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Understanding landscape dynamics of the Sierra de Juarez, southern Mexico: An exploratory approach using inherited luminescence signals

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ABSTRACT

We explore inherited luminescence signals to generate information about different mechanisms involved in mobilization of debris flows in rivers ($n = 12$) of the Sierra de Juárez (Oaxaca, Mexico), that flow across the Oaxaca and Donaji faults. Sediment samples composed of poly-mineral and poly-grain sizes were optically stimulated using a Pulsed-Photon Stimulated Luminescence unit. In most of the rivers, the luminescence signals intensities fall with increasing distance from their source and the luminescence of different grain size fractions were variable. Our results suggest that mineral grains were transported in the water column without any stratification based on grain sizes, indicating debris flows and/or hyper-concentrated flows. A correlation between the inherited luminescence signals and the mean basin slope provides information about the river basin topography. Our results suggest that mobilization of sediments is related to the steepness of topography produced by the Oaxaca fault formation and inherited luminescence signals has a good potential to unravel the processes involved in the transport of fluvial sediment in mountainous settings of southern Mexico.

1. Introduction

The use of Optically Stimulated Luminescence (OSL) for dating geomorphic processes has increased in the last two decades (Rittenour, 2008). For OSL dating, it is assumed that prior to the deposition and burial of a deposit, the surface of mineral grains has been exposed to sunlight. This process results in zeroing of the geochronological clock of quartz and feldspars (Huntley et al., 1985; Aitken, 1998). The exposure of minerals to sunlight produces an instantaneous resetting, at least in the case of quartz minerals (Godfrey-Smith et al., 1988). There are, however, situations in which the massive transport of mineral grains occurs in turbid fluids and the full resetting of grains is not achieved (Wallinga, 2002; Bishop et al., 2011). Under this condition, the mineral grains contain residual luminescence signals (Aitken, 1998). The residual luminescence is also known as inherited luminescence signals, because a fraction of this luminescence results from the past burial of sediment that is added up to the luminescence produced by the most recent burial event. Inherited luminescence signals are problematic for OSL dating because they produce an overestimation of ages (Galbraith et al., 1999; Duller, 2008). To reduce errors in the age calculation of partially reset deposits, the contribution of inherited luminescence signals needs to be considered. In the last decades, several statistical methods have been proposed to overcome the problem related to the inherited luminescence signals such as the use of radial plots (Galbraith et al., 1999), the application of Minimum Age Models (Cunningham et al., 2011) and the use of the single-grain analysis protocol (Duller et al., 1999; Bush and Feathers, 2003).

Currently, major efforts have been done to reduce the effect of inherited luminescence signals in OSL dating, however, few studies have focused on investigating how inherited signals can be used to provide information about the mechanisms involved in the mobilization of sediment prior to its burial. Rink and Pieper (2001) studied natural residual luminescence signals of the sand grains

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extracted from surface and subsurface of the beach-dune ridges from the Peninsula of Florida. Rink (2003) reported that inherited OSL signals decreased in samples collected from nearshore to offshore in the coast of Israel that receives sediment from the Nile River. Bishop et al. (2005) found inherited luminescence signals in tsunami deposits collected few weeks after the tsunami of 26th of December 2004 hit the coast of Thailand and proposed that the inherited luminescence signals were sourced in sediments dragged from the ocean floor by the tsunami. In another study Bishop et al. (2011) studied the changing of luminescence signals depending on grain sizes in the sediment trapped in a mill dam in Scotland (UK) where the largest grains contained higher luminescence than the smaller what was interpreted as incomplete resetting of large grains transported like bedload as consequence of not being fully exposed to sunlight. Muñoz-Salinas et al. (2012) evaluated luminescence values in lahar deposits of Popocatépetl volcano and observed that for the 1997 lahar, the luminescence values increased with the bulking of a hyper-concentrated flow. Castillo et al. (2014) investigated the presence of inherited luminescence values in rivers incising the Jalisco Block (central west of Mexico), a tectonically active landscape, where erosion rates are believed to be high. These authors regressed the OSL signals with the mean basin channel steepness, in which the latter is indicative of active tectonic zones in the landscape, finding that in the western sector of the Jalisco Block there is a tight and positive correlation between the OSL signals and the mean basin channel steepness. King et al. (2014a; b) explored inherited luminescence signals in fluvio-glacial deposits in Jostedalen, Southern Norway, in order to unravel the processes of sediment transport in proglacial environments. Reimann et al. (2015) tested the degree of OSL signals resetting in several samples obtained from aeolian and coastal environments located at the Dutch Coast (Netherlands) to evaluate the potential of these samples for OSL dating. More recently, Portenga and Bishop (2015) demonstrated that inherited luminescence signals are present in the post-settlement alluvium deposits at the Tablelands in Southwest Australia. They related the presence of inherited luminesce signals with the perturbation of the landscape produced after arrival of Europeans in the 19th Century. At that time the fluvial dynamics was modified from diluted flows, that formed swampy meadows, to hyper-concentrated flows. It is highly possible that the hyper-concentrated flows were formed by the clearing of vast areas of woodlands.

Motivated by the potential in using inherited luminescence signals to evaluate landscape dynamics, the main goal of this study was to assess how inherited luminescence signals can be used in understanding the mobilization of sediments in relatively steep small mountain rivers. For this purpose, we analyzed the sediment extracted from a selection of twelve active channels of Sierra de Juárez (SJ), which is located in Southern Mexico in a tectonically active area. Additionally, topographical and hydrologic metrics are calculated for each of these channels using a GIS and a digital elevation model (DEM).

At SJ, the caliber of sediment and bulky deposits in active channels suggest that these rivers are capable of transporting large volumes of materials. Our main hypothesis is that the sediment in active channels contains inherited signals. We support this hypothesis based on the fact that grains transported in mass and turbid flows are commonly not well-reset (Duller, 2008). We also studied how luminescence signals of river sediment change with respect to the luminescence values obtained from rocks where sediment came from halfway up the valley slopes. Additionally, we assessed the scattering of luminescence values from aliquots of a given sample and explored for variations in luminescence due to changes in the grain size. Finally, we investigated the relationship between the luminescence signals from river sediments with the topography of river basins to determine contrast in sediment mobilization between Oaxaca and Donaji faults.

2. Regional setting

SJ is a mountain range located in the northern part of the State of Oaxaca (southern Mexico). We analyzed twelve rivers that perpendicularly cut into the Cenozoic faults of Oaxaca and Donaji (Fig. 1) (Campos-Enriquez et al., 2013). Rivers flow down from the mountain front for ~8 km of distance descending from an altitude of ~3000 m to ~1000 m. Channels are steep, typical of mountain rivers, the adjacent valley slopes are ~30° (Fig. 2A), promoting the transport of highly concentrated sediment laden-flows. These behave mostly as debris flows, what can be observe by deposits composed by large clasts of <1 m large that are surrounded by a matrix (see Fig. 2B). The main lithology of SJ is Mesozoic metasediments from a mylonitic complex which is geographically bounded by Oaxaca, Donaji and Siempre Viva faults (Fig. 1; Flores-Márquez et al., 2001). Using our classification, rivers 1 to 11 are incising into metasediments of the mylonitic complex. The lithology of terrain cut by river 12 is a Paleozoic granodiorite (Fig. 1). Recent geophysical studies suggest that Oaxaca Fault is a normal fault and it is proposed that last time of activity was sinistral movement along Donaji fault in the Miocene. Donaji fault moved as a transfer fault according to Campos-Enriquez et al. (2010). Rivers 1 to 6 cut orthogonally into Oaxaca fault and rivers 7 to 12 obliquely cut into to Donaji fault. Climate in the area is dry with a mean annual total precipitation of ~600 mm that is mostly recorded during the summer season (Fernandez-Eguiarte et al., 2016) when tropical cyclones are frequently affecting this area (Grodsky and Carton, 2003) and promoting that the highest discharge in these rivers takes place during the summer season when heavy rainfalls occur. A montane cloud forest is very well-preserved in SJ which is composed by a wide variety of tropical species (Álvarez-Arteaga et al., 2008).

3. Materials and methods

3.1. Fieldwork

We extracted one sediment sample for each mountain river (Fig. 2B). Sampling sites were mostly selected at the lower parts of the mountain front in at an altitude between 1520 and 2128 m asl (Table 1). In some of these rivers we observed small dams that local communities use for water supply. We always selected the sampling sites upstream these dams to capture the natural processes controlling sediment deposition in these rivers.

The sampling sites in the rivers were located in the active channels where vegetation was absent. We extracted the sediment in one selected point of the channel that was not inundated at the moment of extraction (see examples of selected sites for extracting the samples in the active channels in Fig. 2B) however; selected sites should have been inundated during the last high-discharge event. Because high-discharge events occur every year in SJ and during these events have place the transportation of large amounts of sediments, all the samples were younger than one year and we assume that, in case of finding luminescence signals in the extracted sediment, these will result from the lack of bleaching during their transport.

The sediment sampled on rivers corresponds with the matrix of deposits (grain sizes <6 mm) and we avoided the sampling of cobbles, pebbles and boulders. For the sediment extraction we covered the surface of the sediment in the channel with a black opaque blanket then, we removed the first 2 cm of materials from