Journal of Asian Earth Sciences xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Review

# Segmentation of the Himalayan megathrust around the Gorkha earthquake (25 April 2015) in Nepal

Jean-Louis Mugnier [a,b,*], François Jouanne [a], Roshan Bhattarai [c], Joaquim Cortes-Aranda [a,f], Ananta Gajurel [c], Pascale Leturmy [d], Xavier Robert [e], Bishal Upreti [c], Riccardo Vassallo [a]

[a] Université Savoie Mont Blanc, ISTerre, F-73376 Le Bourget du Lac, France
[b] CNRS, ISTerre, F-73376 Le Bourget du Lac, France
[c] Department of Geology, Tribhuvan University, Kathmandu, Nepal
[d] Université Cergy-Pontoise, France
[e] Université Grenoble Alpes, ISTerre, F-38041 Grenoble, France
[f] Departamento de Ciencias de la Tierra, Universidad de Concepción, Chile

A R T I C L E  I N F O

*Article history:*
Received 31 December 2015
Received in revised form 12 January 2017
Accepted 13 January 2017
Available online xxxx

*Keywords:*
Megathrust
Barriers
Duplex
Himalayan earthquakes
Kathmandu
Structural geology

A B S T R A C T

We put the 25 April 2015 earthquake of Nepal (Mw 7.9) into its structural geological context in order to specify the role of the segmentation of the Himalayan megathrust. The rupture is mainly located NW of Kathmandu, at a depth of 13–15 km on a flat portion of the Main Himalayan Thrust (MHT) that dips towards the N-NE by 7–10°. The northern bound of the main rupture corresponds to the transition towards a steeper crustal ramp. This ramp, which is partly coupled during the interseismic period, is only locally affected by the earthquake. The southern bound of the rupture was near the leading edge of the Lesser Himalaya antiformal duplex and near the frontal footwall ramp of the upper Nawakot duplex. The rupture has been affected by transversal structures: on the western side, the Judi lineament separates the main rupture zone from the nucleation area; on the eastern side, the Gaurishankar lineament separates the 25 April 2015 rupture from the 12 May 2015 (Mw 7.2) rupture. The origin of these lineaments is very complex: they are probably linked to pre-Himalayan faults that extend into the Indian shield beneath the MHT. These inherited faults induce transverse warping of the upper lithosphere beneath the MHT, control the location of lateral ramps of the thrust system and concentrate the hanging wall deformation at the lateral edge of the ruptures. The MHT is therefore segmented by stable barriers that define at least five patches in Central Nepal. These barriers influence the extent of the earthquake ruptures. For the last two centuries: the 1833 (Mw 7.6) earthquake was rather similar in extent to the 2015 event but its rupture propagated south-westwards from an epicentre located NE of Kathmandu; the patch south of Kathmandu was probably affected by at least three earthquakes of Mw $\geqslant$ 7 that followed the 1833 event a few days later or 33 years (1866 event, Mw 7.2) later; the 1934 earthquake (Mw 8.4) had an epicentre ~170 km east of Kathmandu, may have propagated as far as Kathmandu and jumped the Gaurishankar lineament.

This combined structural approach and earthquake study allows us to propose that the MHT in the central/eastern Himalaya is segmented by stable barriers that define barrier-type earthquake families. However for each individual earthquake within a family, the rupture histories could be different. Furthermore, the greatest earthquakes could have broken the barriers and affected the patches of several families. The concept of a regular recurrence of characteristic earthquakes is therefore misleading to describe the succession of Himalayan earthquakes.



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* Corresponding author at: Université Savoie Mont Blanc, ISTerre, F-73376 Le Bourget du Lac, France.
*E-mail address:* jean-louis.mugnier@univ-savoie.fr (J.-L. Mugnier).

http://dx.doi.org/10.1016/j.jseaes.2017.01.015
1367-9120/

## 1. Introduction

The Nepal earthquake of 25 April 2015 followed a serie of great earthquakes that damaged the Kathmandu basin (Chitrakar and Pandey, 1986; Pant, 2002; Mugnier et al., 2011; Bollinger et al., 2014). It is the first event simultaneously recorded by high-rate GPS (e.g. Avouac et al., 2015), teleseismic waves (e.g. Fan and Shearer, 2015), SAR imaging (e.g. Lindsey et al., 2015), strong-motion recordings (e.g. Grandin et al., 2015) and by a local seismometer network (Adhikari et al., 2015).

However, the April 2015 earthquake remains enigmatic in terms of the classical understanding of the Himalayan seismic cycle (e.g. Avouac et al., 2001) for several reasons:

(1) Great earthquakes generally initiate at the brittle/ductile transition of the MHT and propagate along ramp and flat segments of the brittle part of the crust (e.g. Avouac et al., 2001). However, the northern part of the 2015 rupture zone was located several tens of kilometres to the south of the interseismic locking line defined from geodetic data (e.g. Jouanne et al., 2016) and did not show any clear evidence of dip variations on the MHT (e.g. Avouac et al., 2015; Yagi and Okuwaki, 2015). This raises the following questions: did the 2015 earthquake initiate at the brittle transition and did it affect a ramp?
(2) Numerous great earthquakes broke the MHT until they reached the surface (e.g. Kumar et al., 2006) whereas the 2015 earthquake was characterized by a lack of slip on the shallower (southern) part of the MHT (Galetzka et al., 2015) and did not reach the surface. The following questions are then raised: why is there no propagation further south? Is there a stable barrier (Aki, 1979) or a transient effect in the propagation dynamic?
(3) The 2015 rupture followed three earthquakes in the Kathmandu area during the last two centuries (Fig. 1): the 1934 (Dunn et al., 1939), 1866 (Oldham, 1883) and 1833 events (Bilham, 1995). Do they form a repetition of characteristic earthquakes (Schwartz et al., 1981; Schwartz and Coppersmith, 1984)?
(4) Are the ruptures of the successive earthquakes overlapped or separated by strong zones along the MHT that act as barriers when the stress level does not reach the rupture strength or as asperities when they break (Aki, 1984)?

In order to answer these questions, the role of the geological structures in the seismic cycle has to be considered. A consistency between local reductions in stress estimated from strong motion during earthquakes and those inferred from geological observation has been evidenced (Aki, 1984); this consistency supports the possibility of predicting strong motion data for earthquakes directly from the geological interpretation of the causative fault. In a thrust system, a geometric framework based on flats, ramps and related folds is classically used (e.g. Boyer and Elliot, 1982) whereas the geometry can be considered as a succession of kinematic increments (Endignoux and Mugnier, 1990). Seismic events integrate the release of elastic deformation stored during the seismic cycle and therefore furnish the minimum increment of irreversible deformation (Sibson, 1983) that affects a thrust system.

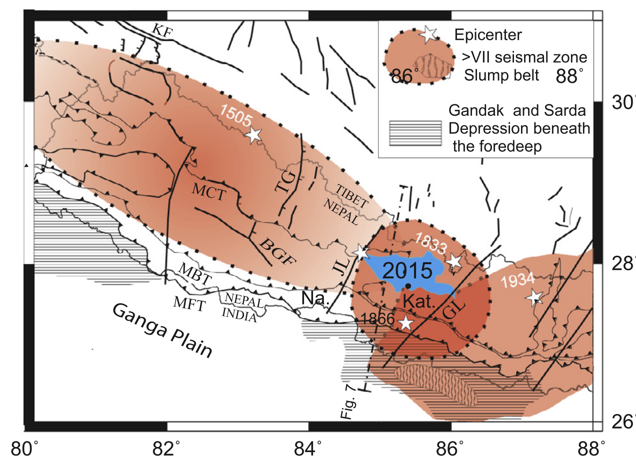


**Fig. 1.** Location of the rupture of the April 2015 earthquake (after Grandin et al., 2015), other historic Himalayan earthquakes and the main Himalayan tectonic structures. MFT, MBT and MCT stand for Main Frontal Thrust, Main Boundary Thrust and Main Central Thrust, respectively. Kat. stands for Kathmandu and Na. for Narayani dun. 1934 epicentre after Chen and Molnar (1977), 1866 epicentre after Szeliga et al. (2010), 1833 epicentre after Mugnier et al. (2013), and 1505 epicentre after Ambraseys and Douglas (2004). The MKS isoseismal contour intensity = VII modified from Ambraseys and Douglas (2004) for the 1934 and 1833 events and inferred for the 1505 event following Ambraseys and Jackson (2003). The lineaments and active faults transverse to the Himalayan belt follow Mugnier et al. (1999), Kayal (2008) and Silver et al. (2015) (GL: Gaurishankar lineament; JL: Judi lineament; BGF: Bhari Gad Fault; TG: Takhola graben; KF: Karakoram Fault).

In order to link earthquakes and geological structures in the central Himalaya, we recall in this paper: (1) the geometry of the crustal-scale structures (e.g. Pearson and De Celles, 2005; Kayal, 2008; Dhital, 2015); (2) the location of the active tectonics of central Nepal (Delcaillau, 1992; Leturmy, 1997; Lavé and Avouac, 2000; Dasgupta et al., 2000); (3) the succession of historic earthquakes (e.g. Chen and Molnar, 1977; Ambraseys and Douglas, 2004; Mugnier et al., 2011) including detailed knowledge of the 2015 earthquake. A detailed comparison is performed between the 2015 earthquake and the geological structures in order to

Please cite this article in press as: Mugnier, J.-L., et al. Segmentation of the Himalayan megathrust around the Gorkha earthquake (25 April 2015) in Nepal. Journal of Asian Earth Sciences (2017), http://dx.doi.org/10.1016/j.jseaes.2017.01.015