our study also reveals spatial and temporal variations. Stress-field solutions for different areas and time periods were calculated from earthquake focal mechanism inversion. A well-resolved rotation of σ_3 was found, from NNE-SSW near the Hebgen Lake fault zone, to ENE-WSW near Norris Junction. In particular, the σ_3 direction changed throughout the years around Norris Geyser Basin, from being ENE-WSW, as calculated in the study by Waite and Smith (2004), to NNE-SSW, while the other σ_3 directions are mostly unchanged over time. The presence of "chocolate tablet" structures, with two sets of nearly perpendicular normal faults, was identified in many stages of the deformation history both in the Norris Geyser Basin area and inside the caldera.

1. Introduction

The silicic Yellowstone volcanic field is a long-lived, voluminous volcanic system located at the eastern edge of the tectonically active Basin and Range Province, 1600 km east of the western North American plate boundary (Fig. 1). A deep-seated mantle plume is thought to provide the source of heat for the long-term volcanic activity at this intraplate hotspot (Yuan and Dueker, 2005; Waite et al., 2006; Smith et al., 2009). The Yellowstone Plateau volcanic field is a clear example of a compositionally bimodal rhyolite-basalt igneous field (Christiansen, 2001). During the past two million years, there have been three caldera-forming eruptions, at 2.0, 1.3 and 0.64 Ma BP, which erupted 2500 km^3, 280 km^3 and 1000 km^3 of material, respectively (Christiansen, 2001). The most recent eruption caused the formation of a 45 km by 70 km collapse caldera that subsided up to 500 m along normal faults on the caldera rim. Two resurgent domes formed by a post-collapse uplift are found within the 0.64 Ma Yellowstone caldera: the eastern Sour Creek dome became resurgent soon after collapse, while a reexamination of the age and history of the western Mallard Lake dome showed that it must be about 160 ka old (Christiansen, 2001).

The youngest known rhyolite flows on the Yellowstone Plateau are about 70 ka old: no magmatic eruptions are known to have occurred within or near the Yellowstone caldera after that time. Nevertheless, Yellowstone is still considered volcanically active, due to high hydrothermal and seismic activity; in addition, episodes of deformation inside and adjacent to the caldera, and the caldera-wide seismic low-velocity zones in the upper (Farrell et al., 2014) and lower crust (Huang et al., 2015) are interpreted to include a fraction of partial melt.

Geodetic (leveling, GPS, and InSAR) measurements, made at Yellowstone since 1923, record the episodic uplift and subsidence of the volcano. Between leveling surveys in 1923 and 1984, there was net uplift of up to 1 m, (15 mm/yr), in the center of the caldera. This was followed by a 20 mm/yr subsidence that exceeded 190 mm through 1995, and a 5-year return to minor uplift starting from early 1996 (Pelton and Smith, 1982; Dzurisin et al., 1994; Wicks et al., 1998). This period of uplift was followed by renewed subsidence (0.9 cm/yr) until 2004, when the caldera started to experience accelerated uplift, at the rate of 7 cm/yr (Chang et al., 2007). Episodes of uplift and subsidence in the caldera have been attributed to combinations of two processes taking place beneath the caldera: pressurization and de-pressurization of an

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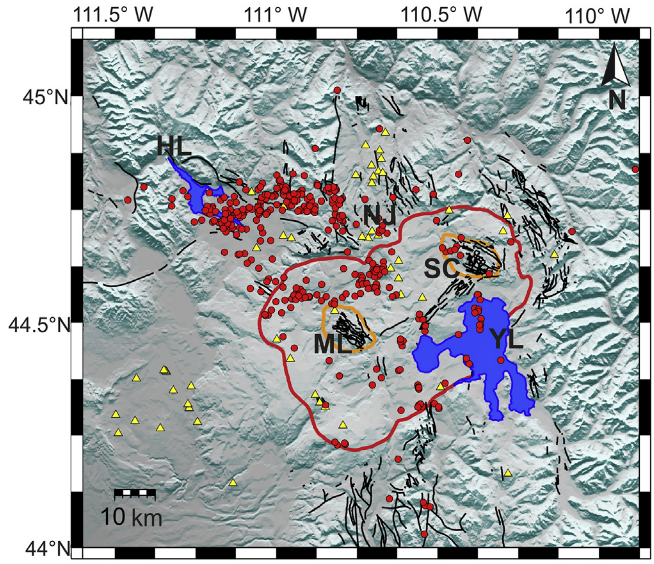

Fig. 1. Relocated earthquakes in Yellowstone from 1988 to early 2010. Earthquake epicenters are shown as red dots, post-caldera vents are shown as yellow triangles and Quaternary faults are shown as black lines. The two resurgent domes are outlined with an orange line. The caldera is outlined in red. YL = Yellowstone Lake, HL = Hebgen Lake, ML = Mallard Lake resurgent dome, SC = Sour Creek resurgent dome, NJ = Norris Junction. The topographic data is provided by the USGS National Elevation Dataset. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

alternately self-sealed and leaking hydrothermal fluid reservoir that traps volatiles exsolved from a crystallizing rhyolitic magma; or movement, formation and crystallization of rhyolitic or basaltic magma (Wicks et al., 2006).

Further evidence of the crustal volcanic activity is the high heat flux in Yellowstone, estimated to be ~1800 mW/m^2, which is 30 times higher than the continental average (Fournier et al., 1976; Smith et al., 2009). The expansive hydrothermal system of the area is caused by the circulation of hot water along fracture systems in the upper crust heated from below by the crystallization of partial melt of basaltic or rhyolitic magma in a midcrustal magma body that underlies the caldera (Fournier, 1989; Miller and Smith, 1999; Husen et al., 2004; Farrell et al., 2014).

Yellowstone is the most seismically active region of the 1300-km-long Intermountain Seismic Belt (Smith et al., 1991). One of the largest recorded events to occur within the 3000 km^2 caldera is the M_L 6.1 (M_S 5.9) 1975 Norris Junction earthquake (Pitt et al., 1979). The largest historic seismic event of the area was the M_W 7.3 Hebgen Lake earthquake (Montana) that occurred in 1959 with an epicenter 25 km northwest of the Yellowstone caldera (Doser, 1985).

A significant proportion of Yellowstone seismic activity is concentrated in the east-west trending zone north of the caldera, extending from the Hebgen Lake area to the northern caldera boundary near Norris Junction (Fig. 1). Further, the caldera itself is characterized by frequent but smaller earthquakes, often occurring in swarms (e.g., Massin et al., 2013). Seismicity is relatively sparse in the area immediately south of the Yellowstone caldera to Jackson Hole (Smith et al., 1991).

Seismic activity in the Yellowstone area varies somewhat according to the changes in the deformation pattern (Chang et al., 2007). In 2002, Waite and Smith argued that the 1985 swarm seismicity was related to magmatic or hydrothermal fluid flow that originated beneath the Mallard Lake resurgent dome: the transport of fluids was towards the northwest, causing earthquakes once they reached the brittle crust (Waite and Smith, 2002). After the 1985 caldera reversal, subsidence continued at a rate of 14 mm/yr until 1995, when the caldera began a 5-year period of minor uplift at a rate of 9 mm/yr, followed by renewed subsidence until the sudden change to accelerated caldera uplift. From the beginning of the 1995 uplift, seismicity started to increase until the onset of accelerated uplift in late 2004, at a rate of up to 7 cm/yr (Chang et al., 2007, 2010; Puskas et al., 2007) (Fig. 2). Uplift slowed following the 2008–2009 Yellowstone Lake swarm (Farrell et al., 2010). In January 2010, the Yellowstone caldera experienced another large earthquake swarm at its northwestern boundary close to the location of the 1985 swarm and in the following five months the caldera started the first overall subsidence since the beginning of uplift in 2004 (Shelly et al., 2013).

The first detailed study (Peyton, 1991) of earthquake focal mechanisms and stresses at Yellowstone used data from 1973 to 1989. Interpretation was limited to the area NW of the caldera, because of the sparse seismicity within the caldera. The study revealed NNE-SSW extension in that area, consistent with geodetic studies that found a similar extension direction across the Hebgen Lake fault zone interpreted as post-seismic deformation following the 1959 earthquake (Dzurisin et al., 1990; Savage et al., 1993; Puskas et al., 2002). Results from permanent and campaign GPS deployments show a rotation of extension from NNE-SSW in the Hebgen Lake area to ENE-WSW south of the Yellowstone caldera (Puskas et al., 2002).

Waite and Smith (2004) examined for the first time the spatially varying stress field at Yellowstone using the catalog of network-recorded earthquakes. A rotation of extensional stress indicators was observed north of the Yellowstone caldera, where the seismicity was the densest according to the available data. It was impossible to resolve the state of stress within and south of the caldera because those areas were characterized by shallow seismicity and unreliable focal mechanisms. It has been suggested that Yellowstone volcanism interrupted the continuity of the N-S-striking normal faults to the north and south of the Yellowstone caldera, and that the alignment of post-caldera volcanic vents within the caldera may represent zones of weakness that link those features (Ruppel, 1972). In their study, Waite and Smith (2004) showed that the N-S-striking faults to the north of the caldera may not be active anymore, according to the minimum principal stress (σ_3) direction that trends N-S in that area. They showed that this N-S extension might be related to a viscoelastic relaxation in the upper mantle and lower crust after the 1959 Hebgen Lake earthquake and to the northeast migration of the Yellowstone hotspot.

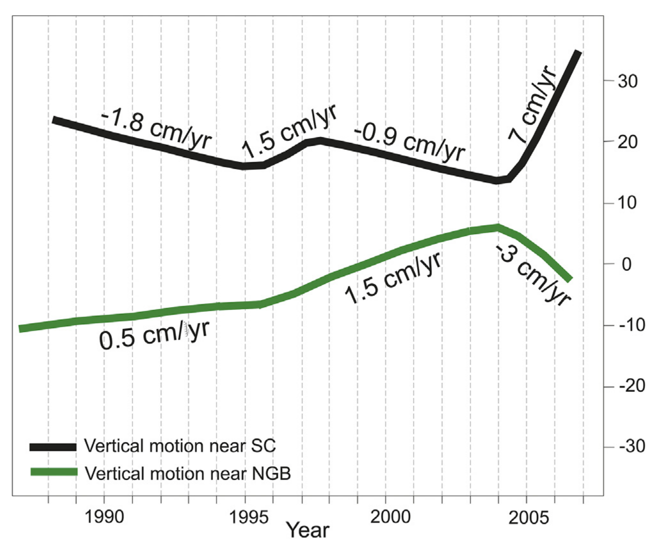

Fig. 2. Time sequence of Yellowstone vertical ground motions. The black line represents the deformation episodes detected within the Yellowstone caldera, in correspondence to the Sour Creek resurgent dome (SC), and the green line in correspondence to the Norris Geyser Basin (NGB) (modified after Chang et al., 2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)