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Spatial analysis of the impacts of the Chaitén volcano eruption (Chile) in three fluvial systems

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A B S T R A C T

The eruption of the Chaitén volcano in May 2008 generated morphological and ecological disturbances in adjacent river basins, and the magnitude of these disturbances depended on the type of dominant volcanic process affecting each of them. The aim of this study is to analyse the morphological changes in different periods in river segments of the Blanco, El Amarillo and Rayas river basins located near the Chaitén volcano. These basins suffered disturbances of different intensity and spatial distribution caused by tephra fall, dome collapses and pyroclastic density currents that damaged hillslope forests, widened channels and destroyed island and floodplain vegetation. Changes continued to occur in the fluvial systems in the years following the eruption, as a consequence of the geomorphic processes indirectly induced by the eruption. Channel changes were analyzed by comparing remote images of pre and post-eruption conditions. Two periods were considered: the first from 2008 to 2009–2010 associated with the explosive and effusive phases of the eruption and the second that correspond to the post-eruption stage from 2009–2010 to 2013. Following the first phases channel segments widened 91% (38 m/yr), 6% (7 m/yr) and 7% (22 m/yr) for Blanco, Rayas and El Amarillo Rivers, respectively, compared to pre-eruption condition. In the second period, channel segments additionally widened 42% (8 m/yr), 2% (2 m/yr) and 5% (4 m/yr) for Blanco, Rayas and El Amarillo Rivers, respectively. In the Blanco River 62 and 82% of the islands disappeared in the first and second period, respectively, which is 6–8 times higher than in the El Amarillo approximately twice the Rayas. Sinuosity increased after the eruption only in the Blanco River but the three study channels showed a high braiding intensity mainly during the first post-eruption period. The major disturbances occurred during the eruptive and effusive phases of Chaitén volcano, and the intensity of these disturbances reflects the magnitude of the dominant volcanic processes affecting each basin. Inputs of sediment from dome collapses and pyroclastic density currents and not ash fall seem to explain morphologic channel change magnitudes in the study segments. The resulting knowledge can facilitate land use planning and design of river restoration projects in areas affected by volcanic eruptions disturbances.

1. Introduction

The morphological characteristics of rivers are functions of the flow regime, sediment supply, historical catchment land use, topography (Rosgen, 1994; Church, 2002), living vegetation and large wood (Buffington, 2012; Gurnell, 2014; Iroumé et al., 2014). Quantitative classifications to evaluate channel patterns and planform geometry have been developed based on parameters such as braided pattern or channel sinuosity (Schumm, 1985; Rosgen, 1996; Buffington and Montgomery, 2013).

Rare but high-magnitude natural events such as volcanic eruptions, wildfires and extreme floods events may supply additional sediment at rates several order of magnitudes higher than

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under presumably undisturbed or less disturbed conditions (Madej, 2001) triggering river channel adjustments (Kataoka and Nakajo, 2002; Dale et al., 2005; Zheng et al., 2014). Among natural events, explosive volcanic eruptions have undoubtedly the potential to disturb entire landscapes provoking substantial hydrological, morphological, ecological responses as well as economic and social impacts (Dale et al., 2005; Pierson and Major, 2014; Zheng et al., 2014). Abundant volcaniclastic material may trigger process-cascades of hydrological and sediment transport process in river systems (Gran and Montgomery, 2005; Pierson and Major, 2014). Specific yields of sediment flushed through watersheds disturbed by eruptions are among the highest recorded (Korup, 2012). The subsequent discharge of sediment and the adjustment of channels may last up to several decades (Hayes et al., 2002; Gran, 2005; Pierson and Major, 2014; Zheng et al., 2014).

Volcanic eruptions may accelerate erosion, dissection and destruction of islands leading to the obliteration of in-channel and riverine vegetation which in turn provides excess material for massive pulses of dead wood into the channels (e.g. Meyer and Martinson, 1989; Ulloa et al., 2015a). In fact, large wood provides potential nuclei for vegetation colonization, forest island growth and coalescence, and, thus, finally forest floodplain development (Fetherston et al., 1995). Hence, islands are vital factors for channel stabilization, aquatic, riverine and riparian biodiversity, trapping sediments, increasing flow resistance (Gurnell and Petts, 2002; Wyrick and Klingeman, 2011; Belletti et al., 2013). Therefore, channel islands may contribute to flood mitigation by lowering flow velocities (Gurnell, 2014).

In a first stage volcanic disturbances are associated primarily with ash fall, dome collapses and pyroclastic density currents (PDCs). Subsequently mass wasting, wood recruitment, fluvial reworking of deposits, and remobilization and re-deposition of tephra takes place. Finally these adjustments may result in a gradual degradation or even a complete elimination of island and floodplain forests (Swanson et al., 2013; Ulloa et al., 2015b). The control of channel island development exerted by vegetation colonization is not static but evolves over time, mainly responding to external factors, such as flow regime, substrate grain size and catchment-scale properties such as geology, land-use and vegetation species pool sustaining colonization (Gurnell, 2014).

The aim of our study is to analyse morphological changes of channel and island systems as well as riparian vegetation cover over time. Therefore, we focus on selected channel segments of three rivers located in the vicinity of the Chaitén volcano that experienced varying disturbances due to diverse earth surface processes of different magnitudes. To this end, we use time series of satellite images covering time steps during both pre- and post-eruption conditions, a methodology which has been validated to identify and classify fluvial island (Picco et al., 2014; Ulloa et al., 2015b) and recognize river morphologic patterns (Ulloa et al., 2015a; Bizzi et al., 2016).

We tested the following hypotheses: (1) major modifications occur immediately after the eruption; (2) the magnitudes of channel geomorphologic changes reflect the dominant volcanic processes and the portion of the catchment affected.

In the subsequent sections we first illustrate the study area, and then we outline the adopted methodology. In the two dedicated final sections we report the obtained results and discuss their main implications with respect to channel morphodynamics of rivers affected by different processes triggered by volcanic activity. We outline as well, based on the insights gained, research priorities to enhance river management from a geomorphic standpoint.

2. Study area

2.1. Chaitén eruption and study area

The Chaitén volcano erupted as the biggest rhyolitic eruption since the eruption of Katmai volcano in 1912 (Pallister et al., 2010; Major and Lara, 2013). The Chaitén volcano (72° 39′7.4 ″W 42° 50′1.2″ S; 1100 m asl in elevation) is located in southern Chile about 150 km south of Puerto Montt and sits about 17 km west-southwest of the much larger and heavily glaciated Michinmahuida volcano (2400 m asl elevation) (Fig. 1). The regional tectonic setting is characterized by active subduction and intra-arc strike-slip tectonics along the Southern Chile Trench and the Liquiñe-Ofqui Fault zone, respectively, and Quaternary arc volcanism in the SVZ (Sepúlveda et al., 2005; Lange et al., 2008; Watt et al., 2011). The latest eruption of the Chaitén produced an ash column to altitudes of about 18–20 km and winds widely dispersed that tephra eastward across Argentina and out to the South Atlantic Ocean (Major and Lara, 2013). About 4 km^2 of forest were severely damaged and the foliage of other approximately 50 km^2 of forest was also affected (Swanson et al., 2013). During the explosive phase between May 2nd and 12th (Major and Lara, 2013) PDCs descending the north-northwest and east-northeast flanks (Major et al., 2013) were followed by an effusive phase lasting approximately nine months. During the first phase, the dome of the volcano rapidly grew accompanied by small collapses, with two major failures occurred between June and November 2008 and again on February 19, 2009. The latter spilled over the crater rim and moved through the Blanco River valley (Major and Lara, 2013; Pallister et al., 2013). The eruption has had several Holocene predecessors (Naranjo and Stern, 2004; Watt et al., 2011; Lara et al., 2013; Amigo et al., 2013).

The process chains induced by the Chaitén eruption comprised tephra fall, dome collapses and pyroclastic density currents that severely damaged hillslope forests, affected the drainage networks, widened channels and destroyed island and floodplain vegetation (Major et al., 2013; Pierson et al., 2013, 2014; Swanson et al., 2013; Ulloa et al., 2015b). Heavy rainfall occurred in May 2008 after the onset of the eruption, causing floods and generating, among others, fast and massive aggradation of the Blanco River due to entrained sediment and large wood (Umazano et al., 2014; Ulloa et al., 2015a). As a consequence, the river changed its course and severely damaged the town of Chaitén, destroying the local airport and forcing the evacuation of the inhabitants (Major and Lara, 2013). In addition, sediment and large wood pulses substantially reduced both island abundance and size in the Rayas River (Ulloa et al., 2015b).

Long-term mean annual rainfall in the city of Chaitén is 3200 mm with a maximum annual rainfall exceeding 4200 mm during the last 15 years (Dirección General de Aguas, online data, www.dga.cl, January 2015). The studied rivers present a rainfall regime with winter peaks and snowfall participation contributing only at higher altitudes. The main 'basins and segments' properties, as well as a detailed description of the major disturbances are summarized in Table 1.

2.2. Study rivers

Here, we focus on three adjacent river basins of Chaitén volcano, namely Blanco (also known as Chaitén), El Amarillo and Rayas (compare Fig. 1 for an overview). Table 1 lists the geomorphic responses to the eruption observed in the distinct basins and their main properties.

The Blanco River headwaters drain the southwest of the Michinmahuida volcanic complex before merging on the southern flanks of Chaitén volcano with Ash or Caldera Creek. The latter drains the