Potential Natural Hazards in Kathmandu, Nepal: Lessons from Stratigraphic Analysis of the Pleistocene Succession in the Kathmandu Valley

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Abstract: The Kathmandu Valley is an intermontane piggyback basin filled with more than 550 m of fluvio-lacustrine deposits overlying irregular bedrock. Over the past two decades, rapid and largely unregulated urban expansion has heightened concerns about geohazards. Stratigraphic and chronological studies conducted over the past 25 years indicate that the basin once hosted an extensive paleolake represented by the Gokarna, Thimi, and Patan Formations, which were deposited during successive lake-level rises between ca. 50 ka and 10 ka.

The Pleistocene succession records several large-scale natural hazards, including subaqueous landslides and associated tsunamis, soft-sediment deformation involving mud softening and fluidization, mud volcanism, widespread lateral spreading, and liquefaction reaching depths of up to 5 m. The most extensive event involved kilometer-scale lateral spreading across the delta plain, most likely triggered by a major paleoearthquake.

These findings demonstrate that the Kathmandu Valley has repeatedly undergone catastrophic deformation of its unconsolidated lacustrine sediments during past seismic events. Because thick, soft muds of the Gokarna Formation still occur widely at shallow depths, similar large-scale ground deformation may recur during future earthquakes. Comprehensive geotechnical studies and stricter control of urban development are urgently needed to mitigate seismic risks in this rapidly expanding basin.

Keywords: ***Kathmandu Valley, Lateral spread, Natural hazards, Pleistocene lake succession.***

Introduction

Nepal's capital city, Kathmandu, has developed within the Kathmandu Valley, a piggyback-type intermontane basin. Over the past two decades, the city has rapidly expanded into surrounding suburban areas, and today, waves of residential and commercial development have spread across the entire basin. However, as shown by the damage caused by the 2015 Gorkha Earthquake, the city remains highly vulnerable to natural disasters. In this presentation, I introduce environmental changes in the basin and various natural hazards recorded in the Pleistocene succession, based on geological investigations conducted in the Kathmandu Valley over the past 25 years.

Geologic Setting

The Kathmandu Valley contains more than 550 m of fluvio-lacustrine deposits underlain by a highly irregular bedrock surface. Near the surface, Pleistocene sediments younger than about 50,000 years are exposed, although many have been removed by erosion or urban development. In the central part of the basin, three major lacustrine terraces—Gokarna, Thimi, and Patan, in descending order of elevation—are distributed. The deposits composing these terraces are as follows: the Gokarna Terrace contains the Gokarna Formation (ca. 50–34 ka), overlain by the Tokha Formation (ca. 19–14 ka); the Thimi Terrace contains the Thimi Formation (ca. 33–25 ka); and the Patan Terrace consists of the Patan Formation (ca. 14–10 ka).

Radiocarbon ages of organic materials obtained from peat and other wetland deposits within these formations indicate that each formation was deposited during a phase of lake-level rise. In the Gokarna Terrace, the Tokha Formation overlies the Gokarna Formation, representing sediments formed during a lake-level rise immediately after the Last Glacial period. In addition, at elevations higher than the Gokarna Terrace, sediments locally known as *Kalomato* ("black mud") are also interpreted as lacustrine deposits. These findings suggest that the entire Kathmandu Valley was once occupied by a large lake and that water may have overflowed through low saddles in the surrounding mountains into adjacent areas.

Record of Natural Hazards in The Pleistocene Succession

Major natural hazards identified from the stratigraphic record include:

- subaqueous landslides and resultant tsunamis;
- fluidization of mud layers accompanied by the formation of mud volcanoes and lateral spreading on the delta plain;
- large-scale liquefaction reaching depths of up to 5 m.

Subaqueous landslide and tsunami deposits are clearly observed in the Gokarna and Thimi Formations in the southeastern part of the Kathmandu Valley, where one of the basin's faults is located. These deposits occur within alternating fine sand and silt layers. Exposed sections consist mainly of blocky masses of mud and sand, typically up to about one meter thick, dipping at approximately 10°, and interpreted as slide deposits that halted on the delta front. The strata containing these mud and sand blocks alternate with fine sand beds exhibiting wave-generated sedimentary structures such as hummocky cross-stratification, suggestive of strong waves. In some places, sand layers with such structures are interbedded within floodplain deposits, indicating repeated tsunami incursions generated by small-scale subaqueous landslides.

Within the delta-plain succession dominated by muddy deposits, numerous mud layers exhibit evidence of subsurface softening or fluidization. Immediately above these layers, mud beds showing contemporaneous brittle deformation are also observed. At several sites, sand–mud layers containing abundant mud clasts with limited lateral distribution have been identified. Considering that these mud clasts are compositionally deformed, that similar deposits are absent in surrounding strata, and that mudflow deposits occur in nearby fluvial successions, these sand–mud layers are interpreted as deposits derived from small-scale mud-volcano activity associated with mud softening and fluidization.

Among the various natural hazard records in the Pleistocene succession of the Kathmandu Basin, the most prominent are the lateral spreads, interpreted as being associated with the fluidized mud layers described above. The displaced mass related to this horizontal movement extends over an area of at least one square kilometer on the delta plain at that time. Part of this mass is thought to have slid into the paleolake, dragging inland portions horizontally and producing a large-scale landslide-like displacement. Strata of the same age throughout the basin contain widespread evidence of this event, including liquefied sand layers up to 5 m thick, subaqueous landslide deposits, small mud volcanoes, and tsunami deposits. Judging from these stratigraphic records, this event represents the largest natural hazard recorded in the basin and was most likely triggered by a major earthquake.

Lessons From Natural Hazard Records

At present, the Kathmandu Basin is undergoing rapid and extensive urbanization. Observations indicate that land development is proceeding with little regulation. Although the ancient lake has long vanished and the risk of tsunamis no longer exists, thick lacustrine muds of these formations still extend from the basin center toward its margins. In areas where these muds lie shallow beneath the surface, the potential for large-scale horizontal deformation during future major earthquakes cannot be ruled out. Therefore, comprehensive geotechnical investigations are urgently needed to prepare for such future hazards.