Is Himalaya consuming the Indo-Gangetic plain?

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Abstract

Controlled source seismic is a powerful method that yields vital insights into subsurface structures, making it a widely utilized technique in geophysical investigations. In our current study conducted in the Kumaon Himalaya, we employed active seismic data to generate a high-resolution image of the subsurface. Our main objective was to investigate the region encompassing the Kaladungi fault (KF), which is recognized as an imbricated fault within the Himalayan Frontal Thrust (HFT) system and Indo-Gangetic plain. By utilizing this approach, we made significant observations regarding the general stratigraphy of the region. Notably, we identified a gentle northward-dipping decollement layer with a two-way travel time (TWTT) range of 3 to 3.2 seconds. Moreover, we observed that the KF causes a distinct break in the Upper Siwalik formation of ~ 0.2 seconds TWTT. The Upper Siwalik rock in this area exhibited velocities ranging from 1.8 to 2.8 km/s. Our seismic image analysis also revealed the development of a new blind fault rooted from the decollement. This newly formed fault has the potential to rupture the Indo-Gangetic plain in the future. By presenting these findings, we contribute to a deeper understanding of the subsurface dynamics in the region. Our study highlights the importance of controlled source seismic investigations in unraveling the complexities of geological structures and assessing potential seismic hazards.

Keywords

Himalayan Frontal Thrust, Earthquake, Fault propagation, Kaladungi Fault, Kumaon Himalaya, Central Seismic Gap

1. Introduction

The ongoing collision between the Indian and Eurasian plates, which started around 55 million years ago (Ma), has had profound geological implications for the Himalayan region. This collision has resulted in various geological phenomena, including crustal shortening, significant uplift of the topography, and the formation of three prominent fold-thrust belts along the Himalayan arc (Valdiya, 2002).

These fold-thrust belts include the Main Central Thrust (MCT) belt, which emerged approximately 20-23 million years ago and separates the Higher Himalayas from the Lesser Himalayan sequence (Kumar et al., 2006). South of the MCT lies the Main Boundary Thrust (MBT), marking the boundary between the Lesser Himalayas and the Sub-Himalayan sequences (Valdiya, 1992). The youngest and most active thrust system is the Himalayan Frontal Thrust (HFT) belt, with an average northward dip of 30°, separating the Sub-Himalayan sediment from the Indo-Gangetic plain (Nakata, 1972; Valdiya, 1992). All of these thrust systems are interconnected and linked to the Main Himalayan Thrust (MHT), which acts as a boundary between the Indian plate and the overlying Himalayan wedge (Zhao et al., 1993).

The ongoing convergence between the Indian and Eurasian plates, with a convergence rate of ~ 50 mm/year, generates slip along the Main Himalayan Thrust (MHT) and has led to significant earthquakes in the past. Notable historical earthquakes include the 1905 Kangra (Mw 7.8), 1934 Nepal-Bihar (Mw 8.4), 1950 Assam (Mw 8.4), 2005 Kashmir (Mw 7.6), and 2015 Nepal (Mw 7.8) earthquakes (Bilham et al., 2001)

Despite the ongoing convergence, significant portions of the active Himalayan arc still remain unruptured. This has led to the existence of three seismic gaps, namely the Kashmir Gap, the Central Seismic Gap (CSG), and the Assam Gap, which span the entire Himalayan arc. Geodetic measurements indicate an accumulation of 15 to 20 mm/year of convergence across the Himalayas (Banerjee and Burgmann, 2002).

The Central Seismic Gap (CSG) has been identified as a region of great vulnerability for future earthquakes. It poses a significant threat to the densely populated Indo-Gangetic plain (Bilham et al., 2001). Therefore, conducting a detailed study of the subsurface structure can provide a better understanding of the ongoing tectonics and enable more accurate hazard assessment planning.

Our study focuses on the Kumaon Himalaya region, aiming to assess the impact of ongoing tectonics on the Indo-Gangetic plain. We utilize an active seismic dataset to gain valuable insights of the subsurface.

2. Study Area

The study area near Pawalgarh in Uttarakhand, India, is situated within the Sub-Himalayan zone of the Kumaon Himalayas (Figure 1), renowned for its high seismic activity (Malik et al., 2014). This region has experienced significant tectonic movements, resulting in the creation of intermontane synclinal valleys such as the Dun and Doon valleys.

The prevalent rock formations in this area primarily comprise alluvial gravel, silt, sandstone, and mudstone, which are part of the Siwalik Formation. These formations have a geological timespan ranging from the Lower Pleistocene to the Middle Miocene (Parkash et al., 1980). Separating the Quaternary alluvial deposits from the Sub-Himalayan zone is the Himalayan Frontal Thrust (HFT), a prominent feature in the region (Nakata, 1972).

The topography of the region is significantly influenced by the Kaladungi Fault (KF), a low-angle fault associated with the HFT (Kumar et al., 2006). The Dabka and Baur rivers have played a significant role in shaping the Kaladungi alluvial fan, with their courses being influenced by ongoing tectonic activities (Kumar et al., 2006; Malik et al., 2014).

KF is characterized as an imbricated fault of the HFT due to ongoing convergence, consequently affecting the surface morphology. Verma et al. (2019 and 2023) have provided an extensive shallow-subsurface velocity model based on the analysis of ambient noise data. Their study reported Rayleigh wave group velocities ranging from 400 m/s to 1300 m/s, indicating loose to semi-consolidated sediment. Additionally, they have determined the orientation of the HFT based on the velocity model. Significant role of the Dabka and Baur rivers in shaping the surface morphology has been noted by previous studies (Malik et al., 2014; Yelisetti et al., 2021). Luirei et al. (2015) have reported low-velocity terrace deposition, a finding that aligns with the velocity model presented by Verma et al. (2021) and Verma and Ghosal (2021).

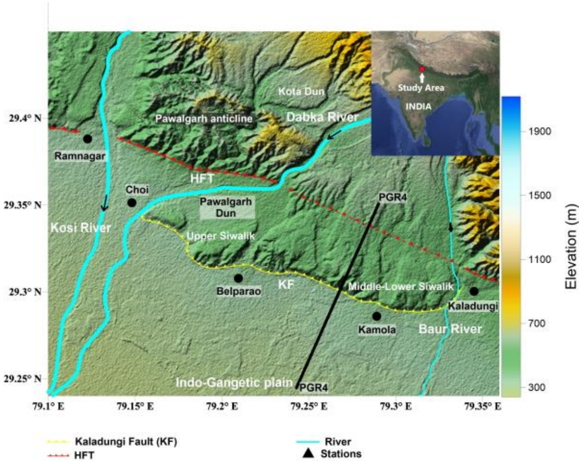

Figure 1: Map of the study area in Uttarakhand, India that depict the River Kosi, Dabka, and Baur, marked with blue lines running from west to east. The Himalayan Frontal Thrust (HFT) and Kaladungi Fault (KF) indicated with red and yellow markings, respectively. To the south of the KF, the map show the Indo-Gangetic plain. Additionally, a black line representing profile PGR4, along which the seismic dataset was collected.

3. Data and Methodology

Seismic data along PGR4 were acquired by Oil India Limited (OIL) using a split-spread configuration (Figure 2). This involved placing 60 channels on each side of the shot. To effectively mitigate shot-generated noise, several measures were implemented.

To begin, a near offset of 250 m was carefully maintained. This decision ensured that the distance between the shot source and the nearest receiver was relatively short, reducing the potential for noise interference. Furthermore, a group interval of 50 m was utilized, and CDP of 25 m, allowing for optimal spacing between receivers.

In addition, a far offset of 3200 m was selected, providing a sufficient distance between the shot source and the farthest receiver. This ensured that the seismic data collected reflected a broader range of subsurface information.

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During the acquisition process, blast holes were drilled to a depth of 15 m, and a load of 5 kg was applied. These parameters were carefully chosen to generate the desired energy for the seismic survey while maintaining safety considerations.

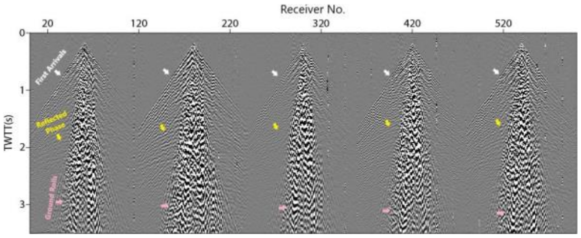

Figure 2: The raw shot gather collected along PGR4 depicts different phases, including first arrivals, reflected phases, and ground rolls.

Overall, the split-spread configuration, combined with the specific offsets and blast parameters, allowed for effective acquisition of seismic data along PGR4, minimizing shot-generated noise and enhancing the quality of the acquired data.

3.1. Reflection seismic processing: Reflection seismic, has emerged as a widely employed geophysical method for obtaining high-resolution subsurface images (Powers et al., 1998).

Firstly, we performed pre-processing to remove unwanted noise and artifacts from the acquired seismic data, enhancing the signal-to-noise ratio and improving the quality of the subsurface image. Additionally, band-pass filtering was applied to isolate the desired frequency range of the seismic waves.

To address low-frequency noise caused by ground rolls, which can obscure subsurface information, we applied a low-frequency array filter. This filter suppressed the ground roll noise and enhanced the visibility of subsurface reflections.

Accurate estimation of subsurface velocities is crucial for correctly positioning seismic events in time. Followed by velocity analysis to determine the velocity field of the subsurface layers. Then we applied Normal Moveout (NMO) correction to account for the varying arrival times of reflections at different offsets, aligning them to their common midpoint position.

Stacking, the process of combining seismic traces from different source-receiver pairs, was performed using a smooth root-mean-square (RMS) velocity model. This stacking process helped enhance the signal-to-noise ratio and produce a coherent and clear image by accounting for average velocity variations within the subsurface.

Finally, employed post-stack time migration, which involved repositioning the stacked seismic data to their correct spatial locations. This migration process accounted for lateral velocity variations in the subsurface, resulting in a more accurate depiction of the subsurface structure and the orientation of the KF.

3.2 Travel time tomography: Seismic Refraction Travel Time Tomography (TTT) is a widely utilized method for creating high-resolution depth models of P-wave velocity. It relies on the analysis of first arrivals in seismic data (Van Avendonk et al., 1998). In this study, we implement the algorithm developed by Van Avendonk et al. (2004) on seismic dataset along PGR4, this technique also known for its effectiveness in heterogeneous media (Van Avendonk et al., 1998).

The initial velocity model is derived from NMO velocity of reflection seismic data. For forward modeling, we employ the shortest path method and ray bending techniques (Moser, 1991; Van Avendonk et al., 2004). The goal is to minimize the misfit between observed and calculated travel times using a least-squares scheme (Van Avendonk et al., 1998, 2004).

To refine the velocity model, we apply a regularization technique to the cost function and adjust the smoothing lengths, following the approach outlined by Toomey et al. (1994), Verma and Ghosal (2021). This helps improve the fitting of the model to the observed data.

The workflow for the travel time tomography can be summarized as follows:

1. First arrivals in the seismic data are carefuly selected and recorded as travel times.
2. An initial velocity model is created based on reflection seismic data.
3. Ray tracing is performed, and the velocity model is updated accordingly.
4. The final velocity model is determined if the misfit between the picked travel times and the synthetic travel times is close to unity.

4. Results and Discussion

Our findings are based on the extensive observations conducted by Powers et al. (1998) in the sub-Himalayas. By correlating our results with their studies, we gained valuable insights.

To accurately classify the stratigraphy, we divided it into three distinct sections: Upper Siwalik, Middle Siwalik, and Lower Siwalik. These divisions were determined based on the two-way travel time (TWTT). Figure 3 provides a visual representation of these divisions. In the Indo-Gangetic plains, specifically south of the KF, the Upper Siwalik extends from the surface to 0.8 s TWTT. Moving further, the Middle Siwalik ranges from 0.8 s to approximately 2 s TWTT. Beyond that, the Lower Siwalik spans from 2 s to around 3 s TWTT. KF displaces the Upper Siwalik ~0.2 s TWTT toward the Hanging wall side due to its emergence.

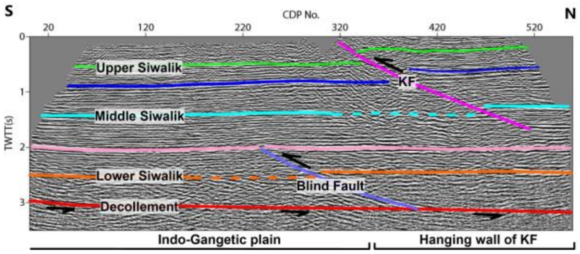

Figure 3: Time-migrated post stack seismic section along PGR4,

Our analysis also revealed the presence of a distinctive feature known as the Decollement. This interface gently dips towards the north, acting as a boundary between the overlying Himalayan wedge and the under-thrusting Indian plate. Its location was identified at 3 to approximately 3.2 s TWTT. One significant fault we examined is the KF, which belongs to the imbricated fault system of the HFT. The KF displaces the Upper Siwalik and reaches the surface near CDP no. 320. Its presence causes a notable disruption in the local topography, as depicted in Figure 1.

The ongoing collision between tectonic plates leads to ruptures within the Siwalik formation. The Himalayan faults are characterized by fault bend folding and the gradual progression of faults towards the foreland. The KF serves as a prime example of fault propagation resulting from the intense stress build-up due to the collision.

Intriguingly, we observed a deformation of the Lower Siwalik due to ongoing tectonic activity south of the KF. This deformation resulted in a distinct break of 0.0368 s TWTT (Verma and Ghosal, 2022). It is likely caused by the development of another fault, currently identified as a blind fault originating from the Decollement.

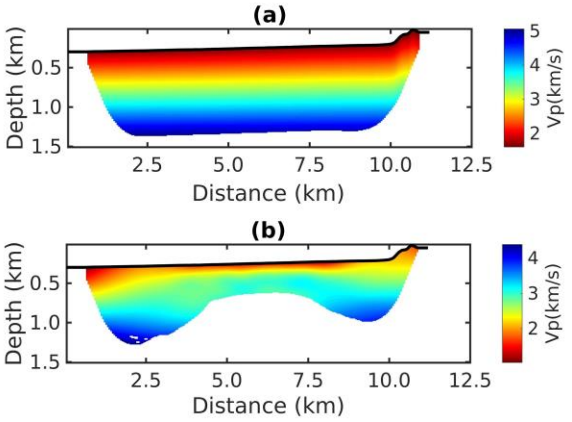

Figure 4: (a) chosen initial model based on the velocity estimates from reflection seismic, (b) inverted final velocity model after 9 iterations

The travel time tomography analysis yielded a velocity model that provides valuable information about the subsurface structure down to a depth of 1.2 km from the surface. The model primarily characterizes the Upper Siwalik formation, including the upper portion of the middle Siwalik. The velocity values exhibit variation ranging from 1.2 to 3.8 km/s, as illustrated in Figure 4b.

Notably, the topmost layer, with velocities ranging from 1.2 to 1.8 km/s, signifies the presence of alluvial sediments influenced by the Dabka and Baur rivers, which overlay the Upper Siwalik. Additionally, the velocity information obtained for the upper Siwalik formation (1.8-2.8 km/s) correlates well with the observations and velocity model presented by Powers et al. (1998).

To obtain the final velocity model (Figure 4b), we performed nine iterations (as shown in Figure 5b), refining the model at each step. The model misfit ($\chi 2$)

with respect to the initial model (Figure 5a) was significantly reduced from 84 to 4.263 (Figure 5b). Furthermore, the histogram of the relative travel time misfit demonstrated that after nine iterations, the distribution of travel time residuals approached zero. This validates the accuracy and reliability of the inverted model (Figure 5c).

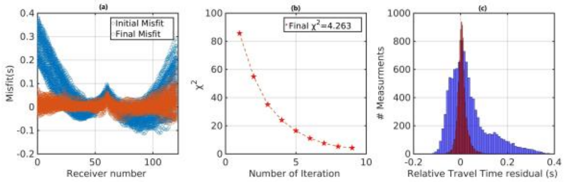

Figure 5: (a) The misfit between the initial travel time (represented by blue circles) and the final travel time (represented by red circles). (b) The L-curve depicts the reduction in χ2 (chi-squared) values after each iteration, demonstrating the iterative improvement in the model's fit. (c) The histogram illustrates the distribution of travel time residuals. The blue bars represent the initial travel time residuals, while the red bars represent the final travel time residuals.

5. Conclusions

The active Himalayan Frontal Thrust (HFT) system is at high risk of rupture due to the tremendous stress buildup caused by the ongoing convergence between the Indian plate and the Eurasian plate. In this context, the KF is recognized as an imbricated fault within the HFT system.

Based on our observations from the present study, we speculate the development of a blind fault originating from the Decollement. This newly formed fault has the potential to rupture the Indo-Gangetic plain in the future. Our study not only delineates the general stratigraphy of the region but also provides a high-resolution velocity model.

The geometry of the KF and the newly developed blind fault, along with the Decollement, offers crucial insights into the ongoing tectonic activity of the region. Understanding these dynamics is essential for accurately assessing the risks associated with future large-scale earthquakes.

Considering the significance of our findings, we propose conducting similar studies that assess the subsurface structure by integrating various geophysical and geological techniques. Such an approach would provide a more reliable and detailed understanding of the hazards associated with earthquakes.

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