Inversion of travel times to estimate Moho depth in Shillong Plateau and Kinematic implications through stress analysis of Northeastern India

by

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Plan

a. Tectonics and Seismicity

b. Inversion of travel times to estimate Moho

c. Stress analysis
Epicentral map of earthquake of magnitude 4.0 and above occurred in NE India since 1964-2008.
The map showing epicenters of 184 well located earthquakes; smaller circles indicate lower magnitude (M<3.0) and bigger circles higher magnitude (M>3.0) earthquakes. 26 fault-plane solutions shown, are obtained by wave form inversion (2001-2004).

(a) The pop-up tectonic model of the Shillong Plateau [after Bilham and England, 2001], (b) cross section of the events across the Dapsi/Oldham/Brahmaputra fault zone, the considered events are shown by the shaded zone A-A' (Fig.3), and (c) cross section of the inferred fault planes of the selected events.
INVERSION OF TRAVEL TIMES TO ESTIMATE THE MOHO DEPTH
Map showing the major tectonic features of the study region. The epicenter of Great earthquake of 12 June, 1897 (M=8.7) is shown by a star. Green triangles represent the digital broadband seismic station.
Hypocentral distributions of earthquakes along with depth sections. (a) Open and solid circles denote shallow and intermediate-depth earthquakes, respectively illustrated by different magnitude range. (b) Depth section plot along Longitude. (c) Depth section plot along Latitude.
Uncertainties involved in the estimates of epicenters:

203 earthquakes used, 966 reflected (PmP & SmS) and 70 (PS & SP) converted phases.
A schematic illustration of ray path of reflected and converted waves

We consider two cases of ray propagation corresponding to the reflected wave and the converted wave at the Moho. One is the ray propagates in medium 1(velocity V1) and is reflected at the interface with medium 2. The other is that the ray propagates from the medium 2(velocity V2) into the medium 1 with a phase conversion at the interface.

V1 and V2 denote the velocity in each medium. Θ shows incident angle of reflected waves. Θ1 and Θ2 represent emergent and incident angles of converted waves, respectively.
An example of rotated three-component seismogram of a shallow earthquake recorded at station TEZPUR (TZR). Prominent later phases (PmP and SmS) can be seen after the first P- and S-wave arrivals, respectively. Particle motions of P, PmP, S and SmS phases are also shown.
An example of rotated three-component seismogram of an intermediate depth earthquake recorded at station JPA. A prominent later phases (PS) can be seen about 3.8 s after the P-wave arrival. Particle motions of P, PS and S phases are also shown.
An example of rotated three-component seismogram of an intermediate depth earthquake recorded at (JPA). A prominent later phase (SP) can be seen about 3.1 s before the S-wave arrival. Particle motions of P, SP and S phases are also shown.
Theoretical consideration

The reflected, refracted phases and converted phases (PS and SP) at Moho are observed in seismograms for local earthquakes. Travel times of these phases are inverted to estimate depth of the Moho discontinuity. Depth distribution of the Moho are expressed as a function of latitude and longitude. The Moho depth (Hm) at a location (Φ´,λ´) is expressed as:

\[
Hm (\Phi´, \lambda´) = C_0 + C_1 \Phi´ + C_2 \lambda´ + C_3 \Phi´^2 + C_4 \Phi´ \lambda´ + \cdots + C_{14} \lambda´^4
\]

where Φ´ and λ´ are the latitude and longitude respectively. C_k’s are unknown parameters which may be determined by inversion of the observed travel time data.

Nakajima 2002
Travel time residuals can be written as:

\[ T_{p2-p1}^{obs} - T_{p2-p1}^{cal} = \sum_k \left( \frac{\partial T_{p2}}{\partial C_k} - \frac{\partial T_{p1}}{\partial C_k} \right) \Delta C_k + e \]  \hspace{1cm} (2)
Change in Travel times for reflected and converted

The travel time change for the reflected wave due to change in depth of the interface as expressed by

\[
\frac{\partial T}{\partial H_m} = \frac{2\partial H_m \cos \theta}{V_1}
\]

and we obtain

\[
\frac{\partial T}{\partial H_m} = \frac{2\cos \theta}{V_1}
\]

Similarly, we obtain the partial derivative \(\partial T/\partial H_m\) for the converted wave as

\[
\frac{\partial T}{\partial H_m} = \frac{\cos \theta_1}{V_1} - \frac{\cos \theta_2}{V_2}
\]

(A) Travel time change of reflected waves due to the depth change of the Moho

(B) Travel time change of converted waves due to the depth of the Moho.
Eq. (2) can be expressed by matrix form as

\[ d = G m + e \]  \hspace{1cm} \text{(7)}

where

- \( d \) = the column vectors of residuals between observed and theoretical travel time difference
- \( G \) = matrix of partial derivatives
- \( m \) = column vector of correction term of unknown parameters \( \Delta C_K \)
- \( e \) = error vector

This equation can be written as follows by solving with least squares method:

\[ m = (G^T G)^{-1} G^T d \] \hspace{1cm} \text{(8)}

This calculation is carried out iteratively until \( \Delta C_K \) becomes sufficiently small.
Root Mean Square (RMS) residuals versus number of iterations

Moho depth obtained for each data point. Circles and squares denote reflection and conversion points, respectively.
Contour diagram represents the RMS residuals of each of the iteration.

Results

Iteration 1

Iteration 2

Iteration 3

Iteration 4

Iteration 5
Depth distribution of Moho obtained at the reflection and conversion points
STRESS ANALYSIS IN NORTHEASTERN INDIA AND ITS KINEMATICS IMPLICATIONS
SEISMIC STATIONS IN NE INDIA

- ▲ = NEIST Station
- ▼ = M.U. Station
- △ = IIG Station
- ▽ = NGRI Station
WAVEFORM INVERSION OF 19 AUGUST 2009 EVENT
MAP DISTRIBUTION OF EPICENTERS OF 285 EARTHQUAKES CONSIDERED IN THIS STUDY
ROSE DIAGRAMS SHOWING THE ANGULAR DISTRIBUTION OF THE TREND (UPPER ROW) AND PLUNGES (LOWER ROW) OF THE INDIVIDUAL B-AXES, P-AXES AND T-AXES
LARGE ARROWS SHOW INFERRED TREND OF COMPRESSION (CONVERGENT PAIRS OF ARROWS) AND EXTENSION (DIVERGENT ONES).

(A) WHOLE SET OF DATA, WITH 285 EARTHQUAKE FOCAL MECHANISMS.

(B) COMPRESSIVE SUBSET, INCLUDING 182 MECHANISMS.

(C) EXTENSIONAL SUBSET, INCLUDING 103 MECHANISMS
STEREOPLOTS SHOWING THE DENSITY DISTRIBUTION OF PRESSURE AND TENSION ON THE SPHERE OR ALL SPATIALLY DEFINED SUBSETS.
RESULTS OF INVERSIONS TO OBTAIN AVERAGE STRESS TENSOR
RESULTS
OF
STRESS
INVERSIONS
COUPLED WITH
STRESS
SEPARATION
OF FOCAL
MECHANISMS
FOR
1. BHUTAN
HIMALAYA
2. ARUNACHAL
HIMALAYA
3. MISHMI THRUST
4. TRIPURA BELT
5. SHILLONG
PLATEAU
6. ASSAM VALLEY
7. SOUTHERN INDO-
BURMA REGION
8. EASTERN INDO-
BURMA REGION
AND
9. SAGAING FAULT
REGION
SYNTHESIS OF MAIN STRESS REGIMES. PAIRS OF CONVERGENT ARROWS FOR COMPRESSION, DIVERGENT ARROWS FOR EXTENSION.
Map of focal mechanism solutions in the Indo - Burma Ranges. The three maps correspond to different earthquake depth ranges in the same area: (a) 0-45 km (56); (b) 45-90 km (39) and (c) 90-160 km (38).
MAJOR KINEMATIC FEATURES OF NORTHEAST INDIA. (a) PRESENT DAY AVERAGE VELOCITIES RELATIVE TO LASHA, TIBET: 1 WESTERN EDGE OF SUnda PLATE 2 CENTRAL MYANMAR BASINS 3 BENGAL BASIN 4 SHILLONG-MIKIR MASSIF. (b) TO THE EAST, VELOCITY OF 1 wrt. 2 (c) MAINLY ACCOMOMODATED ALONG SAGAING FAULT, (d) TO THE WEST, VELOCITY OF 2 wrt. 3 ACCOMOMODATED ACROSS VARIOUS FAULTS OF BURMESE ARC AND TRIPURA BELT

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CONCLUSION

• North-South compression, in a direction consistent with India-Eurasia convergence, prevails in the whole area from the Eastern Himalayas to the Bengal Basin through Shillong-Mikir-Assam Valley block and the Indian Craton.

• The Indo-Burma ranges reveals complex stress pattern.

• Indo-Burma ranges are under compression as a result of oblique convergence between the Sunda and Indian plates. The maximum compressive stress rotates from NE-SW across the inner and northern arc to E-W near Bengal Basin.
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