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Spatial distribution analysis of mass movements triggered by the 2005 Kashmir earthquake in the Northeast Himalayas of Pakistan

Muhammad Basharat [a,*], Joachim Rohn [b], Mirza Shahid Baig [a], Muhammad Rustam Khan [a]

[a] Institute of Geology, University of Azad Jammu and Kashmir, Muzaffarabad, Pakistan
[b] GeoZentrum Nordbayern, Friedrich-Alexander-University Erlangen-Nuremberg, Germany

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ABSTRACT

Distribution of the mass movements triggered by the 2005 Kashmir earthquake was analysed in the vicinity of Jhelum Valley, Neelum Valley, and Muzaffarabad in the Northeast Himalayas of Pakistan. Mass movements were mapped using SPOT satellite imagery and field investigations. Geographic information systems (GIS) were used to analyse the relations of the distribution of these mass movements using various parameters, such as distance from an earthquake source (epicentre and fault), topographic parameters (slope steepness, slope aspect, and elevation) and geological units.

The results of the analysis indicate that the mass movement concentration decreases with increased distance from the earthquake epicentre and the reactivated Muzaffarabad Fault. The maximum concentration of mass movements is near the epicentre and a fault. A significant occurrence and concentration of mass movements were evident at slope angles between 31–40°. The preferred orientations of the mass movements were in southerly directions. The concentrations of mass movements differ substantially among various geological units. Mass movements are widely distributed in the Miocene Murree Formation, whereas the concentration of mass movements is higher in the Cambrian Muzaffarabad Formation.

The median mass movement concentration inflicted by the epicentre and the Muzaffarabad Fault exhibited no significant differences ($KS = 0.505$; $p = 0.961$). The results of the PCA reveal that the largest variance in mass movement concentration is attributed to the distance from the epicentre and the Muzaffarabad Fault. The findings suggest that the mass movement concentration is primarily dependent on the distance from the earthquake source. In addition, the topographic parameters and geological units played subordinate roles in the distribution of mass movements.

1. Introduction

The Kashmir Earthquake, which measured a magnitude of M_w 7.6, occurred at 3:50:40 UTC on October 8, 2005. The epicentre was located 18 km north-northeast of Muzaffarabad, the state capital of Azad Jammu and Kashmir, with a focal depth of 26 km (USGS, 2006; Fig. 1). The devastating earthquake is considered the worst natural disaster in Kashmir over the past 100 years (Bendick et al., 2007). The earthquake killed more than 73,000 people, injured 69,000 people and displaced 2.8 million people. The earthquake-related economic loss was estimated at 5.2 billion US $ (Asian Development Bank and World Bank, 2005).

A noteworthy characteristic of this earthquake is the pre-existing active Muzaffarabad Fault (Baig and Lawrence, 1987), which was reactivated along a northwest–southeast striking and northeast dipping (60–85°) fault rupture during the Kashmir earthquake (Baig, 2006; Fig. 1). The fault rupture forms the topographic front. Based on aerial photograph interpretation, Nakata et al. (1991) mapped the main part of this fault, which was known as the active Tanda Fault, prior to the earthquake. The satellite images after the 2005 Kashmir earthquake suggested coseismic surface faulting for an approximately 70 km stripe from Balakot to Bagh (Avouac et al., 2006; Fujiwara et al., 2006; Kaneda et al., 2008). The field evidence of the surface rupture was first reported by Baig (2006). However, the first detailed field mapping of the surface rupture associated with the 2005 Kashmir earthquake was presented by Kaneda et al. (2008). They suggested that the surface rupture extended from Balakot to Bagh with a maximum vertical separation of 7.5 m. The mapped surface rupture trace indicated that the active fault or the fault segments within the Sub-Himalayas was responsible for the earthquake, rather than the Main Boundary Thrust (MBT) or the Main Frontal Thrust (MFT). The fault coincides with the surface trace of the MBT but with an opposite sense of separation. The rupture was initiated in the deep sections of the northern and central segment boundaries.

The earthquake affected an area of approximately 7500 km^2 (Owen et al., 2008). The total number of mass movements exceeded 2400 (Sato et al., 2007). The mass movements primarily consist of rock falls, debris falls, soil collapse, rock slides and rock avalanches (Classification after Varnes, 1978). The maximum volume of the mass movements extends 9.8×10^7 m^3, which was estimated for the Hattian Bala rock avalanche (Basharat et al., 2012).

* Corresponding author. Tel.: +92 3009860651.
E-mail address: basharatgeo@yahoo.com (M. Basharat).

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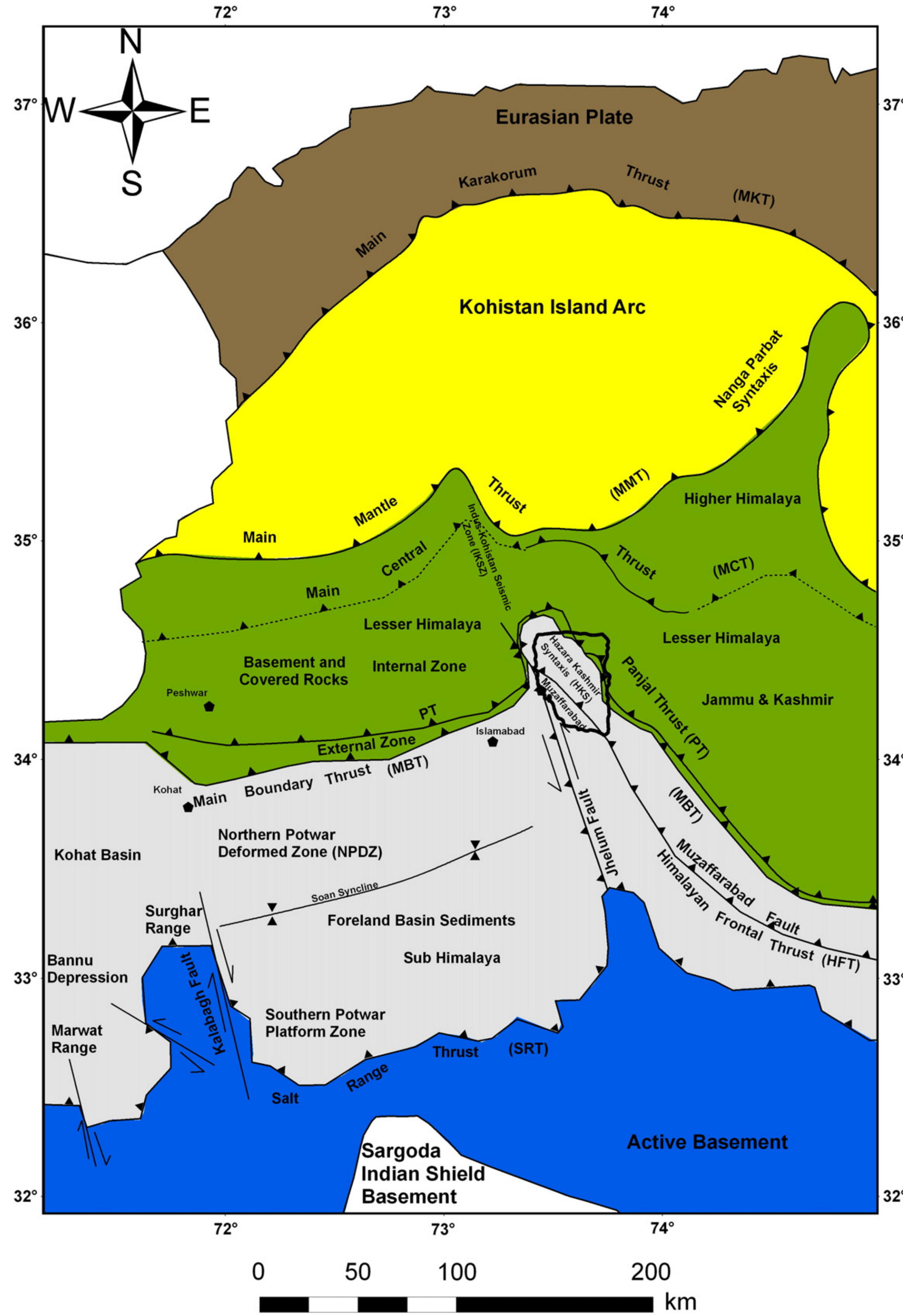

Fig. 1. Regional tectonic map of the northwest Himalayas in Pakistan. The investigated area is located near the Muzaffarabad Fault and the epicentre of the 2005 Kashmir earthquake, which is denoted by a polygon (Compiled after Wadia, 1931; Calkins et al., 1975; Baig and Lawrence, 1987; Greco, 1991; Avouac et al., 2006). The geographical location map of Pakistan (compiled from Kamp et al., 2008).

Numerous studies have been conducted on the correlation of mass movement distribution with geological units, distance from the earthquake source and slope steepness (Keefer, 2000; Khazai and Sitar, 2003; Wang et al., 2006; Qi et al., 2010). Various studies have been conducted on mass movements associated with the 2005 Kashmir earthquake. Sato et al. (2007) studied the distribution of mass