24. At a late phase of this project, we became aware of an independent sequence of A. tumefaciens Cs8 genome. The work of these authors is published jointly in this issue [D. Wood et al., Science 294, 2317 (2001)]. The two independently derived sequences are in excellent overall agreement, with single nucleotide discrepancies far below current accuracy standards (99.99%) for finished sequence. Our sequence contains two small insertions relative to that of Wood et al.; one in each of the circular chromosome and pAtCS8. Further work will determine which of the observed discrepancies reflect strain differences and which reflect errors.

27. Supplementary Web material is available on Science Online at www.sciencemag.org/cgi/content/full/294/5550/2323/DC1.
28. DNA sequence and protein predictions are available at the NIAID Center for Biotechnology Information’s Entrez Genomes Server (www.ncbi.nlm.nih.gov/PMGifs/Genomes/micr.html). The GenBank accession numbers are NC_003062 (circular chromosome), NC_003063 (linear chromosome), NC_003064 (pAtCS8) and NC_003065 (pTC8).
39. Kahng and Shapiro analyzed the appearance of hemi-methylated DNA, upon passage of a replication fork, at the att locus in A. tumefaciens. At the time of their study, att was believed to reside on the circular chromosome, but we correctly locate it on pAtCS8. Thus, at least one repABC origin, and probably all three, is coordinated with the cell cycle.
40. K. Skarstad (personal communication) has shown by flow cytometry that all DNA replication is restricted to a relatively short time span within the cell cycle of A. tumefaciens.

Earthquake Recurrence and Rupture Dynamics of Himalayan Frontal Thrust, India

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The Black Mango fault is a structural discontinuity that transforms motion between two segments of the active Himalayan Frontal Thrust (HFT) in northwestern India. The Black Mango fault displays evidence of two large surface rupture earthquakes during the past 650 years, subsequent to 1294 A.D. and 1423 A.D., and possibly another rupture at about 260 A.D. Displacement during the last two earthquakes was at minimum 4.6 meters and 2.4 to 4.0 meters, respectively, and possibly larger for the 260 A.D. event. Abandoned terraces of the adjacent Markanda River record uplift due to slip on the underlying HFT of 4.8 ± 0.9 millimeters per year or greater since the mid-Holocene. The uplift rate is equivalent to rates of fault slip and crustal shortening of 9.6 ± 2.0 millimeters per year and 8.4 ± 1.6 millimeters per year, respectively, when it is assumed that the HFT dips 30° ± 10°.

The ongoing collision of India into Eurasia has produced four major thrust earthquakes along the ∼2500-km length of the Himalayan front during the past ∼100 years (1), yet none of the events reportedly produced coseismic surface ruptures (2, 3) (Fig. 1A). Here, we report paleoseismological evidence of the size and timing of surface-rupturing thrust earthquakes along the HFT as well as a quantitative bound on the rate of fault slip on the HFT, from a site located about 80 km northwest of Dehra Dun.

Regional setting. The collision of India with Eurasia since the Eocene has accommodated 2000 to 3000 km of convergence (4). The boundary between the Indian and Eurasian plates forms an arc that extends ∼2500 km across the continent (Fig. 1A). Plate motion models and recent Global Positioning System (GPS) measurements indicate that convergence between the Indian and Eurasian plates is between about 40 and 50 mm/year (5, 6). Between about 10 and 20 mm/year of the total 40 to 50 mm/year of convergence is taken up by thrust motion along the Himalayan arc, with the remainder taken up farther to the north by a combination of thrusting, crustal extension, and strike-slip motion within the Eurasian Plate (5, 7–9). Three major south-verging thrust faults strike the length of the Himalayan arc (Fig. 1). The northernmost of the three faults is the Main Central Thrust (MCT), which merges along the southern edge of the High Himalaya and has not been observed to break Quaternary deposits and, hence, is generally considered inactive (10). The Main Boundary Thrust (MBT) marks the southern edge of the Lesser Himalaya, is expressed in bedrock along the arc, and is locally observed to displace Quaternary deposits (10, 11). The southernmost thrust is the HFT, which is now considered to be the most active of the three and delineates the northern limit of the exposed Indian Plate.
The HFT displaces Tertiary and Quaternary sediments of the Siwalik Group over the Indo-Gangetic plain (11) (Fig. 1). The region of most severe shaking and damage associated with the major historical earthquakes along the Himalayan arc is generally bounded by the MCT to the north and the HFT to the south (1) (Fig. 1A). Instrumentally recorded seismicity of moderate magnitude events is concentrated beneath the MCT at depths between about 10 and 20 km (12) (Fig. 1B). Active deformation along the HFT is expressed by scarps, uplift, and folding of late Quaternary and Holocene deposits (10, 11). The largest earthquakes have been interpreted to occur along a shallowly dipping décollement that extends beneath the Lesser and Sub-Himalayas and emerges as the HFT (Fig. 1) (1). It remains today somewhat of a conundrum that geological evidence of late Quaternary surface rupture is visible along the HFT, yet none of the major historical earthquakes have reportedly produced surface rupture (2, 3).

**Structural setting.** The Black Mango tear fault is located along the northwestern portion of the HFT between two areas of intense shaking associated with the magnitude (Ms) 7.8 1905 earthquake (13) (Fig. 1). The fault transforms motion between two segments of the HFT and passes through the small town of Kala Amb (Fig. 2) (14). Scars in Quaternary alluvium are not distinct along the main trace of the HFT near Kala Amb. Displacement on the underlying HFT has produced an asymmetric south-verging anticline within the Siwalik Group in the hanging wall (Fig. 3). Near Kala Amb, Siwalik beds on the back limb of the anticline show northerly dips ranging between 20° and 40°. Dip directions reverse and are as steep as 60° to the south on the forelimb of the anticline (15). Similar structures are observed elsewhere along the HFT and have been attributed to fault-bend or fault-propagation folding (8). Uplift observed on the east side of the Black Mango fault is due to displacement on the underlying and dipping HFT (Fig. 2). The dip of the underlying HFT beneath the back limb of the fold is equal to or greater than the dip of strata in the back limb (30° ± 10°), depending on the presence or absence of internal shearing in the hanging wall (16).

Longer term uplift along the HFT is reflected in fluvial strath terraces of the Markanda River, which are abruptly truncated by the Black Mango fault and now sit about 27 m above the active stream grade (14). The terraces occur as thin remnants along the Black Mango fault and as broad well-preserved flats along the Markanda River (14). The strath deposits rest on Siwalik bedrock, are generally about 7 m thick where not eroded, consist of rounded pebble-cobble gravels, and are commonly capped by 1 to 2 m of fine-grained loamy sand. Radiometric dates on two fragments of charcoal collected from a finer grained lens 4.7 m below the terrace surface provide a maximum age of the terrace surface: 4896 ± 68 and 5069 ± 205 calendar years before present (cal years B.P.), respectively (16). Abandonment of the Markanda terrace is attributed to tectonic uplift on the basis of the truncation of the terraces by the Black Mango fault. Dividing the 27-m relative uplift of the terraces by the younger detrital charcoal date yields a minimum bound on the uplift rate of 4.8 ± 0.9 mm/year. If we assume that the dip of the HFT beneath the Siwalik hills is 30° ± 10°N and that the uplift of the terraces reflects displacement on the underlying HFT, the rate of slip on the HFT is limited to 9.6 ± 7.0 mm/year. The equivalent rate of horizontal contraction for these fault dips and slip rate is 8.4 ± 7.3 mm/year.

**Earthquake displacement and recurrence.** We excavated a trench across a scarp of the Black Mango fault expressed in younger alluvium to place bounds on the size and recurrence time of the most recent of the earthquakes that have produced uplift of the Markanda terraces (Fig. 4). The trench is located near the village of Kheri Taprion, where the fault curves and joins with the HFT. Vertical separation between the hanging and footwall surfaces of the well-expressed scarp at the trench site is ~4.8 m. The ~55-m-long trench exposure shows that the scarp is principally the result of slip and folding associated with four low-angle thrusts, labeled F1, F2, F3, and F4 in Fig. 4.

Sheared and faulted packages of Siwalik-derived colluvium and weathered bedrock units on the hanging wall above fault strand F1 are the oldest in the exposure and labeled unit 1 in Fig. 4. The intensity of shearing within these hanging wall units indicates that the hanging wall has been deformed by several earthquakes. No scarps are associated with the shears within the Siwalik colluvium and bedrock that reach the surface, although the overlying soil is...
stripped and the accommodation of strike-slip motion on these shears is likely. The unconformity between the fan gravel units (unit 2) to the southwest and the Siwalik materials on the hanging wall is a scarp, probably tectonic in origin and predating deposition of fan gravel units. The now buried scarp may reflect displacement on trace F4 observed only at the very base of the trench. The fan gravel unit includes two distinct facies: coarser channel fill deposits of pebble-cobble size clasts with few boulders (unit 2a) and intervening massive fine and medium silty sand (unit 2b). The fan gravel unit dips 14° southwestward in the exposure and is displaced by fault strands F1, F2, and F3. The southwesternmost flat-lying beds on the footwall (unit 3) are a sequence of younger medium to fine silty sand and pebbly fine sand that contain two distinct buried soil horizons, Qb1 and Qb2, respectively.

Fault strand F3 cuts the lower soil Qb1 but not the upper Qb2 soil. The soil Qb1 on the footwall is interpreted to have been at the ground surface, perhaps buried by a thin veneer of younger sediment, at the time of displacement of fault strand F3. Displacement on F3 resulted in shearing of soil horizon Qb1 and plucking of sediments now preserved immediately beneath the upward termination of the F3 strand. A sequence of radiocarbon dates on detrital charcoal immediately beneath Qb1 places the maximum age of the Qb1 surface and, hence, displacement on F3, at 1349 ± 55 A.D. (sample C-18 in Fig. 4 and Table 1). Displacement on F3 was followed by continued accumulation and onlap of the fine-grained sands of unit 2b on the footwall and development of soil Qb2. The uppermost portion of unit 2b on which Qb2 soil is developed is probably scarp-derived colluvium composed of unit 2b materials. Fault strand F2 cuts higher in the section and disrupts sediments at the level of the Qb2 soil horizon. Cross-cutting relationships were not sufficient to uniquely determine whether F2 disturbs sediments of unit 3 above soil Qb2. A colluvial layer from which a radiocarbon sample (C-24) yielded a modern age is the oldest unit unambiguously not disturbed by F2. The age of detrital charcoal recovered from soil horizon Qb2 (sample C-15 in Fig. 4 and Table 1) places a maximum bound on the age of the F2 displacement at 1523 ± 99 A.D. Strand F1 reaches within a meter of the surface and probably occurred coeval with displacement on F2 but may also have slipped earlier with F3. In sum, displacements on fault traces F1, F2, and F3 are interpreted to be the result of two earthquakes having occurred during the past 600 years, between 1349 ± 55 A.D. and 1523 ± 99 A.D. and after 1523 ± 99 A.D.

The amount of slip in each earthquake is not

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Fig. 3. Geology and schematic cross section of Kala Amb area shows location of Black Mango fault (12). Box outlines portion of the area examined during this study.

Fig. 4. Map of trench wall showing fault traces (bold), amount of offsets (parentheses, in meters), and radiocarbon sample locations and labels. Dendrochronologically corrected calendar age ranges in years B.C./A.D. are shown for sample C-18 and C-15. Locations of discrete displacements on traces F1, F2, and F3 are enlarged in insets. The units used to measure fault offset are shaded black in the insets.
Table 1. Radiocarbon analyses of charcoal samples from trench (see Fig. 4 for sample location).

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample no. and Laboratory no.*</th>
<th>8^13C</th>
<th>14C age† (1σ)</th>
<th>Calendar age range‡ (in calendar years A.D./B.C.) (2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trench samples</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit 3</td>
<td>C-24 (71081)</td>
<td>-28.2</td>
<td></td>
<td>1530–1947 A.D.</td>
</tr>
<tr>
<td>Unit 3</td>
<td>C-22 (71079)</td>
<td>-25.3</td>
<td>230 ± 40</td>
<td>1423–1519, 1593–1622 A.D.</td>
</tr>
<tr>
<td>Unit 3</td>
<td>C-15 (71076)</td>
<td>-25.1</td>
<td>420 ± 40</td>
<td>1281–1402 A.D.</td>
</tr>
<tr>
<td>Unit 3</td>
<td>C-13 (71075)</td>
<td>-11.4</td>
<td>650 ± 40</td>
<td>1294–1405 A.D.</td>
</tr>
<tr>
<td>Unit 3</td>
<td>C-18 (71217)</td>
<td>-25.8</td>
<td>620 ± 30</td>
<td>1262–1399 A.D.</td>
</tr>
<tr>
<td>Unit 3</td>
<td>C-21 (71078)</td>
<td>-25.6</td>
<td>680 ± 50</td>
<td>1021–1217 A.D.</td>
</tr>
<tr>
<td>Unit 3</td>
<td>C-19 (71216)</td>
<td>-26.7</td>
<td>940 ± 40</td>
<td>1017–1211 A.D.</td>
</tr>
<tr>
<td>Unit 2</td>
<td>C-53 (77315)</td>
<td>-25</td>
<td>1300 ± 70</td>
<td>539–775 A.D.</td>
</tr>
<tr>
<td>Unit 2</td>
<td>C-26 (71082)</td>
<td>-24.6</td>
<td>1420 ± 40</td>
<td>559–673 A.D.</td>
</tr>
<tr>
<td>Unit 2</td>
<td>C-50 (77313)</td>
<td>-25</td>
<td>1450 ± 50</td>
<td>535–665 A.D.</td>
</tr>
<tr>
<td>Unit 2</td>
<td>C-27 (71083)</td>
<td>-24.5</td>
<td>1470 ± 40</td>
<td>534–657 A.D.</td>
</tr>
<tr>
<td>Unit 2</td>
<td>C-5 (71074)</td>
<td>-24.1</td>
<td>1520 ± 40</td>
<td>429–639 A.D.</td>
</tr>
<tr>
<td>Unit 2</td>
<td>C-2 (71073)</td>
<td>-24</td>
<td>1600 ± 40</td>
<td>385–558 A.D.</td>
</tr>
<tr>
<td>Unit 2</td>
<td>C-52 (77314)</td>
<td>-24</td>
<td>1630 ± 50</td>
<td>261–541 A.D.</td>
</tr>
<tr>
<td>Unit 2</td>
<td>C-23 (71080)</td>
<td>-25</td>
<td>1900 ± 60</td>
<td>38 B.C. to 243 A.D.</td>
</tr>
</tbody>
</table>

| **Terrace samples** |                                |       |              |                                                  |
| MT001-5 (77316)     | -25                              | 4300 ± 40 | 3015–2878 B.C. |                                                  |
| MT001-3 (77305)     | -28.4                            | 4410 ± 40 | 3325–2915 B.C. |                                                  |

*RAMS Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. †Reported 14C ages use Libby’s half-life (5568 years). Delta 13C values are assumed when given without decimal places. ‡Dendrochronologically calibrated age ranges were calculated with the University of Washington calibration program Calib 4.2, using the intercepts method (20), and age ranges are often discontinuous. Discrete intervals provided only for Qb1 and Qb2.

References and Notes
14. Supplementary material is available at www.sciencemag.org/cgi/content/full/294/5550/2328/DCT.
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