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The Himalayan Ellipse Model: Finite Element Analysis (FEA) Approach

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Abstract
This study employs Finite Element Analysis (FEA) to investigate the complex crustal deformation, uplift, and erosion patterns within the Himalayan syntaxial bends, specifically at Nanga Parbat (west) and Namcha Barwa (east). These "hairpin" turns, heavily influenced by the northward, counter-clockwise rotation of the Indian Plate, are simulated using continuum mechanics and viscous/viscoelastic material properties. The Himalayan arc, characterized by an elliptical shape, is modeled with a semi-major axis of 1200 km and pinned at its ends by major strike-slip faults. FEA is used to predict strain partitioning, seismic stress accumulation on the Main Himalayan Thrust (MHT), and surface deformation, considering major faults like the MFT, MBT, and MCT. The lithosphere is treated as a viscoelastic material, and the curvature of the syntaxial bends is calculated using sophisticated governing equations. Simulations reveal strike-slip dominance and bimodal seismicity patterns in the syntaxes. The Eastern Himalayan Syntaxis is identified as having maximum seismic risk, while Nepal's seismicity is attributed to the Main Himalayan Thrust (MHT). The veracity of FEA simulation study over the Himalayan arc is severely limited by the author's lack of access to robust software tools, and it is left to future scholars to address. Building infrastructure along the Himalayan arc requires strict adherence to earthquake-resistant standards due to its classification as Zone V.

Keywords: *Finite element analysis, Himalayan ellipse, Syntaxial arc, Differential calculus, Geometrial model, Nanga Parbat, Nacha Barwa, viscousity*

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I. Core Concepts And Locations

Finite element analysis (FEA) of Himalayan syntaxial bending, located at Nanga Parbat (west) and Namcha Barwa (east), **simulates the intense crustal deformation, uplift, and, in some cases, rapid erosion (up to 7 mm/year) caused by the Indian Plate's collision and rotation**. These 3D models typically use continuum mechanics and viscous or viscoelastic material properties to analyze the "hairpin" turns, showing that the structures are heavily influenced by the northward, counter-clockwise rotation of the Indian Plate.

The **Himalayan syntaxial bends** are sharp, hairpin-like southward turns at the western and eastern extremities of the mountain range. These bends occur where the east-west trending Himalayan chain abruptly terminates and curves toward the south.

- **Western Syntaxial Bend**: Located near **Nanga Parbat** (8,126m). Here, the Indus River has carved a deep gorge, and the mountains bend toward the south, meeting the Hindu Kush and Karakoram ranges.
- **Eastern Syntaxial Bend**: Located near **Namcha Barwa** (7,782m) in Arunachal Pradesh. Beyond the Dihang (Brahmaputra) gorge, the range turns sharply south to form the Purvanchal (Eastern Hills) along the India-Myanmar border.
- The Himalayan arc experiences tectonic rotation, with anticlockwise rotation at the western syntaxis (near Nanga Parbat) and clockwise rotation at the eastern syntaxis (near Namcha Barwa). This is due to the Indian plate's collision with the Eurasian plate, where the northwestern part acted as a hinge for the anticlockwise rotation, while crustal material at the eastern edge rotates clockwise around the syntaxial bend. These rotations create sharp bends in the mountain range and lead to major rivers like the Indus and Brahmaputra taking abrupt southward turns.

Key Reasons for the Discrepancy:

Essentially, the 2400 km is the total length of the arc, while 1200 km represents the structural semi-axis in scientific models of the fold belt.

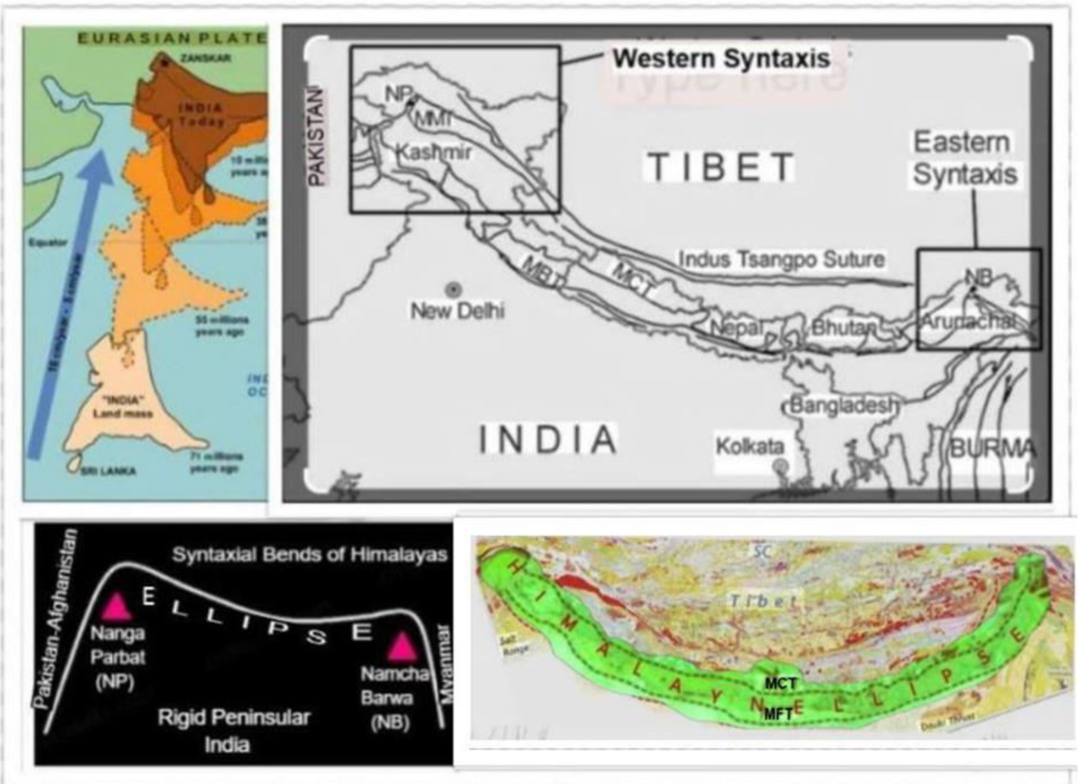
The distinction between the 2,400 km length of the Himalayan range from Nanga Parbat in the west to Namcha Barwa in the east and the 1,200 km axis value arises from the difference between the arc length (the distance along the curved mountain range) and the semi-major axis (half the total length) used in geomathematical elliptical modeling to define the elliptical curvature of the Main Frontal Thrust (MFT) and Main Central Thrust (MCT), not the total linear length of the entire chain.

- **Arc Length vs. Radius:** The 2400 km is the total path length, while the 1200 km represents the distance from the center of the ellipse to its furthest tip (the semi-major axis).
- **Geological Modeling:** Studies treating the Himalayan arc as a geometrical ellipse (often used to model the collision of the Indian plate) calculate a semi-major axis of approximately 1200 km, with foci situated near Nanga Parbat and Namcha Barwa.
- **Structural Curvature:** The mountains are not a straight line; they curve sharply at the syntactic bends. The 1200 km measure is a geometrical simplification, not a direct end-to-end measurement.

Primary Fault Systems

The Himalayan elliptical model defines the "boundary" as a sequence of stacked, north-dipping thrust faults rather than a single line. These faults allow for north-south compression, which gives the range its elliptical arc structure.

- **Main Frontal Thrust (MFT / HFT)**:
  - **Location**: The southernmost boundary, separating the Himalayan foothills (Siwaliks) from the Indo-Gangetic Plain.
  - **Role**: It is the most active fault currently, representing the leading edge where the Indian plate is sliding under the range.
- **Main Boundary Thrust (MBT)**:
  - **Location**: Positioned north of the MFT, it separates the **Lesser Himalayas** from the **Outer Himalayas (Siwaliks)**.
  - **Role**: Older than the MFT but still active, it often marks a significant jump in mountain elevation.
- **Main Central Thrust (MCT)**:
  - **Location**: Separates the **Greater Himalayas** (high peaks) from the **Lesser Himalayas**.
  - **Role**: This is a fundamental tectonic boundary where deep, high-grade metamorphic rocks have been pushed over younger rocks.
- **Main Himalayan Thrust (MHT)**:
  - **Role**: The Main Himalayan Thrust (MHT) is regarded as the single fundamental mega-thrust deep beneath, from which all of the above faults (MFT, MBT, and MCT) are "splays" that eventually branch off to form the Himalayan ellipse.



The Ellipse Parameters

The Himalayan ellipse is "pinned" at its two ends (the Nanga Parbat and Namcha Barwa) by major strike-slip faults. Its dimensions are typically:

Parameter	Value (Approx)	Significance
Semi-Major Axis	1200 km	Defines the easy-west span between syntaxial "pins"
Semi-Minor Axis	400 km	Aligns with the peak convergence zone in Nepal
Aspect Ratio	3.1	The ratio of the major axis to the minor axis
Eccentricity	0.8	Explains why thrusting is 3 times faster in the center than the ends signifying an ellipse shape rather than a circular one

Lithology and rock properties within the Himalayan ellipse

The region between the Main Central Thrust (MCT) and the Main Frontal Thrust (MFT) constitutes the Lesser Himalaya (LH) and the Sub-Himalaya (Siwaliks), comprising a complex, intensely deformed, and sheared zone that acts as a major source of regional seismic activity. The lithology generally consists of Proterozoic to Early Paleozoic low-to-medium grade metasedimentary rocks in the north (near MCT) and Cenozoic, weakly consolidated sandstones and mudstones in the south (near MFT).

FEA Applications in Himalayan Context

Finite Element Analysis (FEA) is a powerful mathematical tool for simulating the complicated, nonlinear deformation of the Himalayan orogenic wedge. The "Himalayan Ellipse" model, which describes the mountain range's arcuate shape as a confocal ellipse pinned by a syntaxial strike-slip fault, employs FEA to predict strain partitioning, seismic stress accumulation on the Main Himalayan Thrust (MHT), and surface deformation.

- **Modelling Arcuate Deformation:** FEA indicates that the range's elliptical shape causes slip rates to vary, with larger rates in the center and lower rates around the syntaxes, which is consistent with observations.
- **FEA simulations** of interseismic strain building on the Main Himalayan Thrust (MHT) indicate substantial locking up to ~100 km from the surface front.
- **Active Tectonics and Faulting:** Models contain major faults (MCT, MBT, and HFT) to investigate the evolution of stress and strain, frequently explaining the coexistence of compressive and tensional states.
- **Syntaxial Pinning:** FEA shows how the two syntaxes (Nanga Parbat and Namche Barwa) function as structural pins, influencing the range's elliptical deformation pattern.

Mathematical Framework for Curvature (*k*)

The curvature (k) of the Himalayan syntaxial bends is calculated and drawn using Finite Element Analysis (FEA), which simulates the lithospheric response to the Indian plate's northward indentation. Researchers utilize these models to solve sophisticated governing equations derived from continuum mechanics rather than basic geometric equations.

To "draw" or visualize these in an AI/FEA tool (like ANSYS or Abaqus):

- **Define Geometry:** Import coordinates for the **Main Frontal Thrust (MFT)** and **Main Central Thrust (MCT)**.
- **Assign Rheology:** Treat the lithosphere as a **viscoelastic material** using Stokes equations for ductile flow in the lower crust.
- **Apply Boundary Conditions:** Simulate the northward indentation of the Indian plate (rigid indenter) against the Eurasian plate.
- **Solve for k:** Use the second derivative of the displacement field (d^2y/dx^2) to map the distribution of curvature across the syntaxial arc.
- **Elliptical Fitting:** The overall shape of the Himalayan arc and its syntaxes can be described by fitting them to ellipses in map view.
- **Axis Ratios:** Curvature is quantified by calculating the major-to-minor axis ratios of these ellipses, which typically range from **2.5 to 3**.
- **Curvature Calculation (k):** For a fitted curve or circle at the vertex of these bends, the absolute maximal curvature (K_{max}) is calculated as the inverse of the radius (1/R) of the best-fit circle.where R is rhe radius of curvature. Given the sharp "knee-bend" flexures, the radius of curvature at these pins is significantly smaller than the central Himalayan arc, resulting in localized high-strain zones.

Viscoelasticity and the "Himalayan Ellipse"

In geodynamics, the value 10^{20} **Pa · s** represents the characteristic **dynamic viscosity** of the Earth's lower crust and upper mantle in the Himalayan-Tibetan region. This parameter is fundamental in **viscoelastic** models used to explain how the lithosphere deforms over long time scales following major earthquakes or under the weight of the mountain range

- **Viscoelastic Definition:** The lithosphere behaves as a **viscoelastic** medium, meaning it acts like an elastic solid on short time scales (causing earthquakes) but flows like a highly viscous fluid over thousands of years.
- **Himalayan Ellipse:** Recent geodetic research describes the 2,500 km Himalayan arc as a broad **elliptical shape** pinned by syntaxial strike-slip faults. The deformation within this "ellipse" is controlled by the flow of the underlying crust.
- **Role of 10^{20} Pa · s:** This specific viscosity value is often cited as the **lower bound** or steady-state viscosity for the Tibetan lower crust and the underthrusting Indian plate.
  - It is high enough to maintain the plateau's extreme topography.
  - It is low enough to allow for **channel flow** or post-seismic relaxation, where stress from an earthquake is gradually transferred through the ductile lower layers

Key Geological Implications

- **Post-Seismic Relaxation:** After events like the 2015 Gorkha earthquake, researchers use 10^{20} Pa · s to model how the ground continues to move (uplift or subside) as the deep crust relaxes.
- **Crustal Flow:** A viscosity of 10^{19} to 10^{21} Pa · s is required to explain the "gravitational spreading" of the Tibetan Plateau toward the Indian shield.
- **Temperature Sensitivity:** This viscosity level typically corresponds to temperatures of **500--800 °C** at depth, where rocks begin to transition from brittle to ductile behavior.

Core Mathematical Components

The mathematical framework for modeling this elliptical growth, incorporating kinematic boundary conditions (e.g., India-Asia convergence rates of ~15-20 mm/yr). typically involves:

• **Governing Equations**: Models transition from simple bending equations to sophisticated **continuum mechanics**.
○ **Conservation of Momentum and Mass**: Used for continuous medium simulations.
○ **Stokes Equations**: Frequently employed for modeling incompressible, viscous flow in the lower crust or mantle.
• **Constitutive Laws**: These define how rock materials respond to stress.
○ **Viscoelastic/Viscous Models**: Used for long-term lithospheric deformation.
○ **Elasto-plasticity**: Often applied to the upper crustal strata to simulate brittle faulting and shield-induced volume loss.
• **Boundary Conditions**: Simulations use **velocity boundary conditions** to represent plate convergence rates (e.g., the changing northward speed of the Indian plate over millions of years).

Governing Equations

The governing equations using differential calculus for such geodynamic simulations are based on the conservation of momentum and mass for a continuous medium. When modelling lower crust or mantle flow related to tectonic processes, the Stokes equations for incompressible, viscous flow are often employed:

- **Momentum Conservation (Force Balance):**
  $$\frac{\partial \sigma_{ij}}{\partial x_j} - \frac{\partial P}{\partial x_i} = -\rho g_i$$
  where:
  - σ_{ij} is the deviatoric stress tensor.
  - P is pressure.
  - ρ is density.
  - g_i is the gravity acceleration vector.
- **Mass Conservation (Incompressibility):**
  $$\frac{\partial v_i}{\partial x_i} = 0$$
  where:
  - v_i is the velocity vector.

Constitutive Laws

These equations are coupled with **constitutive laws** that describe how the geological materials (different rock types at various pressures and temperatures) deform under stress. This is crucial for modeling the syntaxis, which involves a range of behaviors from brittle faulting in the upper crust to ductile flow in the lower crust and mantle.

- **Viscous Flow:** Rocks at high temperatures and pressures in the lower crust and mantle behave as a viscous fluid over geological timescales. The relationship between stress and strain rate is defined by:
  $$\sigma_{ij} = 2\eta\dot{\varepsilon}_{ij}$$
  where:
  - η is the effective viscosity (which can vary by many orders of magnitude).
  - $\dot{\varepsilon}_{ij}$ is the strain rate tensor ($\dot{\varepsilon}_{ij} = \frac{1}{2}(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i})$).
- **Elastic and Elasto-plastic Behavior:** For the shallower, cooler crust, models incorporate parameters like **Young's modulus**, **Poisson's ratio**, and failure criteria such as the **Mohr-Coulomb criterion** to simulate brittle deformation and faulting.

FEA Modeling Tools

FEA simulates the "hairpin-like" turns at the Nanga Parbat (western) and Namche Barwa (eastern) extremities. We need Finite Element modeling (FEM) or Geodynamic Simulation software (Non-Linear and Dynamic-time dependent effects rather than just static snapshots).

- **Governing Equations:** Simulations often solve the **Stokes equations** for incompressible viscous flow to model the lower crust and mantle.
- **Material Behavior:** The lithosphere is treated as a **viscous or viscoelastic material**, incorporating constitutive laws that account for varying rock types, pressures, and temperatures.
- **Software Tools:**
  - **PECUBE:** A specialized 3D finite element code often used for thermochronological and geodynamic modeling.
  - **ANSYS:** A commercial FEA suite used to simulate stress patterns and crustal deformation.
  - **DOUAR:** A 3D finite element code designed to solve Stokes and heat transfer equations in tectonic settings.
- The veracity of the FEA simulation study addressing the Himalayan arc is significantly constrained by the author's inadequate access to robust software tools, compelling future researchers to solve this issue.

Predicted Failure Modes and its implications

FEA simulations identify the first two primary failure mechanisms that differ from the typical arc-normal thrusting of the Central Himalayas:

- **Strike-Slip Dominance (The "Escaping" Mode):** In both syntaxes, the sharp curvature forces material to move laterally around the "pins". FEA shows that while thrusting occurs at shallow depths, **strike-slip motion** becomes dominant along the flanks of the syntaxial domes (e.g., the Raikhot Fault in the west).
- **Bimodal Seismicity:** Models suggest a bimodal pattern where "blind" earthquakes (up to M_w \approx 7.8) cluster in the downdip parts of the seismogenic zone, while infrequent, great earthquakes (M_w > 8) are required to propagate all the way to the frontal thrusts.
- Regarding earthquake hazards, the **Eastern Himalayan Syntaxis** (also known as the **Assam Syntaxial Bend**), most notably the **1950 Assam-Tibet earthquake** (magnitude 8.6) along the Himalayan arc, where the Eastern Syntaxis is a sharp bend where the Himalayan range meets the Indo-Burmese arc, creating a complex triple junction of the Indian, Eurasian, and Burmese plates. is generally considered to have the maximum risk compared to the Western Syntaxis, (Kashmir-Hazara) is also highly unstable (1905 Kangra, 2005 Muzaffarabad quakes).
- In the context of seismicity, Nepal falls on the active Main Himalayan Thrust (MHT) arc at the convergence of the Indian plate and the Eurasian plate (often referred to as the Asian plate or **Tibetan plateau**). The hazards in this zone are driven by the ongoing collision of the Indian and Eurasian tectonic plates, specifically along the Main Himalayan Thrust (MHT). This same convergent process is responsible for the primary source of seismic hazard in Nepal, such as the devastating **7.8 magnitude Gorkha earthquake** in 2015.
- Building infrastructure along the Himalayan arc requires strict adherence to earthquake-resistant standards due to its classification as **Zone V** (the highest risk category in India). Key precautions involve site-specific geological assessments, advanced structural engineering, and the use of flexible, high-quality materials.

II. Conclusions

In conclusion, the Himalayan Ellipse Model, as evaluated using finite element analysis (FEA), gives unique insights into the region's tectonic intricacies. The unique syntaxial bends at Nanga Parbat and Namcha Barwa, caused by the Indian Plate's collision and rotation, indicate the geological significance of the elliptical model's parameters. FEA models also show seismic risks and structural issues that are critical for infrastructure development throughout the Himalayan arc, underlining the importance of earthquake-resistant standards and site-specific geological studies.

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