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An embryonic fold and thrust belt south of the Himalayan morphological front: examples from the Central Nepal and Darjeeling piedmonts

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30 shortening (LPS) is not detected by Global Navigation Satellite System (GNSS) data, and such
31 deformation would therefore absorb less than $0.5 \text{ mm}\cdot\text{yr}^{-1}$. The geodetic data that suggest the aseismic
32 growth of some of the structures are highly controversial. ii) For the rest of the deformation of the
33 embryonic thrust wedge, it is yet to be proven whether deformation occurs during rare great earthquakes
34 affecting the piedmont during medium earthquakes and/or during post-seismic deformation related to
35 great earthquakes. The amplitude of this long-term low deformation is too limited to significantly reduce
36 the seismic hazard in the seismic gaps of the Himalayan belt. iii) In some portions of the Himalayan
37 front, such as Darjeeling (India), the thrust deformation related to great earthquakes propagates several
38 tens of kilometres south of the morphological front in the zone previously affected by the long-term low
39 deformation. It induces multi-metre surface ruptures in the piedmont and a mean shortening of 8.5 ± 6.2
40 $\text{mm}\cdot\text{yr}^{-1}$. iv) Pre-existing faults in the bedrock of the Indian craton, often oblique to the Himalayan
41 structures, are locally reactivated beneath the foreland plain with low deformation rates.

42 **Keywords:** Himalayan mountain front, piedmont, foreland, blind thrusts, geomorphology,
43 embryonic thrust wedge, layer parallel shortening

44

45

46 1. Introduction

47 The present-day tectonics of the Himalayas are characterised by the under-thrusting of
48 the Indian lithosphere along the Main Himalayan Thrust (MHT) (Zhao et al., 1993) (Fig. 1).
49 Himalayan tectonics are believed to follow a simple seismic cycle that displays a succession of
50 ruptures along the MHT and finally transfers the entire convergence to the front of the
51 Himalayas during giant earthquakes (e.g., Bilham, 2019; Dal Zilio et al., 2019). Therefore, the
52 Holocene shortening of the Himalayas is frequently considered as almost entirely concentrated
53 in the frontal thrust ramp, namely, the main frontal thrust (MFT) (e.g., Lavé and Avouac, 2000).

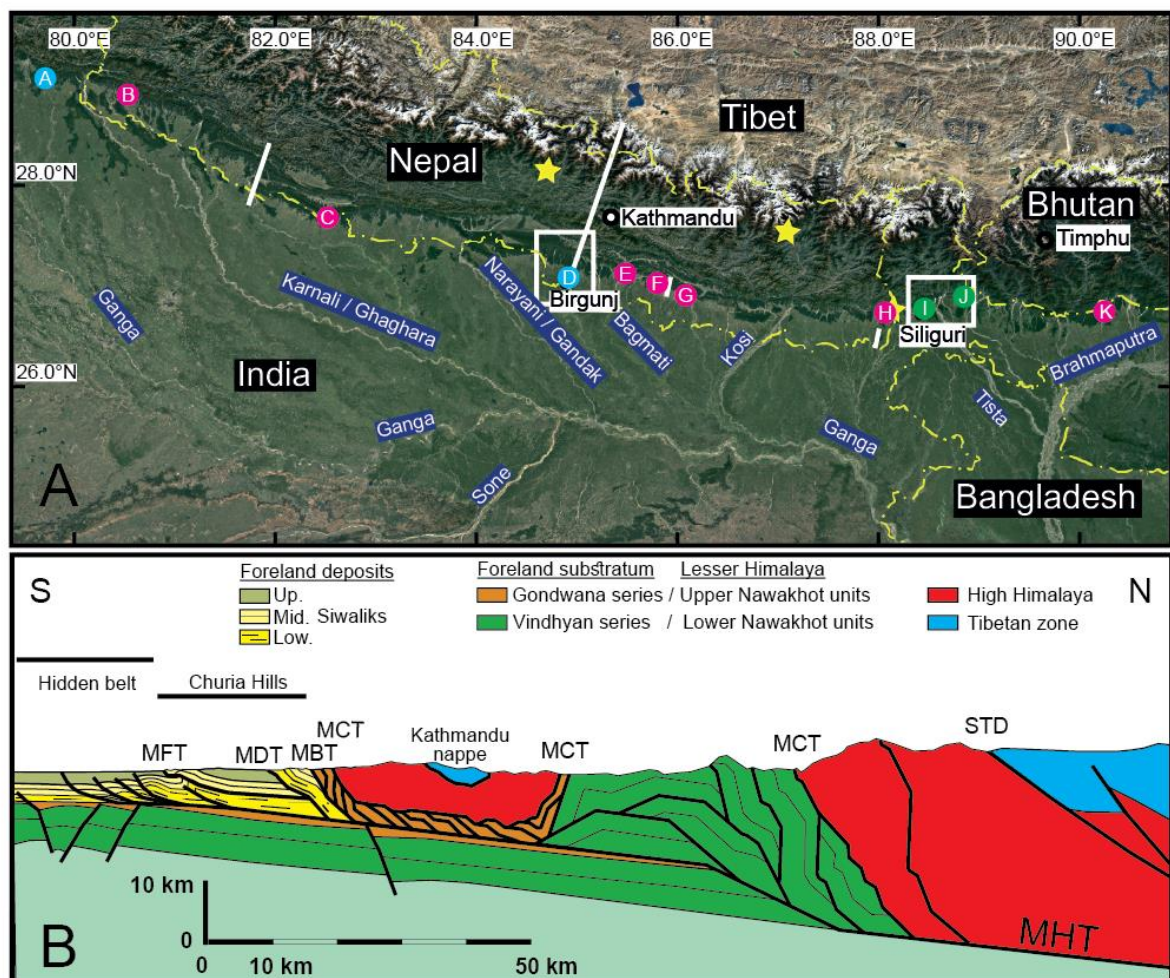
54 This is contrary to the shortening of numerous accretionary wedges and active mountain belts
55 that are not currently concentrated in a unique frontal zone, but are distributed in an embryonic
56 thrust zone (e.g., Le Béon et al., 2019; Gonzalez-Mieres and Suppe, 2011).

57 The incipient structures observed ahead of numerous active thrust belts or accretionary
58 prisms are characteristic of embryonic thrust belts (Gonzalez-Mieres and Suppe, 2011). They
59 are related to slow tectonic processes (Gonzalez-Mieres and Suppe, 2011) and frequently match
60 large-scale pure shear deformation, classically defined as regional layer parallel shortening
61 (LPS) (e.g., Mitra, 1994). Furthermore, detachment folds grow and induce heterogeneous layer-
62 parallel thickening (Mitra, 2003). As shortening accumulates, the fold limbs steepen (Suppe et
63 al., 2004) and the folds may evolve into classical fault-bend folds with ramps that accommodate
64 kilometres of slip (Suppe, 1983). An aseismic deformation component has been suggested in
65 the embryonic thrust belt ahead of the Taiwan thrust belt (Le Béon et al., 2019), but the link
66 between the fold development and seismic cycle is still poorly understood (Suppe, 2014).
67 Nonetheless, numerical modelling suggests that folding does not occur steadily over time, but
68 is modulated by earthquake cycle stresses (Mallick et al., 2021).

69 Nonetheless, various surface deformations have been observed both at the sharp
70 morphologic mountain front and south in the piedmont that forms the northern part of the Ganga
71 and Brahmaputra plains. In numerous cases (Fig. 1A), weak tectonic uplift has been observed
72 in the piedmont (e.g., Thakur et al., 2020; Srivastava et al., 2017; Kar et al., 2014; Yeats and
73 Thakur, 2008) south of portions of the morphologic front where the palaeo-seismological
74 activity of the Main Frontal Thrust (MFT) has been documented (e.g., Le Roux-Mallouf et al.,
75 2020; Wesnousky et al., 2019; Kumar et al., 2006). This uplift of the piedmont is, in some cases,
76 linked to the lateral propagation of the frontal thrust (e.g., Almeida et al., 2018; Delcaillau et
77 al., 2006; Champel et al., 2002), but in most cases, it is located ahead of the frontal thrust (e.g.,
78 Thakur et al., 2020; Yeats and Thakur, 2008). Present-day deformation in the proximal foreland
79 has been suggested by spirit levelling data (Jackson and Bilham, 1994), radar interferometry

80 (Bhattacharya et al., 2014; Yhokha et al., 2015), and GNSS data (Mullick et al., 2009); Gupta
 81 et al., 2017), but none of these studies are robust (Bilham et al., 2017). Further south, alluvial
 82 surfaces are uplifted, warped, and tilted and may form scarps up to 20 m (e.g., Pati et al., 2012).
 83 Some of the scarps were investigated using ground-penetrating radar and were attributed to the
 84 surface extent of thrust splays parallel to the Himalayan front (Yeats and Thakur, 2008) or
 85 oblique faults (Pati et al., 2012), with the latter likely linked to the reactivation of deeply buried
 86 ridges (e.g., Godin and Harris, 2014). Petroleum seismic reflection profiles (Duvall et al., 2020;
 87 Yeats and Thakur, 2008; Bashyal, 1998; Raiverman et al., 1994) and passive seismic data (Large
 88 et al., accepted) suggest that the top of the Middle Siwalik is folded and/or faulted by an
 89 incipient deformation linked to an embryonic thrust wedge south of the MFT.

90



91

92 *Figure 1: Overview map and cross-section of the areas of interest. (A) Satellite image of the Himalayan*
93 *orogeny. The white boxes show the two study areas. The white lines indicate, from west to east, the*
94 *location of the cross-sections of Fig. 2A, Fig. 1B, and Figs 3B and 3A. Circles A to J represent the*
95 *combination of recent deformation south of the MFT and of the recent activity of the MFT from previous*
96 *studies (see Table 2 for their description). The red circles represent geologic evidence of both the slightly*
97 *uplifted zone in the piedmont and seismic rupture on the MFT. The green circles represent evidence of*
98 *seismic rupture in the piedmont, and the yellow stars show the instrumental epicentres of $M_w > 8$*
99 *earthquakes [1934 AD and 2015 AD earthquakes, from Bilham (2019)]. (B) Structural cross-section of*
100 *the Himalayas [modified from Mugnier et al. (2017), Pearson and DeCelles (2005), and Bashyal*
101 *(1998)]. MFT: Main Frontal Thrust; MDT: Main Dun Thrust; MBT: Main Boundary Thrust; MCT: Main*
102 *Central Thrust; STD: South Tibetan Detachment; MHT: Main Himalayan Thrust.*

103

104 Many studies have been conducted in the Himalayan piedmont (Table 2), but only a few
105 have systematically compared imaged structures beneath the plain with the current surface
106 deformation documented by geomorphological studies. In this study, we associated the surface
107 deformations of the Himalayan proximal foreland south of the mountain front to the deep
108 structures in two key zones (Fig. 1A). One is in east-central Nepal (Birgunj area), close to one
109 of the best-studied cross-sections throughout the Himalayas (Fig. 1B) (e.g., Mugnier et al., 2017;
110 Pearson and DeCelles, 2005; Lavé and Avouac, 2000) and the other is in Darjeeling/India (Siliguri
111 area), where one of the best pieces of evidence of piedmont deformation through propagating
112 thrust faults has been studied for a long time (Nakata, 1989). In addition to previous works
113 concerning deformed surfaces and drainage system anomalies, we developed an analysis of
114 river incision using a digital elevation model to quantify surface deformation. For the deep
115 structures, we referred to a recent ambient seismic noise study as well as numerous published
116 seismic reflection studies. The comparison between the geometry of the subsurface structures
117 and the geomorphology shows that uplifted alluvial surfaces are located above an embryonic
118 thrust and fold belt in the Birgunj and Siliguri areas. A quantitative analysis of the tectonics of
119 the embryonic thrust wedge was performed by first estimating the uplift and then by estimating
120 the shortening using simple kinematic models and balancing procedures. Indeed, although
121 shortening is subject to more uncertainty than uplift, it allows for an easier comparison with the

122 general evolution of the Himalayan belt. Fold and thrust belt structures have been analysed for
123 over 50 years (e.g., Butler, 2020, 1982; Boyer, S. E., and Elliott, D. 1982, Dahlstrom, 1970),
124 and the kinematic models used in this paper have been developed and tested in regions where
125 foreland basin sediments have been incorporated into fold and thrust belts (e.g., Le Béon et al,
126 2019; Suppe, 2014, 1983; Gonzalez-Mieres and Suppe, 2011, 2006; Suppe et al, 2004; Husson
127 and Mugnier, 2003; Lavé and Avouac, 2000; Suppe and Medwedeff, 1990). These previous
128 works limit interpretations of structural geometry to a narrow range of possible shapes in the
129 areas studied in this paper where geometric observations are rare. Nevertheless, we have
130 favoured the classical method of excess areas (Goguel, 1952; Chamberlin, 1910), which
131 remains powerful (Moretti and Callot, 2012) even in such a case. In addition, special attention
132 was paid to the uncertainties associated with the shortening estimate. Our results show that the
133 embryonic thrust belt in the east/central Himalayas deformed at a slow rate, whereas the hidden
134 belt in Darjeeling has recently deformed faster and is affected by large earthquake ruptures.

135

136 Our study improves and contributes to the knowledge on deformation in the Himalayan
137 range. A better understanding of the seismic cycle, development of the embryonic thrust belt,
138 and their relationship in a continental subduction range is of academic interest. Furthermore,
139 the aseismic deformation near and south of the MFT is inconsistent with three decades of GPS
140 data and most of the theoretical models of the genesis of great Himalayan earthquakes (Bilham
141 et al., 2017; Dal Zillo et al., 2019), although some physical models (Berger et al., 2004)
142 involving aseismic slip on the entire décollement were consistent with the previous and
143 controversial levelling data (Jackson and Bilham, 1994). Therefore, identifying the seismogenic
144 active structures and understanding the propagation in the foreland of seismic ruptures at a
145 greater time scale than the seismic cycle is of utmost importance for assessing seismic hazards
146 in this region, where the seismic risk is of significant societal importance owing to the high
147 population density in these areas.

148 *Table 1 List of abbreviations in the text*

FAULTS	
MHT	Main Himalayan Thrust
MFT	Main Frontal Thrust
MFT1 to MFT6	Different fault segments of the MFT
MDT	Main Dun Thrust
MBT	Main Boundary Thrust
RT	Ramgarh Thrust
GTF	Gish Transverse Fault
R1	Basement fault inferred from the Birgunj geophysics
F2	Main thrust inferred from the Birgunj geophysics
Tf	Tista thrust inferred from the Tista River geophysics
TERRACES	
T1 to T4	River terraces in the Darjeeling area
TECHNICS AND CONCEPTS	
LPS	Layer Parallel Shortening
GNSS	Global Navigation Satellite Systems
Mw	Moment magnitude of an earthquake
GEOMETRIC PARAMETERS	
S	Shortening at the trailing edge
S_f	Sliding along a ramp
ΔA	Excess area
ΔAr	Increment of relief growing
T_0	Initial Thickness
T_{or}	Thickness at the trailing edge
U	Uplift
θ	Dip of the ramp
V_{sed}	Long-term sedimentation rate at the footwall
V_{upl}	Uplift rate at the hanging wall

149

150 **2. Geological setting of the Himalayas**

151

152 **2.1. The structure of the Himalayan range**

153 The Himalayas are formed by a stack of thrust sheets (Le Fort, 1975) separated by major
154 north-dipping faults that branch off the main Himalayan thrust (MHT) (Fig. 1B). In the southern
155 part, the Lesser Himalayan domain overthrusts the sedimentary rocks of the Neogene Foreland
156 Basin (Siwaliks) along the Main Boundary Thrust (MBT) system and displays complex
157 duplexes in both the lower and upper Nawakhot units (DeCelles et al., 1998; Stöcklin, 1980).
158 The Siwaliks overthrust the modern foreland basin (Indo-Gangetic and Brahmaputra alluvial
159 plains) along the Main Frontal Thrust (MFT). Several thrusts have developed in the Siwaliks,
160 the major one being the Main Dun Thrust (MDT). Although out-of-sequence episodes have

161 occurred (Wobus et al., 2005; Hodges et al., 2004; Mugnier et al., 2004), the entire Himalayan
162 fault system essentially propagates towards the south (e.g., DeCelles et al., 1998). The MHT
163 absorbs approximately $18\text{--}20\text{ mm}\cdot\text{yr}^{-1}$ of convergence in Nepal (Mugnier and Huyghe, 2006;
164 Lavé and Avouac, 2000; Bilham et al., 1997), and more in eastern Assam (Burgess et al., 2012).
165 The geometry of the MHT is characterised by a southern frontal ramp (the MFT) (e.g., Schelling
166 and Arita, 1991), a shallow décollement at the boundary between the Indian Craton and the syn-
167 orogenic sediments of the Siwaliks (Mugnier et al., 1999a), a detachment beneath the Lesser
168 Himalayas, a crustal ramp cutting through the crust of the Indian craton (Avouac et al., 2001),
169 and a lower flat that extends far to the north beneath the Tibetan Plateau (Fig. 1B).

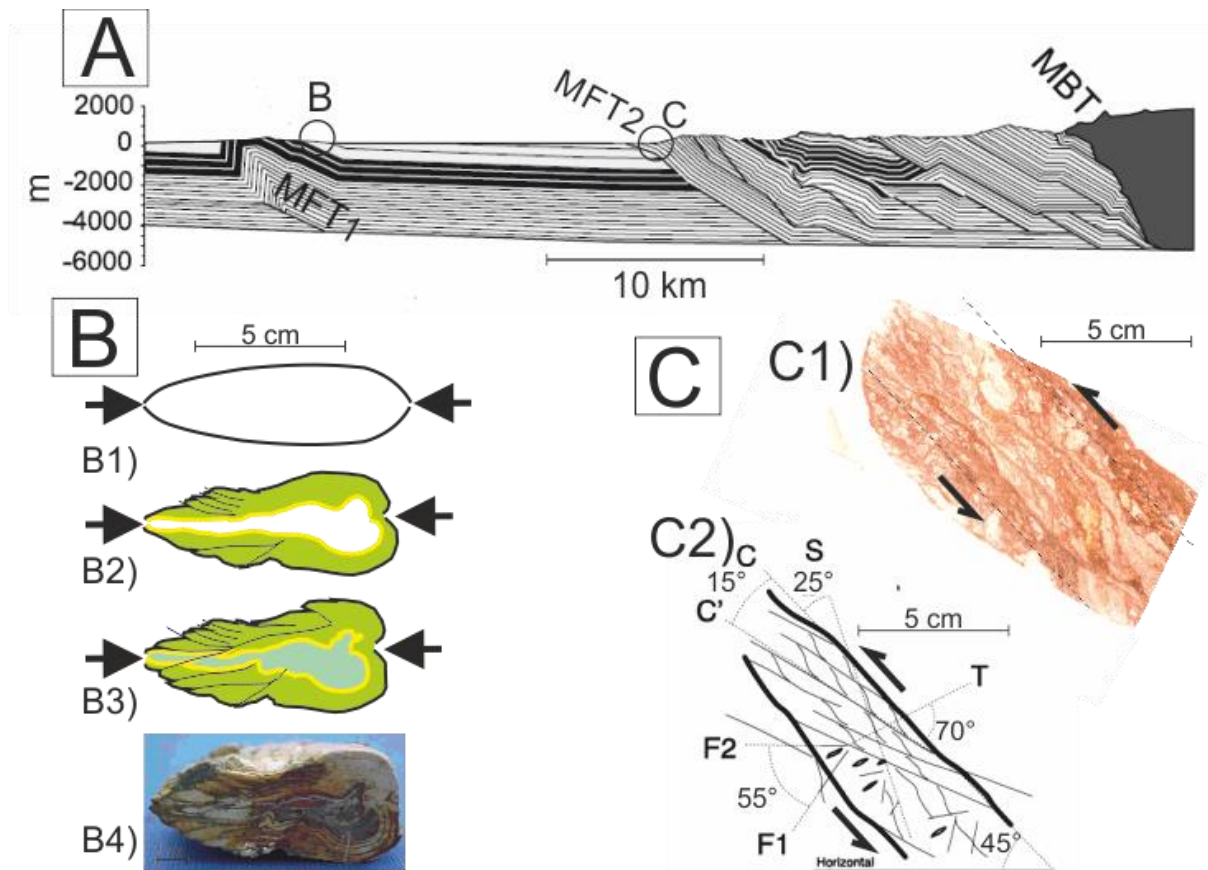
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171 2.2. The frontal structure of the Himalayan range

172 The forward propagation of the Himalayan deformation resulted in the inversion of the
173 Neogene Siwalik Foreland Basin and a thin-skinned thrust belt forming the Churia Hills. The
174 large-scale structures (Fig. 2A) consist of a series of asymmetric fault-related folds with a steep
175 frontal limb, which is frequently completely eroded, and a preserved northern limb that dips
176 $20\text{--}30^\circ$ northward (Mugnier et al., 1999a).

177 In the field, the hanging wall of the MFT is parallel to the bedding at the base of the
178 Lower Siwalik series, and restoration procedures suggest that the footwall flat lies at a depth of
179 approximately 5 km below the Churia Hills in the central Himalayas (Lavé and Avouac, 2000;
180 Mugnier et al., 1998). This result agrees with the interpretation of seismic lines in the western
181 Himalayas (Powers et al., 1998). A shallower décollement has also been documented at a depth
182 of approximately 2 km in the Middle Siwaliks in Nepal (Fig. 3) (Almeida et al., 2018; Schelling
183 and Arita, 1991), and the superposition of décollements leads to a complex duplex-like
184 geometry (Powers et al., 1998).

185



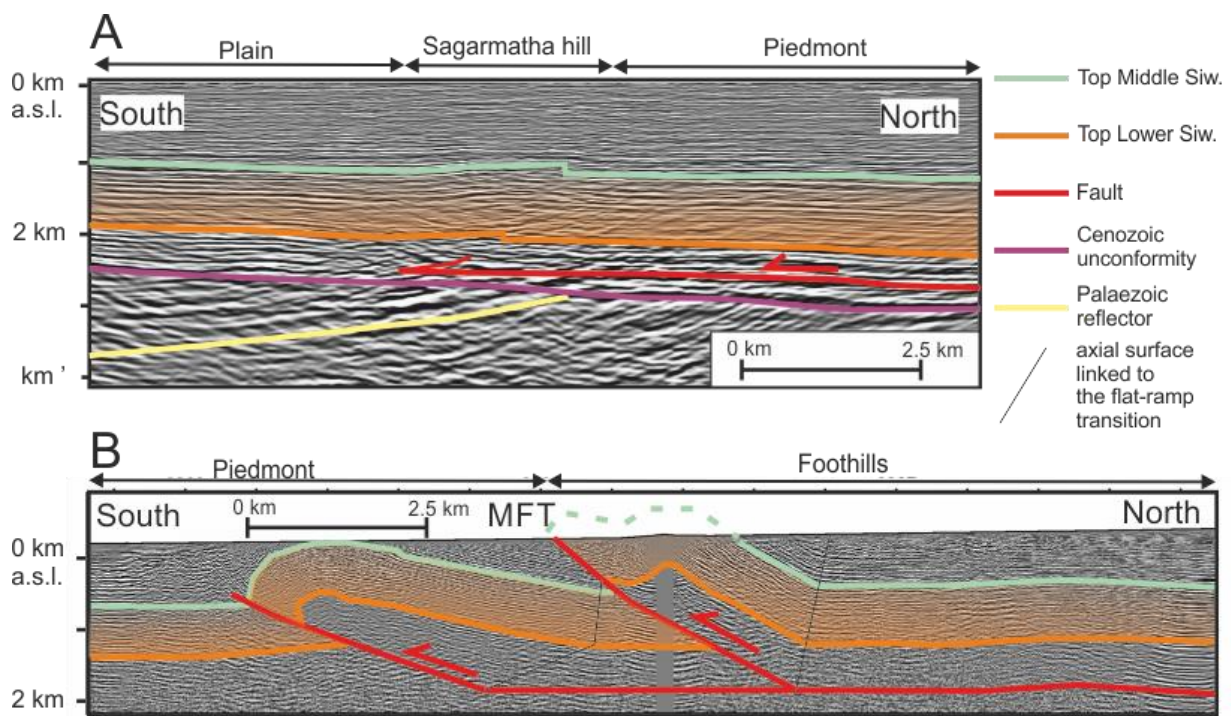
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187 *Figure 2: Types of deformation at the front of the Himalayas from examples of western Nepal.*
 188 *(A) Cross-section through the Siwalik beds of the Churia range [adapted from Mugnier et al.*
 189 *(1999a)] illustrating the succession of fault-propagation folds and folds where only the syncline*
 190 *part is preserved. The circles B and C refer to the location of samples B and C. (B) Internal*
 191 *layer-parallel shortening recorded by the deformation of a bivalve fossil. B1, B2, and B3:*
 192 *progressive deformation from the initial bivalve till the final geometry. The green and yellow*
 193 *levels refer to progressive calcite filling of the shell and (B4) section through the fossil. (C)*
 194 *Simple shear deformation related to major thrusts with C1) showing the section through a shear*
 195 *zone and C2) showing an interpretation of the deformation features in the shear zone. S:*
 196 *pressure solution cleavage; C and C' Riedel fractures; T Tension crack; F1 and F2 late small-*
 197 *scale fractures [from Mugnier et al. (1998)].*

198

199 The MFT is considered to be the youngest and southernmost thrust of the Himalayan
 200 fault system, although other structures have been imaged beneath the plain using seismic
 201 reflection profiles (e.g., Duvall et al., 2020). In particular, incipient triangular zones related to
 202 back-thrust (Fig. 3A) (von Hagke and Malz, 2018) and folds related to the initial stage of fault
 203 propagation (Suppe and Medwedeff, 1990) are locally found on the frontal structures (Fig. 3B)

204 (Almaida et al., 2018). Furthermore, the MFT reaches the surface in most cases at the sharp
 205 topographic front of the range, but has also been observed at the base of smaller reliefs in the
 206 piedmont of eastern Nepal (Delcaillau, 1986), Darjeeling (India) (Nakata, 1989), and Bhutan
 207 (Dasgupta et al., 2013). Specifically, the MFT is not a continuous fault throughout the entire
 208 range, but consists of a succession of segments that branch on each other or depict an echelon
 209 pattern (Mugnier et al., 1999a; Delcaillau, 1986). This segmentation is partly controlled by
 210 subsurface basement structures beneath the foreland sediment (Divyadarshini and Tandon,
 211 2022). A numbering system is frequently used to define different fault segments, such as MFT1
 212 to MFT3 in western Nepal (Mugnier et al., 1999a), MFT1 to MFT6 in central Nepal
 213 (Divyadarshini and Singh, 2019), and MFT1 to MFT4 in the Darjeeling area (Large et al.,
 214 accepted).



215

216 *Fig. 3. Structures imaged by seismic lines (location on Fig. 1A), A) in the piedmont*
 217 *[adapted from Duvall et al. (2020)] and B) at the front of Himalayas [adapted from Almaida et*
 218 *al. (2018)].*

219

220 Thrust faults are formed by very narrow (a few tens of centimetres to a few metres)
221 shear zones (Fig. 2C), and the superimposition of a cataclastic deformation in the vicinity of
222 the faults (Mugnier et al., 1998) on a pressure-solution deformation suggests discontinuous slip
223 during earthquakes (Gratier and Gueydan, 2007). The deformation in the thrust sheets is mainly
224 related to their motion above the fault system, but layer parallel shortening (LPS) is evidenced
225 by the preferred orientation of the grain shape (Srivastava and Mukul, 2020) and the
226 deformation of rare fossils (Fig. 2B). Furthermore, the geometries of the folds linked to fault
227 propagation (Fig. 3B) suggest that axial surfaces above the flat-ramp transition are sheared, and
228 that internal deformation occurs within the levels located above the décollement (Suppe et al.,
229 2004).

230

231 2.2.1. Late Pliocene to Pleistocene formation of the MFT

232 In the western Himalayas (Pakistan), frontal structures developed as early as 2.5 Ma
233 (Pennock et al., 1989) and are absorbing the Himalayan shortening at a rate of $8.4 \pm 1 \text{ mm}\cdot\text{yr}^{-1}$
234 (Cortés-Aranda et al., 2017; McDougall et al., 1993). In western and central Nepal, the MFT
235 has been developing since 2 Ma, as evidenced by syn-tectonic sedimentation (Mugnier et al.,
236 2004) and apatite fission track analysis (Robert, 2009; Van der Beek et al., 2006). A Holocene
237 slip rate of $19 \pm 6 \text{ mm}\cdot\text{yr}^{-1}$ to $21 \pm 1.5 \text{ mm}\cdot\text{yr}^{-1}$ was established for the frontal zone of the
238 Siwaliks (Mugnier et al., 2004; Lavé and Avouac, 2000). In the eastern Himalayas, the MFT
239 was initiated later than 1 Ma (Chirouze et al., 2013) and a minimum slip of $23.4 \pm 6.2 \text{ mm}\cdot\text{yr}^{-1}$
240 was established for the MFT throughout the Holocene (Burgess et al., 2012). The Quaternary
241 propagation of the front induces piggyback basins (Ori and Friend, 1994), locally known as
242 duns, in numerous portions of the Himalayas.

243

244

245

246 2.2.2. The Himalayan seismic cycle and the recent activity of the Main Frontal

247 Thrust

248 The only surface rupture observed in the field for a Himalayan earthquake was linked
249 to the 7.6 Mw 2005 Kashmir earthquake, but was along the MBT (Kaneda et al., 2008). Even
250 for the 8.4 Mw 1934 Eastern Nepal earthquake or the 8.4 Mw 1950 Assam earthquake, no direct
251 observations of their surface ruptures were archived, and they were only inferred from trenching
252 studies performed by Sapkota et al. (2013) and Priyanka et al. (2017).

253 Nonetheless, historical archives of the damage (e.g., Bilham, 2019) and palaeo-
254 seismological trenches (e.g., Kumar et al., 2010) indicate that large earthquakes with >8
255 moment magnitude (M) have episodically ruptured several hundred-kilometre-long segments
256 of the southern part of the MHT (Chandra, 1992). The magnitude of the highest events remains
257 a matter of debate (e.g., Mugnier et al., 2013), particularly in the seismic gaps underlined by
258 historical seismicity (e.g., Bilham, 2019; Seeber and Armbruster, 1981). The areas within the
259 scope of this study are located in major seismic gaps in central Nepal and Darjeeling (Bilham,
260 2019).

261 Most of our knowledge about earthquakes that ruptured the MFT is summarised in a
262 conceptual model based on palaeo-seismology, tectonic geomorphology, historical archives,
263 and geodesy (Bilham, 2019). In this model, large earthquakes (typically Mw ~ 8) rupture the
264 entire length of the MHT from its downdip to the external part (Dal Zilio et al., 2019). They
265 uplift (Avouac et al., 2001) and deform (Whipple et al., 2016) the entire Himalayas. Most of
266 them reach the emerging MFT and delineate the morphologic front; however, it remains
267 uncertain whether all great earthquakes reach the surface (Wesnousky et al., 2018).

268 The along-strike distribution of large earthquakes remains largely debated (e.g., Pierce
269 and Wesnousky, 2016; Mugnier et al., 2013). In the studied zone, between the 1505 AD west
270 Nepal earthquake rupture zone (Yule et al., 2006) and eastern Bhutan, no historic earthquake
271 clearly ruptured the MFT. The respective extensions of 1255 AD (Mishra et al., 2016; Sapkota

272 et al., 2013) or approximately 1100 AD (Kumar et al., 2010; Lavé et al., 2005) ruptures remain
273 under discussion. Similarly, the 1934 AD Bihar Nepal earthquake surface rupture was initially
274 inferred to extend more than 100 km along the MFT (Sapkota et al.; 2013), an interpretation
275 later disproved by Wesnousky et al. (2018). Therefore, the initial hypothesis of a rupture of the
276 1934 earthquake extending under the plain (e.g., Seeber and Armbruster, 1981; Dunn et al.,
277 1939) cannot be definitively discarded because it remains in agreement with geodetic data and
278 with the strong aftershock located near the Indian border, four days after the main earthquake
279 (Bilham et al., 1998).

280 Several observations suggest the occurrence of giant earthquakes greater than ~ 8.4 Mw
281 historical events, because the great earthquakes of the past three centuries are insufficient to
282 explain the transfer of the measured convergence towards the frontal thrust belt (Bilham, 2001)
283 and because seismological trenching is indicative of events with more than 10-m displacements
284 (e.g., Sapkota et al., 2013; Kumar et al., 2010; Lavé et al., 2005) (Table 2). Giant earthquakes
285 would rupture the entire locked part of the MHT, from its downdip up to the MFT surface
286 outcrops, and transfer more than 10 m of displacement from the hinterland to the MFT with a
287 recurrence of 500 to 1200 years (Bollinger et al., 2014).

288 Medium earthquake ruptures, typically $M_w \leq 7.8$, only extend along a portion of the
289 seismological MHT. They either reach the surface out-of-sequence, similar to the 2005 Kashmir
290 earthquake (Kaneda et al., 2008), or end several tens of kilometres north of the MFT, similar to
291 the 2015 Gorkha earthquake (Avouac et al., 2015). Their slip is larger than 4 m and locally
292 reaches up to 9.6 m (Pathier et al., 2006) or 7 m (Grandin et al., 2015) (the Kashmir and Gorkha
293 earthquakes, respectively). They transfer stress in the outer domains and lead to small thrust
294 reactivations in the Churia range of a few tens of centimetres, which is two orders of magnitude
295 below the total slip recorded along the MHT (Elliott et al., 2016). Stress loading of the MFT
296 occurs on the lateral terminations of great earthquakes and south of medium earthquake
297 ruptures. However, the release of stress loading remains poorly understood. This occurs when
298 greater ruptures reach the MFT (Dal Zilio et al., 2019; Bilham et al., 2017), but numerous

299 observations (Table 2 and Appendix A: Supplementary data) suggest a complex deformation
300 pattern beneath the piedmont.

301

302 2.3. The foreland of the Himalayan range

303 2.3.1. Geology of the Neogene to modern Himalayan foreland

304 Seismic data have imaged a thick Tertiary sedimentary wedge beneath the foreland plain
305 in Nepal (e.g., Duvall et al., 2020; DMG, 1990) and India (e.g., Srinivasan and Khar, 1996;
306 Raiverman et al., 1994), where wells have been drilled (e.g., Mugnier and Huyghe, 2006). The
307 Tertiary sediments are thinned out southward and unconformably cover the Indian shield
308 formed in the Late Palaeozoic to Mesozoic Gondwana series (lateral equivalent of the upper
309 Nawakhot series of the Lesser Himalayas) or the Late Proterozoic to Early Palaeozoic Vindhyan
310 series (lateral equivalent of the lower Nawakhot series).

311 The Tertiary sedimentary wedge consisted of two groups of foreland sediments. The
312 oldest group is related to the thin Palaeocene to Miocene series, the oldest of which was
313 deposited via a forebulge basin (DeCelles et al., 1998). The Siwalik group consists of mid-
314 Miocene to Pleistocene molasses deposited in a foreland basin and nourished by the erosion of
315 the hinterland mountains, which is traditionally divided into three lithologic units: the Lower,
316 Middle, and Upper Siwaliks (Gansser, 1964). The total thickness of the three units is up to 5
317 km (Raiverman et al., 1994).

318

319

320

321

322 *Table 2. Studies of active tectonics at the Himalayan morphological front and within the*
323 *piedmont (from west to east).*

	Site name	Latitude/ Longitude	Ref	Type of study	Description of the deformation	Type of structures	Label
1	Lilla	32.323556°N/72.274373°E	(1)	Seismic lines	Hidden fault-related anticline (Western syntax)	b1	
2	Pabbi Hills	32.770263°N/73.697979°E	(1)	Seismic lines	Emergent fault-related anticline (Western syntax)	b2	
3	Hajipur	31.978567°N/75.734766°E	(2)	Seismol. trenching	Seismic rupture along the MFT (lateral propagation)	a1	0
4	Bamonwal-Siprian	31.961803°N/ 75.710387°E	(2)	Geomorph. study	Degraded scarp ~3 km south of the MFT	b1?	
5	Bhatpur	31.304522°N/76.163889°E	(3)	Seismol. trenching	Seismic rupture along the MFT	a1	
6	Masol	30.916264°N/ 76.429419°E	(4b)	Geomorph. study	River diversion and degraded scarp x km south of the MFT	b1	0
7	Chandigarh	30.714666°N/76.873244°E	(4)	Seismol. trenching	Seismic rupture along the MFT	a1	
8	Kala Amb	30.473456°N/77.212165°E	(5)	Seismol. trenching	Seismic rupture along the MFT	a1	
9	Rampur Ganda	30.475024°N/77.213303°E	(4)	Seismol. trenching	Seismic rupture along the MFT	a1	
10	Saharanpur	30.034152°N/77.617100°E	(6)	Seismic lines	'Flower structures' above N-S basement faults	d	
11	Mohand	30.101817°N/77.884437°E	(7)	Radar interferom.	Present uplift expressed along the rivers	c2	0
12	Roorke	30.017155°N/77.873015°E	(1)	Geomorph. study	Tilted and uplifted piedmont – 'Piedmont Fault'	b2, c1?	
13	Lal Dhang	29.848533°N/78.321797°E	(4)	Seismol. trenching	Seismic rupture along the MFT	a1	
14	Najibabad	29.677052°N/78.343195°E	(8)	Remote sensing	15-km uplifted zone-'subsurface Najibabad Fault'	b2, c1?	
15	Ramnagar	29.390559°N/79.127987°E	(4)	Seismol. trenching	Seismic rupture along the MFT	a1	
16	Haldwani	29.088890°N/79.690601°E	(9)	Radar interferom.	20-km present uplifted zone in the piedmont	c2	A
17	Tanakpur	28.846776°N/80.068869°E	(10)	Geomorph. study	Transverse active faults	d	
18	Mohana Khola	28.916808°N/80.527963°	(11)	Seismol. trenching	Seismic rupture along the MFT	a1	B
19	Sarda to Babai River	28.910824°N/80.131557°E 27.978155°N/81.694145°E	(12)	Remote sensing analysis	Western and eastern ends of a NW-SE lineament in the piedmont	b2?	
20	Babai River to Tulsipur	27.779350°N/81.916719°E 27.539566°N/82.411773°E	(12)	Remote sensing analysis	Western and eastern ends of a WNW-ESE lineament in the piedmont	b2?	C
21	Koilabas	27.685344°N/82.526895°E	(13)	Geomorph. study	Seismic rupture along the MFT	a1	
22	Tribeni	27.454052°N/83.916384°E	(14)	Seismol. trenching	Seismic rupture along the MFT	a1	
23	Birg.-Hetauda road	27.081926°N/84.917899°E	(15)	Spirit levelling	30-km uplifted zones in the piedmont	c1	
24	Birg.-Hetauda road	27.081926°N/84.917899°E	(16)	Seismic line	A hidden thrust splay	c2	D
25	Birgunj	27.009030°N/84.870566°E	(17)	Seismic line	Basement fault reactivation	d	
26	Baghmata (front)	27.135514°N/85.487162°E	(14)	Seismol. trenching	Seismic rupture along the MFT	a1	E
27	Baghmata (plain)	26.323662°N/85.508750°E	(18)	Geomorph. study	Tectonic lineament in the piedmont	d	
28	Khayarmara	27.068840°N/85.797880°E	(19)	Seismol. trenching	Scarp 400 m south of the MFT	a2	
29	Marha Khola	27.051167°N/85.818206°E	(20)	Seismol. trenching	Scarp 1.2 km south of the MFT	a2	
30	Sir Khola	27.048373°N/85.871830°E	(21)	Seismol. trenching	Seismic rupture along the MFT	a1	
31	Bhabsi River	27.019091°N/85.878766°E	(22)	Seismic lines	Fault-propagation anticline 3 km south of the mountain front	b2	F
32	Gangetic plain	26.200081°N/85.921142°E	(23)	Geomorph. study	Topographic breaks in the plain	d	
33	Charnath-Aurahi	26.918399°N/86.082130°E	(24)	Seismol. trenching	MFT	a1	G
34	Ratmate	26.912765°N/86.090750°E	(24)	Geomorph. study	Blind thrust 500 m south of the mountain front	a2	
35	Damak	26.733000°N/87.699000°E	(25)	Seismol. trenching	MFT	a1	
36	Sagarmatha	26.467947°N/87.990733°E	(26)	Geomorph. study	Growing anticlinal 30 km south from the morphologic front	b1	
37	Sagarmatha	26.467947°N/87.990733°E	(27)	Seismic line	Anticline above a back-thrust	b1	H
38	Hokse	26.759746°N/88.074739°E	(28)	Seismol. trenching	MFT	a1	
39	Tokla Tea Estate	26.644997°N/88.185671°E	(28)	Geomorph. study	Anticlinal 15 km south from the morphologic front	b1	
40	Singhimuni	26.591722°N/88.204280°E	(28)	Seismol. trenching	Strike slip fault 20 km from the front	d	
41	Tista River	26.766499°N/88.519789°E	(29)	Geomorph. study	Two scarps 25 km south from the morphological front	a3	
42	Siliguri area	27.081926°N/84.917899°E	(29)	Geophysical study	A hidden thrust splay	c2	I
43	Samsing	26.990649°N/88.796921°E	(30)	Geomorph. study	Scarp (MBT) located above a fan	a1?	
44	Matiali	26.941269°N/88.810272°E	(30)	Geomorph. study	Scarp (MFT1) located above a fan	b1	
45	Batabari	26.839273°N/88.819424°E	(31)	Geomorph. study	Lineament in the piedmont	b2?	
46	Chalsa area	26.872660°N/ 88.803580°E	(32)	GPS study	Geodesy through MFT1, MFT2, and MBT	a, b1	J
47	Bharadighi	26.788411°N/88.839102°E	(30)	Geomorph. study	North facing scarp in the piedmont	d, b1?	
48	Panijhora	26.882931°N/88.853980°E	(33)	Seismol. trenching	Seismic ruptures (MFT2) located in the piedmont	a3	
49	Chalsa	26.880971°N/88.867943°E	(34)	Seismol. trenching	Seismic ruptures (MFT2) located in the piedmont	a3	
50	Piping	26.722853° N/89.759980°E	(35)	Seismol. trenching	Seismic rupture along the MFT	a1	
51	Lalbeti	26.744331°N/90.2°E	(36)	Geomorph. study	Fault-related anticline 15 km south of the front	b2	K
52	Sarpang	26.858934°N/90.257642°E	(37)	Seismol. trenching	Seismic rupture along the MBT	a1	
53	Kokrajhar area	26.562453°N/ 90.289895°E	(38)	GPS and geomorph.	Geodesy through MFT1 and a growing anticline	a1, b2	
54	Nameri	26.915017°N/92.752704°E	(34)	Seismol. trenching	Seismic rupture along the MFT	a1	
55	Harmutty	27.133190°N/93.850572°E	(34)	Seismol. trenching	Seismic rupture along the MFT	a1	
58	Himebasti	27.430368°N/94.201264°E	(39)	Seismol. trenching	Seismic rupture along the MFT	a1	
59	Marbong	27.973233°N/95.228520°E	(40)	Seismol. trenching	Seismic rupture along the MFT	a1	
60	Pasighat	28.078065°N/95.332326°E	(41)	Seismol. trenching	1950 AD seismic rupture along the MFT	a1	
61	Kamlang Nagar	27.757485°N/ 96.355718°E	(42)	Seismol. trenching	1950 AD seismic rupture (Mishmi Thrust, Eastern syntax)	a1	

324 The column-labelled site name is used for the location of the sites on Google Earth (see Appendix A:

325 Supplementary data). The column-labelled Type of Structures refers to the diagrams proposed in Figure

326 15. a1) Geologic evidence of seismic rupture at the sharp transition between the Himalayas and the

327 *piedmont; a2) seismic ruptures located less than 2 km from the sharp morphologic transition; a3)*
 328 *seismic ruptures in the piedmont (more than 2 km from the sharp morphologic transition); b1) hidden*
 329 *fault-related anticline that is submerged by the sediment and diverts river drainage; b2) emergent fault-*
 330 *related anticline incised by rivers; c1) hidden thrust splay; c2) monitoring of present-day uplifted zones*
 331 *in the piedmont; d) structures linked to basement fault reactivation. The column-labelled Label refers to*
 332 *the zones where several types of structures were found on the same transverse cross-section (location in*
 333 *Fig. 1A for the A to K labels, labelled 0 for the sites outside Fig. 1A). Reference column: (1) Yeats and*
 334 *Thakur (2008); (2) Malik et al. (2010); (3) Kumahara and Jayangondperumal (2013); (4b) Singh and*
 335 *Tandon, 2008; (4) Kumar et al. (2006); (5) Kumar et al. (2001); (6) Raiverman et al. (1994); (7)*
 336 *Bhattacharya et al. (2014); (8) Kralia and Thakur (2021); (9) Yhokha et al. (2015); (10) Goswami*
 337 *(2012); (11) Yule et al. (2006); (12) Misra et al. (2020); (13) Mugnier et al. (2005); (14) Wesnousky et*
 338 *al. (2017a); (15) Jackson and Bilham (1994); (16) Bashyal (1998); (17) DMG, 1990); (18) Jain et Sinha*
 339 *(2005); (19) Wesnousky et al. (2019); (20) Lavé et al. (2005); (21) Sapkota et al. (2013) and Wesnousky*
 340 *et al. (2018); (22) Almáida et al. (2018); (23) Pati et al. (2012); (24) Rizza et al. (2019); (25) Wesnousky*
 341 *et al. (2017b); (26) Sapkota (2011); (27) Duvall et al. (2020); (28) Upreti et al. (2000); (29) Large et*
 342 *al., in press; (30) Nakata (1989); (31) Srivastava et al. (2017); (32) Mullick et al. (2009); (33) Mishra*
 343 *et al. (2016); (34) Kumar et al. (2010); (35) LeRoux-Mallouf et al. (2020); (36) Dashgupta et al. (2013);*
 344 *(37) LeRoux-Mallouf et al. (2016); (38) Gupta et al. (2017); (39) Pandey et al. (2021); (40)*
 345 *Jayangondaperumal et al. (2011); (41) Priyanka et al. (2017); (42) Singh et al. (2021).*

346

347 In some sections of Nepal (Mugnier et al., 1999a) and Darjeeling (Chakraborty et al.,
 348 2020), a clear angular unconformity is observed as the boundary between the Upper Siwaliks
 349 and an overlying Quaternary alluvium unit. Nonetheless, this boundary is often difficult to
 350 precisely define (Sinha et al., 2007; Jain and Sinha, 2003).

351 The sedimentary wedge beneath the foreland in the Nepal Himalayas is affected by
 352 numerous faults and fold structures related to an incipient fold and thrust system located above
 353 a décollement at the base of the Tertiary (Fig. 3B) (Duvall et al., 2020; Bashyal, 1998;
 354 Friedenreich et al., 1994). Furthermore, the Tertiary reactivation of basement faults has been
 355 locally imaged (Manglik et al., 2022; Adilakshmi et al., 2021). Similar tectonic features within
 356 the sedimentary wedge and its basement have also been found in western (e.g., Yeats and
 357 Takhur, 2008) and eastern India (Karunakaran and Rao, 1976).

358

359 2.3.2 Morphology of the Himalayan piedmont

360 The geomorphology and stratigraphic architecture of the Himalayan piedmont mainly
361 depend on mountain-fed, foothill-fed, and plain-fed river source areas (Sinha et al., 2010).
362 Megafans develop at the mountain exit of the major Himalayan rivers (Ghaghara, Gandak, Kosi,
363 and Tista Rivers on Fig. 1A) that transport prodigious quantities of detrital material. They are
364 spread over vast areas with low gradients and consist of multi-storied sand sheets (Chakraborty
365 and Gosh, 2010; Sinha et al., 2007).

366 Inter-megafan areas are drained by foothills and plain-feeding rivers. Furthermore, their
367 deposits correspond to overbank deposits forming mud-dominated intervals in the Quaternary
368 alluvium or small stream-dominated alluvial fans that extend south of the mountain front down
369 to 10–15 km, depositing locally coarse reworked material such as the Bagmati fan (Fig. 1A).
370 Therefore, deposits of the inter-megafan piedmont just south of the mountain exit consist of
371 poorly sorted boulders, cobbles, pebbles, and narrow sand bodies interbedded in muddy
372 sequences (Dhital, 2015; Sinha et al., 2005).

373 The assumption of a unique piedmont surface (piedmont fan surface) (Singh, 1996) at
374 the Himalayan scale is an oversimplification (Sinha et al., 2007), because fan deposition is
375 discontinuous and controlled by the balance between transport capacity and sediment supply.
376 Aggradation and incisional events occur when the Indian monsoon intensifies or decreases (Dey
377 et al., 2016). Landforms that originated in major humid climate periods of reasonable duration
378 were related to widespread alluviation and planation, whereas fans linked to shorter climatic
379 events have smaller lateral extents and are alluviated above the previous, more planar
380 landforms, which are only locally preserved in the piedmont. Therefore, the inter-megafan
381 piedmont surface is diachronic and has variable ages, ranging from 24 ka (Vassallo et al., 2015)
382 to 4.8 ka (Thakur et al., 2007) in the western Himalayas, 90 ka (Gibling et al., 2005) to 4.8 ka
383 in the central Himalayas (Srivastava et al., 2003; Parkash et al., 2000), to 60 ka to 3.5 ka in the
384 eastern Himalayas [see section 4.2 and Appendix B: Supplementary data for a compilation of

385 the results of Goswami et al. (2019), Singh et al. (2016), Starkel et al. (2015), Kar et al. (2014),
386 Kumar et al. (2010), and Guha et al. (2007)].

387 The fluvial deposits of the modern foreland basin are covered by soils, the development
388 of which varies with local geomorphologic stability. Remnants of soils are preserved in uplifted
389 zones, whereas soils are usually reworked in flooded lower zones (Pati et al., 2012). Changing
390 the soil character is also controlled by decreasing the geomorphic slope down megafan surfaces
391 away from the mountain front (Hartley et al., 2013).

392 Finally, inland/terminal fans develop in the modern foreland approximately 50–100 km
393 south of the mountain front (Pati et al., 2015). Their distribution in the distal plain has been
394 partly attributed to faulting activity along the E-W and NE-SW topographic break scarps (Pati
395 et al., 2012). The latter could be associated with the reactivation of basement faults that
396 delineate tectonic blocks characterised by fluvial anomalies (Jain and Sinha, 2005) and are too
397 distant (more than 50–100 km) to be related to the frontal propagation of the Himalayan tectonic
398 prism (e.g., Chalaron et al., 1995).

399 Some fans are strongly incised in the piedmont zone by tens of metres up to a hundred
400 metres (Abrahami et al., 2018), and the origin (tectonic or climatic) is discussed in Sections 3.2
401 and 4.2.

402

403 2.3.3 Present-day deformation of the plain and the Churia range

404 Topographic measurements were undertaken in east/central Nepal nearly half a century
405 ago (Jackson and Bilham, 1994), spatial geodetic measurements have been in progress over the
406 entire Himalayan range for nearly 30 years (Dal Zilio et al., 2019; Bilham et al., 1997), and
407 interferometry techniques have been tested since the beginning of the millennium.

408 The synthesis of global navigation satellite system (GNSS) measurements and their
409 models suggests that the convergence in the Himalayas is expressed by the creep of the MHT
410 beneath the northern Himalayas and by elastic deformation (e.g., Ader et al., 2012). Indeed, the

411 southern part of the MHT is locked between great earthquakes (e.g., Dal Zilio et al., 2019) and
412 the Himalayan elastic deformation is progressively attenuated towards the south and ends close
413 to the Himalayan front.

414 GNSS data indicate that the deformation of the foreland basin zone and the southern
415 part of the Himalayas is smaller than the level of detection of the GNSS data in this area (Bilham
416 et al., 2017). This level of detection is more than 0.5 mm/yr and 1.5 mm/yr for horizontal and
417 vertical GNSS data, respectively, owing to the high noise level of GNSS continuous time series
418 from the Himalayas, even after correction for monsoon loading effects and residual seasonal
419 signals (Mencin et al., 2016; Flouzat et al., 2009). Nonetheless, local deformation rates of
420 several millimetres per year have been inferred via interferometry techniques (Yhokha et al.,
421 2015; Bhattacharya et al., 2014) or local GNSS networks (Gupta et al., 2017; Mullick et al.,
422 2009). However, a critical analysis of these data shows a low level of confidence; Bhattacharya
423 et al. (2014) only found a significant Sar interferometry signal along the rivers, a location
424 suggesting that the signal recorded geomorphologic/hydrologic processes. Yhokha et al. (2015)
425 did not perform a quality analysis of the calculated persistent-scattered-insar ground
426 displacement field. The several-millimetre GNSS signal found by Gupta et al. (2017) was
427 related to a velocity estimated in an Indian-fixed frame, but the signal does not exceed the
428 uncertainty of the data if expressed in a frame fixed to the front of the Himalayas, because the
429 motion is probably linked by the clockwise rotation of the Brahmaputra Valley and Shillong
430 Plateau (Vernant et al., 2014). The shortening estimated at 4.2 ± 1.5 mm/yr through the piedmont
431 of the Gorubathan recess (Mullick et al., 2009) could be related to the elastic deformation at the
432 Himalayan scale in a zone where the locked zone of the MHT is narrow (Vernant et al., 2014).

433 The levelling data of Jackson and Bilham (1994) were cited by most studies concerning
434 the present-day deformation of the Himalayas (Dal Zilio et al., 2019; Bilham et al., 1997).
435 Nonetheless, they were recorded during a period of very limited microseismicity, as evidenced
436 by seismological studies (Pandey et al., 1999), which is in disagreement with the slow events

437 below the foothills and piedmont zones. Finally, the vertical motion in the plain evidenced by
438 levelling was re-interpreted as groundwater withdrawal subsidence (Bilham et al., 2017), a
439 point that is discussed in Sections 3.2 and 5.3.

440 Even during a medium earthquake, such as the 2015 Gorkha earthquake, no significant
441 motion affected the piedmont and frontal part of the Himalayas (Grandin et al., 2015). After
442 this earthquake, only the GNSS station located at Dhukuwa (Fig. 4) indicated a displacement
443 of a few centimetres of the MFT hanging wall, and no post-seismic deformation occurred in the
444 piedmont (Jouanne et al., 2019). Nonetheless, post-seismic creep processes may have affected
445 the easternmost part of the Himalayas during the 1947–1970 sequence of four earthquakes that
446 progressively ruptured the up-dip of the MHT (Bilham et al., 2017).

447

448 **3. The embryonic thrust wedge of the Birgunj area (east/central Nepal)**

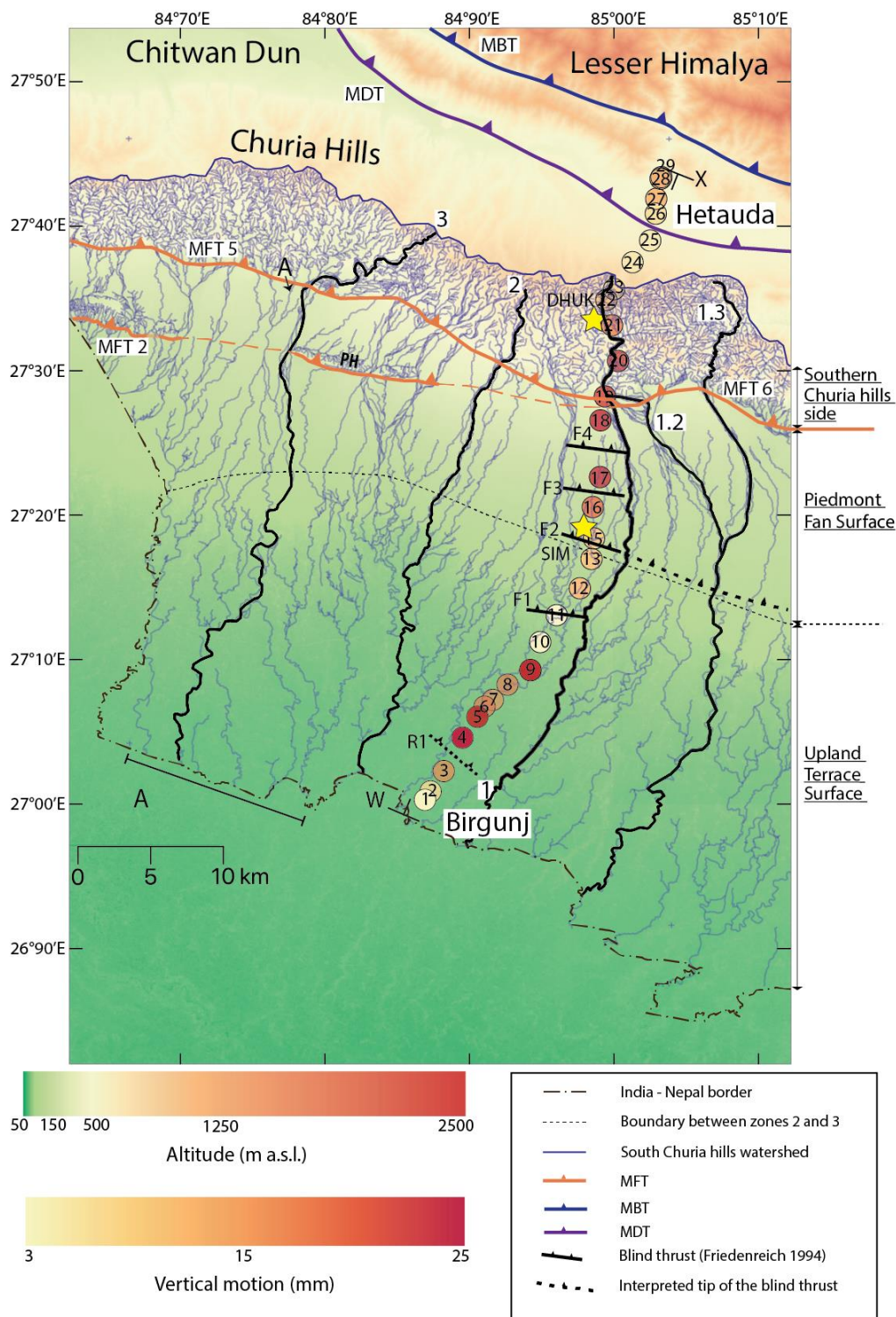
449

450 **3.1 The tectonics of the Birgunj-Hetauda area**

451 In the Churia ranges of east/central Nepal, six MFT segments have been defined by
452 Divyadarshini and Singh (2019). Here, their nomenclature is used, although the studied zone
453 includes only the MFT2, MFT5, and MFT6 segments (Fig. 4). The evolution of the topographic
454 metrics between MFT5 and MFT6 indicates that the long-term uplift rate of MFT6 was greater
455 than that of MFT5 (Divyadarshini and Singh, 2019), suggesting that MFT6 cumulates the
456 shortening of MFT5 and MFT2 that merge close to Birgunj-Hetauda road (Mugnier et al., 2017)
457 (Fig. 4). In the Hetauda area, a tight asymmetric anticline with a steep southern flank is exposed
458 in the Middle Siwalik sediments just north of the MFT, forming the topographic front of the
459 Churia range. This is interpreted as a fault-propagation fold (Wahyudi et al., 2021) located at
460 the hanging wall of an intermediate décollement (Leturmy, 1997). A deeper décollement at the
461 base of the Lower Siwaliks is evidenced eastward (Lavé and Avouac, 2000) and the MDT
462 branches on this décollement (Schelling et al., 1991). A piggyback basin (Chitwan-Hetauda

463 Dun) is located above this décollement north of the frontal anticline and is delimited northward
 464 by the MDT (Fig. 4).

465



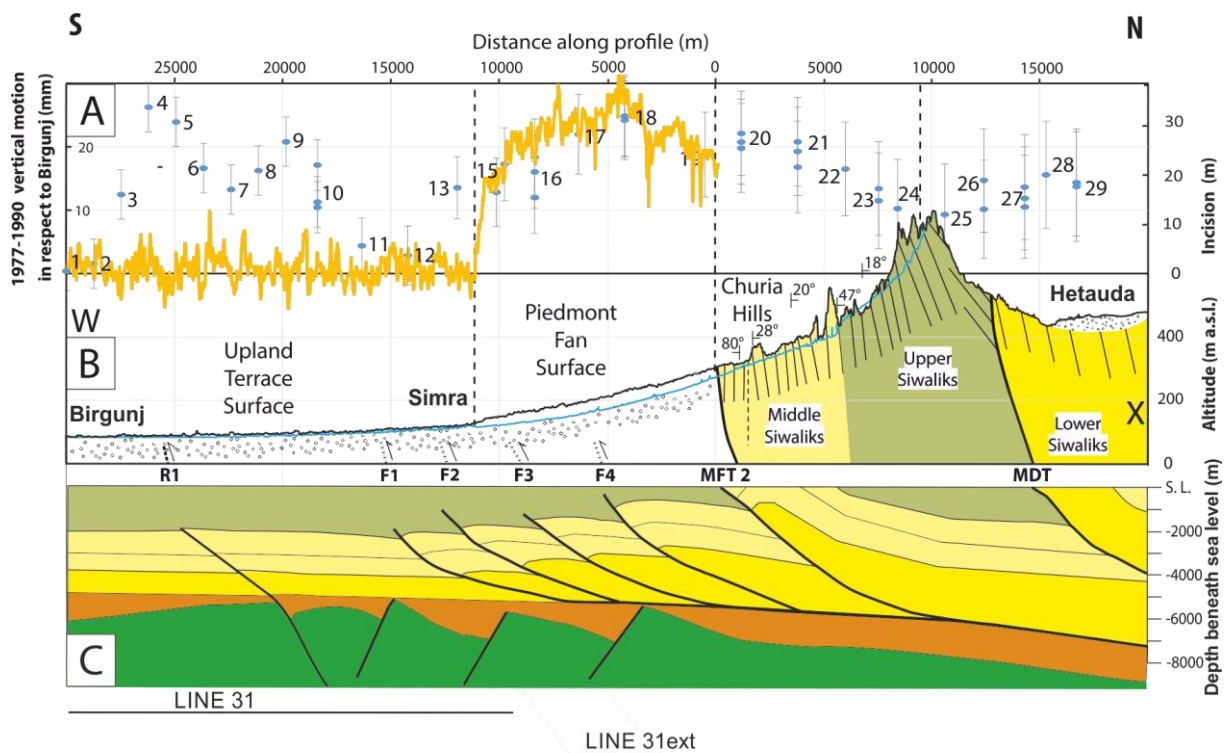
466

467 *Figure 4: Structural and hydrological map of the Himalayan piedmont in the Birgunj area. The*
 468 *highlighted rivers 1, 1.2, 1.3, 2, and 3 refer to the profiles of Figure 6. MFT: Main Frontal Thrust; MDT:*
 469 *Main Dun Thrust; MBT: Main Boundary Thrust; PH: Parsa Hills; DHUK and SIM: Dhukuwa and*
 470 *Simra GNSS stations, respectively. The MFT location was obtained from Divyadarshini and Singh*

471 (2019) and Mugnier et al. (2017). The altitude (a.s.l.) was obtained from the ASTER (2011) Digital
 472 Elevation Model. The drainage network was extracted from 1:25,000 topographic maps of the Nepal
 473 government. The numbered dots refer to the levelling sites along the Birgunj-Hetauda road (Jackson
 474 and Bilham, 1994). Their vertical motion relative to Birgunj is shown with a colour coding ranging from
 475 yellow (1 mm) to heavy red (28 mm). W-X: the location of Figure 5.
 476

477 Beneath the piedmont, the seismic line 31ext (dots 9–29 in Fig. 4) suggests that several
 478 thrusts with spacing less than 10 km branch on the basal décollement at the base of the Tertiary
 479 wedge (Fig. 5) (Bashyal, 1998; Friedenreich et al., 1994; DMG, 1990). The elevation difference
 480 between the beds at the anticline axes and in the undeformed foreland is of the order of a few
 481 hundred metres. Thrust F2 (Fig. 5C) is clearly imaged, whereas the details of the other faults
 482 are poorly documented, and their offsets are difficult to quantify. These structures south of the
 483 MFT are considered in the following as an embryonic thrust wedge (Gonzalez-Mieres and
 484 Suppe, 2011).

485 Seismic line 31 (dots 1–15 in Fig. 4) (DMG, 1990) suggests reactivation of a basement
 486 fault (R1) (Fig. 5C) that forms the southern boundary of the Vindhyan graben.



487

488 *Figure 5: Comparison among incision, 1977–1990 vertical motion from levelling data, topographic*
489 *profile through piedmont, river profile, and tectonic structures. The horizontal scale is similar for A, B,*
490 *and C. (A) River incision (yellow line) and 1977–1990 vertical motion in the Birgunj area (blue dots)*
491 *(Jackson and Bilham, 1994). (B) The black and blue lines represent the piedmont profiles (W-X on Fig.*
492 *4) and river profiles (river 1 on Fig. 4), respectively. The surface dips of the Siwalik strata were obtained*
493 *from Schelling et al. (1991). (C) Interpretation of seismic profiles. The MDT (Main Frontal Thrust),*
494 *MFT (Main Frontal Thrust), and southernmost thrusts were obtained from Bashyal's (1998)*
495 *interpretation of seismic line 31 ext. The reactivated basement fault R1 data were obtained from Jackson*
496 *and Bilham's (1994) interpretation of seismic line 31 (DMG, 1990). The horizontal and vertical scales*
497 *are the same.*

498

499 3.2 Morphology and incision of the piedmont

500 The Birgunj area lies in the piedmont between the Gandak megafan and Bagmati fan
501 (Fig. 1A). The interfan surface is characterised by small rivers that do not presently cross the
502 southern ridge of the Churia Hills and originate from its southern flank. Nonetheless, rivers
503 would have crossed the MFT2/MFT5 frontal system until ~50 ka (Divyadarshini et al., 2020)
504 because the MFT5 had propagated at that time towards the west (Divyadarshini and Singh,
505 2019), leading to the capture of the Chitwan Dun drainage system by the Narayani/Gandak
506 River (Fig. 1). This capture led to a major reorganisation of the drainage of the Birgunj
507 piedmont, and the old piedmont fan surface recognised along with transverse profiles 1, 1.2,
508 and 1.3 (Fig. 6) in this area could be abandoned due to this reorganisation. In contrast, the
509 younger upland terrace surface that aggraded above the old piedmont fan surface could be
510 related to the last 3.5–9 ka aggrading event (Srivastava et al., 2003, and other references in
511 Appendix B).

512 The boundaries between the Southern Churia Hills, Piedmont Fan Surface, and Upland
513 Terrace Surface morphologic zones (Srivastava et al., 2003) have been mapped in the area (Fig.
514 4) using the individual channel type changes, namely, braided, meandering, or straight

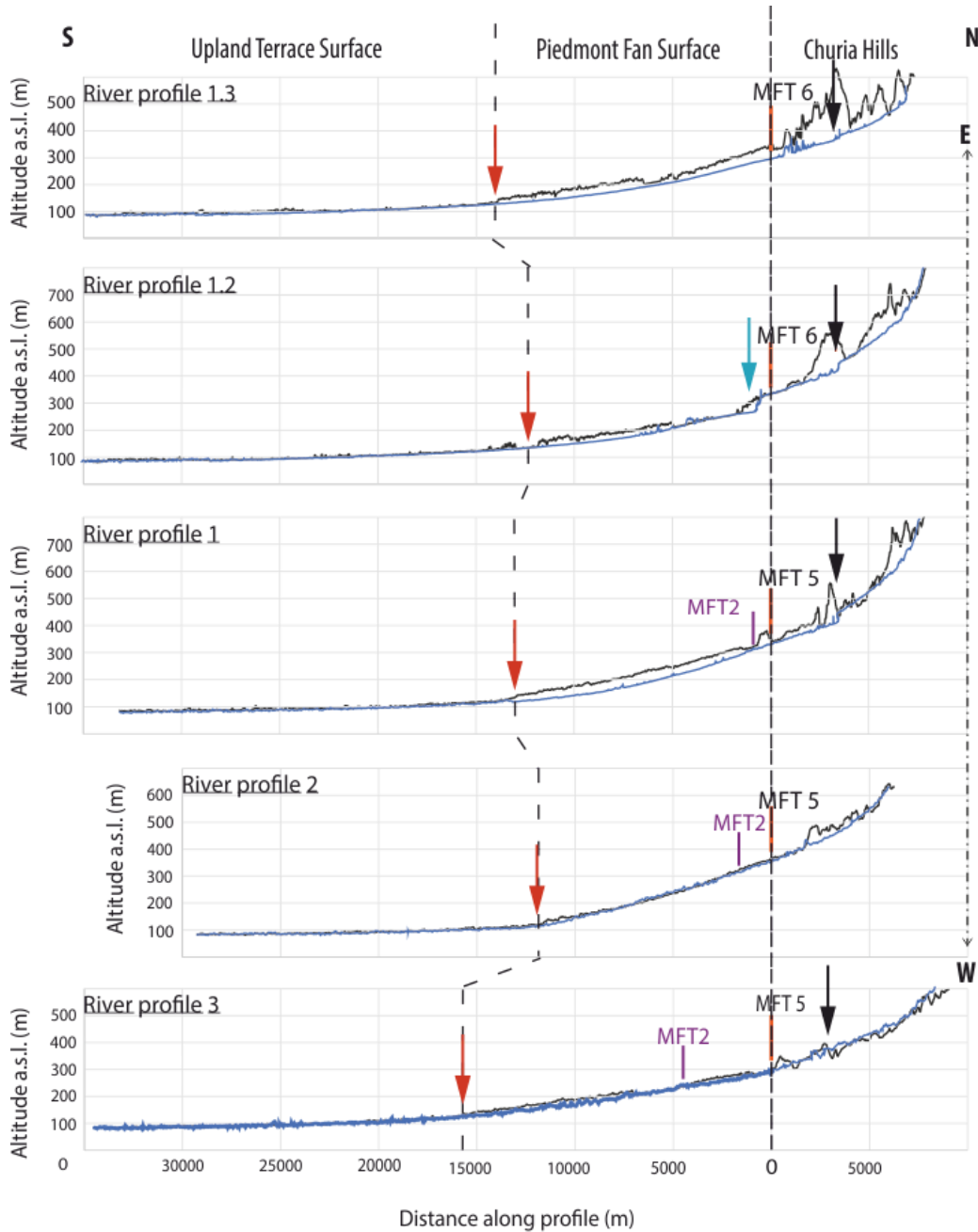
515 (Schumm, 1985), because a change in channel pattern is a subtle indicator of a slope change
516 (Miall, 2013; Schumm and Khan, 1972). The northern zone displays small converging dendritic
517 drainage systems corresponding to the southern Churia Hills, ranging from 400 to 800 m a.s.l.
518 On the piedmont fan surface, rivers become more linear, with locally braided channels, as the
519 altitude decreases to ~150 m a.s.l. through a slightly convex south-facing slope of $1.22 \pm 0.05^\circ$
520 to $0.63 \pm 0.05^\circ$. The boundary between the piedmont fan surface and the upland terrace surface
521 correlates with a change from a generally slightly convex area (1.22° – 0.63°) to a nearly planar
522 and very gently dipping (0.15° – 0.11°) area (Fig. 6). Nonetheless, river profile 2 showed a strong
523 slope variation ($\sim 1^\circ$) from a nearly planar piedmont fan surface to a nearly flat upland terrace
524 surface. Finally, numerous small streams develop on the Upland Terrace Surface and create a
525 dendritic pattern between the largest rivers that become slightly more sinuous.

526 Knickpoints affect the profiles of the rivers crossing the topographic front
527 (Divyadarshini and Singh, 2019), but it is difficult to determine their origin. They could indicate
528 changes in lithology or locations of active faults (Hack, 1973; Keller and Pinter, 2002), because
529 the thrusts most often place distinct lithologies in contact with older and more indurated rocks
530 in the hanging wall compartment. The major knickpoints in the Churia Hills (Fig. 6) could also
531 be relics of knickpoints related to MFT surface ruptures that migrate upward (Cook et al., 2012).
532 Finally, knickpoints in the piedmont could be located where the rivers split into an anastomosed
533 system (river profile 1.2, Fig. 6).

534 A general anastomosed system developed south of the mountain front. West of the
535 Birgunj-Hetauda road (Fig. 4), all the funnel-shaped geometries issued from the hill/plain
536 boundary are interconnected, and the outlets at the hill/plain boundary, such as River A (Fig. 4),
537 are finally distributed at the Nepal/Indian border in more than four rivers within a large 10-km
538 zone. The anastomosed system is less extended east of the Birgunj–Hetauda road, although
539 rivers 1, 1.2, and 1.3. (Fig. 4) are interconnected.

540 The large-scale anastomosed pattern to the west of the Birgunj-Hetauda Road could be
541 linked to several avulsions triggered by extreme monsoon floods (Makaske, 2001).

542 Nonetheless, anastomosed river systems can form when the base level is increased by a
 543 localised uplift zone (Grimaud et al., 2017; Makaske, 2001), and the river splits occurring
 544 around the Siwalik Hills of Parsa (Fig. 4) are probably linked to moderate MFT2 tectonic
 545 activity (Burbank and Anderson, 2011).



546
 547 *Figure 6: River (blue lines) and terrace (black lines) profiles from the southern flank of the Churia Hills*
 548 *(location in Fig. 4). The MFT5 and MFT6 locations are vertically aligned. MFT2 is indicated in purple.*
 549 *Black arrows show knickpoints in the Churia Hills. The blue arrow indicates the greatest knickpoint*
 550 *located south of the MFT. The red arrow indicates a noticeable break in the river slope.*

551

552 The eastern part of the piedmont fan surface (profiles 1.3 and 1) (Fig. 6) shows an
553 approximate 20–40 m incision. As the sizes and topographic metrics of the catchments in the
554 Churia Hills are similar for all the rivers of the studied area (Divyadarshini and Singh, 2019),
555 sediment delivery is probably similar. Therefore, the greater incision of the eastern piedmont
556 could be related to the greater uplift. Along river profile 1, an incision of up to 40 m occurred
557 with respect to the adjacent terrace (Fig. 5B). In this particular case, the incision only furnishes
558 a minimum bound for the uplift (Vignon et al., 2017), because the aggradation occurring in the
559 upland terrace zone induces an increase in the relative base level, and the river slope probably
560 increases as a result of decreased flow associated with the capture of the upstream portions of
561 the watersheds by the Narayani River (Divyadarshini et al., 2020). Assuming that the old
562 piedmont surface was deposited close to, and possibly before, ~50 ka (Divyadarshini et al.,
563 2020), the 40 m incision suggests that the uplift rate affecting the piedmont is weak, less than
564 $0.8 \text{ mm}\cdot\text{yr}^{-1}$.

565

566 The change in elevation between 1977 and 1990 was estimated using spirit levelling
567 (Jackson and Bilham, 1994) (Fig. 5A) and reached 28 mm with respect to Birgunj. A
568 comparison between incision and reiteration of the levelling profiles indicates that no incision
569 affects the morphology of the plain south of Simra (Fig. 4), where levelling reiteration shows
570 that the plain has risen (points 4-9) relative to the Birgunj (points 1-3) and Simra (points 10-15)
571 areas (Fig. 5A). This comparison supports the re-analysis of the levelling data by Bilham et al.
572 (2017), which suggests that two zones underwent subsidence due to recent (few tens of years)
573 and intense groundwater withdrawal in the vicinity of the Birgunj and Simra settlements, and
574 that the intermediate zone (point 4-9) remained stable, with no tectonic uplift during the
575 considered period.

576

577

578

579 3.3 Estimation of the deformation rates from deep structure geometry and relief
580 development

581 The upper Siwalik units were deposited but thinned above the hidden structures, and the
582 uplift rate at the hanging wall of these structures was thus lower than the deposition rate in the
583 foreland (Fig. 5). The long-term subsidence of the foreland basin in central Nepal was ~ 0.4
584 $\text{mm}\cdot\text{yr}^{-1}$ over the last 10 Ma, according to the Raxaul drilling located south of Birgunj
585 (Srinivasan and Khar, 1996; Sastri, 1979), and the short term deposition rate in the plain was
586 estimated to be $0.6 \text{ mm}\cdot\text{yr}^{-1}$ to $1.4 \text{ mm}\cdot\text{yr}^{-1}$ for the few last millenniums (Sinha et al., 1996).
587 Therefore, the uplift rate at the hanging wall of the hidden thrust structures was less than 1.4
588 $\text{mm}\cdot\text{yr}^{-1}$. Despite significant uncertainties, these values are one order of magnitude lower than
589 the uplift rate estimated to be $15 \pm 2 \text{ mm}\cdot\text{yr}^{-1}$ at the hanging wall of the MFT in the east-central
590 Himalayas (Lavé and Avouac, 2000).

591 The shortening rate in thrust belts can be estimated using a simple and powerful method
592 based on the conservation of volume. The excess area method is derived from the conservation
593 of volume through the conservation of the surface in the cross-section (Goguel, 1952;
594 Chamberlin, 1910) and is one of the more robust assumptions of quantitative structural geology
595 (Moretti and Callot, 2012). The total horizontal shortening of a structure can be estimated by
596 applying:

$$597 \quad S = \Delta A/T_0, \quad (1)$$

598 where T_0 is the initial (stratigraphic) thickness, ΔA is the excess area, and S is the shortening.
599 This method, based on the estimation of two geometric quantities, is influenced by several
600 assumptions and uncertainties. The uncertainty values indicated below for the excess area
601 combine those for the current position measurement, initial position estimate, and volume
602 change. The uncertainty values indicated for the initial thickness combine those for the
603 measurement of the depth of the décollement level, the influence of the slope of the décollement
604 level, and the deformation-related stratigraphic thickness change. Finally, the estimate of
605 shortening is affected by the uncertainty that results from the propagation of all uncertainties

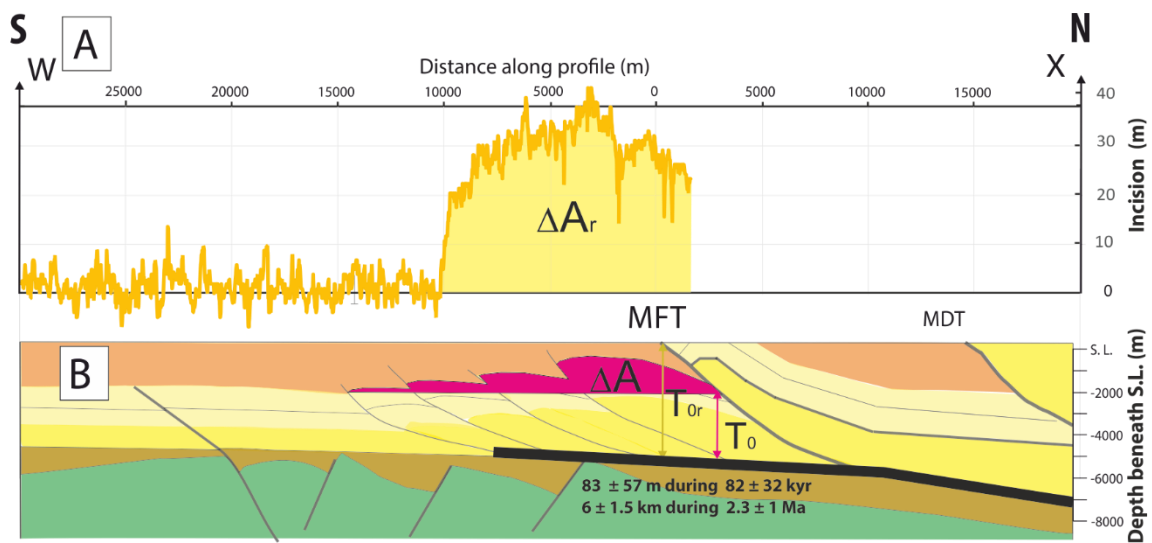
606 (details in Appendix C: Supplementary Data).

607 In the case of the Birgunj profile, the initial stratigraphic thickness T_0 of the Middle and
608 Lower Siwaliks series is estimated from field work (Lavé and Avouac, 2000; Harrison et al.,
609 1993) and from the Raxaul drill hole (Sastri, 1979) and is 2.8 ± 0.6 km. The excess area ΔA
610 (Fig. 7) is $16.9 \pm .32$ km², leading to a 6 ± 1.5 km shortening.

611 The seismic lines had poor resolution, and most of the reflections were very tenuous.
612 However, some of them would suggest onlaps above the top of the Middle Siwaliks
613 (Friedenreich et al., 1994), thus indicating the activity of the hidden structures during the Upper
614 Siwalik deposition. The beginning of the latter is estimated to be 1.8 ± 0.5 Myr in west/central
615 Nepal (Gautam and Rösler, 1999) and 2.8 ± 0.5 Myr in eastern Nepal (Ojha et al., 2009).
616 Considering the 6 ± 1.5 km shortening estimated from the excess area method, the long term
617 (millennium to million-year scale) shortening rate distributed in the hidden belt would be $2.6 \pm$
618 1.3 mm·yr⁻¹. The uncertainty of this estimation is large, but the shortening rate in the hidden
619 belt is nearly one order lower than that in the Churia belt, estimated to be 21 ± 1.5 mm·yr⁻¹
620 (Lavé and Avouac, 2000).

621 A method based on the adaptation of Eq. (1) (Epard and Groshong, 1993) was developed
622 to link relief growth and incremental shortening in embryonic thrust belts (Gonzalez-Mieres
623 and Suppe, 2006). In the case of a deformed and incised terrace, the surface of the deformed
624 terrace refers to the final state, whereas the present-day river profile indicates the initial state
625 because the present-day river profile is assumed to be the same as the palaeo-river profile when
626 the terrace was abandoned at the end of its deposition. The increment of relief growth ΔAr (Fig.
627 7A) was estimated from the difference between the terrace profile and the river profile, that is,
628 by summing the incision of the terrace along the cross-section, and the initial thickness (T_{0r}) is
629 the thickness of the embryonic thrust wedge at its back. In the case of the Birgunj profile, the
630 old piedmont surface is not defined north of the MFT, and ΔAr cannot be estimated above the
631 inner part of the embryonic thrust belt located beneath the MFT. Therefore, the calculation, in

632 which $\Delta A_r = 0.43 \pm 0.3 \text{ km}^2$ and $T_{0r} = 5.2 \pm 0.6 \text{ km}$, underestimates the shortening with a value
 633 of $83 \pm 58 \text{ m}$, or $1 \pm 0.8 \text{ mm}\cdot\text{yr}^{-1}$ during 50 to 115 ka.



634
 635 *Fig. 7: Estimated excess areas and initial thickness for the Birgang cross section [See Figure*
 636 *S1 in Appendix C: Supplementary Data for details of assumptions made when applying the*
 637 *excess area method (Chamberlin, 1910) and the area relief method (Gonzales-Mieres and*
 638 *Suppe, 2006)]. . A) Relief areas created during the deformation of the old piedmont surface*
 639 *(yellow zone: $\Delta A_r = 0.43 \pm 0.3 \text{ km}^2$). B) Location on the interpreted seismic line of the*
 640 *detachment (thick black lines) and of the excess area (red shaded zone; $\Delta A = 16.9 \pm .32 \text{ km}^2$)*
 641 *defined from the Upper to Middle Siwalik boundary. The initial thickness of the Lower and*
 642 *Middle Siwaliks above the décollement and the thickness of the embryonic thrust belt at the*
 643 *vertical of the MFT are $T_0 = 2.8 \pm 0.6 \text{ km}$ and $T_{0r} = 5.2 \pm 0.6 \text{ km}$, respectively. Slip values*
 644 *inferred along the detachment at the kilo-years and million-years refer to the application of the*
 645 *excess area with respect to the old piedmont surface, and to the Upper to Middle Siwalik*
 646 *boundary, with a décollement at the base of the Lower Siwalik (see explanation in Section 3.4).*

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652 4. The hidden thrust belt of Darjeeling (Siliguri zone, India)

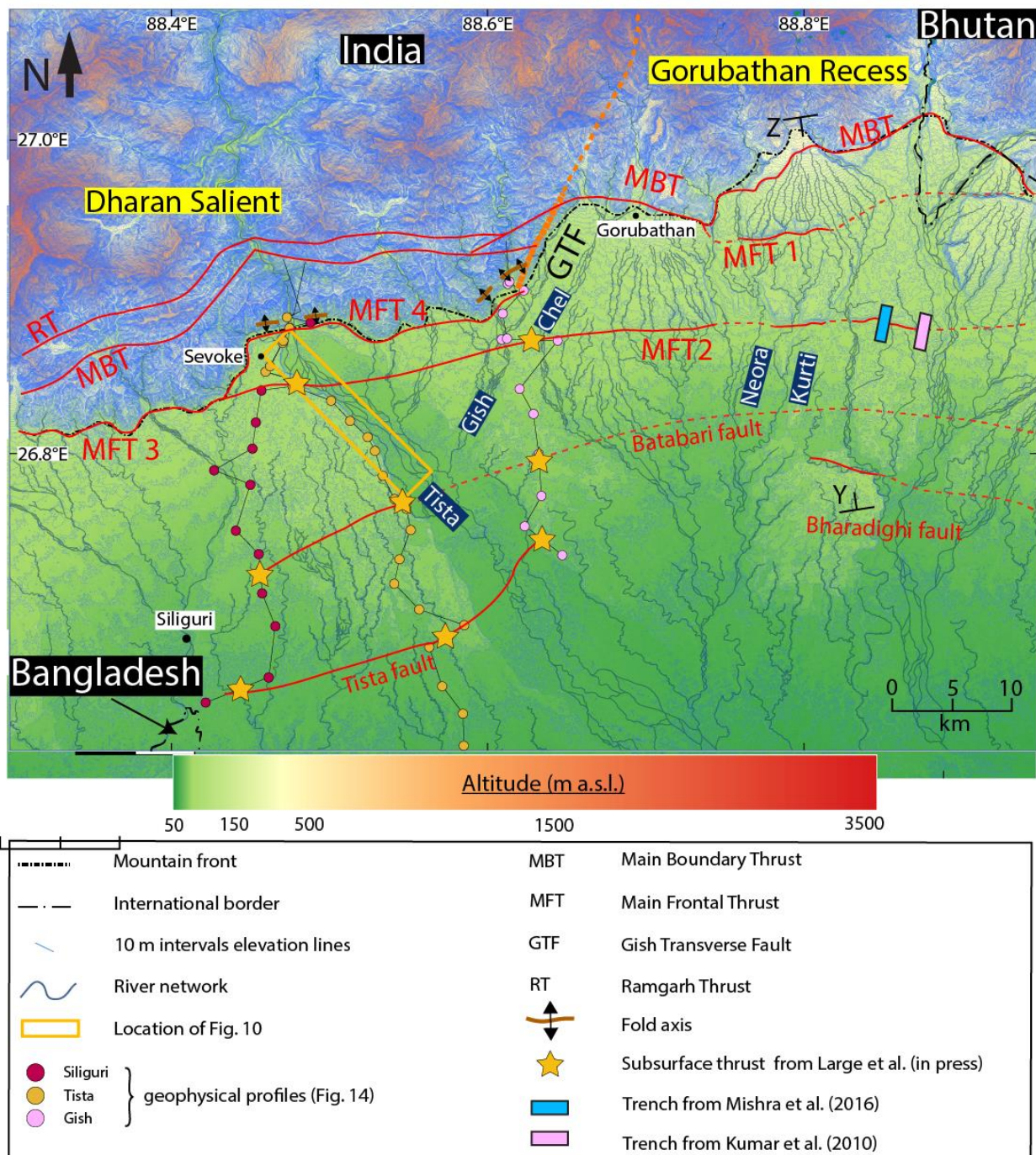
653

654 4.1 The tectonics of the Darjeeling zone

655 In the Darjeeling area (Fig. 8), the Himalayan mountain front is sinuous, and the Dharan
656 salient is separated from the Gorubathan recess by the main Gish transverse fault (GTF). The
657 GTF is both a tectonic lineament that extends northward to southern Tibet (Mukul, 2010), and
658 a lateral ramp that offsets the MFT and MBT at the hanging wall of the MHT.

659 The topographic front is alternatively formed by Siwalik foothills or Lesser Himalayan
660 reliefs in contact with Quaternary alluvia, as Siwalik exposures are missing in the Gorubathan
661 Recess (Gansser, 1983). The recess could have originated from transverse faults in the Indian
662 shield (Mukul, 2010), and the absence of Siwaliks could be linked to the erosional control of
663 the thrust wedge dynamics (DeCelles and Carrapa, 2021; Chalaron et al., 1995).

664 East of the GTF, various adaptations of the classical Himalayan thrust nomenclature
665 have been proposed owing to the absence of the Siwalik (Srivastava et al., 2017; Mishra et al.,
666 2016; Nakata, 1989). Herein (Fig. 8), the MBT is considered as the contact between the Lesser
667 Himalayan rocks and Quaternary sediments and MFT1 and MFT2, as defined by Mishra et al.
668 (2016). MFT1 is singular because it is a footwall splay of the MBT (Fig. 9) with clear eastern
669 and western branch points that only deform quaternary fans and terraces (Nakata, 1989).
670 Furthermore, its dip flips over at its eastern termination (Goswami et al., 2019) in relation to
671 the transverse faults (Goswami et al., 2013). MFT2 also deforms Quaternary sediments and is
672 the emergence of historic seismic ruptures (Kumar et al., 2010). The Bharadighi fault is a back-
673 thrust fault defined by Nakata (1989). The Batabari fault was inferred from the river
674 morphology between the MFT2 and Bharadighi faults (Srivastava et al., 2017) and probably
675 extends westward according to a passive seismic study (Large et al., in press).

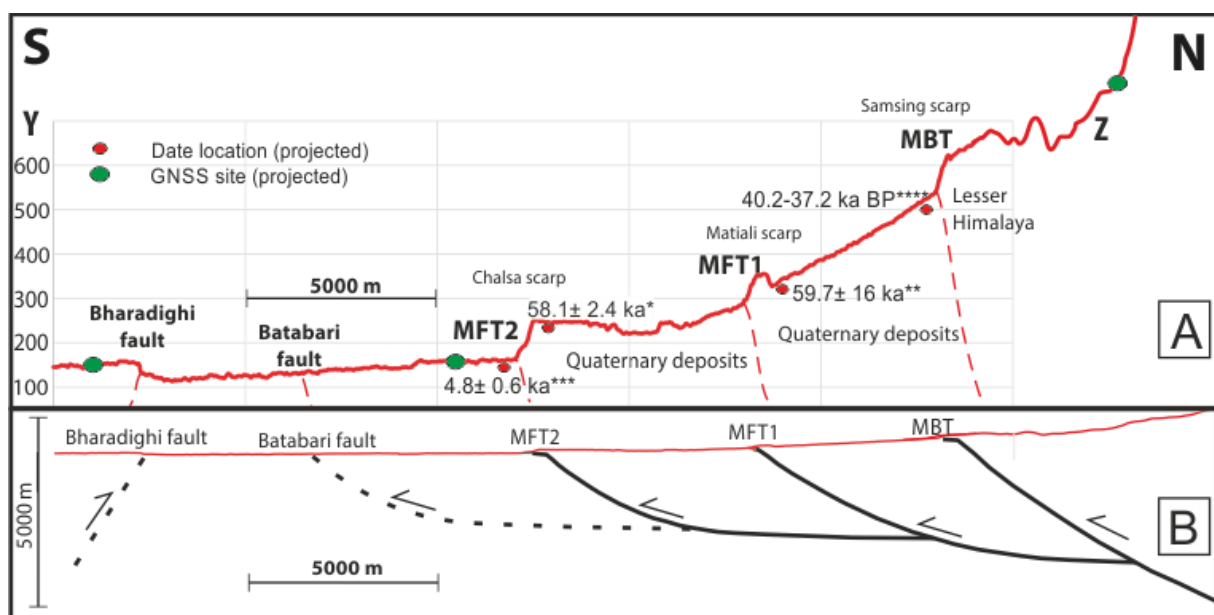


676
 677 Figure 8: Map of the Siliguri area. Altitude from the ASTER (2011) Digital Elevation Model. River
 678 network extracted from satellite images (Maxar technologies). The Gish Transverse Fault (GTF)
 679 separates the western Dharan Salient from the eastern Gorubathan Recess and is indicated by the
 680 orange line. Thrusts (MFT: Main Frontal Thrust; MBT: Main Boundary Thrust; RT: Ramgarh Thrust;
 681 Tf: Tista fault) are represented in red. Z-Y stand for the location of Fig. 9. The yellow rectangle stands
 682 for the location of Fig. 10.

683
 684 West of the GTF, the frontal structure above the MFT is mainly formed by a Middle
 685 Siwalik anticline with a narrow south flank that dips $\sim 60^\circ$ to the south and a gentle dip to the

686 north flank (Taral, 2017). Three distinct segments of the MFT were defined based on their
 687 branch patterns. MFT2 is imaged south of the front beneath the piedmont by three passive
 688 seismic profiles (Large et al., accepted) and is in the continuity of the fault trenched in the
 689 Gorubathan Recess (Mishra et al., 2016) (Fig. 8). It branches with the frontal structures at the
 690 transition between the MFT3 defined by Jayangondaperumal (personal communication) and the
 691 MFT4. The MBT and RT (Ramgarh Thrust) were defined by Mukul (2010), and the mapping
 692 of these thrusts close to the GTF was performed by Patra and Saha (2019). The Tista fault (Tf)
 693 and the west extension of the Batabari fault are inferred from the geophysical profiles located
 694 above the Tista megafan and the Gish River fan (Large et al., accepted). Tf is located ~20 km
 695 south of the morphologic front and induces a 200–400 m offset of the top of the Middle Siwaliks
 696 on the geophysical profiles (Large et al., accepted) (Fig. 10). Recent trenches suggest that the
 697 MFT3 has not been active for several thousand years (Jayangondaperumal, personal
 698 communication), whereas the late Quaternary alluvium of the Tista River onlaps the Middle
 699 Siwaliks and seals the MFT4 (Taral 2017). Thermoluminescence dating of fault gouges suggests
 700 that MFT4 and a splay of faults at its hanging wall were still active 40 kyrs and 20 kyrs ago,
 701 respectively (Mukul et al., 2007), whereas geomorphologic markers suggest that the MBT fault
 702 system is still active in the Dharan Salient (Mukul, 2000).

703



704 *Figure 9: Regional cross-section through the Matiali fan in the piedmont of the Gorubathan*
705 *Recess (profile Y-Z on Fig. 8). A) Topographic profile (the vertical axis is magnified by 12) illustrating*
706 *the location of the faults: Main Boundary Thrust (MBT) at the Samsing scarp and Main Frontal Thrust*
707 *(MFT1) at the Matiali scarp and (MFT2) at the Chalsa scarp. Key datings were obtained from Starkel*
708 *et al. (2015): *; Singh et al. (2016): **; Kar et al. (2014): ***; Guha et al. (2007): ****). The GNSS*
709 *site was obtained from Mullick et al. (2009). The profile was constructed from the ASTER (2011) Digital*
710 *Elevation Model. B) Deepest fault trajectories inferred for balancing procedures with no vertical*
711 *exaggeration. See text and Appendix D: Supplementary data for the method.*

712 A small GNSS network of eight non-permanent sites was installed in Darjeeling
713 (Mullick et al., 2009) and provided an estimate of the present-day deformation between
714 December 2005 and March 2008. A significant extension is suggested across the Gish
715 transverse fault, whereas in the Gorubathan Recess we found a 4.2 ± 1.5 mm/yr N-S shortening
716 between the sites at the footwall of the MFT2 and at the hanging wall of the MBT, respectively
717 (Fig. 9).

718

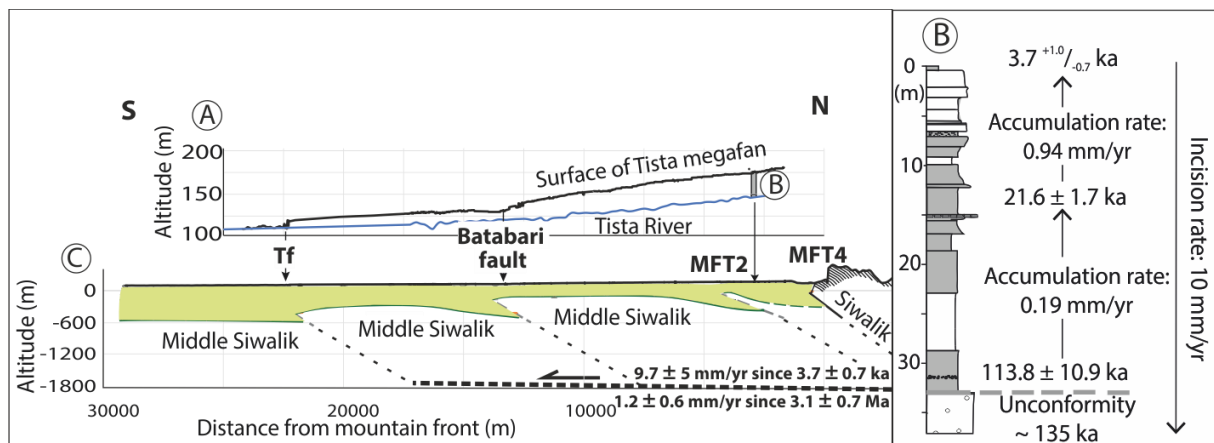
719 4.2 Morphology of the piedmont

720 Two types of river were observed in the Darjeeling piedmont. The first type originates
721 north of the mountain front and has large catchments, such as the Tista, Chel, Neora, Murti, and
722 Jaldhaka Rivers (Fig. 8). Most of these rivers incise the piedmont surface and display a braided
723 pattern on the plain. The second type of river is located at the interfluves of the main rivers.
724 These rivers originate south of the mountain front from palaeo-fans developed by the main
725 rivers (Fig. 8) or, like those close to Gorubathan city, from smaller piedmont fans (Nakata,
726 1989). These small rivers display a radial drainage pattern on piedmont fans and are deflected
727 across faults. These small and some of the large streams show an increase in the channel
728 sinuosity and often develop a meandering pattern with well-developed scroll bars as they cross
729 the piedmont zone and enter a low-gradient alluvial plain 18–25 km south of the mountain front.
730 The evolution of the piedmont in this area is punctuated by a clear succession of incision-

731 deposition events in relation to variations in stream power and sedimentary supply during
 732 climate fluctuations (Dey et al., 2016). This succession led to the development of several
 733 encased (Kar et al., 2014) and/or superposed (Kar and Chakraborty, 2014) sedimentary units
 734 related to alluvial fans, fill terraces, or fill-cut terraces (Goswami et al., 2013).

735 In the Dharan salient, a large megafan developed from the deposition of material
 736 transported by the Tista River and extended from the Himalayan front down to its confluence
 737 with the Brahmaputra (Fig. 1). It is characterised by a very gentle slope ($\sim 0.5\%$), and its apex
 738 is strongly incised from the mountain front 25 km downstream (Fig. 10A). The incision along
 739 the Tista River reaches 37 m at the apex and starts at 3.7 ± 0.7 ka (Abrahami et al., 2018) at an
 740 average rate of 10 ± 2.2 mm \cdot yr $^{-1}$ (Fig. 10B). The incision of the megafan is significantly faster
 741 than the contemporaneous incision in the Himalayan belt, which is less than 2.5 mm \cdot yr $^{-1}$
 742 (Abrahami et al., 2018). The incised sediments were previously deposited above an
 743 unconformity (Fig. 10B), with an average sedimentation rate of 0.19 ± 0.03 mm \cdot yr $^{-1}$ between
 744 113.8 ka and 21.6 ka and 0.94 ± 0.10 mm \cdot yr $^{-1}$ after that time (Abrahami et al., 2018).

745



746

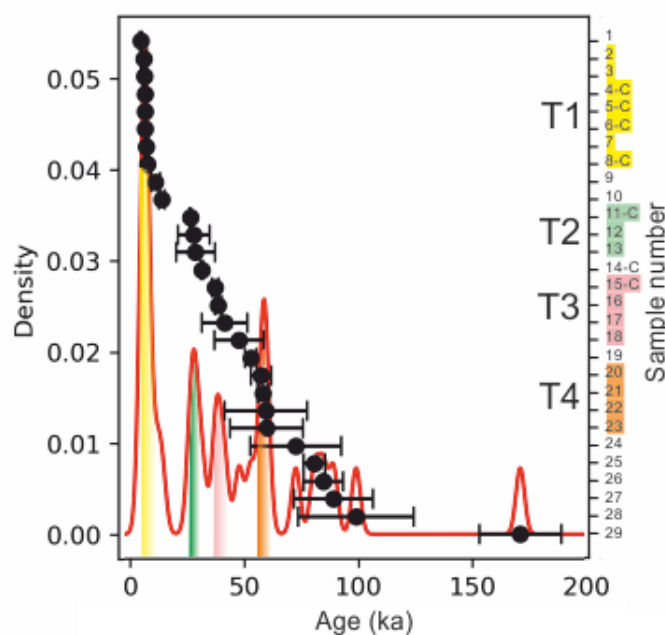
747 *Figure 10: Comparison of the incision of the Tista megafan and the underlying structures. A)*
 748 *Topographic profiles of the Tista megafan and Tista River from Real-Time Kinematic Global Network*
 749 *Satellite System data. B) Log of the late Quaternary sediments of the fan and inferred*
 750 *sedimentation/incision story. (C) Inferred structures at depth from passive seismic profiles (Large et al.,*
 751 *accepted) (western profile on Figure 8). The dashed line indicates the minimum depth of the base of the*

752 *Siwalik group inferred from its stratigraphic thickness (Taral and Chakraborty, 2018) that is the*
 753 *probable location of the décollement. Thousand years and million years' time scale shortening rates are*
 754 *estimated in Sections 4.4 and 4.5, respectively. The details of the uncertainties calculation are detailed*
 755 *in appendix C: supplementary data. Tf: Tista fault; MFT: Main Frontal Thrust.*

756

757 The surface elevation of the Tista megafan abruptly dropped by 9 ± 1 m at ~ 13 km and
 758 ~ 23 km downstream of MFT4 (Fig. 10A), forming steps that are located in the jungle and
 759 difficult to follow laterally. Nonetheless, they are interpreted as tectonic scarps because they
 760 are located above the Batabari and Tf structures (Fig. 10C), as evidenced by passive seismic
 761 records (Large et al., accepted). Therefore, much of the incision is related to localised fault-
 762 related uplift, whereas some is due to more distributed uplift or climatic fluctuations, as shown
 763 in Abrahami et al. (2018).

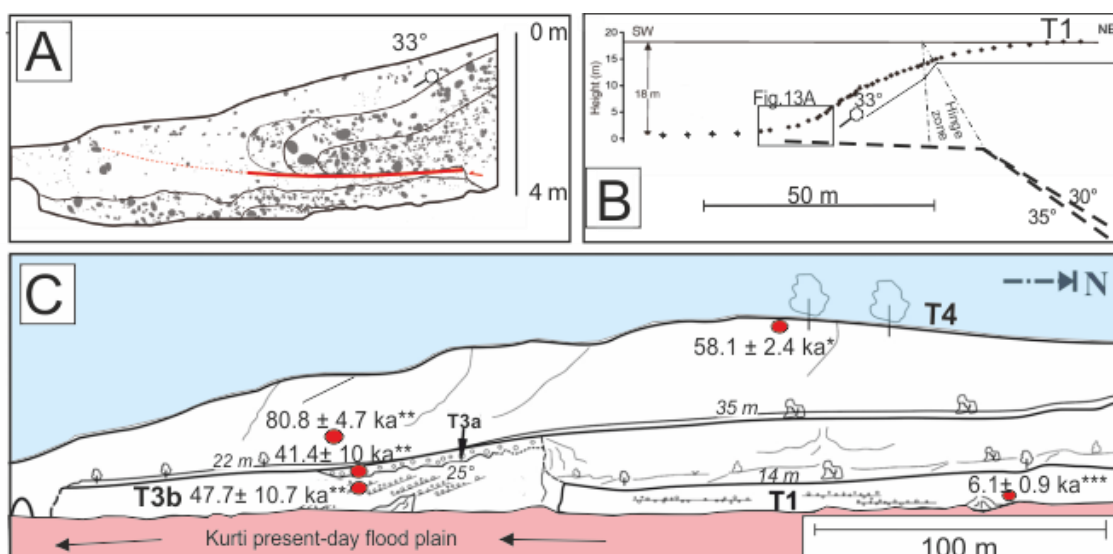
764 In the Gorubathan Recess, alluvial fans developed directly south of the mountain front.
 765 The compilation of 32 data ages and related mapping performed in the Gorubathan Recess area
 766 (Appendix B and location red pines in Appendix A: Supplementary data) suggests the
 767 deposition of three main sedimentary units (Fig. 11), the surfaces of which were abandoned at
 768 approximately 3.5–5, 37–40, and 58–60 ka, respectively. Another unit may have been
 769 abandoned at 23–28 ka (Singh et al., 2016, Guha et al., 2007).



770

771 *Figure 11: Age distribution of the sediment dated in the Gorubathan Recess. Individual*
 772 *data (numbers on right axis and black dots) from Goswami et al. (2019), Singh et al. (2016),*
 773 *Starkel et al. (2015), Kar et al. (2014), Kumar et al. (2010), and Guha et al. (2007), are*
 774 *presented in Appendix B: Supplementary data. Most of the data are obtained by Optically*
 775 *Stimulated Luminescence techniques. For the ^{14}C results (sample numbers with a '-c'), the ages*
 776 *have been calibrated using the Oxcal program (Ramsey, 2009) calibrated with the IntCal13*
 777 *data set (Reimer et al., 2013). The common date used to mix Optically Stimulated Luminescence*
 778 *and ^{14}C results is 2020 AD. Density distribution (left axis and red curve) was obtained from the*
 779 *summation of individual probability distributions (Wegmann and Pazzaglia, 2009).*

780 The 3.5–5 ka surface refers to the lower river terrace T1 (Nakata, 1989) and to large
 781 portions of the piedmont surface, while the 23–28 ka surface refers to a local river terrace T2.
 782 The 37–40 ka surface refers to a higher river terrace T3 encased in the Matiali fan (Singh et al.,
 783 2016), and 58–60 ka refers to the main surface of the Matiali fan (T4) (Fig. 12). The older units
 784 underlying the fans were dated between 80 ka and 171 ka. They are involved in the folds (Fig.
 785 13) at the hanging wall of the faults, but their boundaries are difficult to precisely identify.
 786 Nonetheless, there is an unconformity between 135 ka and 114 ka in the Tista area (Abrahami
 787 et al., 2018) (Fig. 10C).



788

789 *Figure 12: Tectonic origin of the scarps and trenches in the Gorubathan Recess. A) Illustrative log of a*
 790 *trench through the MFT2 east of the Matiali fan (location on Fig. 8) showing an earthquake rupture*
 791 *that occurred before 1152 AD (Mishra et al., 2016). B) Topographic profile of the scarp affecting terrace*
 792 *T1 [adapted from Mishra et al. (2016)]. The inferred thrust geometry is based on the*
 793 *Jayangandaperumal et al. (2013) method. C) A tracing from a photograph showing the disposition of*
 794 *terraces north of the Chalsa scarp along the west bank of the Kurti River [adapted from Kar et al.*
 795 *(2014); location on Fig. 13A; dating location from Starkel et al. (2015): *, Singh et al. (2016): **, Kar*
 796 *et al. (2014): ***]. Shown are the elevations of the terraces T1 and T3 above Kurti River.*

797

798 The Matiali fan is the most developed alluvial fan (Goswami et al., 2012) and is located between
 799 the Murti and Neora Rivers (Fig. 8). The size of the clasts decreased from megagravel in the apex part,
 800 with local blocks larger than 7 m, to finer pebble gravel and pebbly sand in the downstream part. The
 801 latest date is near the apex (Guha et al., 2007) and suggests that debris flows were still deposited at 40.2–
 802 37.2 ka cal BP and overlaid the older (~60 ka), finer-grained deposits characteristic of the rest of the
 803 Matiali fan. This fits with the initial interpretation of the two diachronic surfaces (Rangamati and
 804 Samsing surfaces) proposed by Nakata (1989). However, there are few dates from the different levels
 805 of the Matiali Fan, and we conclude that they only bracket the main period of growth of the fan from
 806 37.2 ka to ~60 ka during the last glacial phase (Singh et al., 2016; Starkel et al., 2015).

807 Three steep south-facing scarps (Fig. 9A) offset the surfaces of the alluvial fan and the
 808 younger terraces (Goswami et al., 2013; Nakata, 1989). The scarps are located above tilted beds
 809 that are attributed from north to south to folding deformation over MBT, MFT1, and MFT2
 810 (Srivastava et al., 2017; Kumar et al., 2010).

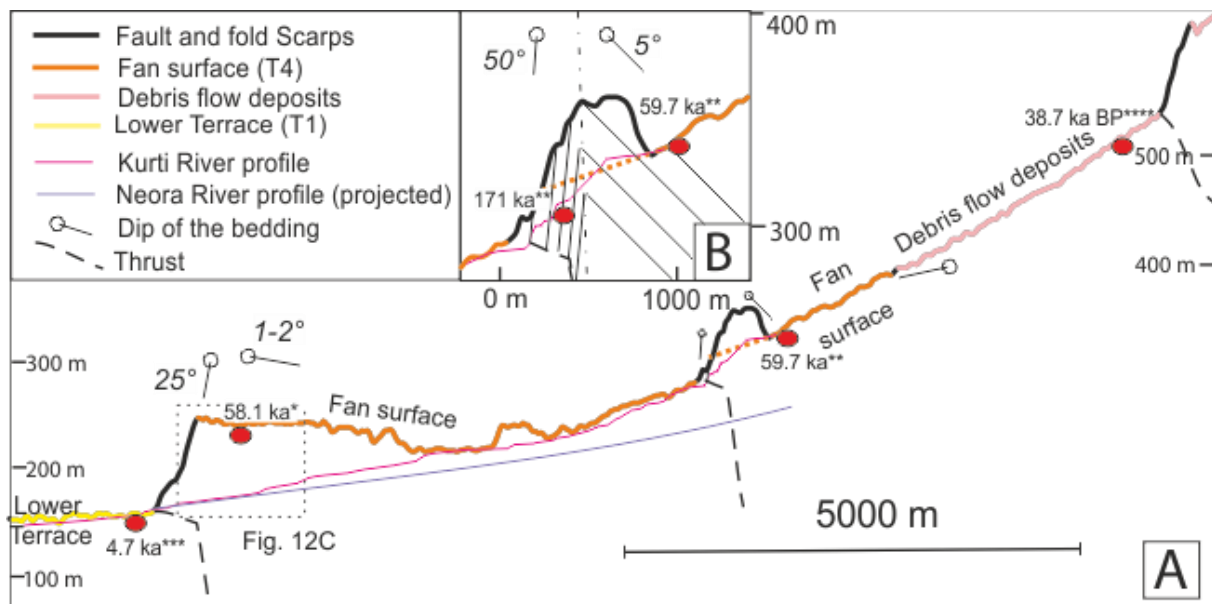
811

812 4.3. Fold and fault geometries

813 The detailed geometries of the faults and folds beneath the Matiali Fan and Tista
 814 megafan are poorly understood. The middle/upper Siwalik interface is characterised by faults
 815 and folds in the Tista area (Fig. 10). Analogous to the deformation imaged beneath the piedmont
 816 of the east-central Himalayas (Fig. 5C) (Bashyal, 1998), the upper sediments above the upper
 817 interface were syn-orogenic and were deposited above an embryonic thrust wedge that branched
 818 off the same deep décollement as the MFT (Figs. 10). In the area of the Matiali Fan, the style

819 of folding is considered by several authors to be related to fault-propagation folds (e.g., Guha
820 et al., 2007; Srivastava et al., 2017).

821



822

823 *Figure 13: A) Topographic profile through the Matiali fan illustrating the main surfaces, the scarps*
824 *above the MBT (Samsing scarp), MFT1 (Matiali scarp), and the MFT2 (Chalsa scarp) and the location*
825 *of key datings [from Starkel et al. (2015): *; Singh et al. (2016): **; Kar et al. (2014): ***; Guha et al.*
826 *(2007): ****]. The profiles of the Kurti and Neora Rivers are projected on the cross-section to illustrate*
827 *the incision. Profiles from the ASTER (2011) Digital Elevation Model. B) Magnified image of the Matiali*
828 *scarp. The vertical scale is magnified by 12 in A) and B).*

829

830 An anticlinal structure is visible in the hanging wall of the western part of the Matiali
831 Scarp (Das and Chattopadhyay, 1993; Nakata, 1989) (Fig. 13). Remnants of the fold were
832 formed by mounds elevated at least 37 ± 12 m above the upstream Matiali fan surface and by
833 the Matiali scarp offsetting the T4 fan surface, the offset of which was re-estimated from the
834 DEM as 40 ± 10 m in the middle part of the fan (Kurti River) and 35 ± 10 m on the east bank
835 of the Neora River.

836 The southern flank of the anticline is steeper than the slope of the Matiali scarp (30° on
837 average) and dips southward by up to 50° , whereas the northern flank dips at a maximum of 5°
838 to the north (e.g., Guha et al., 2007) (Fig. 13B). The stratigraphic thickness of the frontal limb
839 of the anticline was at least 400 m (Das and Chattopadhyay, 1993). Therefore, the mounds are

840 remnants of a currently highly eroded fold, which is significantly higher than the mounds. This
841 suggests that part of the development of the fold preceded the development of the scarp that
842 offset the surface of the T4 fan.

843 The terraces deformed above the Chalsa Fault show an anticlinal fold with a
844 progressively southward-tilted flank. In particular, the sediments beneath the T3b terrace were
845 tilted more than the T3b surface, which was only slightly tilted (Fig. 12C). Bedding at the main
846 scarp south of the T4 surface is difficult to observe, but Nakata (1989) indicated that it is steeper
847 than the scarp slope. The T4 surface north of the scarp was weakly tilted to the north.

848 Field conditions make structural observations difficult, but a few trenches, made for
849 construction (Guha et al., 2007) or paleoseismological studies (Mishra et al., 2016; Kumar et
850 al., 2010) give clues to understanding thrust-fold relationships. Thrust was observed at the base
851 of the Chalsa scarp (Mishra et al., 2016), suggesting that even if a fault-propagation fold could
852 have initially developed, this fold is now cut and carried by the fault. The trenches excavated
853 through the Chalsa Thrust (MFT2) show a nearly flat fault (Fig. 12A) (adapted from Mishra et
854 al., 2016). However, a ramp is required to account for the 15–18 m uplift of the low T1 terrace
855 a few tens of metres farther north (Fig. 13B), as well as for the more than 30° hanging wall
856 tilting of the layers. Balancing methods (Jayangandaperumal et al., 2013) applied to T1 scarp
857 geometry suggest that the ramp dips 30°–35° to the north.

858 Owing to the poor dataset on the faults beneath the Matiali Fan, their geometry can only be
859 estimated using balancing procedures applied to the surface geometry of the scarps and deformed fan.
860 This procedure is based on area conservation during landform development (Gonzalez-Mieres and
861 Suppe, 2006), supplemented by equations linking uplift, fault dip, and shortening (Suppe, 2014). The
862 analysis of the procedures (see Appendix D: Supplementary data) shows that the uncertainties related to
863 the calculation of the décollement depth are mainly linked to the estimates of the excess area and dip at
864 the upper part of the thrust ramp. The depths of the décollement linked to the Chalsa scarp (MFT2)
865 and the Matiali scarp (MFT1) were then calculated between 2,300 m and 800 m and between
866 4,000 m and 1,000 m, respectively (see Appendix D: Supplementary data).

867 The stratigraphic thickness of the sediments in the foreland basin of this area is of the
868 order of a few kilometres (Karunakaran and Rao, 1976). Therefore, the depth of the décollement
869 associated with MFT2 north of the Chalsa scarp, although affected by a large uncertainty,
870 appears to be consistent with a décollement close to the base of the syn-orogenic sediment. For
871 MFT1, the depth of the detachment level is close to the thickness of the foreland basin sediment.

872

873 4.4 The active tectonic rates affecting the piedmont at a scale of 10,000
874 years

875 When fault geometry is poorly understood, the shortening rate can nonetheless be
876 estimated from the uplift rate using simple kinematic models. To estimate the uncertainty
877 associated with this approach, two end-member models are used. The vertical simple shear
878 model (Molnar, 1987) is the simplest kinematic ramp-flat model that links sliding (S_f) and uplift
879 (U) above a ramp to the dip (θ) of the ramp using Equation (2):

$$880 \quad S_f = U / \tan \theta. \quad (2)$$

881 The kinematic ramp-flat model based on the preservation of the stratigraphic thickness
882 (e.g. Suppe, 1983), can also be reduced to a single equation that links sliding along a flat and
883 uplift above a ramp, using Equation (3):

$$884 \quad S_f = U / \sin \theta. \quad (3)$$

885 For a given uplift and dip, a greater shortening value was obtained using the kink-like
886 model than using the vertical simple shear model. The uncertainties concerning the model
887 choice, uplift, fault dip, and timing of fault slip are analysed in Appendix C: Supplementary
888 data. The maximum and minimum shortening estimates were obtained using the smallest
889 estimate of the dip (20° from Almeida et al., 2018) in the kink-like model and the greatest
890 estimate of the dip (35° from Mugnier et al., 1999a) in the simple shear model. Therefore, we
891 estimated the shortening rate and its uncertainty for the following fault scarps:

892 - The offsets of the 3.7 ± 0.7 ka old surface of the Tista megafan by the MFT2 and
893 Batabari fault scarps are both 9 ± 1 m (Fig. 10A), resulting in a vertical throw rate of 2.7 ± 0.6
894 $\text{mm}\cdot\text{yr}^{-1}$. For each fault, the slip rate transferred along the basal décollement is 4.9 ± 3.6 $\text{mm}\cdot\text{yr}^{-1}$,
895 leading to a total shortening rate of 9.7 ± 5 $\text{mm}\cdot\text{yr}^{-1}$ for the thrust system beneath the Tista
896 megafan.

897 - For MFT2, at the trench performed by Mishra et al. (2016) close to the Matiali fan, the
898 offset of the 4.5 ± 1 ka regional T1 terrace is 18–15 m (Fig. 12B). Therefore, the uplift rate is
899 $3.6^{+1.5}/_{-0.9}$ $\text{mm}\cdot\text{yr}^{-1}$ and the shortening rate is 7.3 ± 5 $\text{mm}\cdot\text{yr}^{-1}$.

900 - For MFT2 at the Chalsa scarp of the Matiali fan (Fig. 9), the age of the T4 surface is
901 $59^{+1.5}/_{-6.5}$ ka (Singh et al., 2016; Starkel et al., 2015). The latter was buried at the footwall of
902 the fault beneath the T1 terrace, and the minimum uplift was 80 ± 10 m. This leads to an uplift
903 rate of 1.4 ± 0.3 $\text{mm}\cdot\text{yr}^{-1}$ and a shortening rate of 2.8 ± 2 $\text{mm}\cdot\text{yr}^{-1}$.

904 For the MFT1 at the Matiali fault scarp (Fig. 9), the vertical offset of the fan surface is
905 40 ± 10 m. Therefore, the uplift rate is 0.7 ± 0.2 $\text{mm}\cdot\text{yr}^{-1}$, and the shortening rate since 58–60
906 ka is 1.4 ± 1.1 $\text{mm}\cdot\text{yr}^{-1}$.

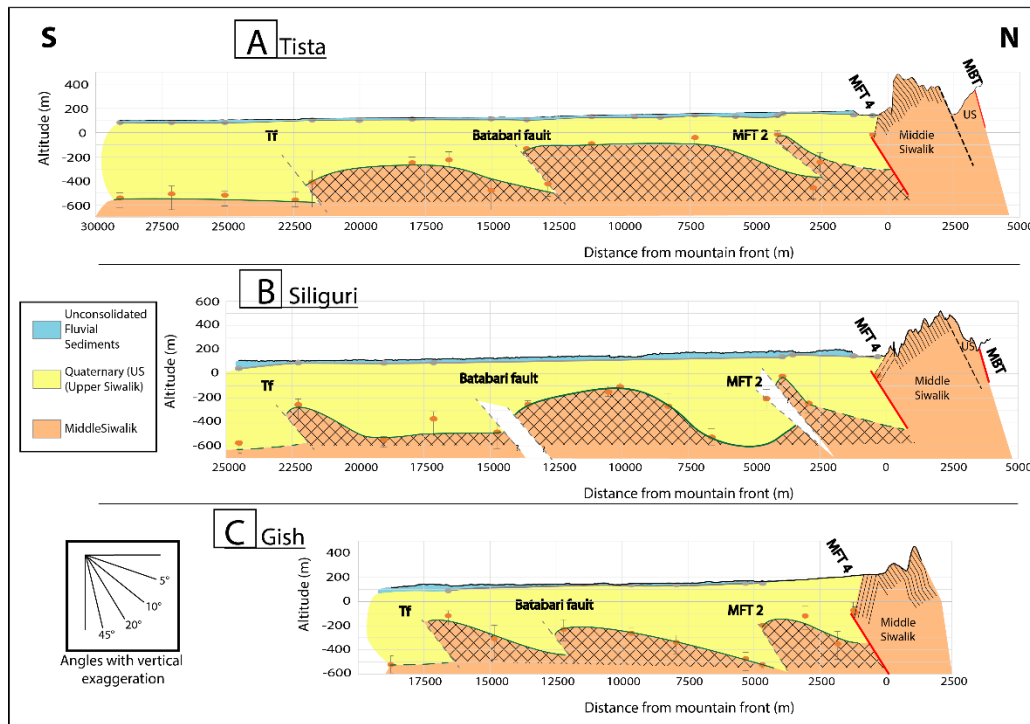
907 In summary, the development of scarps began earlier in the Matiali fan than in the Tista
908 megafan, but the shortening rates estimated with the balanced methods are affected by more
909 than 50% relative uncertainty and are only useful for estimating the order of magnitude of the
910 shortening. Since 3.5–5.5 ka, the shortening rate has been 8.5 ± 6.2 $\text{mm}\cdot\text{yr}^{-1}$ in the Darjeeling
911 piedmont, whereas the shortening rate for the piedmont was 4.2 ± 2.3 $\text{mm}\cdot\text{yr}^{-1}$ for the 5 ka to
912 60 ka period.

913

914 4.5 The active tectonic rates affecting the piedmont at a million year scale

915 Subsurface structures down to depths of a few hundred metres have been explored along
916 three approximately N-S trending profiles in the Siliguri area (Large et al., accepted) using the
917 horizontal-to-vertical spectral ratio method (Nakamura, 1989 (Fig. 14) (location in Fig. 8). This

918 method only displays the major interfaces characterised by strong velocity contrasts and does
 919 not provide a detailed picture of the subsurface structures (Guéguen et al., 2007; Hinzen et al.,
 920 2004).



921
 922 *Figure 14: Interpretation of three profiles inferred from ambient seismic data in the Siliguri area (Large*
 923 *et al., accepted). Location of the profiles in Figure 8. The dips of the Siwalik strata along the Gish and*
 924 *Tista sections are from the data of the present authors and Acharyya et al. (1987). Green lines indicate*
 925 *the boundary between Upper Siwalik and Middle Siwalik sediments. Suggested thrusts are indicated by*
 926 *dashed grey lines. Gridded surfaces refer to the excess area surfaces, estimated at $6.6 \pm 2.4 \text{ km}^2$, 6 ± 2.5*
 927 *km^2 , and $3.5 \pm .51 \text{ km}^2$ for the Tista ([A]), Siliguri ([B]), and Gish ([C]) cross-sections, respectively.*
 928 *Note that the vertical scale is strongly exaggerated, and the bottom left inset indicates the real values of*
 929 *the fault dips. Tf: Tista fault; MFT: Main Frontal Thrust; Mbt: Main Boundary Thrust; US: Upper*
 930 *Siwalik.*

931 The excess area method (Eq. 1) (Goguel, 1952) is well suited for estimating the
 932 shortening related to such imaged structures, because the method is insensitive to the details of
 933 the upper interface geometry. The interface between soft sediment and stiffer sediment is
 934 interpreted as the top of the Middle Siwalik rocks, the age of which is $3.1 \pm 0.7 \text{ Ma}$ (Chakraborty
 935 et al., 2020; Coutand et al., 2016), and the décollement is not deeper than the base of the
 936 Siwaliks. The ΔA values of the three cross-sections Tista, Siliguri, and Gish are $6.6 \pm 2.5 \text{ km}^2$,

937 $6 \pm 2.4 \text{ km}^2$, and $3.5 \pm 1.5 \text{ km}^2$, respectively (Fig. 14). The maximum initial thickness T_0 was
938 $1,800 \pm 300 \text{ m}$ in the Tista area (Taral and Chakraborty, 2018) and $1,300 \pm 300 \text{ m}$ in the Gish
939 area (Chakraborty et al., 2020). The shortenings and uncertainties were calculated using Eq. 1
940 and Appendix C: Supplementary data. The shortening values are $3.7 \pm 1.5 \text{ km}$, $3.3 \pm 1.5 \text{ km}$, and
941 $2.7 \pm 1.3 \text{ km}$ (Fig. 14), respectively for the three cross-sections.

942 The difference between the three cross sections is not meaningful owing to significant
943 uncertainties. The shortening is therefore considered to be 5.8–1.4 km and the mean shortening
944 rate at the million-year scale is $1.1 \pm 0.7 \text{ mm} \cdot \text{yr}^{-1}$. This long-term shortening rate was smaller
945 than the short-term rate averaged at 3.7 ka (Section 4.4). This increase in velocity probably
946 post-dated the last phase of sedimentation of the Tista megafan, which still occurred between
947 113.8 ka and 3.7 ka at rates close to the long term subsidence (Fig. 10B).

948

949 5. Summary

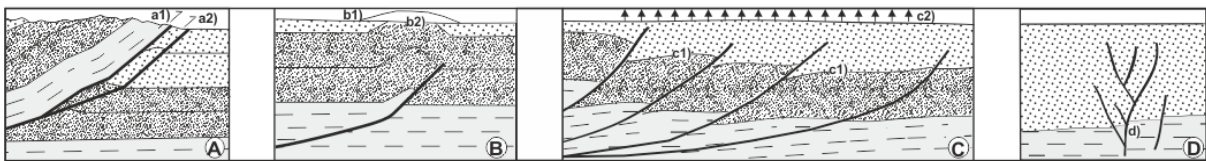
950 Our synthesis in both east-central Nepal and the Darjeeling piedmonts reveals that
951 uplifted surfaces and/or drainage perturbations were observed 10–40 km south of the mountain
952 front. Subsurface data strongly suggest that these morphological features are linked to the
953 development of several thrusts and associated folds below the piedmont. The geometry and
954 kinematics of these hidden structures forming 25–40 km south of the MFT and that branch off
955 the MHT are summarised below.

956

957 5.1. Structural style beneath the piedmont of the Himalayas

958 The geometries obtained from the Himalayan piedmont illustrate the concepts of syn-
959 sedimentary tectonic structures. The analysis of tectonic/sediment relationships provides simple
960 and robust information about the uplift rates of the embryonic fold and thrust belt beneath the
961 Himalayan piedmont (Fig. 15). In the case of syn-sedimentary thrusts above a décollement, the

962 geometry is classically interpreted with regard to the ratio ($V_{\text{sed}}/V_{\text{upl}}$) between the long-term
 963 sedimentation rate at the footwall (V_{sed}) and uplift rate at the hanging wall (V_{upl}) (e.g., Barrier
 964 et al., 2013; Bonnet et al., 2008). When the sedimentation rate is significantly higher than the
 965 uplift rate, evidence of tectonics at the surface remains limited (Fig. 15C) ('c' structure type in
 966 Table 2); however, sedimentation around the structures is disturbed and displays specific
 967 angular relationships (Almeida et al., 2018). When the uplift rate was close to the sedimentation
 968 rate, the hanging wall emerged slightly (Fig. 15B), and syn-kinematic sedimentation exerted a
 969 strong influence on the trajectory of emergent thrusts (Butler, 2020; Mugnier et al., 1997;
 970 Suppe, 1983), whereas tectonics greatly influenced the drainage pattern (Roy et al., 2021;
 971 Delcaillau et al., 2006). When the uplift rate was higher than the sedimentation rate, thrusts and
 972 their hanging walls emerged, footwall sediments were extensively sub-thrusted, and the
 973 hanging wall eroded (Fig. 15A) ('a1' structure type in Table 2).



974
 975 *Figure 15: Typical syn-kinematic sediment/thrust relationships at the front of the Himalayas. (A)*
 976 *Emergent frontal thrust. The mean uplift rate is greater than the mean sedimentation rate; a1) thrusting*
 977 *of the Neogene Siwalik beds above the piedmont; a2) ruptures can locally occur along the footwall splay*
 978 *of the MFT and affect the piedmont. (B) Fault-related anticline. The mean uplift rate was close to the*
 979 *mean sedimentation rate; b1) emergent fault-related anticline (when the sedimentation is less than the*
 980 *uplift); b2) hidden fault-related anticline (sedimentation momentarily greater than the uplift). (C)*
 981 *Hidden thrust splay; c1) the long-term uplift rate is smaller than the long-term sedimentation rate; c2)*
 982 *a small change in the present-day surface is detectable. (D) Structural reactivation of basement fault.*
 983 *Examples of a1), a2), b1), b2), c1), c2), and d) are indicated in the right column of Table 2.*

984

985 Finally, reactivations affected the steep basement structures beneath the foreland basin
 986 ('d' type of structure in Table 2). They can be characterised either by thrust or normal faulting;
 987 the latter is linked to the flexure of the lithosphere beneath the foreland basin (Duroy et al.,
 988 1989). However, a strike-slip component frequently occurs because most of the pre-existing

989 faults in the basement are oblique to the Himalayan structures (e.g., Godin et al., 2019; Mugnier
990 et al., 2017), often resulting in flower structures in the overlying sediment pile (Fig. 15D)
991 (Raiverman et al., 1994). For example, basement reactivations could explain the recent
992 deformations highlighted by the inland/terminal fan alignments located along NW-SE fault
993 scarps in the Ganga plain (Pati et al., 2012).

994 Thus, this analysis of the tectonic/sediment relationships provides a classification of the
995 foreland and piedmont tectonic structures (Fig. 15), allowing for a better understanding of the
996 variety of studied structures (Table 2).

997

998 5.2. Deformation rates in the piedmont of the Himalayas

999 All of the above quantifications lead to the following results (Table 3):

1000 For the most recent period (less than 3.7–4.5 ka), values of 4.7 to 12.3 mm·yr⁻¹ are
1001 consistent with both the Tista and Matiali shortening rates across the Darjeeling piedmont if
1002 uncertainties are taken into account. Furthermore, at least one of the shortening rates is between
1003 2.3 and 14.7 mm·yr⁻¹. Therefore, we estimated the shortening rate to be 8.5 ± 6.2 mm·yr⁻¹ in the
1004 Darjeeling piedmont for this period.

1005 For the long term (million years' scale), if uncertainties are taken into account, the 1.4
1006 mm·yr⁻¹ value is compatible with the shortening rates across the piedmont of the Birgunj and
1007 Darjeeling zones. Furthermore, at least one of the shortening rates is between 0.4 and 3.8
1008 mm·yr⁻¹. Thus, the shortening rate is estimated to be $1.4^{+2.4}_{-1}$ mm·yr⁻¹ for the entire piedmont.

1009 For the period covering a few tens of thousands of years, the rate of 1.4 mm·yr⁻¹ in the
1010 Birgunj area is compatible with the estimated long time shortening (on a million-year scale). In
1011 the Matiali area, the shortening rate is more important, and this moderate increase in the mean
1012 shortening rate may be induced by the large increase evidenced in this area for less than 4.5 Ka
1013 recent period.

1014

1015

1016 *Table 3: Parameters used and estimates of the shortening rates at different time scales.*1017 *The propagation of uncertainties related to the balancing procedures is detailed in Appendix*1018 *C: Supplementary data.*

Cross-sections	Figure	Age	Excess area	Initial thickness	Uplift	Uplift rate	Shortening	Shortening rate
Million years scale		Ma	Km ²	km			km	mm·yr ⁻¹
Birgunj	Fig. 7B	2.3 ± 1	16.9 ± 2	2.8 ± 0.6			6.0 ± 1.5	2.6 ± 1.2
Siligury	FIG. 14B	3.1 ± 0.7	6 ± 2	1.8 ± 0.3			3.3 ± 1.5	1.1 ± 0.4
Tista	FIG. 14A	3.1 ± 0.7	6.6 ± 2	1.8 ± 0.3			3.7 ± 1.5	1.2 ± 0.5
Gish	FIG. 14C	3.1 ± 0.7	3.5 ± 2	1.3 ± 0.3			2.7 ± 1.3	0.9 ± 0.5
Millenium yrs Scale		ka	Km ²	km	m	m·yr ⁻¹	m	mm·yr ⁻¹
Birgunj	Fig. 7A	82 ± 32	0.43 ± 0.3	5.2 ± 0.6			83 ± 56	1.0 ± 0.8
	<i>Matiali (MFT2)</i>	<i>Fig. 9A</i>			<i>80 ± 10</i>	<i>1.4 ± 0.2</i>	<i>160 ± 114</i>	<i>2.8 ± 2.0</i>
	<i>Matiali (MFT1)</i>	<i>Fig. 9A</i>			<i>40 ± 10</i>	<i>0.7 ± 0.2</i>	<i>80 ± 60</i>	<i>1.4 ± 1.1</i>
Matiali (MFT2 + MFT1)	Fig. 9A	56.5 ± 4					240 ± 128	4.2 ± 2.3
East of Matiali (MFT2)	Fig. 12B	4.5 ± 1			16.5 ± 1.5	3.7 ± 0.9	33 ± 23	7.3 ± 5.0
	<i>Tista (MFT2)</i>	<i>Fig. 10A</i>			<i>9 ± 1</i>	<i>2.4 ± 0.5</i>	<i>18 ± 13</i>	<i>4.9 ± 3.6</i>
	<i>Tista (Batabari F.)</i>	<i>Fig. 10A</i>			<i>9 ± 1</i>	<i>2.4 ± 0.5</i>	<i>18 ± 13</i>	<i>4.9 ± 3.6</i>
Tista (MFT2 + Batabari F.)	Fig. 10A	3.7 ± 0.7					36 ± 18	9.7 ± 5.0

1019

1020

1021 **5.3. A present-day deformation in the embryonic thrust belt?**

1022 Present-day deformation in the piedmont has been suggested in a few places, from the

1023 central Himalayas to the eastern Himalayas (Table 2) (Gupta et al., 2017; Yhokha et al., 2015;

1024 Bhattacharya et al., 2014; Mullick et al., 2009). Nonetheless, none of these studies showed a

1025 high level of confidence (see section 2.3.3).

1026 The 1977–1990 levelling data of east-central Nepal (Jackson and Bilham, 1994) (Fig.

1027 5A) have been used and mixed with the 1991–2015 GNSS data in most of the studies of the

1028 inter-seismic deformation of the Himalayas, since the pioneer work of Bilham al. (1997) to the

1029 work of Dal Zilio et al. (2020). However, the mixing of data acquired during different periods
1030 and with different spatial distributions is difficult. Furthermore, this can be misleading because
1031 the levelling signal recorded in the piedmont was first interpreted as tectonic (Jackson and
1032 Bilham, 1994) before a re-interpretation of groundwater withdrawal subsidence (Bilham et al.,
1033 2017). Although historical levelling is non-reproducible owing to the disappearance of
1034 benchmarks, the hypothesis of groundwater withdrawal subsidence that would have continued
1035 to the present is testable. The Simra GNSS (SIM) permanent station (Fig. 4) has recorded a
1036 subsidence of 2.88 ± 1.1 mm/yr in the vicinity of the leveling profile since 1995 (Jouanne et al.,
1037 2017) and has not indicate significant horizontal motion with respect to the Indian plate
1038 (Jouanne et al., 2017; Ader et al., 2012), suggesting that the groundwater withdrawal subsidence
1039 hypothesis (Bilham et al., 2017) is the most plausible one.

1040 While slow slip events are evidenced in many subduction zones around the world
1041 (Jolivet and Frank, 2020), there is no unambiguous geodetic or seismological evidence of such
1042 events in the Himalayas and its piedmont. The initial evidence of slow slip in east-central Nepal
1043 (Jackson and Bilham, 1994) was predicated by the perceived credibility of levelling data before
1044 the advent of precise CGPS data. Subsequent decades of geodetic studies in the Himalayas have
1045 been unable to confirm this inference, and their precision [~ 0.5 mm/yr (Mencin et al., 2016;
1046 Flouzat et al., 2009)] furnishes an upper bound for a hypothetical slow slip.

1047

1048 **6. Discussion**

1049 The MFT is a piggyback transported by the embryonic thrust belt and, by definition, the
1050 motion along the MFT is out-of-sequence. Nonetheless, the main point is that the deformations
1051 of the hanging wall of the MFT and the embryonic thrust belt are synchronous at the Quaternary
1052 time scale but occur at very different rates (Fig. 16). The long term shortening rate is in the
1053 order of $20 \text{ mm}\cdot\text{yr}^{-1}$ for the Himalayan belt (Lavé and Avouac, 2000), whereas the shortening
1054 rate of the embryonic thrust belt is only $1.4^{+2.4}/_{-1} \text{ mm}\cdot\text{yr}^{-1}$ at the long term scale (Sections 3.3

1055 and 4.5). Although the uncertainties are great, the deformation of the embryonic thrust belt is
 1056 clearly slower (Fig. 16A) than the Himalayan belt deformation and is probably one order of
 1057 magnitude slower.
 1058

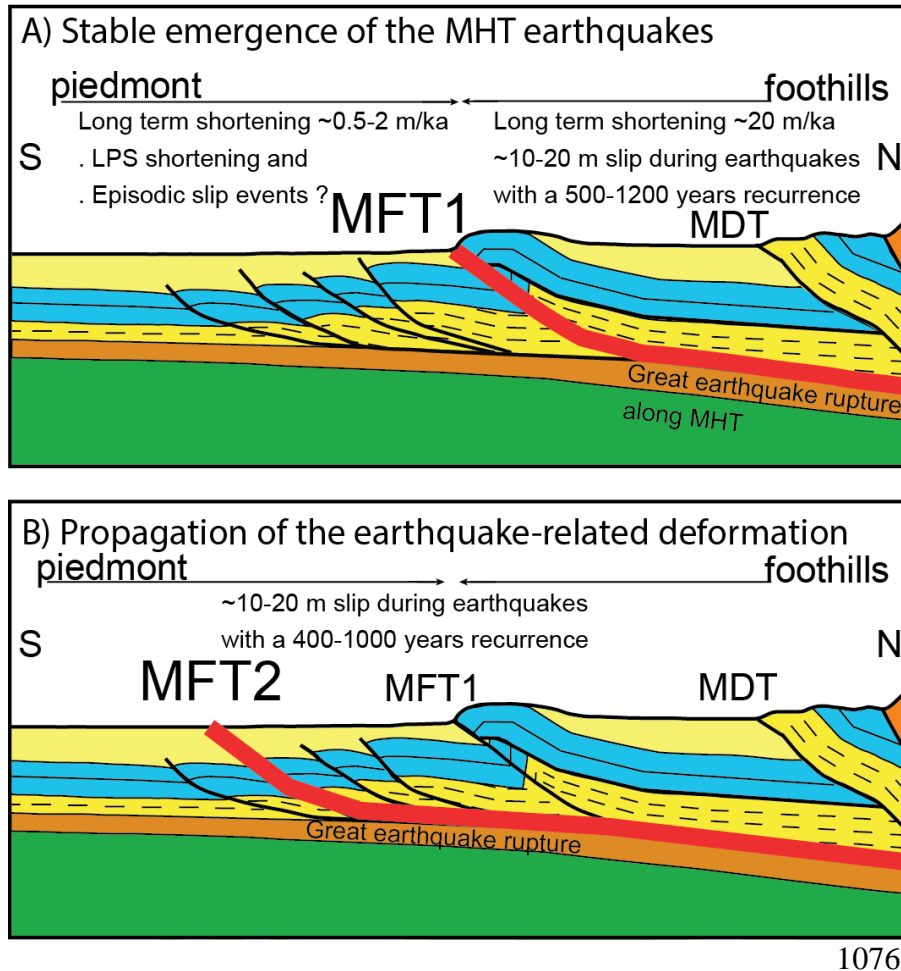


Figure 16: Schematic diagram of the contrasted deformation between the embryonic foreland belt and the faster hinterland uplifted belt. A) Stable emergence of the MHT earthquake events at the frontal structure (MFT1); B) forward propagation of the emerging MHT (MFT2): incorporation of the embryonic belt in the thrust belt.

1077
 1078 These contrasting deformation rates agree with the findings in other mountain belts and
 1079 accretionary wedges (Gonzalez-Mieres and Suppe, 2011), where the shortening is not currently
 1080 concentrated in the morphologically elevated zones, but where embryonic thrust belts develop
 1081 ahead of the thin-skinned thrust belt. In these embryonic zones, typical shortening rates are in
 1082 the range of $0.1\text{-}3\text{ mm}\cdot\text{yr}^{-1}$ and represent only 1–10% of the regional plate tectonic rates ($2\text{-}6$
 1083 $\text{cm}\cdot\text{yr}^{-1}$) (Gonzalez-Mieres and Suppe, 2011).

1084 No historical or instrumental data have recorded the growing structure or faulting during
 1085 earthquakes in the embryonic thrust belt. Therefore, the deformation mechanism of the

1086 embryonic thrust belt remains enigmatic and various hypotheses are discussed below.

1087 A) A part of the long-term deformation of the Himalayan embryonic thrust belt could be
1088 large-scale horizontal pure shear shortening (LPS) (e.g., Weil and Yonkee, 2012; Mitra, 1994),
1089 which occurs ahead of a thrust belt prior to, or during, the earliest motion on a thrust. During
1090 the LPS stage, incipient large-scale (more than a kilometre) faults, folds, and smaller-scale de-
1091 formation structures develop. At the front of the Taiwan thrust belt (Le Béon et al., 2019), the
1092 LPS stage combines small-scale buckle folds, contraction faults, compaction and internal short-
1093 ening parallel to the layers. These small-scale processes could occur in the hidden thrust belt
1094 south of the Himalayas, but are not directly observable. The internal deformation evidenced in
1095 the beds of the Churia ranges (Fig. 2B) absorbs less than 7% of the total horizontal shortening
1096 (Srivastava and Mukul, 2020) and could be partly related to such an embryonic stage. Further-
1097 more, the geometry of the axial surfaces of the frontal folds (Almáida et al., 2018) (Fig. 3B)
1098 suggests a shearing above the décollement (Suppe et al., 2004). As GNSS does not detect a
1099 present deformation, any steady-state penetrative deformation rate would have to be smaller
1100 than the $0.5 \text{ mm}\cdot\text{yr}^{-1}$ GNSS precision. Then, the strain rate in the embryonic thrust belt would
1101 be less than $1.5\cdot 10^{-15} \text{ s}^{-1}$ if such a shortening rate is distributed along a 10 km long structure,
1102 which is in agreement with the common strain rates averaged over long-term geological times
1103 (Fagereng and Biggs, 2019).

1104 B) The long-term deformation rate and short-term deformation rate in the piedmont are 1.4
1105 $^{+2.4}_{-1} \text{ mm}\cdot\text{yr}^{-1}$ and $< 0.5 \text{ mm}\cdot\text{yr}^{-1}$, respectively. Although the uncertainties are large, deformation
1106 with an episodic character is probably necessary to reconcile a long-term deformation of a few
1107 $\text{mm}\cdot\text{yr}^{-1}$ with nearly null instantaneous deformation. The time scale and origin of such episodic
1108 deformations are not yet known, and many scenarios have been proposed. Thus, hypotheses
1109 such as large earthquakes, comparable to the 1934 earthquake, which would propagate under
1110 the piedmont with a recurrence on the order of 10 millennia (Duvall et al., 2020), or moderate
1111 slips of a few tens of centimetres with a hundred-year recurrence cannot be excluded. The dis-
1112 sipation of post-seismic stresses in small events, which would follow great events occurring

1113 along the MHT and MFT, is an issue that should be explored because the stresses associated
1114 with the rupture of the great Himalayan earthquakes are probably the primary forces responsible
1115 for the southward growth of the Himalayas.

1116 C) Nonetheless, great earthquakes rupture in the Darjeeling piedmont of the Himalayan
1117 chain, as in the case of the Matiali fan (Fig. 12B) (Mishra et al., 2016) or possibly of the Tista
1118 megafan (Fig. 10A). These great earthquakes induce a millennium scale shortening rate ($13^{+7}/$
1119 $5 \text{ mm}\cdot\text{yr}^{-1}$) that is one order of magnitude faster than the long time scale shortening rate ($0.35-$
1120 $2.5 \text{ mm}\cdot\text{yr}^{-1}$) of the embryonic thrust belt, suggesting that they are related to a forward
1121 propagation of the MFT, which is frequently affected by great earthquakes (Fig. 16B).

1122 Therefore, we suggest that the embryonic fold and thrust belt has been slowly deforming
1123 for millions of years, resulting in a deformation rate one order of magnitude lower than that of
1124 the Himalayan thrust belt. Its incorporation into the Himalayan belt occurs when the frontal
1125 thrust propagates forward, cuts, or reactivates previous structures and slips during large
1126 earthquakes.

1127

1128 7. Conclusion

1129 A compilation of 61 geomorphological studies indicates that the piedmont ahead of the
1130 active frontal structure of the Himalayan thrust belt is affected by deformation inducing uplift,
1131 creating relief, disturbing the drainage pattern, and locally inducing a strong incision. This
1132 deformation is evidenced from the western end to the eastern end of the Himalayas and is related
1133 to an embryonic thrust belt south of the Himalayan morphological front.

1134 Blind thrusts and folds were imaged using several seismic profiles from the foreland
1135 basin. In the Birgunj area, the 10,000 year-scale and the 1,000,000 year-scale shortening rates,
1136 deduced from the incision and from the sediment/structure relationships, respectively, are $1 \pm$
1137 $0.4 \text{ mm}\cdot\text{yr}^{-1}$ and $2.6 \pm 1.2 \text{ mm}\cdot\text{yr}^{-1}$, respectively. In the Darjeeling area, blind thrusts and folds
1138 were evidenced by passive seismic records located south of the MFT. They deform the buried

1139 Siwalik sediments below the Gish fan and the apex of the Tista megafan at a $1.1 \pm 0.7 \text{ mm}\cdot\text{yr}^{-1}$
1140 million year-scale shortening rate. Therefore, the shortening of the embryonic thrust belt is less
1141 than 20% and probably less than 10% of the Himalayan shortening.

1142 In the Darjeeling area, two scarps of approximately 10 m affect the Tista megafan and
1143 are related to a $9.7 \pm 5 \text{ mm}\cdot\text{yr}^{-1}$ 1,000 year-scale shortening rate. The frontal scarp of the Matiali
1144 Fan deforms the fan with a $7.3 \pm 5 \text{ mm}\cdot\text{yr}^{-1}$ 1,000 year-scale shortening rate, whereas several
1145 metre-scale slip events related to earthquakes of magnitude greater than eight were detected at
1146 the base of the MFT2 scarp. The Matiali fan is also affected by two other scarps (MBT and
1147 MFT1) active since at least 60 ka, and the 10,000 year-scale shortening rate through the entire
1148 Matiali fan is $4.2 \pm 2.3 \text{ mm}\cdot\text{yr}^{-1}$. The recent increase in the shortening rate in the piedmont of
1149 Darjeeling is likely related to the recent propagation of seismic ruptures through the previously
1150 slowly deformed embryonic thrust belt in the piedmont of the Himalayas.

1151 The deformation of the piedmont is spatially too limited, and its rate is too small to
1152 significantly reduce the seismic hazard linked to extremely large or large earthquakes affecting
1153 the MHT, even in a seismic gap such as that in west-central Nepal. Nonetheless, the energy
1154 absorbed during the deformation of the embryonic thrust belt was not negligible. If the elastic
1155 component is released during earthquakes, such events would be significantly damaging in the
1156 densely populated piedmont because their epicentres would be at shallow depths beneath the
1157 piedmont. Therefore, it is of utmost importance to image and precisely characterise blind
1158 structures to obtain better estimations of seismic hazards in the plain.

1159 The different types of structures described and analysed herein provide a conceptual
1160 framework for interpreting the tectonics of the piedmont and Himalayan front and are based on
1161 A) the development of the sharp Himalayan morphological front above the emergence of great
1162 seismic ruptures along the MFT and B) the lateral and/or frontal propagation in the piedmont
1163 of seismic cycle-related deformation (these seismic rupture-related scarps are superposed to
1164 previous structures). C) The latter structures are expressed at the surface by bulges or tilts of

1165 the topography that develop at a slow geological rate and (D) basement tectonics occur beneath
1166 the foreland basin.

1167 The embryonic thrust belt south of the Himalayas may have remained poorly observed
1168 because of its hidden location beneath the plain. New developments in geophysics or geodetic
1169 studies, such as satellite image interferometry or precise DEM construction, will provide new
1170 data and will allow a better understanding of the present-day Himalayan deformation. It would
1171 be worthwhile to pursue interdisciplinary studies across a wide area to better determine the
1172 mechanism of long-term deformation in this setting.

1173

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1183

1184 **Declaration of Competing Interest**

1185 We declare that we do not have any conflicts of interest.

1186 **Author contributions**

1187 J-L. M. performed the regional synthesis. E. L. performed the morphological analysis
1188 during his master's thesis. P.H. led the project and acquired the horizontal-to-vertical
1189 spectral ratio data that she processed with the help of E.L. and B.G.. F. J. processed the
1190 dislocation models based on GNSS data. T. C. and P. H. completed the structural synthesis
1191 in the Darjeeling area. All the authors have discussed and contributed to the writing of the
1192 manuscript. J-L.M., P.H., and E.L. drafted and finalised the manuscript.

1193 **Data Availability**

1194 Appendix A: Interactive Map Data (a *.kmz file). Yellow pines for the location of the studies
1195 compiled in Table 2; red pines for the location of the dating compiled in Fig. 10 data
1196 (Appendix B).

1197 Appendix B: Supplementary data: Dating in the Darjeeling Piedmont (Fig. 10).

1198 Appendix C: Supplementary data: Propagation of uncertainties related to the balancing
1199 procedures.

1200 Appendix D: Supplementary data: Calculation of the depth of the décollement beneath the
1201 Matiali fan using balancing procedures.

1202

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