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Catastrophic valley fills record large Himalayan earthquakes, Pokhara, Nepal

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ABSTRACT

Uncertain timing and magnitudes of past mega-earthquakes continue to confound seismic risk appraisals in the Himalayas. Telltale traces of surface ruptures are rare, while fault trenches document several events at best, so that additional proxies of strong ground motion are needed to complement the paleoseismological record. We study Nepal's Pokhara basin, which has the largest and most extensively dated archive of earthquake-triggered valley fills in the Himalayas. These sediments form a 148-km^2 fan that issues from the steep Seti Khola gorge in the Annapurna Massif, invading and plugging 15 tributary valleys with tens of meters of debris, and impounding several lakes. Nearly a dozen new radiocarbon ages corroborate at least three episodes of catastrophic sedimentation on the fan between ~700 and ~1700 AD, coinciding with great earthquakes in ~1100, 1255, and 1344 AD, and emplacing roughly >5 km^3 of debris that forms the Pokhara Formation. We offer a first systematic sedimentological study of this formation, revealing four lithofacies characterized by thick sequences of mid-fan fluvial conglomerates, debris-flow beds, and fan-marginal slackwater deposits. New geochemical provenance analyses reveal that these upstream dipping deposits of Higher Himalayan origin contain lenses of locally derived river clasts that mark time gaps between at least three major sediment pulses that buried different parts of the fan. The spatial pattern of ^{14}C dates across the fan and the provenance data are key to distinguishing these individual sediment pulses, as these are not evident from their sedimentology alone. Our study demonstrates how geomorphic and sedimentary evidence of catastrophic valley infill can help to independently verify and augment paleoseismological fault-trench records of great Himalayan earthquakes, while offering unparalleled insights into their long-term geomorphic impacts on major drainage basins.

1. Introduction

Destructive earthquakes such as the ones that killed nearly 9000 people in Nepal in 2015 are a direct consequence of the rapid convergence of the Indian and Eurasian continental plates, and call for reliable seismic risk assessments to mitigate future losses in the Himalayan region. The record of instrumental records of strong seismic ground shaking is limited to few decades, so that researchers rely on methods of paleoseismology. Historic documents mention several large earthquakes in the past millennium, but the return periods of major fault ruptures and possible connections to geological evidence remain partly elusive (Bollinger et al., 2014). The search for a consistency between historical reports and fault-trench studies has fueled a lively debate about the magnitudes and rupture lengths of potential Himalayan megathrust earthquakes (Mugnier et al., 2013; Sapkota et al., 2013; Rajendran et al., 2015; Bollinger et al., 2016; Mishra et al., 2016). Most paleoseismological data come from fault trenches, historical records, offset river terraces, seismically deformed or liquefied sediments, and have so far been tied to five major earthquakes

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since about 1100 AD (Bollinger et al., 2016). Blind fault ruptures, such as during the 2015 Gorkha earthquakes, however, limit a comprehensive coverage by fault trenching alone. Few trenches reveal data on more than one large fault rupture, and a viable chance of missing out on past large earthquakes remains (Sapkota et al., 2013; Mishra et al., 2016). Other earthquake proxies such as giant rockslide deposits (Blöthe and Korup, 2013) or precariously balanced boulders (Balco et al., 2011) have seen little application in the Himalayas, though demand for alternative sources of information about past earthquakes is high.

To meet this demand, we investigate the Pokhara Formation, a suite of catastrophic valley fills in the Lesser Himalayas of Nepal (Fort, 1987; Fort and Peulvast, 1995; Fort et al., 2009); these valley fills appear to have formed in the wake of several medieval earthquakes (Schwanghart et al., 2016). Our objective is to derive from these valley fills a catalogue of diagnostic sedimentary and geomorphic features of past earthquake-triggered sedimentation. We do so by reviewing, partly building on, and refining previous work (Hagen, 1969; Gurung, 1970; Hormann, 1974; Yamanaka et al., 1982; Fort, 1987; Fort et al., 2009; Schwanghart et al., 2016). We add new radiocarbon, sedimentological and geomorphic, provenance, dGPS, and laser scanning data that highlight how the Pokhara basin aggraded dramatically in at least three major pulses. We consolidate an existing chronology (Schwanghart et al., 2016) of the Pokhara Formation with 11 new ^{14}C ages, demonstrate that the formation took less than a millennium to form, and test further its relation to medieval earthquakes, based on new data on sediment characteristics, lithofacies, and provenance.

2. Study area

The Nepal Himalayas straddle the active collision zone of the Indian and Eurasian tectonic plates, where rock uplift rates are high, monsoonal precipitation is intensive, and erosion is rapid (Lavé and Avouac, 2000, 2001). Nepal's second largest and fastest growing city Pokhara (28°15′N, 83°58′E, 870 m) lies in the "Pahar" (midland) region, pinched between the Lesser Himalaya in the south and the Higher Himalayan Annapurna Massif in the north (Fort, 2010) (Figs. 1 and 2A). More than 300,000 people have settled in and around Pokhara since about 1700 AD, and its population tripled in the past 25 years (Rimal et al., 2015). Elevation rises from 1000 m north of the city to 8000 m over only ~20 km of horizontal distance, forming one of the steepest topographic gradients on Earth. This physiographic transition (Wobus et al., 2003) or High Himalayan Front (Godard et al., 2012) largely coincides with the location of the Main Central Thrust (MCT), a structurally complex, north dipping shear zone (Hodges et al., 1996). The Higher Himalayan Crystalline Series (HHC) (Le Fort et al., 1987; Martin et al., 2005) consists mainly of Precambrian high-grade metamorphic quartzite, schist and gneisses north of the MCT. The South Tibetan Detachment Zone separates High Himalayan metamorphic rocks from Paleozoic and Mesozoic marine calcareous metasediments and limestones of the northern Tethyan Sediment Series (TSS) forming the peaks of the Annapurna Massif (Mascle et al., 2012; Dhital, 2015). South of the MCT, the Pokhara basin features Precambrian metamorphic sandstones, shales, and dolomites, though mostly Paleozoic phyllites and schists of the Lesser Himalayan Series (LHS) (Dhital, 2015).

We focus on the youngest fill of the Pokhara basin, the Pokhara Formation (Yamanaka, 1982; Fort, 1987), which forms an alluvial fan that covers ~148 km^2 from 1350 m to 400 m asl, and sustains most of Pokhara's urban area. The fan is incised by the Seti Khola (= 'river'), which drains the Annapurna massif, originating in Sabche cirque and plunging through a steep and narrow bedrock gorge. The catchment area upstream of the fan head is ~270 km^2, and

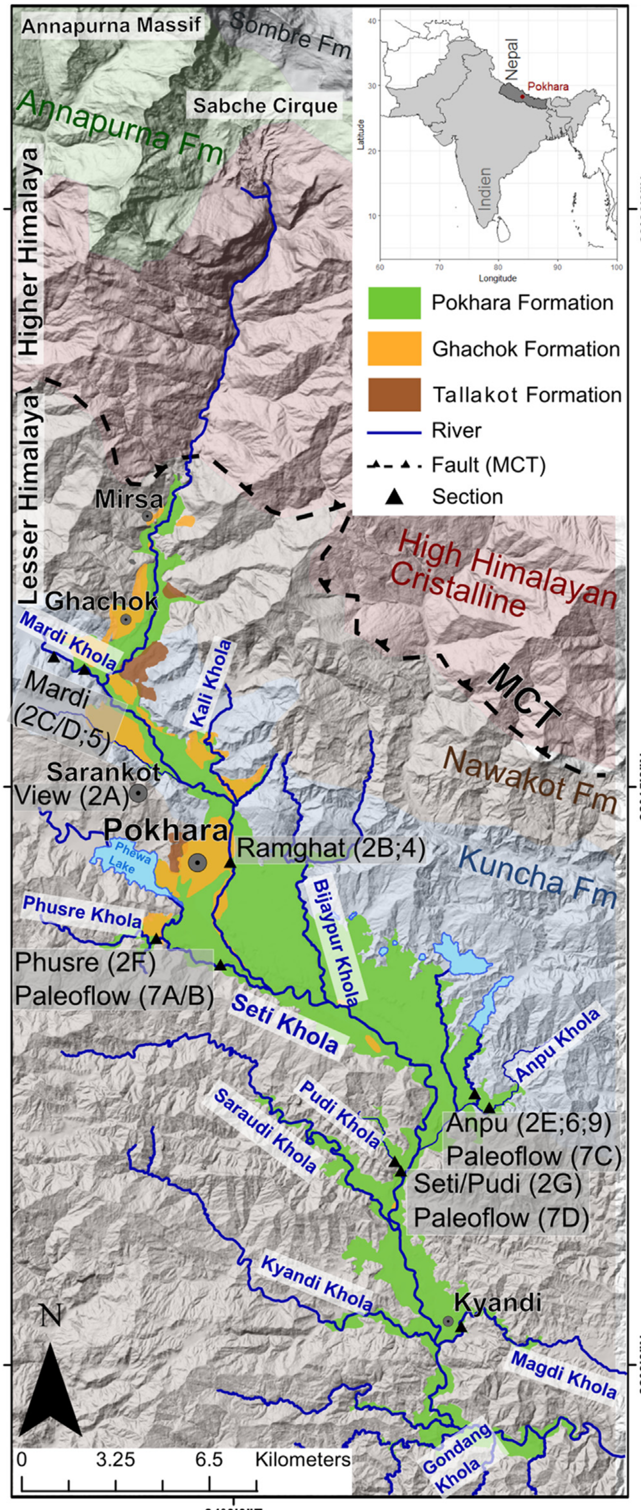

Fig. 1. Overview map of the Pokhara Valley. Topography and simplified stratigraphy of the Pokhara basin, Nepal Himalaya, with the known extent of the three major stratigraphic formations. Numbers and letters in brackets following place names keyed to subsequent figures. Shaded relief data from 15-m digital elevation model. The geological setting is dominated by the Higher Himalayan rocks (Sobre Fm, Annapurna Fm, HHC) featuring mainly gneisses and Nilgiri Limestone, and the Lesser Himalayan rocks known as the Nawakot unit. The Kuncha Formation forms the lower part of this unit and contains mostly phyllites and quartzites (geological map simplified after Martin et al., 2005).