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## Geomorphic evidence for an emergent active thrust along the edge of the Po Plain: The Broni-Stradella fault

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[1] We present here geomorphic evidence for an emergent active thrust along the northwestern Apennine front about 50 km south of Milano. Fieldwork combined with SPOT image analysis attests to the presence of a  $\sim 35$ -km-long, en échelon, cumulative fault scarp, that cuts E-W across Quaternary surface deposits from Casteggio to Sarmato. The scarp offsets vertically alluvial fans and terraces emplaced by tributaries of the Po River that flow northward from the Apennines. Incision by such tributaries occurs only south of the scarp. Valleys of smaller streams stand in hanging position. To the northeast, the buried, east dipping Pavia lateral ramp bounds the San Colombano anticline. We interpret the Montebello-Sarmato scarp to result from the emergence of an active thrust fault dipping south, the Stradella thrust, which splays eastward from that ramp. Total station profiles leveled perpendicular to the Stradella thrust show variable cumulative surface throws ranging from 2 to 25 m. Scarp degradation analysis indicates fairly recent offset of the terrace surfaces (10–100 kyr) suggesting a minimum uplift rate of 0.3 mm/yr. The underlying fault might thus be one of the most active thrust ramps along this segment of the Apennines. N-S to N15°W shortening is consistent with both the E-W strike of this thrust ramp and with coeval oblique sinistral motion on the NNE-SSW trending Pavia lateral ramp. The Vogherese-Bobbiese earthquake of 1828 ( $I \approx IX$ ) south of Casteggio and Broni may have activated one segment of this lateral ramp rather than the Stradella thrust. Other historical events ( $I > 7$ ) that caused damage in Pavia, Piacenza, Lodi, and Milano in the last 2000 years (290 A.D., 1249 A.D., 1276 A.D., 1473 A.D.), may have occurred on the Broni-Stradella thrust or on the blind San Colombano and Lodi thrusts farther north. This makes detailed paleoseismological studies and trenching across its trace mandatory.

**INDEX TERMS:** 8107 Tectonophysics: Continental neotectonics; 8123 Tectonophysics: Dynamics, seismotectonics; 7230 Seismology: Seismicity and seismotectonics; 7223 Seismology: Seismic hazard assessment and prediction; 9335 Information Related to Geographic Region: Europe; **KEYWORDS:** geomorphology and weathering, seismicity and seismotectonics, structural geology, folds and folding, Europe

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### 1. Introduction

[2] The convergence between Africa and Europe causes deformation across the entire Mediterranean [e.g., McKenzie, 1972; Tapponnier, 1977; Anderson and Jackson, 1987; Westaway, 1990; Armijo et al., 1996; Reilinger et al., 1997]. In the central Mediterranean (from 8 to 12°E) this convergence occurs at a rate of 6–8 mm/yr in the  $\sim N25^\circ W$  direction (Figure 1) [DeMets et al., 1990]. Earthquake fault

plane solutions, seismic sections and geomorphic studies indeed indicate that the active tectonics of northern Italy is dominated by folding and thrusting (Figure 1) [Gasparini et al., 1985; Anderson and Jackson, 1987; Frepoli and Amato, 1997; Benedetti et al., 2000]. In the Veneto-Friuli Alps, NW shortening on NE-SW trending thrusts appears to be roughly compatible with the direction of convergence between Africa and Europe (Figure 1b) [Benedetti et al., 2000]. However, in the northern Apennines, the boundary conditions appear to be different, and the kinematics of present-day deformation and its relationship with the seismicity are less well understood.

[3] Along and north of the northern Apennine range front, industrial seismic reflection profiles, across the Po plain [e.g., *Pieri and Groppi*, 1981] show that the 7- to 8-km-thick Plio-Quaternary infill of the Piacenza-Ravenna flexural basin [e.g., *Barberi and Scandone*, 1983] is deformed by a series of generally left-stepping, south dipping blind thrusts and folds that are separated by sinistral lateral ramps [e.g., *Pieri and Groppi*, 1981] (Figure 1). On the basis of the interpretation of such profiles, these structures have been inferred to be mostly inactive [*Pieri and Groppi*, 1981; *Castellerin and Vai*, 1986]. In contrast, earthquake fault plane solutions between Piacenza and Rimini suggest that both the frontal thrusts and the lateral ramps are seismogenic (Figure 1b) [*Gasparini et al.*, 1985; *Boccaletti et al.*, 1985; *Frepoli and Amato*, 1997; *Selvaggi et al.*, 2001]. However, except near Reggio and Parma (Figure 1b), there has been no earthquake recent and large enough to constrain the ongoing deformation kinematics. Thus, in order to better understand potential current motion on those structures, and the magnitude and direction of shortening in the northern Apennines, we have looked for geomorphic traces of recent faulting and deformation in the region.

[4] In this paper, we examine in particular detail the region between Voghera and Piacenza, about halfway between Bologna and Torino and only 50 km south of Milano (Figure 1). Seismic sections show the existence of a curved, WNW to ESE trending, blind thrust, the Pavia-Cremona arc (Figures 1–3). This thrust dips southward and is limited to the west by the NE striking, Pavia-Casteggio lateral ramp (Figures 1 and 3).

[5] Historical and instrumental seismicity catalogues record only two earthquakes of intensity greater than or equal to VIII since 1800 in the region [*Baratta*, 1901; *Boschi et al.*, 1995; *Monachesi and Stucchi*, 1997]. The reconstruction of isoseismal contours from historical descriptions indicates that the event of 1802 (I  $\approx$  VIII) caused damage north of the Pavia-Cremona arc. The 1828 (I  $\approx$  IX) event was clearly located in the mountains south of the Apennine range front (Figures 1b and 3).

[6] Here, we document the existence of a  $\sim$ 35-km-long, emergent cumulative thrust-scarp between the arc and the range front. This scarp strikes approximately E-W between Broni and Sarmato (Figures 1–4). Pleistocene alluvial terraces of different ages, deposited by tributaries of the Po flowing down from the Apennines, are orthogonally cut and uplifted south of this thrust. Measurements of the vertical throw of the terrace surfaces derived from topographic profiles, combined with inferences on the ages of the terraces are then used to obtain plausible estimates of the late Quaternary uplift rate across the scarp. We finally discuss the way in which slip on the Stradella thrust is

related to regional tectonics and might be the source of certain historical earthquakes.

## 2. Geology and Geomorphology: Erosional Versus Tectonic Origin for the Stradella Scarp

[7] North of Casteggio and Piacenza, the Po river flows eastward and meanders in its floodplain at an elevation of  $\sim$ 50 m above sea level (asl). It is fed by tributaries flowing northward from the Apennines and southeastward from the Alps (Figure 1b). This part of the Apennine range peaks at Mount Maggiorasca (1799 m) and Mount Cesina (1724 m) located east and west of the Trebbia river valley, respectively (Figures 3 and 4). The Casteggio-Sarmato scarp lies south of the Po floodplain, where the river comes closest to the northwesternmost prong of the Apennine range (Figures 1–4). East of this prong, the scarp stretches linearly across the Piacenza piedmont plain, in a roughly E-W direction (Figures 1–4). Near Stradella, it meets with the range front and bends to NNE-SSW trend, from Broni to Casteggio (Figure 3). Along this NNE-SSW trending stretch, the scarp thus coincides with the sharp slope-break that marks the range front. North of the Po river, the 7-km-long, 2-km-wide, NW-SE trending San Colombano hill, rises to  $\sim$ 146 m asl. This hill is the only topographic high north of the Po river (Figures 3 and 4).

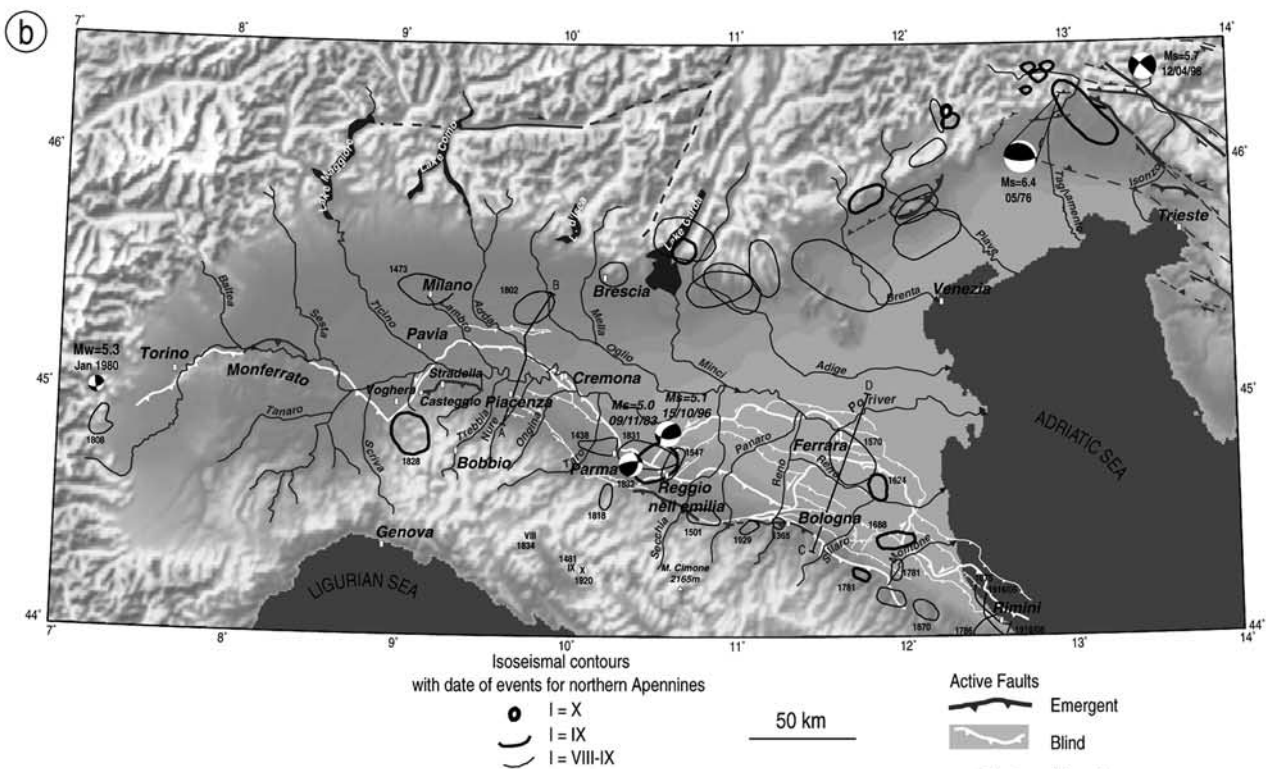
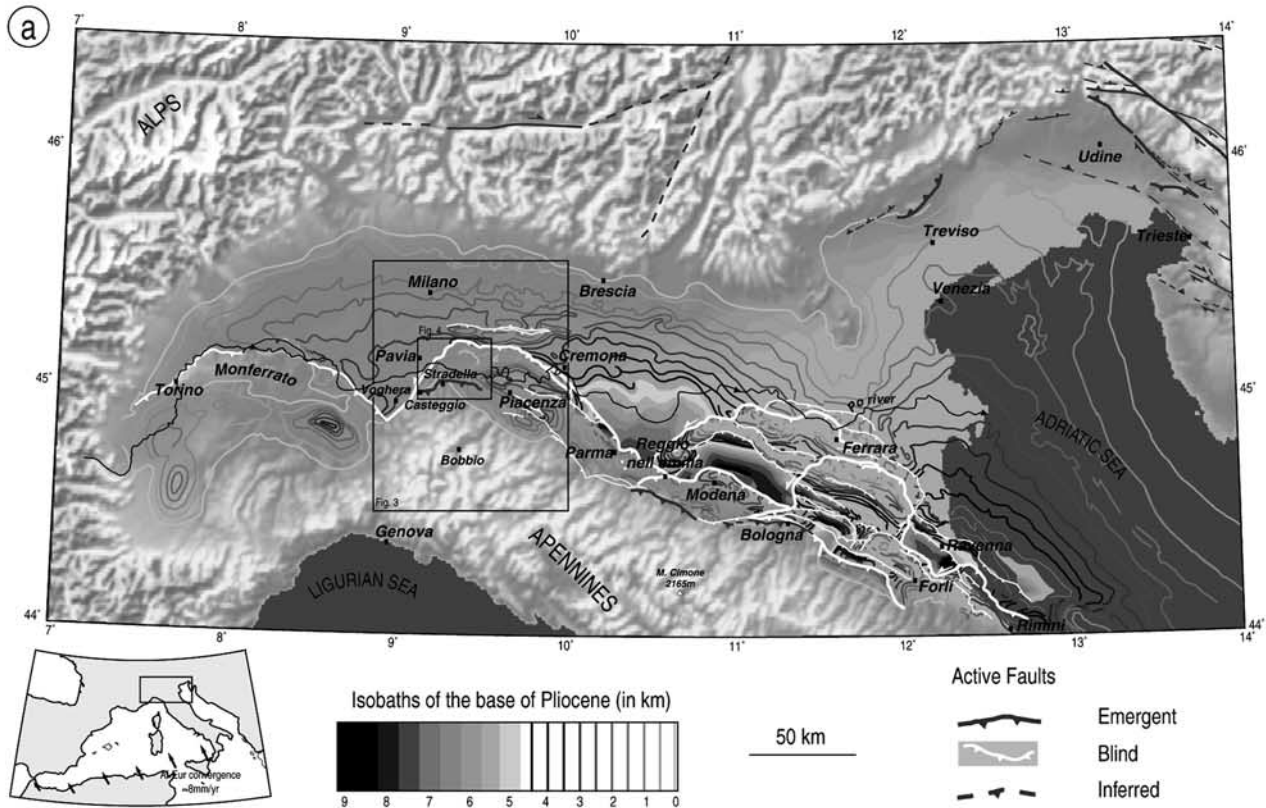
[8] Between Bobbio and the Ligurian sea, the geological structure is chiefly composed of thrust slices of Eocene-Cretaceous limestones and shales (Figure 2), with overthrust ophiolitic fragments lying on top of this north vergent stack of imbricated sedimentary thrust slices (Figure 2) [*Boni*, 1967]. North of Varzi, the Paleogene units are in turn thrust northward over Mio-Pliocene marls and conglomerates. Between Broni and Stradella, the Mio-Pliocene series starts with the marine San Agata marls at the base, and is topped by the Rocca Ticuzzi conglomerates and the Monte Azzolo sandstones, both of which are fluvial deposits [*Boni*, 1967]. The series dips gently southward, south of Stradella, and northward, north of Broni, defining a small syncline between Broni and Stradella. The Rocca Ticuzzi conglomerates contain metamorphic rock pebbles, which implies that they were emplaced by rivers coming from the Alps [*Vercesi and Scagni*, 1984], whereas sedimentological studies of the Monte Azzolo sandstones, the youngest Mio-Pliocene unit show an Apenninic provenance [*Vercesi and Scagni*, 1984].

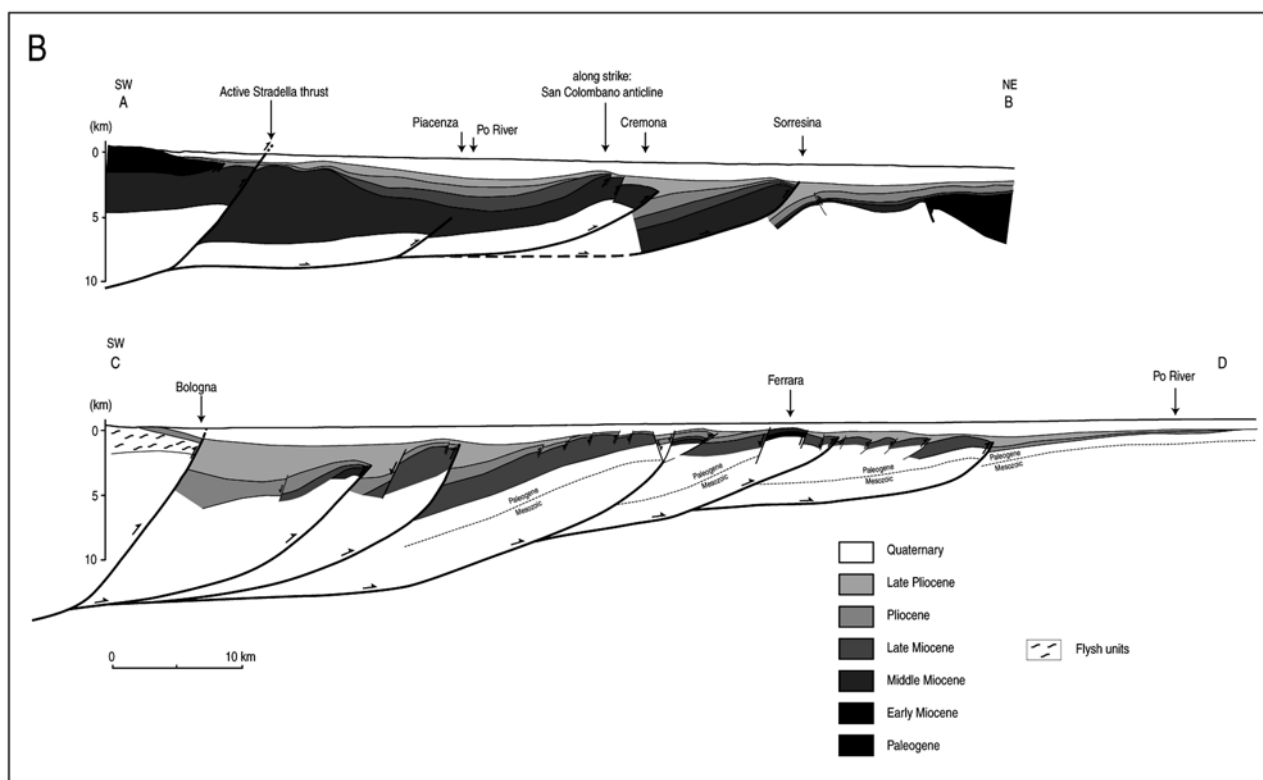
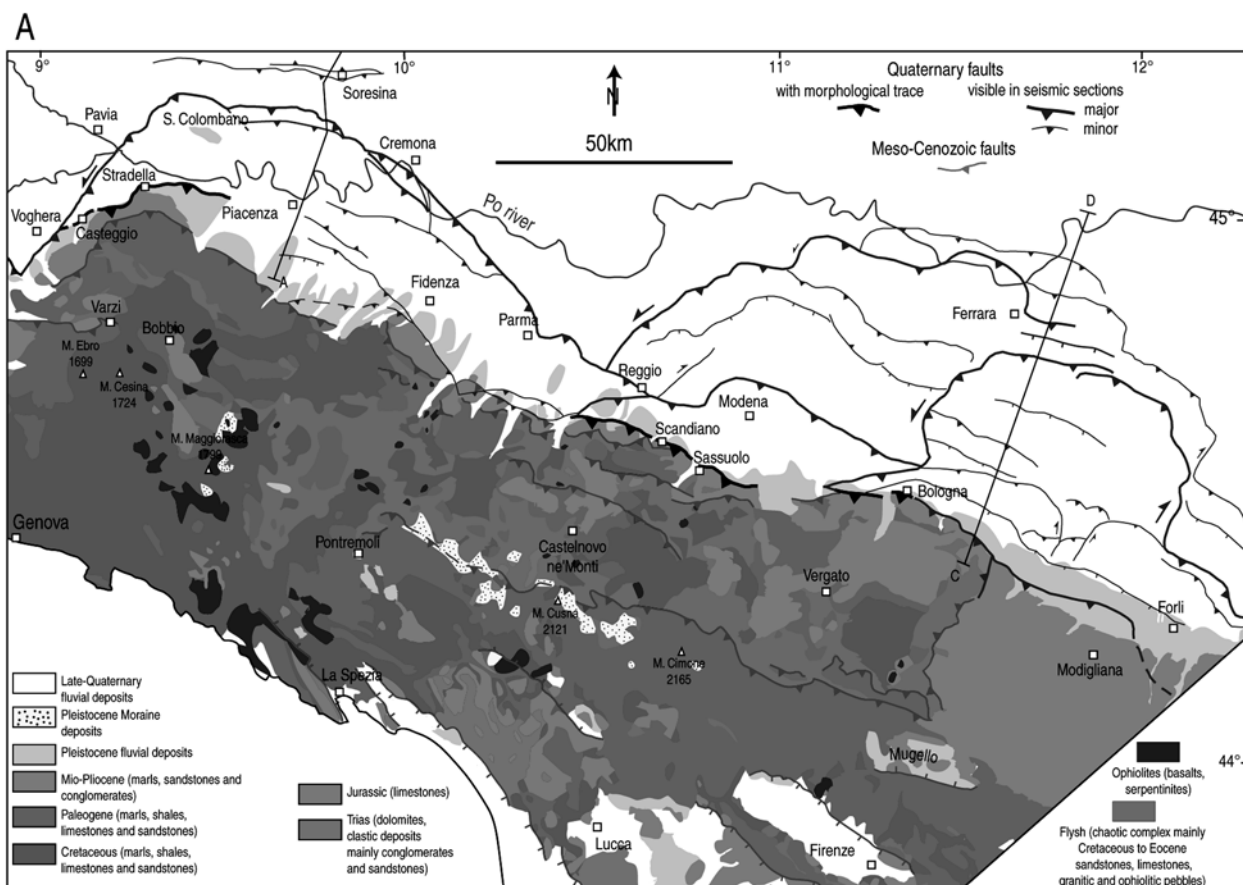
### 2.1. Quaternary Deposits South of the Po River

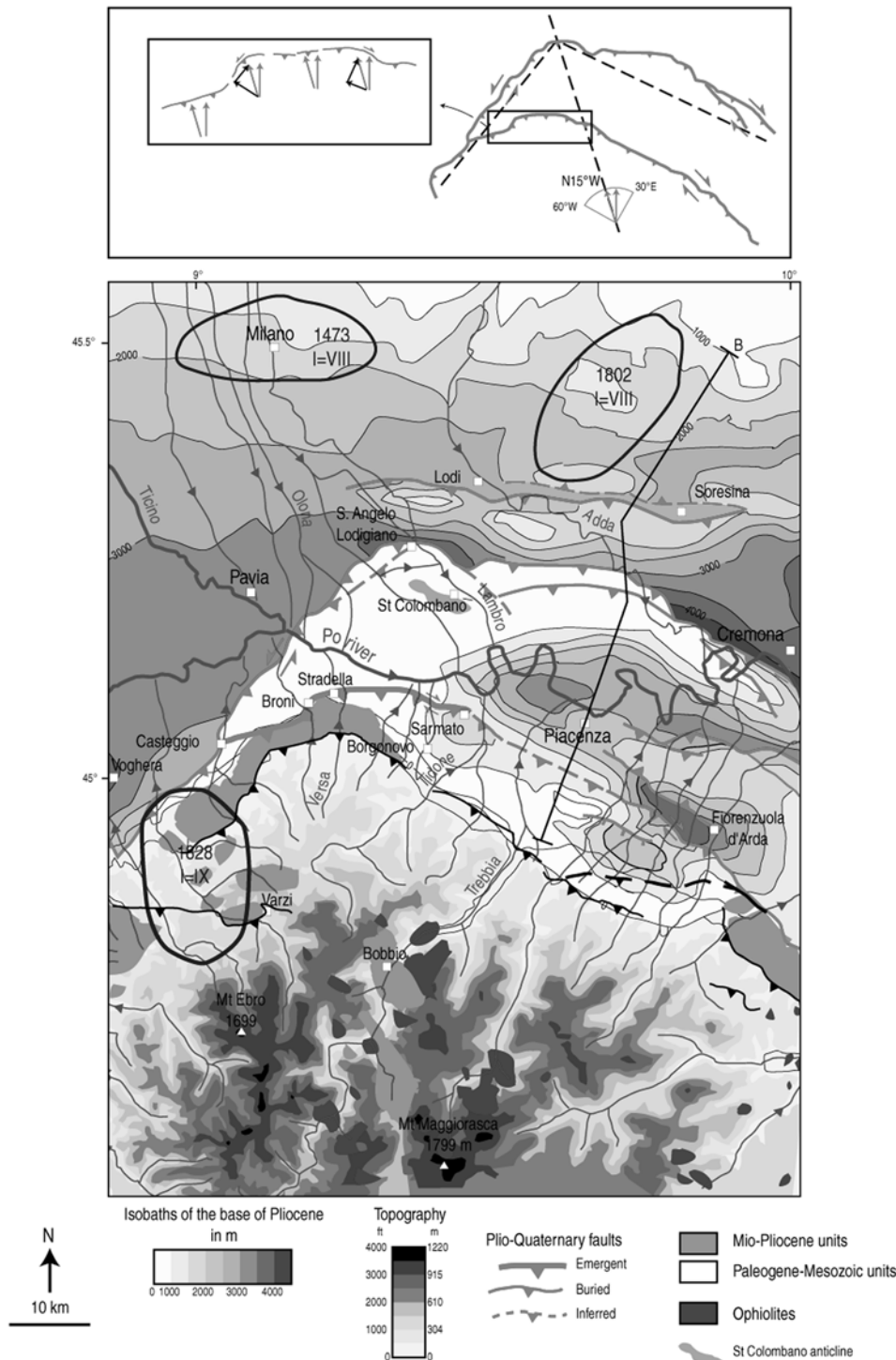
[9] The tributaries of the Po that flow from the Apennines (Coppa, Zeno, Verzate, Scuropasso, Versa, Rivolta, Bardonezza, Carogna, Carona, Panaro, Tidone) incise their own deposits south of the Stradella scarp and southeast of the

**Figure 1.** (opposite) (a) Tectonic map of northern Italy showing emergent Quaternary faults (red) and buried Plio-Quaternary faults (white) with isobaths of base of Pliocene [*Barberi and Scandone*, 1983]. Emergent faults are mapped from fieldwork, SPOT, and Landsat satellite image interpretations. Inset shows Euler vector of Africa/Europe [*DeMets et al.*, 1990]. Study area is indicated by square. (b) Seismotectonic map of northern Italy. Faults are as in Figure 1a. Historical seismicity is from *Baratta* [1901], *Boschi et al.* [1995], and *Monachesi and Stucchi* [1997]. Instrumental seismicity and earthquake fault plane solutions are from Harvard (<http://www.seismology.harvard.edu/data/>). See color version of this figure at back of this issue.





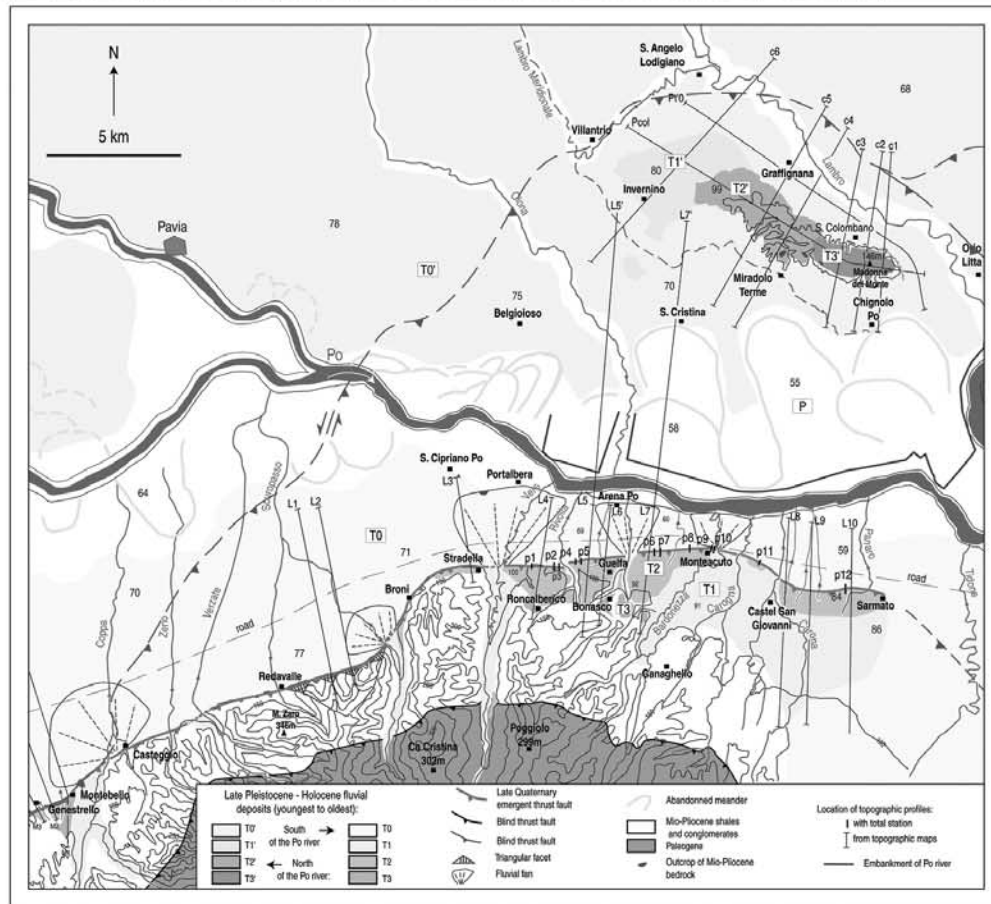
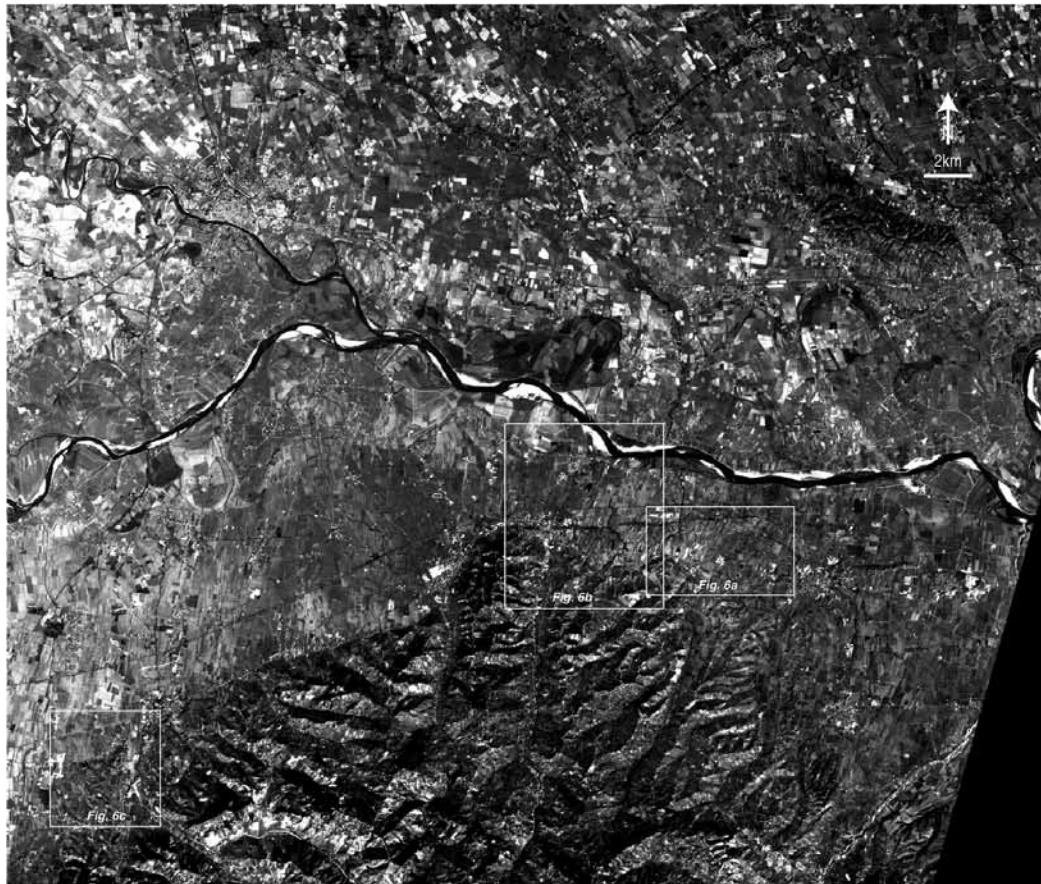




**Figure 3.** Seismotectonic map of Pavia-Piacenza region. Base of Pliocene depth contours, seismicity, and faults are as in Figure 1. Geology is interpreted from Boni [1967] and Barberi and Scandone [1983]. Inset shows geometry of Quaternary faults simplified from Figure 2 with kinematic interpretation and expected motion on faults.  $N15^{\circ}W$  to north shortening accounts best for geometry of faults at large and small scales. See color version of this figure at back of this issue.

**Figure 2.** (opposite) (a) Geological map of the northwestern Apennines interpreted and simplified from Servizio Geologico d'Italia [1983], 1/500,000 scale, and from Barberi and Scandone [1983], 1/500,000 scale. Positions of geological cross sections are indicated. (b) Geological N-S cross sections interpreted from seismic sections [Pieri and Groppi, 1981] of Piacenza and Bologna region (see location on Figure 1b). Topography is shown with no vertical exaggeration. See color version of this figure at back of this issue.



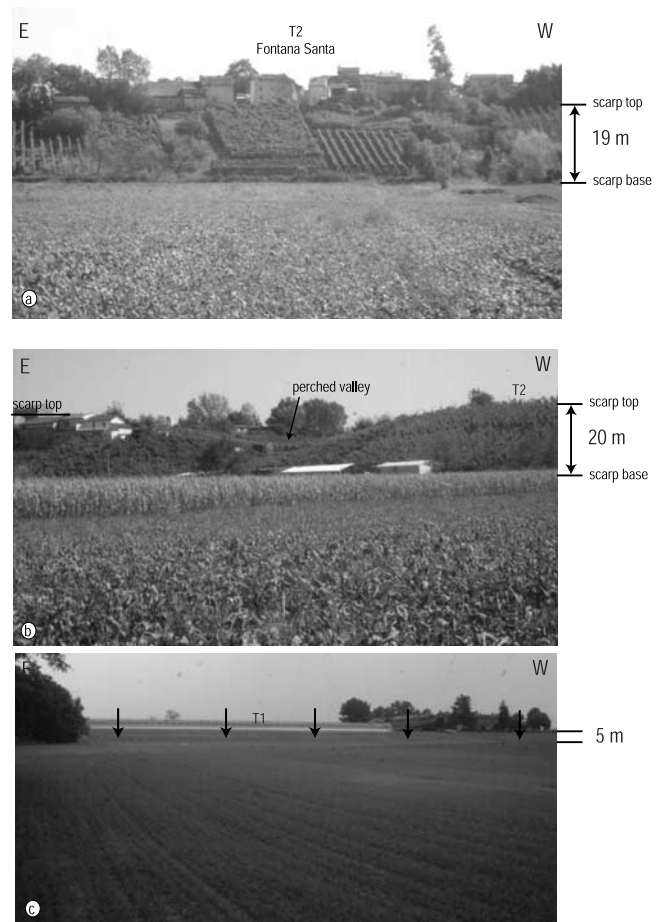


Casteggio-Broni range front (Figure 4). All these deposits are of Pleistocene age [Boni, 1967]. A lower, abandoned terrace level (T1, mean elevation asl.: 80 m) follows the Coppa, Verzate, Scuropasso, Versa, Bardonezza, Carogna, and Carona valleys (Figure 4). T1 is mainly composed of clays with fluvial sands and gravels. Along the Coppa, Verzate, Scuropasso, and Versa valleys, T1 forms rather narrow benches (100–400 m wide), fairly continuous along the river courses. It stands  $\sim 5$  m above the riverbeds (Figure 4). Between the Bardonezza and Carona, T1, also stands about 5 m above the rivers, but forms one broad surface, due to coalescent fanning of the three rivers (Figures 4 and 5).

[10] Between Stradella and Montecuto, and between Castel San Giovanni and Sarmato, all the villages are perched on top of another higher terrace surface (T2) (mean elevation: 100 m), which has been more deeply incised by the rivers (Figures 4, 5, 6a, and 6b). This surface extends  $\sim 15$  km in the E-W direction, along and south of the Stradella-Sarmato scarp, forming a 1–2 km broad ledge between that scarp and the mountain front. It is composed of deposits similar to those of T1, but more weathered, with a brownish-grey color, and thus probably older [Boni, 1967; Pellegrini and Vercesi, 1995]. South of T2, near Bonasco and Roncalberico, there are small remnants of a yet higher surface (T3, mean elevation: 125 m) whose yellow-pinkish alluvial deposits are probably older than those of T2 are [Boni, 1967] (Figures 4, 6a, and 6b).

[11] The Stradella scarp limits the northern edge of the T2 and T1 terraces (Figures 4, 6a, and 6b). For  $\sim 10$  km, between Stradella and Montecuto, it is fairly continuous though divided into four left stepping segments separated by small steps of jogs (Figure 4). East of Montecuto, it veers south-eastward for about 3 km (Figures 4, 6a, and 6b). At Castel San Giovanni, it veers back to its original E-W trend for about 5 km before vanishing into the Tidone valley floodplain (Figure 4). Several rill channels crossing the Stradella scarp stand in hanging position (Figures 5, 6a, and 6b).

[12] Because it is close to the Po floodplain, between Broni and Sarmato, the Stradella scarp has generally been interpreted to be a riser cut by this river [Boni, 1967; Vercesi and Scagni, 1984; Pellegrini and Vercesi, 1995]. Moreover, this is the place where the river skirts most closely the Apennine range (Figures 1–4). However, the strong asymmetry of the Po valley in the area (Figure 4) hints at more than simple erosion and sedimentation by the Po River. In fact, neither T2 nor T1, which are made of Apenninic clay and sands, have been emplaced by the Po. Besides, immediately north of the scarp, all the Apenninic tributaries of the river fan out (Figures 4, 6a, and 6b). Their coalescent deposits form another surface, T0, which is therefore not a terrace of the Po River either. T0 has a mean elevation of 65 m and slopes gently down ( $0.2$ – $0.3^\circ$ ) northward to the Po. It has no equivalent on the north side of the river. Taken together, the asymmetry of terrace deposition in the Po



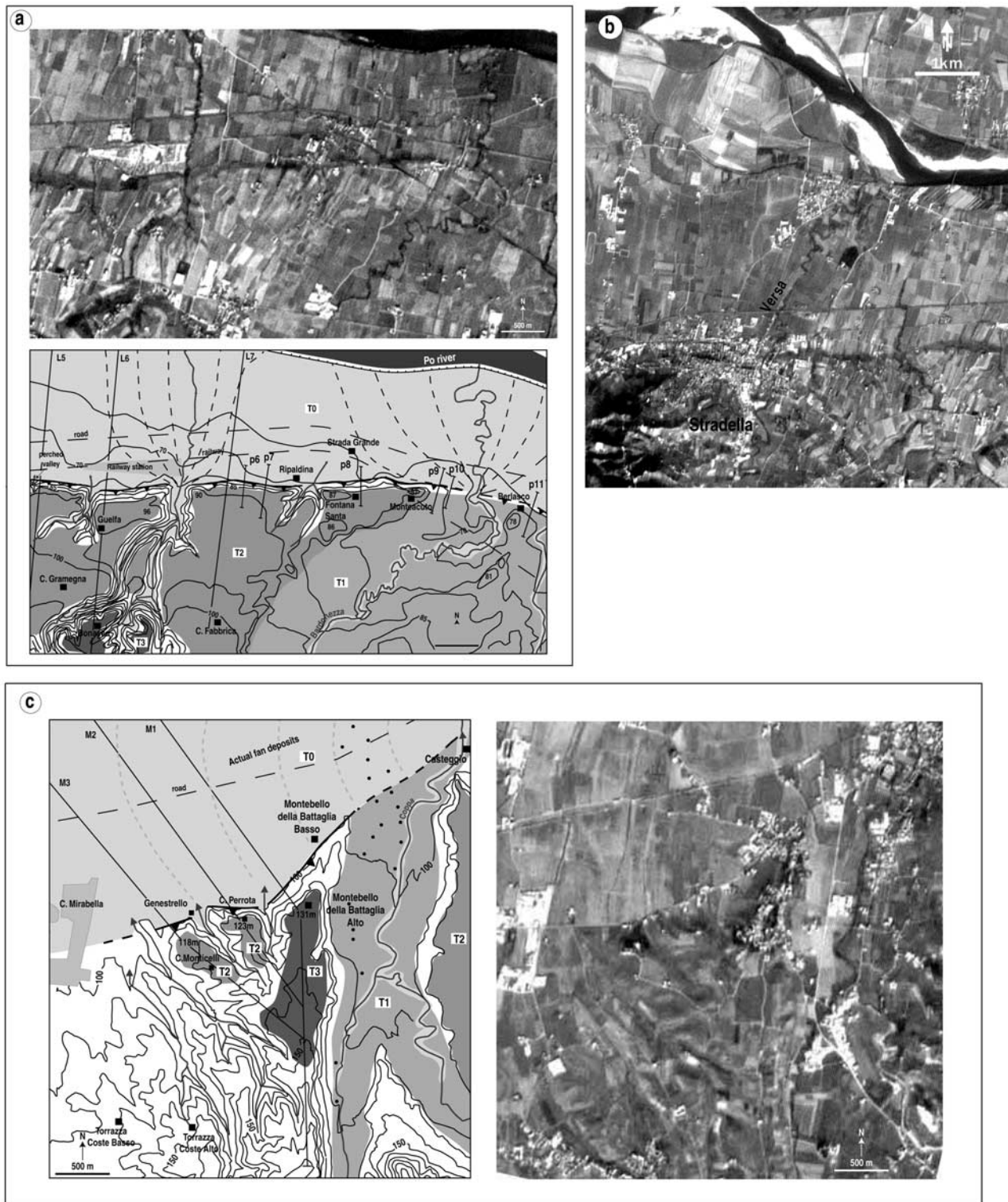
**Figure 5.** (a) View, toward south, of eastern part of Stradella scarp, here  $\sim 17$  m high with Fontana Santa village perched on top of scarp. (b) View, toward south, of hanging valley on Stradella scarp near Guelfa. (c) View toward SSE, of NW-SE segment of Stradella scarp near Berlasco with 5 m vertical offset and warping of T1–T0 terrace in cultivated fields.

valley, the fact that the Stradella scarp cuts and separates terrace surfaces emplaced by Apenninic tributaries of the Po, and the presence of hanging valleys along the scarp, thus imply that it is of tectonic, rather than erosional, origin.

[13] From Stradella to Montebello, the NNE-SSW trending range front is quite steep (average slope  $20^\circ$ , Figure 4). It follows the contact between the Miocene marls and Quaternary sands and clays [Boni, 1967]. Between Broni and Redavalle it is marked by four triangular facets, about 140 m high (Figure 4). Farther southwestward, between Montebello and Genestrello, the scarps cut another flight of three uplifted terrace surfaces separated by incising rivers (Figures 4 and 6c). The highest (131 m) and longest ( $\sim 2$  km) terrace ledge, on top of which Montebello della Battaglia is

**Figure 4.** (opposite) (a) Panchromatic SPOT image (K.J. 57–259, 29 December 1991) of Sarmato-Casteggio area (pixel size is 10 m). Note E-W, en echelon thrust scarp extending from foremost prong of Apenninic relief eastward into plain. Boxes indicate locations of Figures 6a, 6b, and 6c. (b) Geomorphic and geological interpretation of Figure 4a. Geology of Quaternary deposits is emphasized. Topography is from *IGMI* [1960, 1961], 1/100,000 scale. Levee on left bank of Po river is from *Braga and Gervasoni* [1989]. See color version of this figure at back of this issue.





**Figure 6.** Enlargement of SPOT image shown in Figure 4a with geomorphic interpretation for Figures 6a and 6c. Symbols are as in Figure 4. (a) Ripaldina region, (b) Stradella region, note Versa alluvial fan, and (c) Montebello region. Solid circles are topographic trig or selected points for Coppa valley topographic profile. See color version of this figure at back of this issue.

perched, is parallel to the Coppa riverbed, implying that it was emplaced by that river (Figure 6c). So were probably, the two other levels that fan out with decreasing, slightly lower elevations, westward (Figure 6c). Like T2 and T3, the

three terraces thus appear to have been uplifted relative to the T0 bajada, by the continuation of the Stradella scarp (Figures 4 and 6c). Comparing the elevation of these surfaces with those of the terraces near Stradella, we find

that the Montebello surface is slightly higher than T3 near Bonasco. The other two surfaces also stand 5 to 10 m above the mean elevation of T2 near Stradella and Guelfa (Figures 4 and 6c). Those observations suggest that the Montebello scarp is of tectonic origin.

## 2.2. Quaternary Deposits North of the Po River

[14] North of the Stradella scarp, the Po river floodplain is about 5–7 km wide. Between Belgioioso and Orio Litta, the abandoned meanders visible on the satellite image and on the topographic maps [*Istituto Geografico Militare Italiano (IGMI)*, 1961] suggest that the river used to wander preferentially on the northern part of its floodplain [*Braga and Gervasoni*, 1989] (Figure 4). In the 14th century, a left bank levee was constructed between Portalbera and the Tidone confluence, to contain the river and gain arable lands [e.g., *Braga and Gervasoni*, 1989]. As a consequence, the Po now flows straight for ~15 km, all the former meanders having been abandoned [e.g., *Braga and Gervasoni*, 1989, and references therein] (Figure 4). The surface thus created (P) at a mean elevation of 60 m asl, about 5 m above the riverbed, is therefore not older than 600 years. It is mainly composed of fine-grained sand with clay lenses [*Boni*, 1967].

[15] Northward, ~10–15 m above P, a flat and broad surface (T'0) that stands at a mean elevation of ~70 m forms the main level of the Po plain (Figure 4). It is also composed of fine-grained sands, but is more weathered, with a yellow-brownish color [*Boni*, 1967].

[16] Tributaries of the Po coming down from the Alps (Ticino, Adda, Olona, Lambro meridionale and Lambro) all flow toward the SE (Figures 3 and 4). Although they now incise T'0, their deposits have contributed to the aggradation of this surface. About two kilometers north of the San Colombano anticline, the course of the Lambro meridionale divides in two (Figure 4). The main course of the river kinks sharply (~90°) at Villantrio, to meet with the Lambro 7 km northeastward. Between San Angelo Lodigiano and Orio Litta, the Lambro follows the other side of the San Colombano anticline, incising ~5 m into T'0 (Figure 4). Its minor course, which has been channeled, continues southwest of the anticline to join the Po River near Chignolo Po (Figure 4).

[17] Along strike, seismic sections clearly show the anticlinal structure of the San Colombano hill, above a splay of the south dipping Cremona thrust [*Pieri and Groppi*, 1967] (Figures 3 and 2b). The anticline folds cemented Quaternary alluvium (mainly sand), and locally Mio-Pliocene marls [*Boni*, 1967]. The hill is eroded and deeply incised by streams. To the southeast, around Madonna del Monte, however, it is still capped by a ~140-m-high, ancient terrace surface of ochre color (T'3 [*Boni*, 1967]). West of the northwestern extremity of the hill, another terrace surface, the Invernino surface (T'1) stands about 10 m above T'0. Between the Invernino and Madonna del Monte surfaces, a degraded terrace surface of intermediate elevation (T'2, 120 m) is notched by streams incising the south side of the San Colombano hill (Figure 4).

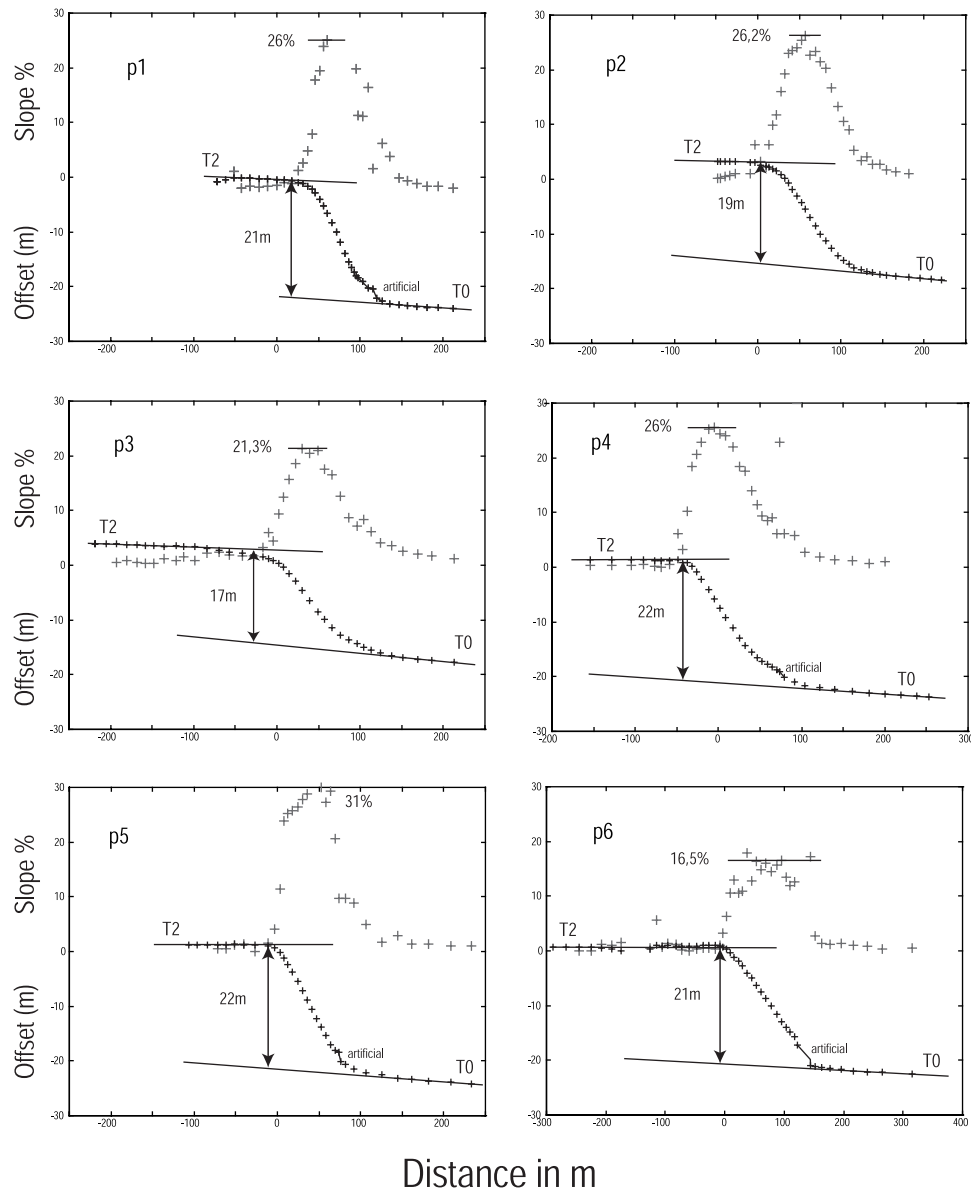
[18] These three terraces (T'1, T'2, and T'3) form a set of NW stepping ledges carved into the San Colombano anticline. Their geometry suggests they might have been abraded, then abandoned by the Lambro meridionale as its main NE flowing course progressively shifted toward the west. Between Invernino and Miradolo Terme, the curved

shapes of the T'1/T'0 and T'2/T'0 risers suggests that they were cut by an older meander of the Po river that reached even farther north than the 600-year-old meanders south of San Cristina and Miradolo (Figure 4). The three terraces of the San Colombano anticline stand above the San Angelo Lodigiano-Cremona thrust. Their arcuate shape (Figure 4) mimics that of the thrust, as it bends to meet with the Pavia lateral ramp. This suggests that they have been uplifted due to the growth of the San Colombano anticline, surface expression of the blind thrust [*Benedetti et al.*, 2000].

## 2.3. Active Thrusting Along the Voghera-Piacenza Mountain Front

[19] The deposits north and south of the Po River appear to be lithologically different. The former are mostly sands while the latter, which are deposited by tributaries from the Apennines, are mainly clays. Numerous fossil bones of mammals that lived in the Po plain during the late Pleistocene and Holocene have been retrieved along the southern riser of the Po floodplain between San Cipriano and Arena Po. Even though these fossils correspond to different epochs and are in different states of preservation, they were found mixed together in the same horizons [*Taramelli*, 1882; *Sacchi Vialli and Pizzochero*, 1958; *Boni*, 1967; *Anfossi and Cantaluppi*, 1988]. This suggests that the Po River returned periodically to the same base level and might not have cut farther south than the present-day southern riser of its floodplain during the Pleistocene [*Boni*, 1967; *Braga and Gervasoni*, 1989]. This is in agreement with the observations that T0 south of the Po is not formed by Po deposits and corroborates the idea that the Stradella scarp may not be a riser cut by the Po River.

[20] The linearity and left stepping segmentation of the Stradella scarp, the hanging valleys along it, the incision of Apenninic tributaries into T2 and T1 south but not north of it, and finally the fact that it limits surfaces of different ages and heights concur to suggest that this scarp results from faulting. It might be possible to interpret the Stradella scarp as an ancient Po river riser if a now buried Po terrace at its base had been subsequently covered by small fans deposited by the Apenninic tributaries of the Po. However, the observations described above and corroborated by the detailed analysis of the topographic profiles presented in the next section are in better agreement with a tectonic interpretation. The rise, farther northward, of the San Colombano anticline, and associated terraces above the arcuate south dipping San Angelo Lodigiano thrust, and the existence of the Pavia lateral ramp to the east, suggest that the Stradella scarp results from slip on a south dipping, active, thrust, splaying from that ramp as the San Angelo Lodigiano thrust does. The Montebello scarp continues along the range front south of the junction of these two active faults. Between Stradella and Montebello, the Broni-Casteggio range front displays prominent morphological evidence of active uplift. We thus infer the Stradella thrust to be active everywhere along strike from Genestrello to Sarmato, a distance of about 35–40 km (Figures 3 and 4). Because the shape of the Stradella scarp, quantified in the next section, is undistinguishable from those of well studied active thrust scarps elsewhere, we also infer this scarp to have grown in height by addition of incremental seismic scarplets. Uplift of the hanging wall south of the thrust trace



**Figure 7.** Total station profiles across Stradella scarp with corresponding slope profiles. Slope amount in percent is indicated for each profile. Numbers are vertical offsets of terraces and maximum slopes of scarp. Note that artificial features are clearly visible on the overall profiles and slope profiles. Location of profiles are given on Figure 4b. Vertical exaggeration is 6.5 except for p6 and p11, where it is 9.

would have led to preservation of the T1, T2, and T3 terraces and to river incision into them, while downthrow of the footwall would have resulted in deposition of the coalescent fan bajada surface, T0, whose elevation is different from that of T'0, north of the Po.

### 3. Quantitative Evidence for Ongoing Uplift

[21] In order to assess the uplift rate along the Stradella thrust and the San Colombano anticline, we measured accurately the topography of the offset terraces along and across both features.

#### 3.1. Stradella Thrust Between Broni and Sarmato

[22] In keeping with the inference that repeated movement on the Stradella thrust produced the variable vertical

cumulative uplift of T1, T2, and T3 above T0 (Figure 4), we leveled a series of 12 transverse topographic profiles to measure this uplift with a Total station (WILD T 2000, DI 3000) (Figure 7). Other profiles were derived from the available IGMI topographic 1/10,000-scale maps (Figure 8).

[23] The total station profiles show that T2 and T1 lie 16–22 m and 4–6 m, respectively, above the T0 bajada (profiles p1 to p12, Figure 7). The topographic map profiles show that the T3 terraces are 42 to 50 m above T0 (profiles L4, L6, and L7, Figure 8a) (Table 1).

[24] Almost all the profiles cross artificial features (walls or roads) that show as disturbances that do not fit with the overall slopes (Figure 7). The maximum slopes of the scarp between T2 and T0 and between T1 and T0 range from 9.4° to 17.2° (16.5% to 31%) and 3° to 5.1° (5 to 9%), respectively (Figure 7). The positions of the maximum



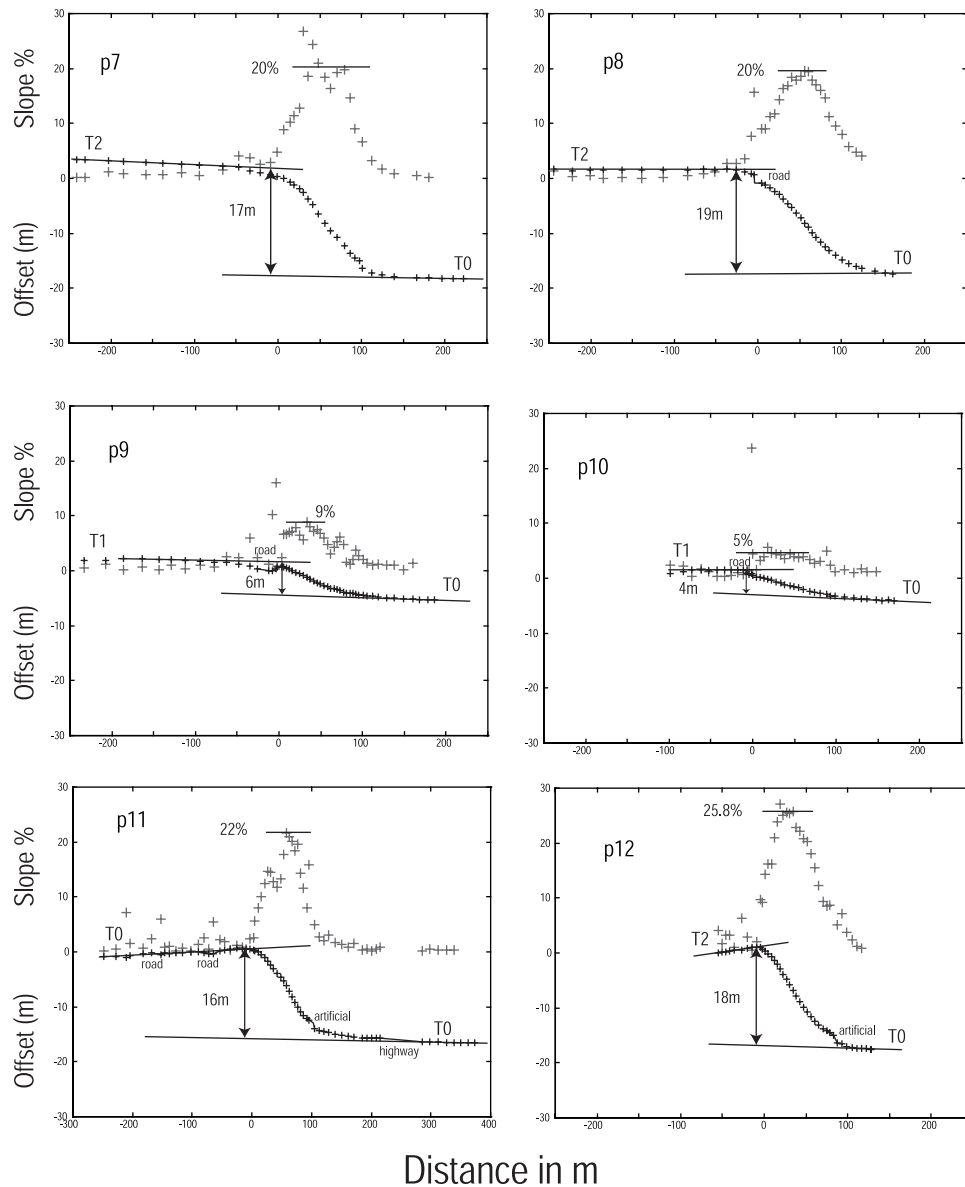


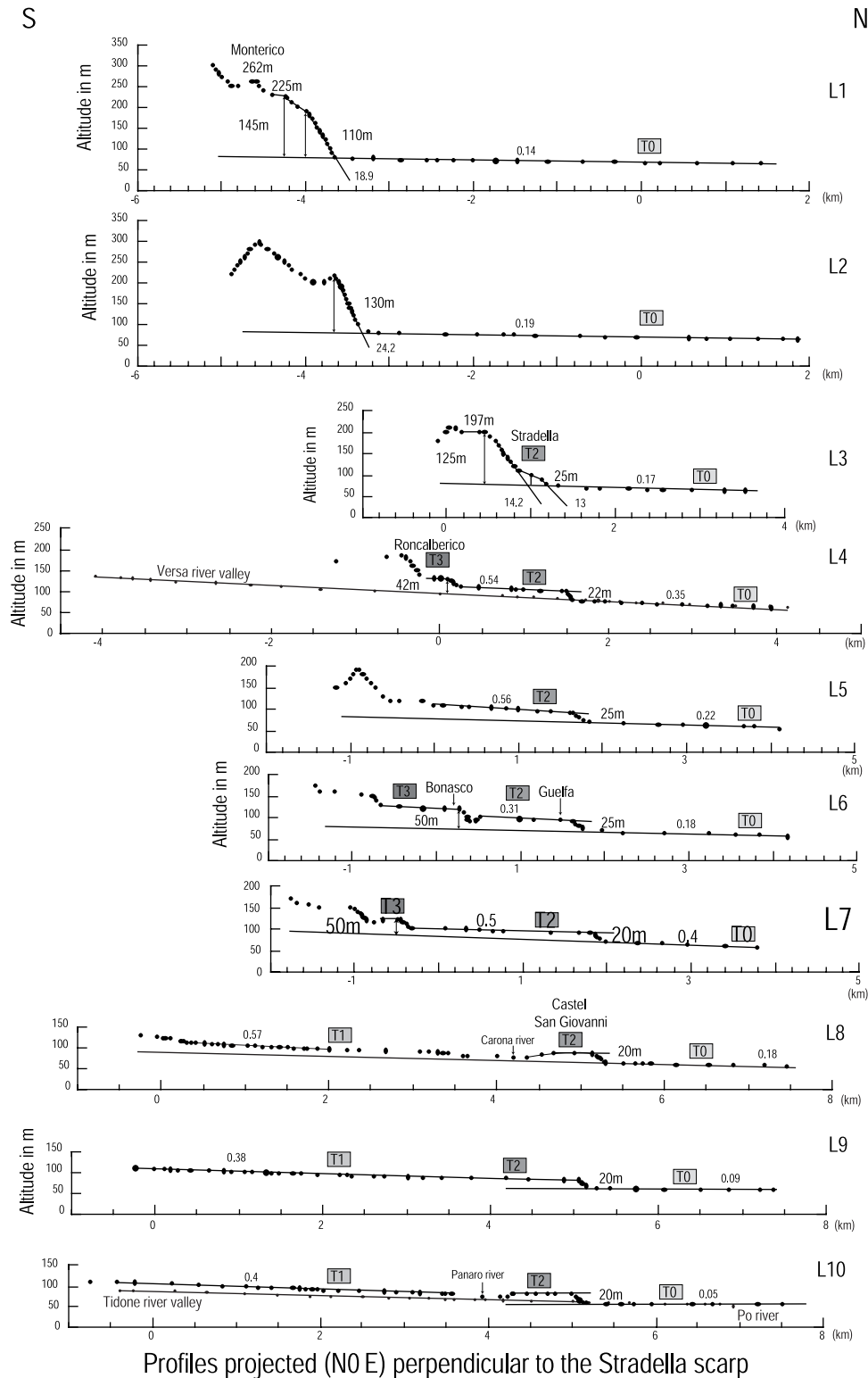
Figure 7. (continued)

slope values change laterally from one profile to the next. There are asymmetric profiles such as p2 or p5. This may suggest that the scarp was rejuvenated at different places by successive seismic events. More likely, however since the scarp runs across arable lands, it is likely that such variations reflect irregular human action.

[25] Westward along the scarp, profile L3 (Figure 8a) shows that the Stradella terrace surface T2 dips more toward the north when adjacent to the steep mountain front (mean slope  $14.2^\circ$ ). Here the front forms a 100-m-high escarpment below the flat surface of Alto Stradella, which is perched at 197 m (Figures 4 and 8a). Farther west, along the NNE-SSW Broni-Casteggio segment, the Stradella surface, hence the corresponding T2/T0 scarp, disappear (Figures 4 and 8a). However, topographic profiles made perpendicular to the triangular facets (L1 and L2) show that the limit between the range front and the T0 fan surface is abrupt, at the base of the steep, 130- to 145-m-high facets ( $19^\circ$  to

$24^\circ$ ) below the small flat surface of Monterico basso ( $\sim 225$  m) (Figure 8a).

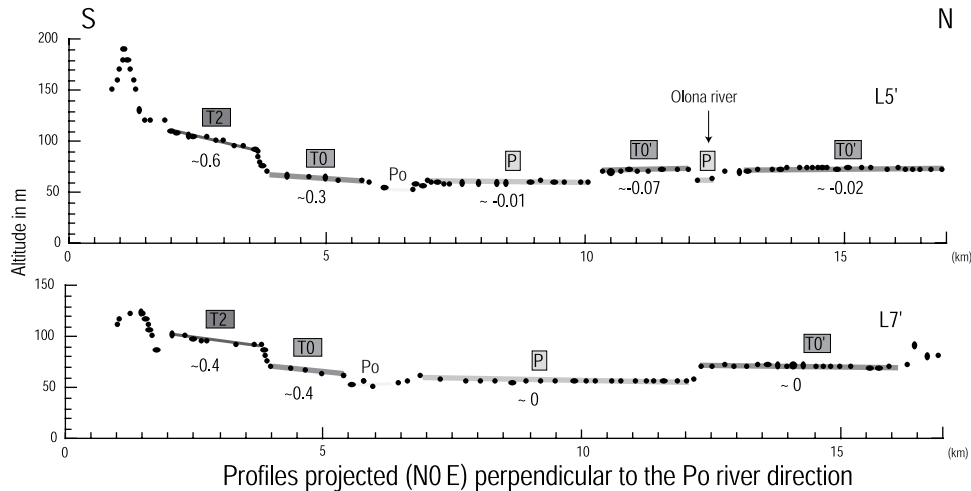
[26] Overall, the terrace surfaces T2 and T1 and the T0 bajada surface have gentle slopes, toward the north, ranging between  $0.56$  and  $0.31^\circ$ ,  $0.38$  and  $0.57^\circ$  and  $0.05$  and  $0.4^\circ$  respectively (profiles L4 to L10, Figure 8a). The slope of T0 is representative of the fluvial fan slopes that form this surface (Figure 4). The slopes of T1 and T2 are only slightly greater than that of T0. This is consistent with the inferences that there are no deposits from the Po river on the T0 bajada surface and that the upper terraces were also fans, initially deposited with slopes toward the north and then vertically offset by the Stradella fault. The half-almond shape of certain parts of T2 also supports this interpretation [e.g., Meyer *et al.*, 1998] (Figure 4). As shown on profiles L5' and L7' (Figure 8b), which are perpendicular to the Po river, the northward slope of T0 ( $0.3$ – $0.4^\circ$ ) south of the Po is 10 to 100 times greater than that of T'0 ( $0.07$  to  $0.005^\circ$ ), north of the Po.



**Figure 8a.** Topographic profiles, from 1/10,000-scale topographic maps [*Regione Lombardia*, 1982; *Regione Emilia-Romagna*, 1977], across Casteggio-Stradella scarp, projected perpendicular to Stradella scarp (N-S). Vertical exaggeration is 5. Note that Castel San Giovanni T2 terrace seems folded. Location of profiles are given on Figure 4b.

[27] Topographic profiles roughly parallel to the Po river, along the top and base of the Stradella scarp and along the top and the base of the T<sub>0</sub>/P riser show that the average down river slopes of the various surfaces toward the east are

4 times steeper south of the Po than north of it (Figure 9). The surface of T<sub>2</sub> is incised by the Apenninic streams and shows distinct steps in the E-W direction (Figures 4 and 9). The warping of T<sub>0</sub> due to fan emplacement at the foot of



**Figure 8b.** Long topographic profiles across Stradella scarp and Po river, projected on N-S direction, from 1/25,000-scale topographic maps [IGMI, 1960]. Vertical exaggeration is 20.

the Stradella scarp is also visible on those E-W profiles (Figure 9). The evidence derived from both transversal and longitudinal profiles thus supports the idea that T0 and T2 were emplaced by rivers flowing down from the Apennines whereas both T'0 and P were emplaced by the Po River. The E-W profiles south of the Po also show a slight increase of the Stradella cumulative scarp height toward the west (Figure 9).

[28] Quantitative analysis of the slope profiles thus strengthens our interpretation that the Stradella scarp is a tectonic thrust scarp rather than a river-cut riser. The profiles yield values of all the offsets recorded by the various surfaces across this thrust (Table 1). On average T3, T2, and T1 have been tectonically uplifted  $47 \pm 3$  m,  $19 \pm 3$  m, and  $5 \pm 1$  m, respectively, above T0 (Table 1). Since the T0 fan bajada surface is a contemporaneous surface that keeps being recovered by new deposits emplaced by the rivers, those offsets are minimum values of the vertical throw of those terraces [e.g., *Avouac et al.*, 1993; *Meyer et al.*, 1998; *Van der Woerd et al.*, 2001].

### 3.2. San Colombano Anticline

[29] As shown by transverse profiles (c1 to c6, Figure 10) the height of the San Colombano anticline (Figure 4) decreases toward the NW. Near the village of San Colombano, the anticlinal hill seems asymmetric (profiles c1 and c2, Figure 10), with slightly steeper slopes on the north than on the south side of the fold. Near Miradolo Terme, T'2 is rather flat (mean elevation 115 m), but profiles c4 and c5 show that it has been eroded and deeply incised by streams (Figure 10). There is no clear riser between the T'0 and T'1 terraces (profile c6); however, profile c6 suggests that T'1 has been warped 5–10 m above T'0. On both sides of the Lambro River, T'0 has almost the same elevation (70–75 m asl, profiles c1 to c6). However while north of the Lambro river T'0 is almost flat, the part of T'0 hugging the anticline, south of the Lambro river, gently slopes 0.7 to 0.5° toward the NE (Figure 10).

[30] The profile along the San Colombano anticline shows that the riser at its southeastern termination, between T'3 and T'0, is high (~70 m) and steep (15.1°) (Figure 10).

This suggests that the Lambro kept eroding this termination for a long period of time, and until recently. Between T'3 and T'2, a still steep, though degraded, riser remains while the transition between T'2 and T'1 is a much gentler slope (Figure 10). Profiles of T'0 made along the Lambro riverbed, south of San Angelo di Lodigiano (Pt'0), and of the Lambro riverbed itself (see location on Figure 6), are shown on Figure 10. The Lambro riverbed stands ~12 m below T'0. Both profiles are parallel and slope gently 0.03° toward the SE (Figure 10). Above T'0 by contrast, the average slope of the San Colombano anticline is toward the NW (0.8°), (Figure 10).

[31] The Quaternary terraces that cap the anticline are perched higher as they are older. The profiles appear to confirm the suggestion that the terraces have been emplaced then abandoned one after the other as the Lambro meridionale kept shifting its course toward the west. Such abandonment and the following uplift of these terraces may result from movement on the south dipping thrust ramp beneath the anticline. Unfortunately, the shapes of the terraces provide no further clue on the dip and depth of such a ramp. It is thus difficult to quantify this uplift.

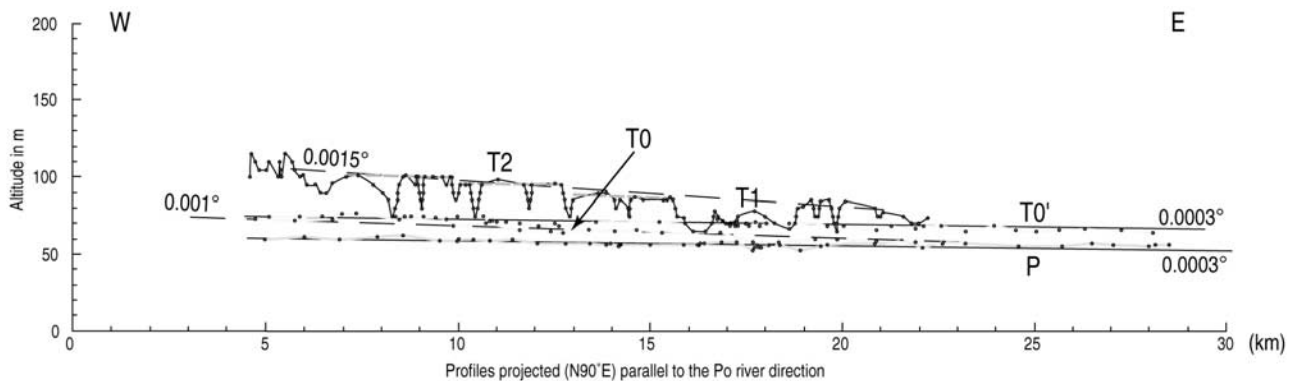
### 3.3. Montebello Scarp

[32] As shown by profiles perpendicular to it, the height of the Montebello scarp decreases toward the southwest (Figures 6c and 11). The northward slopes (0.6° on average) of those terraces are steeper than that of T0 (mean slope 0.14°), and roughly the same as that of the Coppa river south of the

**Table 1.** Mean Terrace Offset for Each Terrace Level Deduced From Topographic Profiles in Figures 8, 9, and 11

	Terrace Level	Mean Terrace Offset, m
Stradella	T3	$47 \pm 3$
	T2	$19 \pm 3$
	T1	$5 \pm 1$
Montebello	T3	~45
	T2	$25 \pm 5$
San Colombano	T3'	~72
	T2'	~42
	T1'	~7





**Figure 9.** Topographic profiles along top and base of Stradella scarp, south of Po river and along top and base of T0'/P riser, north of Po river, from 1/10,000-scale topographic maps (Carta Tecnica Regionale: *Regione Lombardia*, 1982; *Regione Emilia-Romagna*, 1977). Vertical exaggeration is 40. Note that slopes of terraces south of Po river are 10 times steeper than north of it. T2 terrace is composed of smaller ledges at different heights separated by incising valleys, some of them hanging. See color version of this figure at back of this issue.

scarp ( $0.65^\circ$ ) (Figure 11). The scarp itself is steep with a slope ranging between  $11^\circ$  and  $14^\circ$  (Figure 11). The profiles imply that the terraces have been uplifted above T0 with minimum offsets of 20, 30 and 45 m (Table 1).

[33] To summarize, whether between Broni and Sarmato, near Montebello, or at San Colombano terrace profiles provide quantitative support for ongoing tectonic uplift along this part of the Apenninic front as well as values of the vertical offsets recorded by the terrace surfaces across the Stradella thrust and the San Colombano anticline (Table 1).

#### 4. Shortening Mechanisms and Rates in the Pavia-Piacenza Region

##### 4.1. Uplift Rate Along the Stradella Thrust Between Sarmato and Montebello

[34] In order to estimate bounds on the uplift rate of the Stradella thrust the terraces or the scarp need to be dated. We are unaware of direct radiometric dating of alluvium or colluvium on either, but we try, below, to bracket, to a first order, the timing of vertical uplift of T1 and T2 above T0.

[35] On the basis of the characteristics of the soils covering the T2 and T3, near Stradella, Montebello and Bonasco, and on their degree of weathering, these terraces have been inferred to be of Middle Pleistocene age ( $\sim 120$  kyr B.P.) [Pellegrini and Vercesi, 1995; Cremaschi, 1987] (Table 2).

[36] The T2 terrace results from the coalescence of fan deposits emplaced by Apenninic tributaries of the Po. After deposition, at a time when aggradation was less strong, up throw on the thrust induced uplift of the hanging wall and T2 rose while younger deposits of the streams now incising T2 were deposited farther north on the footwall. Between Montecuto and Castel San Giovanni, the action of three adjacent, larger streams (Bardonezza, Carogna, and Carona) kept pace with movement on the Stradella thrust for a longer time leading to more modest uplift of a younger terrace. This scenario implies that the time between deposition of the terraces and incipient vertical offsets of their surfaces was not very long.

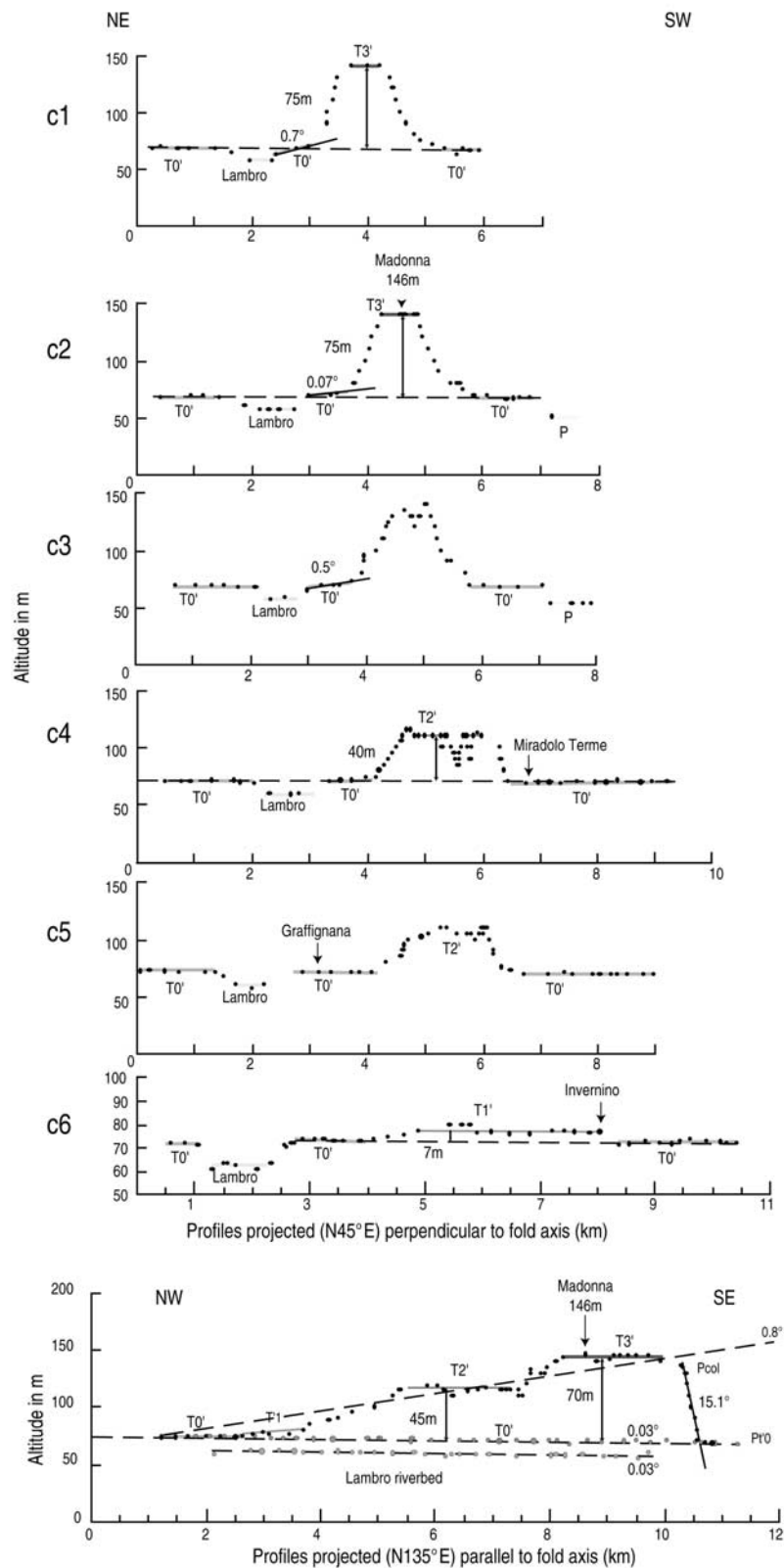
[37] Following the work of Avouac and Peltzer [1993] on cumulative fault scarp degradation by diffusion, we try to

infer the time dependent degradation of the Stradella scarp in order to estimate the age of this scarp and test the inference above. The cumulative scarp is assumed to result from a succession of fault rupture events separated by regular dormancy intervals. Each event produces an elementary scarplet with vertical offset  $\delta h$ , followed by gravitational free face collapse forming a slope at the angle of repose of colluvium, ( $\alpha$ , with  $\tan(\alpha) = 0.6$ ). During the dormancy intervals ( $\delta t$ ) the scarplets undergo degradation,  $\delta \tau$ :

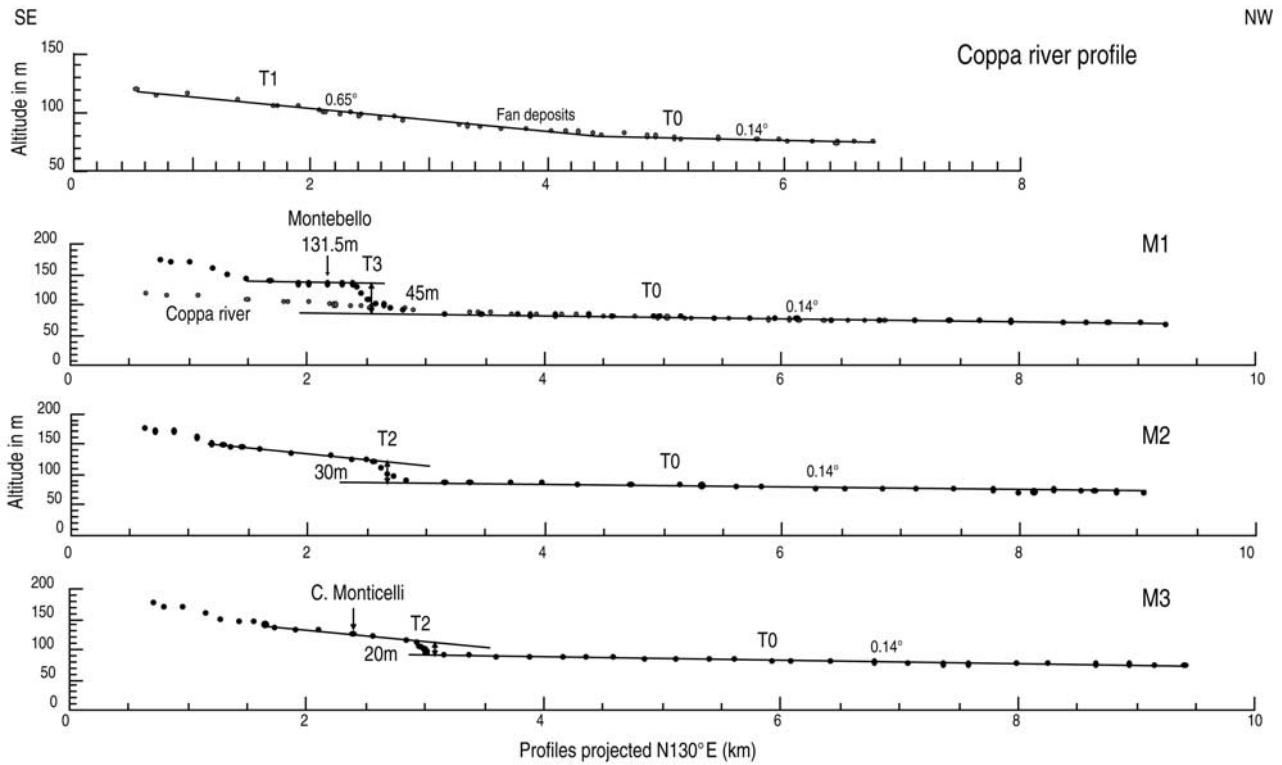
$$\delta \tau = K \delta t, \quad (1)$$

with  $K$  being the mass diffusivity constant of the scarp material under given climatic conditions.

[38] The mass diffusivity constant in the Pavia-Piacenza region is not known and the regional lack of dating of degraded geomorphic markers makes calibration difficult. Values of  $K$  obtained worldwide, however, range between 1 and  $16 \text{ m}^2/\text{kyr}$  [Hanks, 1998]. In western China, for weakly consolidated conglomerates and sands, in a semiarid area, Avouac *et al.* [1993] found a value of  $5.5 \pm 2 \text{ m}^2/\text{kyr}$  for scarps  $< 10$  m high. For higher scarps (10–50 m), in regions with high rainfall and denser vegetation cover, mass diffusivity constants ranging from 11 to  $16 \text{ m}^2/\text{kyr}$  have been estimated. This is the case for instance of Pleistocene fans in the San Gabriel valley (southern California), and of weakly consolidated alluvial debris in the Santa Cruz sea cliffs [Hanks *et al.*, 1984; Hanks, 1998]. As many authors point out, the relationship between  $K$  and factors such as lithology, Sun-facing azimuth, rainfall, vegetation cover, time and topographic amplitude is unclear [e.g., Hanks, 1998]. Nevertheless, it seems that  $K$  might be larger in more humid climatic environments, than in arid or semiarid areas. Moreover, human action on arable land, which would tend to smooth scarps further and faster might mimic a higher rate of degradation, hence would imply greater values of  $K$ . On the other hand, a vegetation cover might consolidate a scarp and thus reduce its degradation. The Stradella scarp appears to have formed in weakly consolidated alluvial deposits. It cuts arable lands south of the Po plain, in a temperate climate with a yearly rainfall of about 500–800 mm. A mass



**Figure 10.** (top) Series of topographic profiles across San Colombano anticline (c1 to c6) all projected perpendicular to fold axis (see Figure 4), (N45°E). (bottom) Topographic profile along San Colombano anticline, T0' terrace, and Lambro river bed projected parallel to fold axis (N135°W). Locations of profiles are given on Figure 4. Vertical exaggeration is 20, except for profile c6, where it is 40.

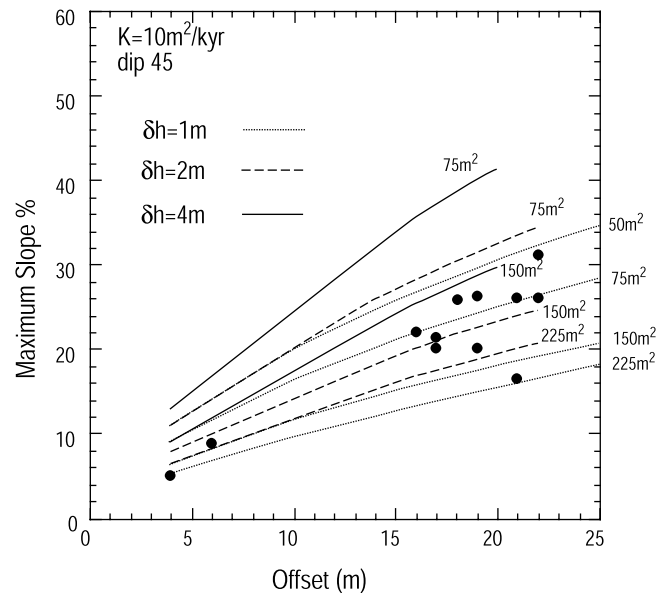


**Figure 11.** Topographic profiles across Montebello scarp projected perpendicular to average direction of scarp (N130°E). Vertical exaggeration is 10. See locations on Figure 6c.

diffusivity constant of  $10 \text{ m}^2/\text{kyr}$ , or greater because of human action is thus plausible as found from modeling of the Bree fault scarp combined with  $^{14}\text{C}$  dating from trenches in the lower Rhine Graben [Meghraoui *et al.*, 2000]. We also assume that the dip of the thrust fault is  $45^\circ$ .

[39] To find an order of magnitude of the degradation ( $\tau$ ) of the Stradella scarp, we plot the reduced scarp slope as a function of scarp offset, and compare the data with synthetic curves obtained by computing a series of synthetic scarps generated with the incremental model of Avouac and Peltzer [1993] (Figure 12a). The model curves closest to the data correspond to ratios of  $\delta h/\tau$  ranging between  $26$  and  $13 \times 10^{-3} \text{ m}^{-1}$ . Synthetic profiles best adjusted with those ratios are presented in Figures 12b and 12c for profiles p4, p8, and p10. Using equation (1), the uplift,  $u$ , during  $10^3$  years is  $u = K\delta h/\tau$ . Thus the ratios deduced imply an uplift rate ranging between  $0.3$  and  $0.1 \text{ mm/yr}$ . Those results suggest that the age of the T2/T0 offset is between  $200$  kyr and  $70$  kyr, while the age of the T1/T0 offset is between  $50$  kyr and  $13$  kyr (Table 2).

[40] In the Po river floodplain, at four sites between Milano and Pavia,  $^{14}\text{C}$  dating of a peat horizon located in fluvial deposits at depth ranging between  $4 \text{ m}$  and  $20 \text{ m}$

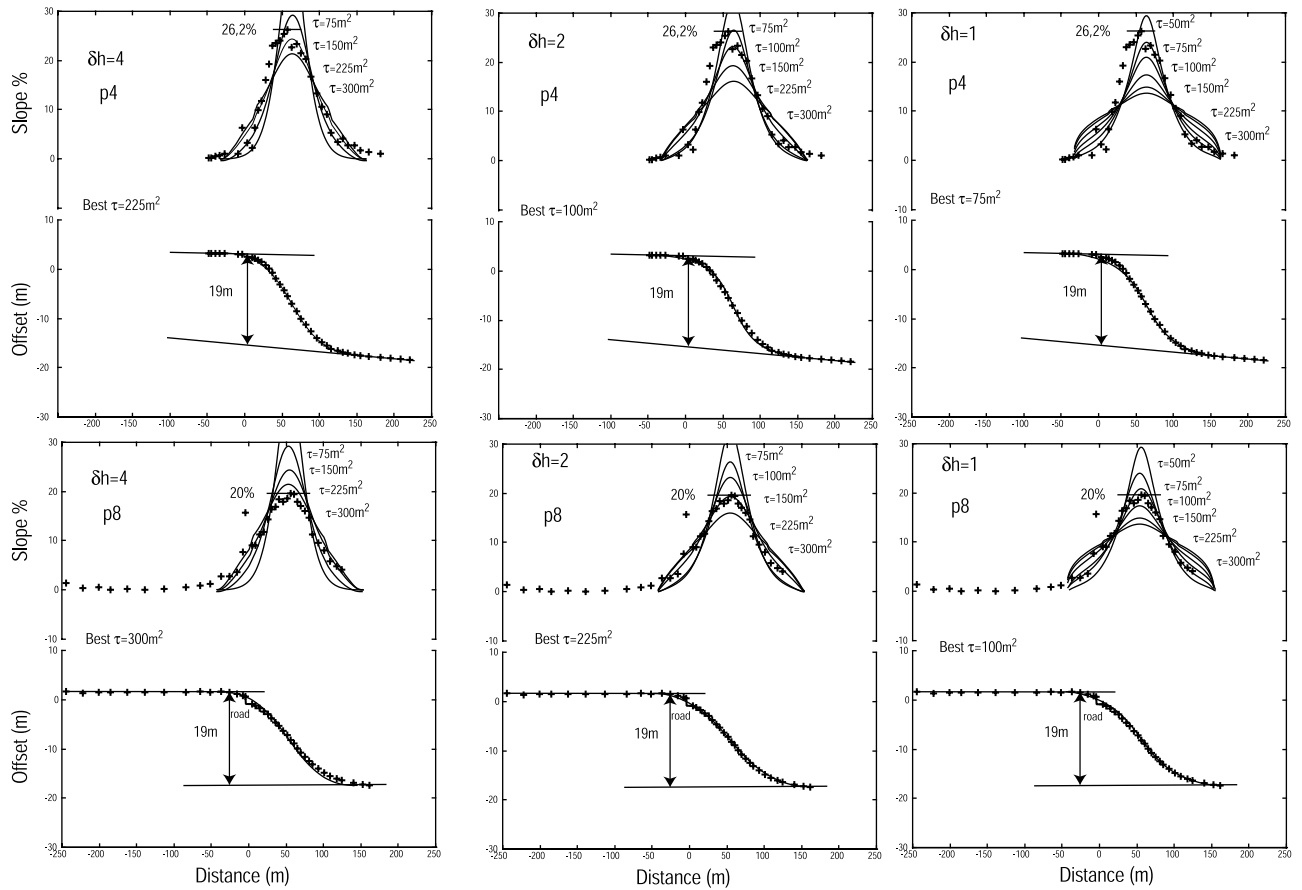


**Figure 12a.** Plot of reduced scarp slope ( $\tan \alpha - \tan \beta$ ), with  $\alpha$  maximum slope scarp and  $\beta$  far field slope, here  $\beta = 0$ ) as a function of scarp height measured on 12 total stations profiles. Curves have been computed from a series of synthetic scarps generated with fault scarp incremental model of Avouac and Peltzer [1993], with fault dip of  $45^\circ$ , different degradation coefficient ( $\tau$ ) and slip ( $\delta h$ ) per event.

**Table 2.** Summary of Inferred Ages of the Terraces

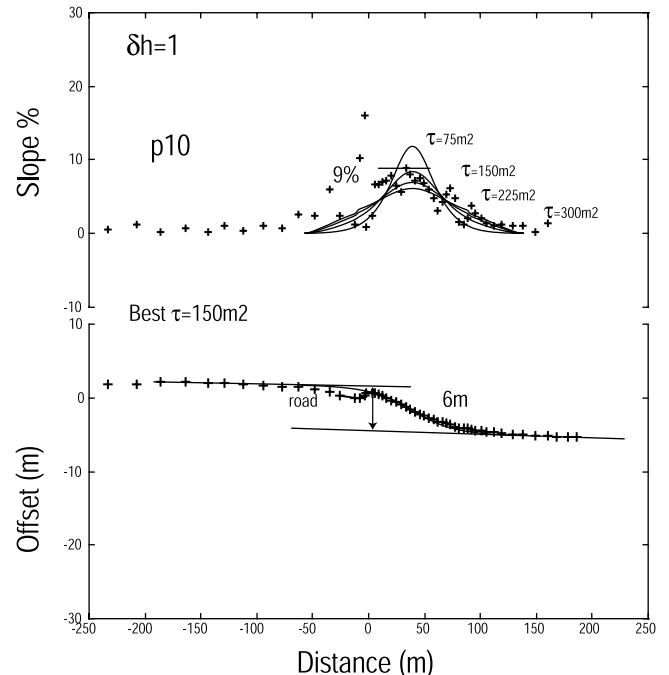
Sources of the Ages	Ages of the Terraces
Tropeano and Olive [1989, 1993] $^{14}\text{C}$ ages	18–36 kyr
Ages deduced from scarp degradation	T2/T0 200–70 kyr T1/T0 50–13 kyr
Inferred ages	T2/T0 $\approx 70$ kyr B.P. T1/T0 $\approx 15$ kyr B.P.





**Figure 12b.** Examples of synthetic profiles (lines) and measurements (crosses) (p4, p8) for slip per event over degradation coefficient ratio that best fit the data (black dots on Figure 12a).

have yielded three ages between 36 and 30 kyr B.P. near the Ticino confluence, and one age at 18 kyr B.P. near the Sesia confluence [Tropeano and Olive, 1989, 1993, and references therein] (Table 2). The sites are all located north of the Po River and <5 km from the riverbeds. On the basis of these results, the authors infer a major period of aggradation in this region between 36 and 18 kyr B.P. Such ages may also indicate two aggradational events, the first one between 36 and 30 kyr B.P. and the second one around 18 kyr B.P. This alternative interpretation would be more in keeping with the chronology of glacially controlled climate change, which appears to govern river aggradation and incision [Fuller et al., 1998; Karner and Renne, 1998; Karner and Marra, 1998]. Taking into account the chronological uncertainties related to regional variation of climatic changes, the first aggradational event might correspond to the sea level highstand before the climax of the last glacial age, isotope stage 3.1, around 30 kyr B.P. [Chappell, 1983; Chappell and Shackleton, 1986], while the second would correspond to the beginning of the last glacial retreat, after the LGM at ~20 kyr B.P. [e.g., Fairbanks, 1989]. During any of these two events a scarp such as that between T1 and T0 would have been smoothed and would have probably disappeared. Moreover, considering the rather small height of the T1/T0 scarp it would probably have disappeared during the last glacial retreat, which caused a particularly powerful aggradational episode. Therefore the ~5 m offset between T1 and



**Figure 12c.** Same as Figure 12b except for p10.

T0 may be younger than 18 kyr B.P. and thus closer to the lowest of the age brackets we deduced from degradation by diffusion (i.e., 13 kyr).

[41] If the offset of T1 above T0 (mean value  $\sim 5 \pm 1$  m) started to be recorded around 15 kyr B.P. and that between T2 and T0 (mean value  $19 \pm 3$  m) started to be recorded around 70 kyr B.P., the minimum uplift rate on the Stradella thrust would be 0.3 mm/yr. Such a value is plausible for thrust faults in general [e.g., *Avouac et al.*, 1993; *Meghraoui and Doumaz*, 1996; *Meyer et al.*, 1998; *Van der Woerd et al.*, 2001]. The sedimentation rate in the Po plain is high,  $\sim 2$  mm/yr [*Tropeano and Olive*, 1993; *Barberi and Scandone*, 1983]. At places, such as north of Stradella, this may result in part from subsidence of the Po plain flexural basin due to footwall sinking induced by movement on the Apenninic frontal thrust. The throw rate on the Stradella thrust is thus unlikely to exceed 2.5 mm/yr.

[42] This scenario is far from unique and rests on unverified assumptions that require testing by trenching and direct radiometric dating, but it accounts for the young morphological aspect of the scarp, is consistent with a plausible mass diffusivity constant ( $K \approx 10 \text{ m}^2/\text{kyr}$ ) and plausible degradation coefficients ( $\tau$ : 75–300 m<sup>2</sup>), with the <sup>14</sup>C ages measured in the region and with the fact that aggradation and degradation are governed by climate change.

#### 4.2. Deep Geometry of Frontal Thrusts in the Northwestern Apennines and Amounts of Finite Shortening

[43] On the basis of seismic sections [*Pieri and Groppi*, 1981] and geological maps [*Boni*, 1967], as well as field observations, two large-scale, interpretative, deep sections across the northwestern Apenninic front may be proposed (Figure 2b). The first one (AB) is located near Piacenza, and the second one (CD), near Bologna (Figures 1 and 2a).

[44] The map of the isobaths of the base of the Pliocene [*Barberi and Scandone*, 1983] (Figures 1 and 3) suggests that the Stradella thrust may correspond along the strike to the subsurface thrust visible on the seismic section, south of Fiorenzuola d'Arda (Figure 2b, AB). The ramp responsible for the growth of the San Colombano anticline probably corresponds to that visible south of Cremona [*Pieri and Groppi*, 1981] on the seismic section. It appears to be locally shallower than the eastward continuation of the Stradella thrust.

[45] South of the Stradella fault, Cretaceous limestones overthrust Mio-Pliocene marls and conglomerates. However, there is little geomorphic evidence of Quaternary movement on this latter thrust. Thus present-day slip is probably transferred to the Stradella ramp by means of a decollement that probably roots into a deeper thrust ramp beneath the range [e.g., *Meyer et al.*, 1998] (Figure 2b).

[46] By comparison with other environments of active thrusting [*Meyer et al.*, 1998], it seems unlikely that the growth of the San Colombano anticline and the uplift along the Stradella thrust, which lie only 15 km from one another, reflect active thrusting on two independent faults. We suspect them to be connected by a shallow, flat decollement. That both terminate against the Pavia lateral ramp supports this inference. It is less certain that the Sorresina-Lodi thrust is connected to the San Colombano ramp by a decollement because its link with the Pavia lateral ramp is not clear. For

section CD to the east, shallow south dipping ramps and flats probably also connect the Bologna and Ferrara thrusts even though they are 60 km apart. We have little constraint on the depths of the flats they are probably guided by less competent interfaces, for instance near the base of the Mesozoic scaglia cinerea [e.g., *Castellerin et al.*, 1985].

[47] On both sections, one can estimate amounts of recent shortening by retrodeforming the base of the late Pliocene. For section AB, near Piacenza, the minimum shortening value obtained is  $\sim 7$  km, while for section CD, near Bologna, it is  $\sim 12$  km. The shortening across the Apenninic front near Bologna is almost twice that estimated near Piacenza, about 150 km to the east. Such values are in agreement with the  $\sim 5$  km and  $\sim 10$  km of shortening estimated for the base of the Pliocene (5 Myr) across the western Po plain near Piacenza and Ferrara respectively, by *Castellerin et al.* [1985] from interpreted seismic profiles [*Pieri and Groppi*, 1981]. This implies that the shortening essentially postdates the base of the late Pliocene. This would correspond to average shortening rates of at most 2 to 4 mm/yr in the last 3 Myr. From retrodeforming seismic sections, there appears to be an E-W gradient of cumulative shortening along the northern Apennines, with an increase by a factor of almost 2 over 150 km from west to east. The northern Apennines thus appear to have rotated counterclockwise by about  $2^\circ$  relative to the Po plain during the Quaternary.

#### 4.3. Constraints on the Shortening Direction

[48] The recent tectonics of the northwestern Apennines between Pavia and Piacenza are summarized in Figure 3. There are two main WNW-ESE trending thrust faults composed of right stepping, N90–120°E striking, south dipping segments, the Stradella-Fiorenzuola and San Colombano-Cremona thrust ramps. The Pavia lateral ramp, a N30°E striking oblique thrust, that truncates the western prong of the northern Apennines, extends from south of Voghera to San Angelo Lodigiano. The two WNW-ESE thrusts splay from that lateral ramp in sinistral horsetail fashion (Figure 3). In addition, there appears to be more recent uplift at the surface on faults striking WNW-ESE than on faults striking NNE-SSW. This and the horsetail geometry suggest that mostly left-lateral strike-slip motion presently occurs on the Pavia lateral ramp, as inferred by other authors [*Patacca and Scandone*, 1989]. A direction of shortening probably between N-S and N15°W accounts best for predominant thrusting on the E-W trending, Stradella-Sarmato segment and Redavalle-Casteggio segments (Figure 3 and inset). It is compatible with a sinistral slip component on the Pavia ramp and N20°E trending Broni segment, and with the right-stepping geometry of the E-W thrust faults (Figure 3 and inset).

[49] The fault plane solutions of the two earthquakes (9 November 1983,  $M_s = 5.1$  and 15 October 1996,  $M_f = 5.2$  [*Selvaggi et al.*, 2001]) that occurred near Reggio nell'Emilia on or near a lateral ramp comparable to that at Pavia reflect similar oblique sinistral thrust motion (Figure 1b). Both events are consistent with roughly NNW shortening [*Selvaggi et al.*, 2001].

[50] This roughly N-S direction of shortening is oblique to the average NW-SE direction of the front of the northern Apennines. This may reflect rotation of this boundary of the

Adriatic microplate, as inferred for instance by *Patacca and Scandone* [1989].

[51] The arcuate shape of the Pavia-Cremona thrust has been inferred to result from the existence of a more rigid footwall zone, associated with a positive aeromagnetic anomaly in the basement west of the Pavia ramp [e.g., *Castellerin et al.*, 1985, and references therein]. A similar situation exists in the western Salt range (Pakistan), where the 120-km-long Kalabagh fault zone, a lateral ramp with transpressive, right slip [*Baker et al.*, 1988; *McDougall and Hasan Khan*, 1990] follows a positive, footwall Bouguer gravity anomaly interpreted as a basement high [*McDougall and Hasan Khan*, 1990].

[52] In an experimental study tailored to study the development of transfer zones in a thrust wedge, *Calassou et al.* [1993] investigated the relative importance of mechanical and/or geometrical footwall and backstop irregularities and of boundary conditions. They obtain oblique slip on a lateral ramp and pure thrusting on frontal thrusts by introducing an angle of 35° in the backstop.

[53] In any event, the kinematic compatibility of motions on Quaternary faults in the Pavia-Piacenza region implies an approximately N-S direction of shortening, oblique, by 30–40°, to the overall direction of the Apennine range. This obliquity may have been induced by rotation of the Adriatic plate, and together with inherited structural heterogeneities in the flexed, under thrust basement of the Po plain may have triggered the formation of the Pavia-Cremona, and Reggio-Ferrara arcs (Figure 1). The direction of shortening inferred in this study is rotated about 45° CW relative to that in the Veneto-Friuli region [*Benedetti et al.*, 2000]. This is most simply interpreted to reflect the fact that the northern and southern boundaries of the Po plain lie along two distinct boundaries of the Adriatic microplate with adjacent plates.

## 5. Conclusion and Seismic Hazard Related to the Active Apenninic Thrusts South of Milano

[54] In this study we document the existence of an emergent thrust ramp a few kilometers north of the north-western Apennines range front between Pavia and Piacenza. The corresponding thrust, the Stradella fault, appears to be active. The emergence of this thrust fault has induced uplift of late Pleistocene alluvium deposited by north flowing, Apenninic tributaries of the Po river at a rate of perhaps 0.3 mm/yr. This uplift results from roughly north directed shortening at a comparable rate. The value of the rates rests critically on inferences about the ages of the terraces and of the cumulative scarp, which remain to be confirmed by radiometric dating, given the large uncertainties in the data presently available.

[55] The Stradella fault is located south of blind frontal thrusts, which do not reach the surface. One of these thrusts (San Colombano) is associated with one geomorphologically young, growing ramp anticline and with uplifted terrace levels. We thus infer that both the San Colombano and Lodi thrusts are active but remain buried because their slip rate is not enough to overcome the fast sedimentation rates related to the large Alpine tributaries of the Po. Correspondingly, the Stradella fault would emerge because sedimentary discharge by the Apenninic tributaries south of the Po, which have smaller catchments, is less strong.

[56] Active and Quaternary frontal and foreland thrusts at the foot of most other growing mountain ranges in the world are usually the source of destructive earthquakes [e.g., *Avouac et al.*, 1993; *Meyer et al.*, 1998; *Gaudemer et al.*, 1995; *Yeats and Lillie*, 1991]. Thus we infer the Stradella, San Colombano, and Lodi thrusts to be potential sources of such earthquakes. The relatively low level of historical and instrumental seismicity in the Pavia-Piacenza region (Figure 1b) [*Baratta*, 1901], suggests either long recurrence times or that a significant part of the slip is released aseismically. Without a proper paleoseismological study, it is difficult to determine whether the Stradella fault has produced large earthquakes in the past. Several historical shocks, however, primarily and most strongly felt in Voghera, Lodi, Cremona, and most generally Lombardia (1276 A.D. Cremona I  $\approx$  7, 1642 A.D. Bergamo I  $\approx$  7, 1802 A.D. Lodi I  $\approx$  8, 1828 A.D. Voghera I  $\approx$  9 [*Baratta*, 1901; *Boschi et al.*, 1995; *Monachesi and Stucchi*, 1997]) suggest slip on local faults. It is plausible that the sources of such earthquakes might have been, alternatively, either the Stradella-Fiorenzuola, San Colombano-Cremona, or Lodi-Soresina active thrusts.

[57] Of the most recent events listed in the historical catalogues [*Baratta*, 1901; *Boschi et al.*, 1995; *Monachesi and Stucchi*, 1997], the 1828 A.D. Vogherese-Bobbiese earthquake was the strongest (I = IX, Figure 3), particularly destructive in the mountain villages of Cecima and Bagnaria where many houses fell apart. In the villages near Voghera, the damage reported was less important but many houses were also destroyed in Casteggio and Montebello. The location of the isoseismal contours of this event suggests that it might be due to slip on the Casteggio segment of the Pavia lateral ramp (Figure 3). The 1802 A.D. event north-west of Soresina could have activated the Soresina-Lodi thrusts.

[58] Even though it is beyond the scope of this paper to assess the exact size of the earthquakes that the Stradella fault might have produced and to search back into medieval times or earlier for historical candidates, the occurrence of both historical and recent seismic events of magnitude  $\sim$ 5 along the northern Apennines [*Selvaggi et al.*, 2002] suggests that closer attention should be paid to the seismic potential of the active thrusts and lateral ramp that bound the range near Pavia and Piacenza.

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## References

- Anderson, H., and J. A. Jackson, Active tectonics of the Adriatic region, *Geophys. J. R. Astron. Soc.*, 91, 937–983, 1987.
- Anfossi, G., and G. Cantaluppi, Rivenimento di un cranio di rinoceronte nelle alluvioni quaternarie pavesi, *Atti. Ticubesu Sci. Terra*, 31, 463–468, 1988.
- Armijo, R., B. Meyer, G. C. P. King, A. Rigo, and D. Papanastassiou, Quaternary evolution of the Corinth Rift and its implications for the late Cenozoic evolution of the Aegean, *Geophys. J. Int.*, 126, 1, 11–53, 1996.
- Avouac, J. P., and G. Peltzer, Active tectonics in Southern Xinjiang, China: Analysis of terrace riser and normal fault scarp degradation along the Hotan-Qira fault system, *J. Geophys. Res.*, 98, 21,773–21,807, 1993.
- Avouac, J. P., P. Tapponnier, M. Bai, H. You, and G. Wang, Active thrusting and folding along the northern Tien Shan, and late Cenozoic rotation of



- the Tarim relative to Dzungaria and Kazakhstan, *J. Geophys. Res.*, **98**, 6755–6804, 1993.
- Baker, D. M., R. J. Lillie, R. S. Yeats, G. D. Johnson, M. Yousuf, and A. S. Zamin, Development of the Himalayan frontal thrust zone: Salt Range, Pakistan, *Geology*, **16**, 3–7, 1988.
- Baratta, M., *I terremoti d'Italia*, Arnaldo Forni, Bologna, Italy, 1901.
- Barberi, F., and P. Scandone (Eds.), Structural model of Italy, scale 1/500,000, Progetto Finalizzato Geodin., Cons. Naz. delle Ric., Rome, 1983.
- Benedetti, L., P. Tapponnier, G. King, B. Meyer, and I. Manighetti, Growth folding and active thrusting in the Montello region, Veneto, northern Italy, *J. Geophys. Res.*, **105**, 739–766, 2000.
- Boccaletti, M., M. Coli, C. Eva, G. Ferrari, G. Giglia, A. Lazzarotto, F. Merlanti, R. Nicoloch, G. Papani, and D. Postpischl, Considerations on the seismotectonics of the northern Apennines, *Tectonophysics*, **117**, 7–38, 1985.
- Boni, A., Note illustrative della carta geologica d'Italia, foglio 59, Serv. Geol. d'Italia, Pavia, Italy, 1967.
- Boschi, E., G. Ferrari, P. Gasperini, E. Guidoboni, G. Smriglio, and G. Valentini, Catalogo dei forti terremoti in Italia dal 461 a. C. al 1980, Ist. Naz. di Geofis., Rome, Italy, 1995.
- Braga, G., and S. Gervasoni, Evolution of the Po river: An example of the application of historic maps, in *Historical Change of Large Alluvial Rivers: Western Europe*, edited by G. E. Petts, H. Moller, and A. L. Roux, pp. 113–126, John Wiley, New York, 1989.
- Calassou, S., C. Larroque, and J. Malavieille, Transfer zone of deformation in thrust wedges: An experimental study, *Tectonophysics*, **221**, 325–344, 1993.
- Castellerin, A., and G. B. Vai, South alpine versus Po plain apenninic arcs, in *The Origin of Arcs*, edited by F. C. Wezel, pp. 253–280, Elsevier Sci., New York, 1986.
- Castellerin, A., C. Eva, G. Giglia, and G. B. Vai, Analisi strutturale del Fronte Appenninico Padano, *G. Geol.*, **47**, 47–75, 1985.
- Chappell, J., A revised sea level record for the last 300 000 years from Papua New Guinea, *Search*, **14**(3–4), 99–101, 1983.
- Chappell, J., and N. J. Shackleton, Oxygen isotopes and sea-level, *Nature*, **324**, 137–140, 1986.
- Cremaschi, M., *Paleosols and Ventusols in the Central Po Plain (Northern Italy)*, A Study in Quaternary Geology and Soil Development, 306 pp., Unicopli, Milano, Italy, 1987.
- DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Current plate motions, *Geophys. J. Int.*, **101**, 425–478, 1990.
- Fairbanks, R. G., A 17 000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation, *Nature*, **342**, 637–642, 1989.
- Frepoli, A., and A. Amato, Contemporaneous extension and compression in the northern Apennines from earthquakes fault-plane solutions, *Geophys. J. Int.*, **129**, 368–388, 1997.
- Fuller, I. C., M. G. Macklin, J. Lewin, D. G. Passmore, and A. G. Wintie, River response to high-frequency climate oscillations in southern Europe over past 200 ky., *Geology*, **26**, 275–278, 1998.
- Gasparini, C., G. Iannaccone, and R. Scarpa, Fault-plane solutions and seismicity of the Italian Peninsula, *Tectonophysics*, **117**, 59–78, 1985.
- Gaudemer, Y., P. Tapponnier, B. Meyer, G. Peltzer, G. Shunmin, C. Zhitai, D. Huang, and I. Cifuentes, Partitioning of crustal slip between linked, active faults in the eastern qilian shan, and evidence for a major seismic gap, the 'Tianzhu gap', on the western haiyuan fault, Gansu (China), *Geophys. J. Int.*, **120**, 3, 599–645, 1995.
- Hanks, T. C., The age of scarplike landforms from diffusion-equation analysis, in *Dating and Earthquakes: Review of Quaternary Geochronology and Its Application to Paleoseismology*, edited by J. M. Sowers, J. S. Noller, and W. R. Lettis, Rep. NUREG/CR-5562, 2–497 to 2–535, U.S. Nucl. Regul. Comm., Washington, D. C., 1998.
- Hanks, T. C., R. C. Bucknam, K. R. Lajoie, and R. E. Wallace, Modification of wave-cut and faulting-controlled landforms, *J. Geophys. Res.*, **89**, 5771–5790, 1984.
- Istituto Geografico Militare Italiano (IGMI), Carta topografica d'Italia alla scala di 1/25,000, Map 59–60, Firenze, Italy, 1960.
- Istituto Geografico Militare Italiano (IGMI), Carta topografica d'Italia alla scala di 1/100,000, Map 56–60, Firenze, Italy, 1961.
- Karner, D. B., and F. Marra, Correlation of fluvio-deltaic aggradational sections with glacial climate history: A revision of the Pleistocene stratigraphy of Rome, *Geol. Soc. Am. Bull.*, **110**, 748–758, 1998.
- Karner, D. B., and P. R. Renne,  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology of roman volcanic province in the Tiber river valley: Age calibration of middle Pleistocene sea-level changes, *Geol. Soc. Am. Bull.*, **110**, 740–747, 1998.
- McDougall, J. W., and S. Hasan Khan, Strike-slip faulting in a foreland fold-thrust belt: The Kalabagh fault and western salt range, Pakistan, *Tectonics*, **9**(5), 1061–1075, 1990.
- McKenzie, D. P., Active tectonics of the Mediterranean region, *Geophys. J. R. Astron. Soc.*, **30**, 109–185, 1972.
- Meghraoui, M., and F. Doumaz, Earthquake-induced folding and paleoseismicity of the El Asnam, Algeria, fault-related fold, *J. Geophys. Res.*, **101**, 17,617–17,644, 1996.
- Meghraoui, M., T. Camelbeeck, K. Vanneste, M. Blondeel, and D. Jongmans, Active faulting and paleoseismology along the Bree fault, lower Rhine graben, Belgium, *J. Geophys. Res.*, **105**, 13,809–13,841, 2000.
- Meyer, B., P. Tapponnier, L. Bourjot, F. Metivier, Y. Gaudemer, G. Peltzer, G. Shunmin, and C. Zhitai, Crustal thickening in Gansu-Qinghai, lithospheric mantle subduction, and oblique, strike-slip controlled growth of the Tibet plateau, *Geophys. J. Int.*, **135**, 1–47, 1998.
- Monachesi, G., and M. Stucchi, DOM4. 1, un database di osservazioni macrosismiche di terremoti di area italiana al di sopra della soglia di danno, Gruppo Naz. Per la Difesa dai Terremoti, Milan, <http://emidius.mi.ingv.it/DOM/>, 1997.
- Patacca, E., and P. Scandone, Post-Tortonian mountain building in the Apennines: The role of the passive sinking of a relic lithospheric slab, in *The Lithosphere in Italy*, pp. 157–176, Cons. Naz. Delle Ric., Rome, 1989.
- Pellegrini, G. B., and P. L. Vercesi, Considerazioni morfotettoniche sulla zona a sud del Po tra Voghera (PV) e Sarmato (PC), *Atti Tic. Sci. Terra*, **38**, 95–118, 1995.
- Pieri, M., and G. Groppi, Subsurface geological structure of the Po plain, Italy, *Pubbl. 414*, Cons. Naz. Delle Ric., Agip, Rome, 1981.
- Regione Emilia-Romagna, Carta tecnica regionale alla scala di 1/10,000, Bologna, Italy, 1977.
- Regione Lombardia, Carta tecnica regionale alla scala 1/10,000, Milano, Italy, 1982.
- Reilinger, R. E., S. C. McClusky, M. B. Oral, R. W. King, M. N. Toksoz, A. A. Barka, I. Kinik, O. Lenk, and I. Sanli, Global positioning system measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone, *J. Geophys. Res.*, **102**, 9983–9999, 1997.
- Sacchi Vialli, G., and M. L. Pizzochero, Gli elefanti fossili delle alluvioni quaternarie pavesi, *Atti. Ist. Geol. Univ. Pavia*, **8**, 3, 1958.
- Selvaggi, G., et al., The  $M_w = 5.4$  Reggio Emilia 1996 earthquake: Active compressional tectonics in the Po Plain, Italy, *Geophys. J. Int.*, **144**, 1–13, 2001.
- Servizio Geologico d'Italia, Carta geologica d'Italia alla scala 1/500,000, Firenze, Italy, 1983.
- Tapponnier, P., Evolution tectonique du système alpin en Méditerranée: Poinçonnement et écrasement rigide-plastique, *Bull. Soc. Geol. Fr.*, **XIX**(3), 437–460, 1977.
- Taramelli, T., Descrizione geologica della provincia di Pavia, 2nd ed., 50 pp., Ist. Geogr. de Agostini, Novara, Italy, 1882.
- Tropeano, D., and P. Olive, Vitesse de la sédimentation holocène dans la plaine occidentale du Pô (Italie), *Bull. Assoc. Fr. Etude Quat.*, **2**, 65–71, 1989.
- Tropeano, D., and P. Olive, Eventi geomorfologici nelle alpi italiane e nella pianura occidentale del Po: Inquadramento cronologico in base a radiodattazioni  $^{14}\text{C}$ , *Quaternario*, **6**(2), 189–204, 1993.
- Van der Woerd, J., X. Xu, H. Li, P. Tapponnier, B. Meyer, F. J. Ryerson, A.-S. Meriaux, and Z. Xu, Rapid active thrusting along the northwestern range front of the Tanghe Nan Shan (western Gansu, China), *J. Geophys. Res.*, **106**, 30,475–30,504, 2001.
- Vercesi, P. L., and G. Scagni, Osservazioni sui depositi conglomeratici dello sperone collinare di Stradella, *Rend. Soc. Geol. It.*, **7**, 23–26, 1984.
- Westaway, R., The Tripoli, Libya earthquake of September 4, 1974: Implications for the active tectonics of the central mediterranean, *Tectonics*, **9**, 231–248, 1990.
- Yeats, R. S., and R. J. Lillie, Contemporary tectonics of the Himalayan frontal fault system: Folds, blind thrusts and the 1905 Kangra earthquake, *J. Struct. Geol.*, **13**, 215–225, 1991.

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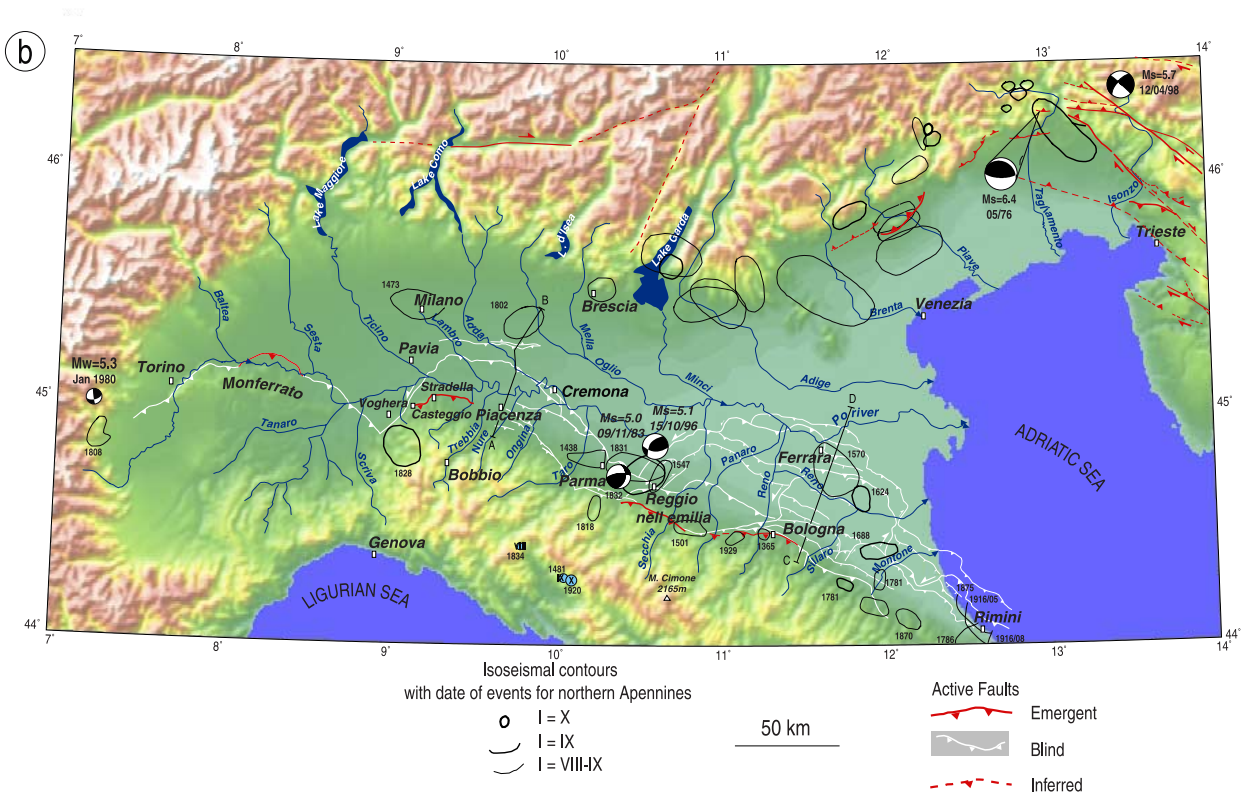
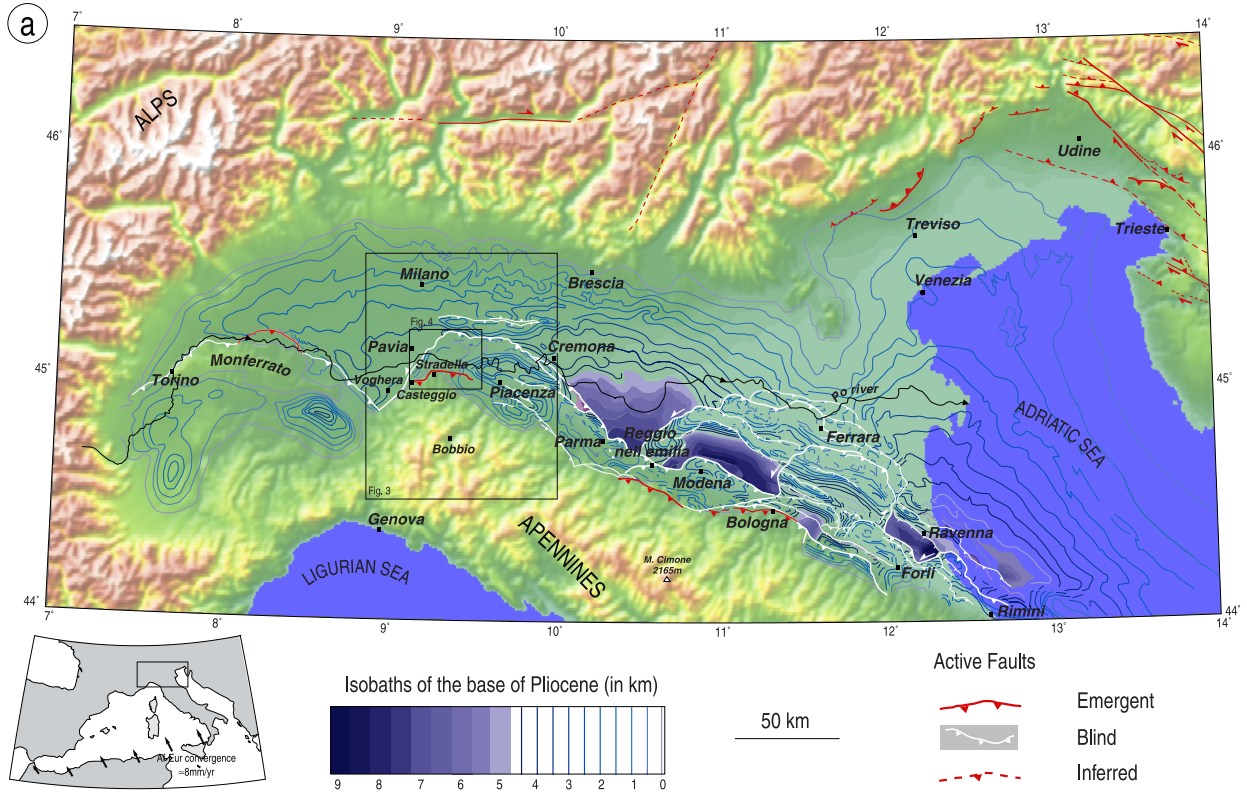
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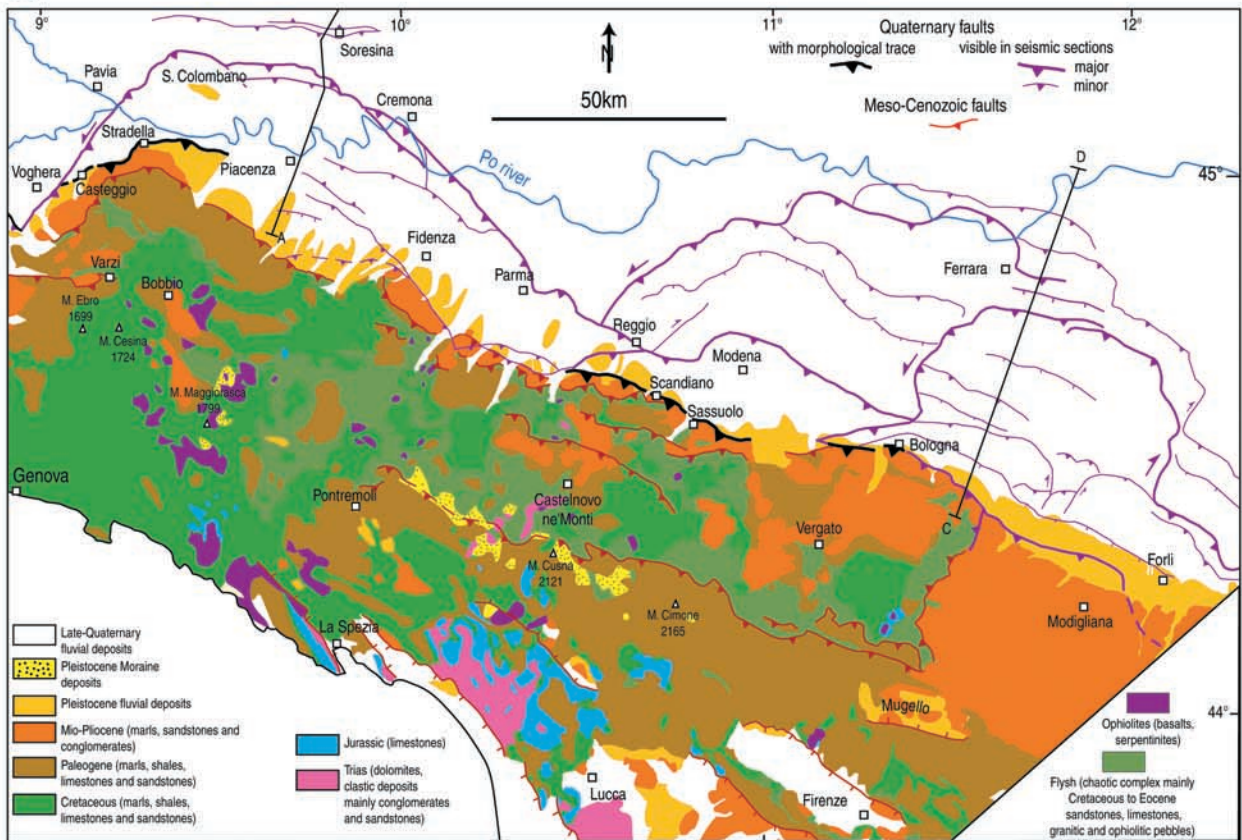


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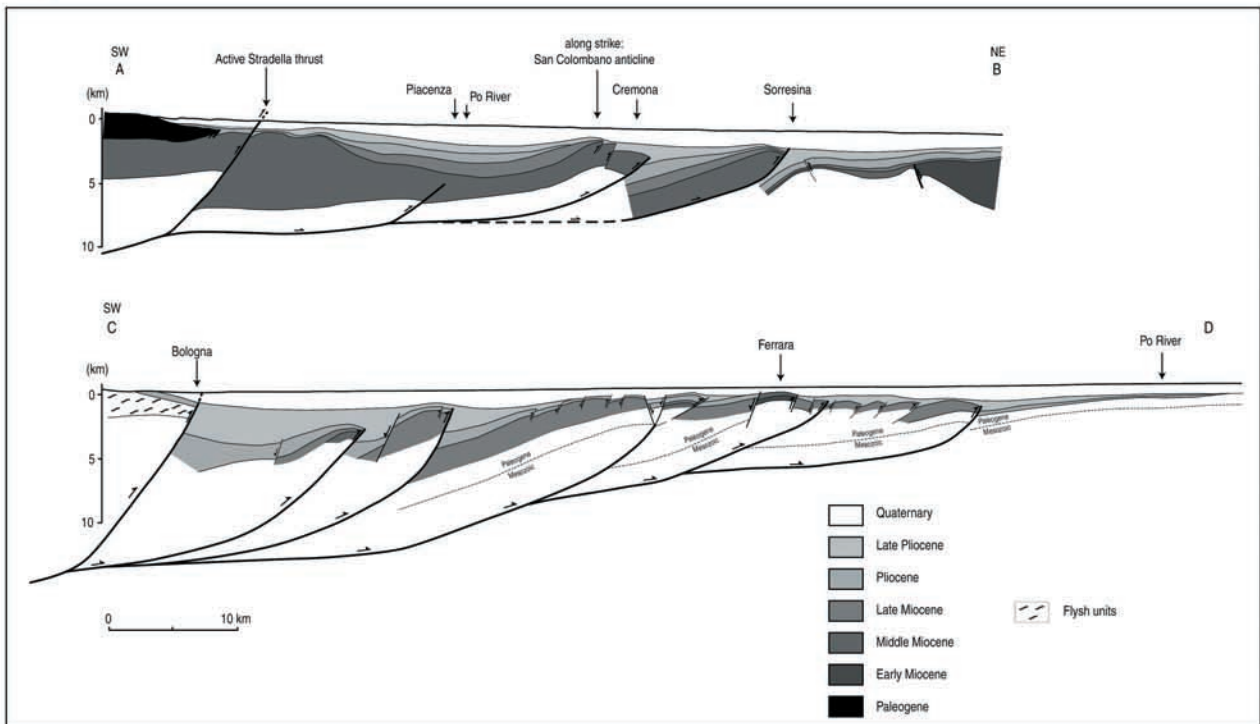
**Figure 1.** (opposite) (a) Tectonic map of northern Italy showing emergent Quaternary faults (red) and buried Plio-Quaternary faults (white) with isobaths of base of Pliocene [Barberi and Scandone, 1983]. Emergent faults are mapped from fieldwork, SPOT, and Landsat satellite image interpretations. Inset shows Euler vector of Africa/Europe [DeMets *et al.*, 1990]. Study area is indicated by square. (b) Seismotectonic map of northern Italy. Faults are as in Figure 1a. Historical seismicity is from Baratta [1901], Boschi *et al.* [1995], and Monachesi and Stucchi [1997]. Instrumental seismicity and earthquake fault plane solutions are from Harvard (<http://www.seismology.harvard.edu/data/>).



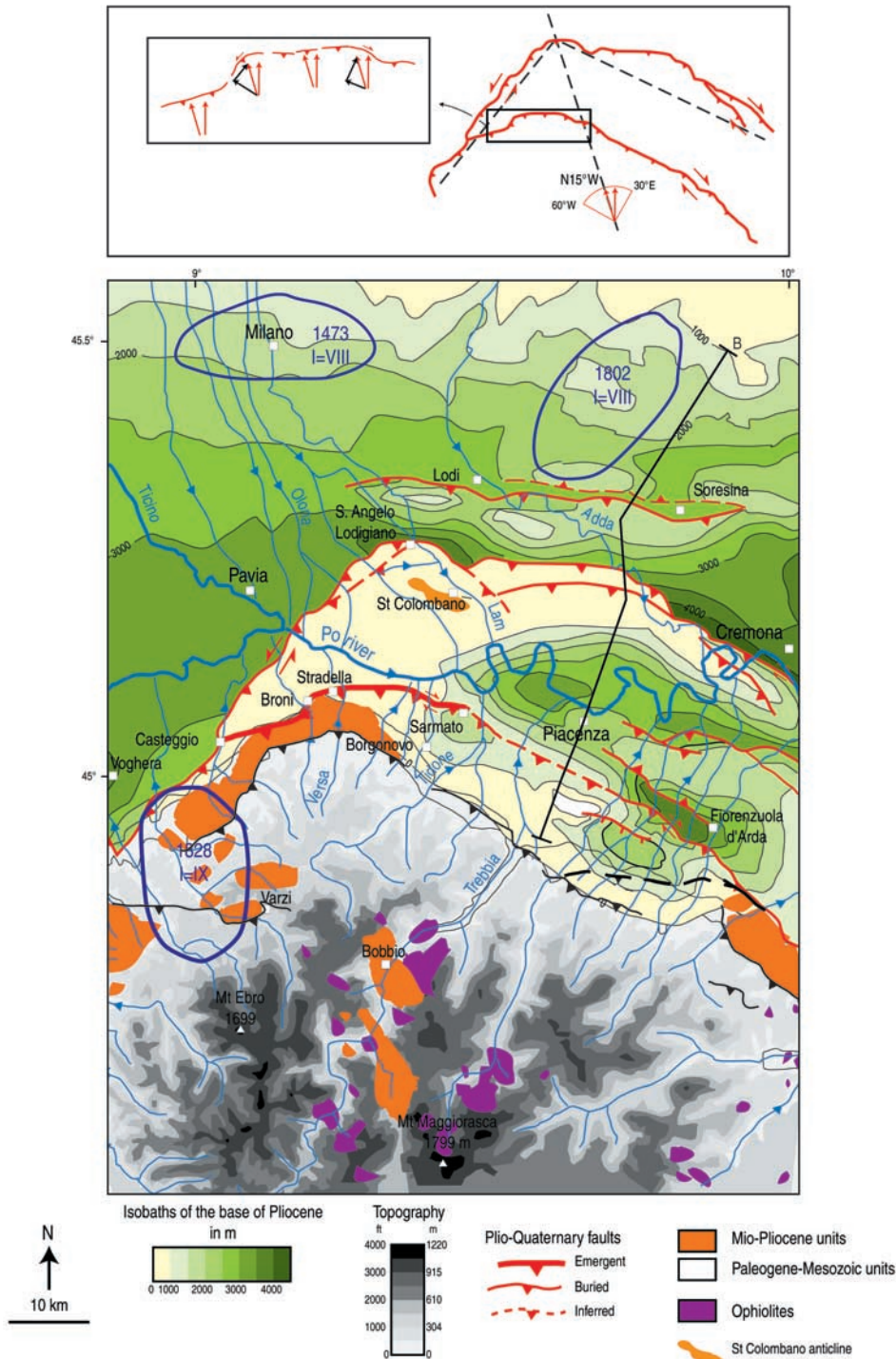
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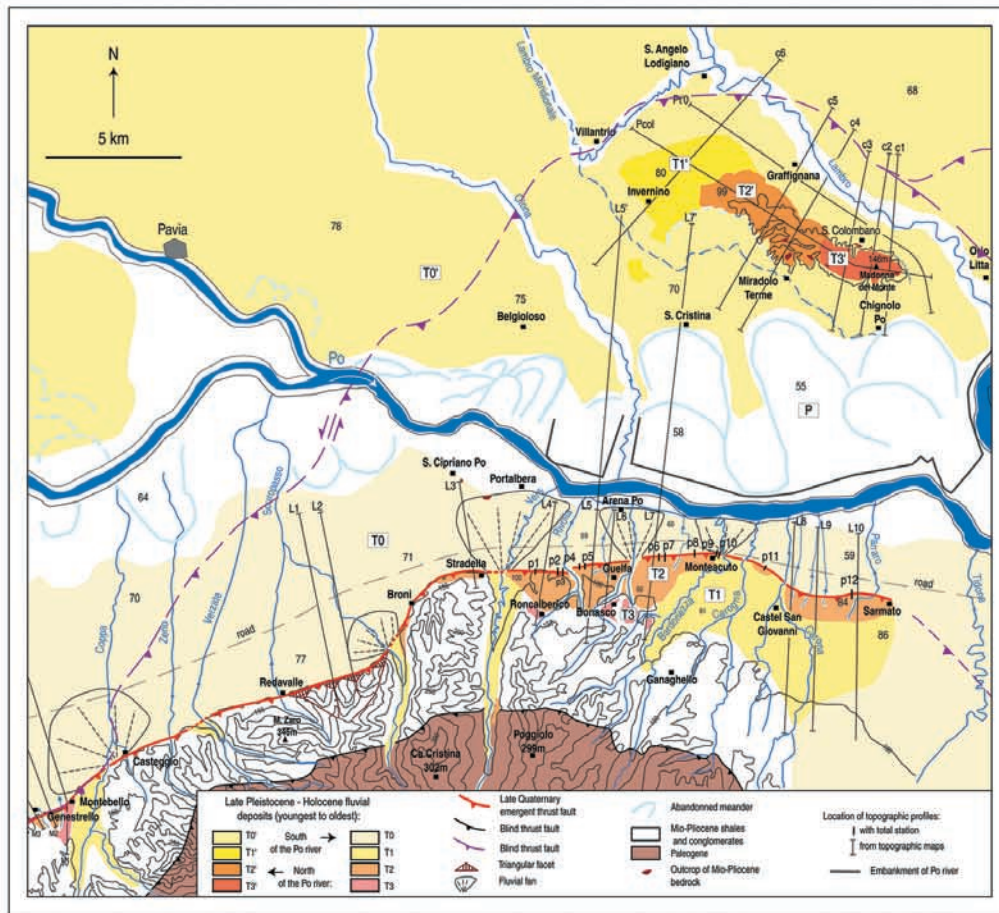




**Figure 3.** Seismotectonic map of Pavia-Piacenza region. Base of Pliocene depth contours, seismicity, and faults are as in Figure 1. Geology is interpreted from Boni [1967] and Barberi and Scandone [1983]. Inset shows geometry of Quaternary faults simplified from Figure 2 with kinematic interpretation and expected motion on faults.  $N15^{\circ}W$  to north shortening accounts best for geometry of faults at large and small scales.

**Figure 2.** (opposite) (a) Geological map of the northwestern Apennines interpreted and simplified from Servizio Geologico d'Italia [1983], 1/500,000 scale, and from Barberi and Scandone [1983], 1/500,000 scale. Positions of geological cross sections are indicated. (b) Geological N-S cross sections interpreted from seismic sections [Pieri and Groppi, 1981] of Piacenza and Bologna region (see location on Figure 1b). Topography is shown with no vertical exaggeration.

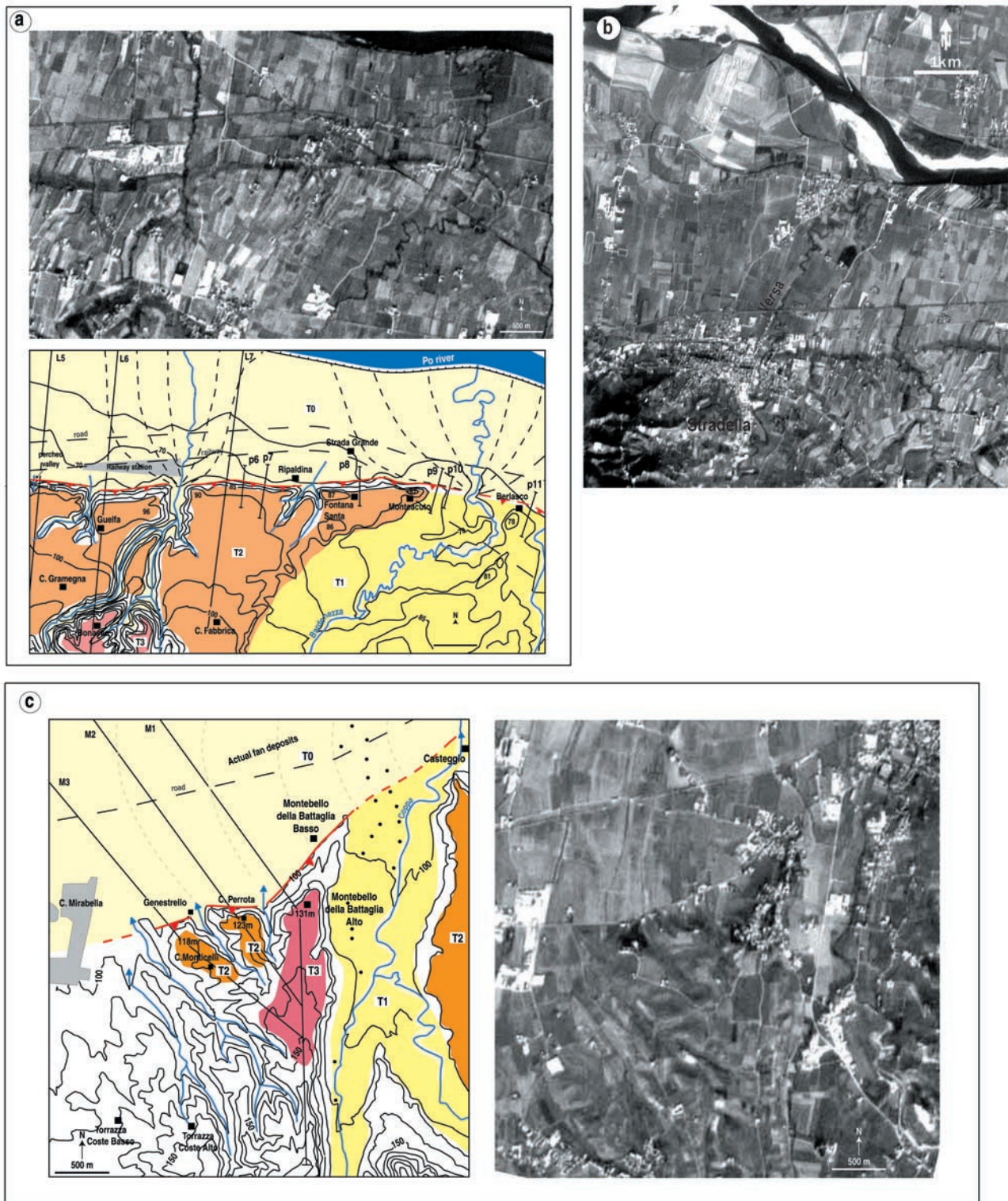




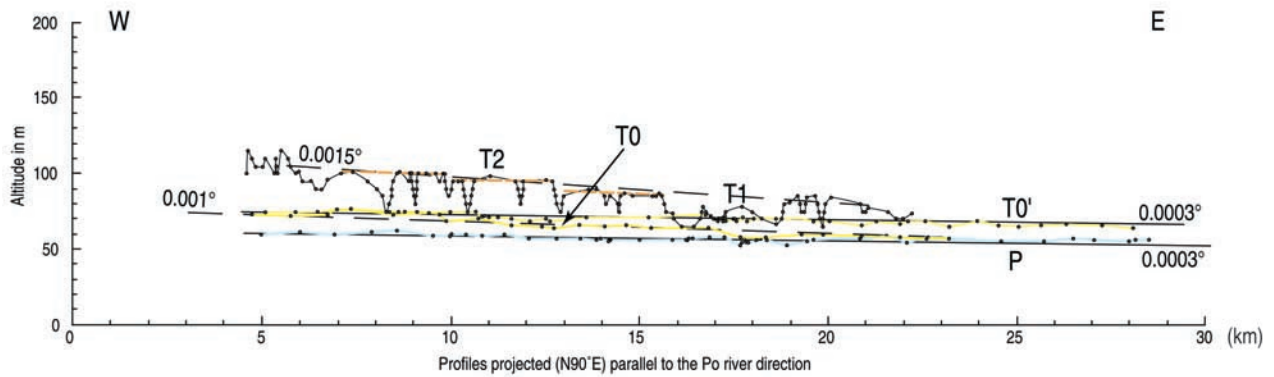
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**Figure 4.** (opposite) (a) Panchromatic SPOT image (K.J. 57–259, 29 December 1991) of Sarmato-Casteggio area (pixel size is 10 m). Note E-W, en echelon thrust scarp extending from foremost prong of Apenninic relief eastward into plain. Boxes indicate locations of Figures 6a, 6b, and 6c. (b) Geomorphic and geological interpretation of Figure 4a. Geology of Quaternary deposits is emphasized. Topography is from *IGMI* [1960, 1961], 1/100,000 scale. Levee on left bank of Po river is from *Braga and Gervasoni* [1989].





**Figure 6.** Enlargement of SPOT image shown in Figure 4a with geomorphic interpretation for Figures 6a and 6c. Symbols are as in Figure 4. (a) Ripaldina region, (b) Stradella region, note Versa alluvial fan, and (c) Montebello region. Solid circles are topographic trig or selected points for Coppa valley topographic profile.



**Figure 9.** Topographic profiles along top and base of Stradella scarp, south of Po river and along top and base of T0/P riser, north of Po river, from 1/10,000-scale topographic maps (*Carta Tecnica Regionale: Regione Lombardia* 1982, *Regione Emilia-Romagna* 1977). Vertical exaggeration is 40. Note that slopes of terraces south of Po river are 10 times steeper than north of it. T2 terrace is composed of smaller ledges at different heights separated by incising valleys, some of them hanging.