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GEOMORPHIC HISTORY AND RESPONSES TO ACTIVE TECTONICS IN AN UPLIFTED FOREARC REGION: RÍO TÉRRABA, SOUTHERN COSTA RICA, CENTRAL AMERICA

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Identification and characterization of fluvial terraces and fluvial geomorphology along Río Grande de Térraba (referred to as Río Térraba), the lower 70 km of the largest river system in Costa Rica (Figs. 1, 2), provide data for assessing the Plio-Pleistocene fluvial adjustments to large-scale tectonic activity in a tropical setting (MAT 27°C, MAP 3500 mm). The forearc region of the convergent plate margin of southern Costa Rica has experienced Pliocene and Quaternary uplift in response to partial subduction of the aseismic Cocos Ridge (Cocos Plate) beneath the Caribbean Plate (Fig. 1). Río Térraba serves as is the outlet for the 175 km long, 5200 km^2 Río General drainage basin, which heads in the Cordillera de Talamanca (max. elev. 3800 m), the igneous core of a Tertiary volcanic arc. Río General and Río Coto Brus flow from opposite ends of the Valle del General between the remnant arc and deformed and thrust-faulted Tertiary forearc basin sediments of the Fila Costeña (coastal range, <2500 m) before joining to become Río Térraba. Río Térraba then flows through a narrow canyon cut through the Fila Costeña to the 20 km wide coastal plain at Palmar Norte.

The geomorphic history of the forearc region and the spatial variation in the tectonic framework were investigated using integrated Quaternary geologic, soils-geomorphic, and field- and office-based fluvial and tectonic geomorphic studies, and radiocarbon dating. Tectonic boundaries, variation in styles and rates of tectonic deformation observed both normal and parallel to the plate margin, similar

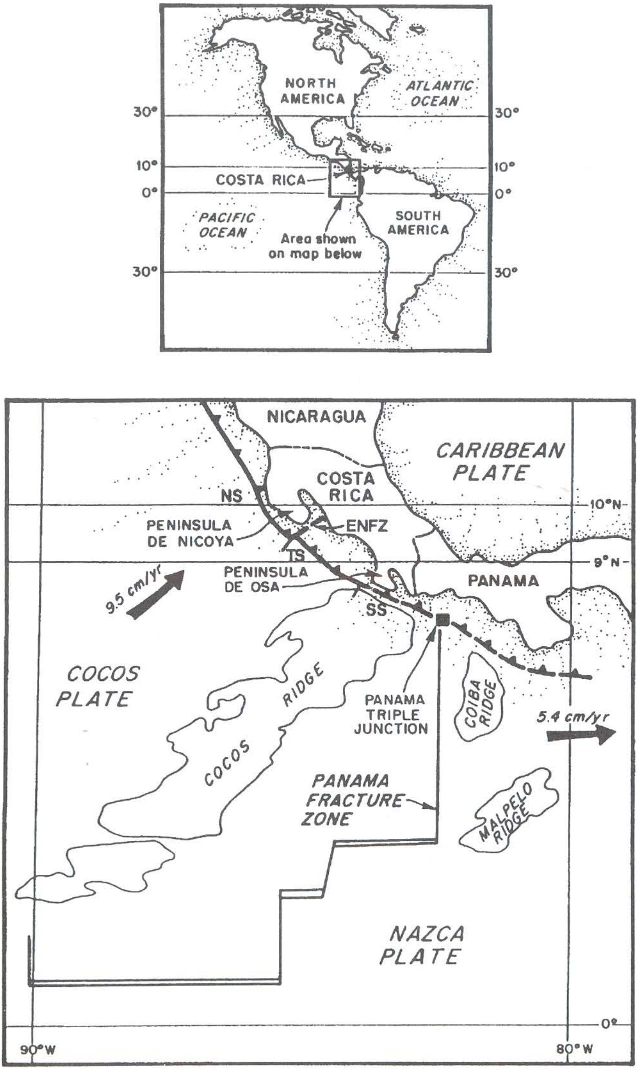

Figure 1. Plate tectonic setting of Costa Rica showing the position of the partially subducted Cocos Ridge. ENFZ refers to the East Nicoya Fracture Zone of Fisher et al (1994); NS, TS, and SS refer to the northern, transitional, and southern segments of the Middle America trench as defined in the study of Wells et al (1988). Rio Terraba is located just north of Peninsula de Osa.

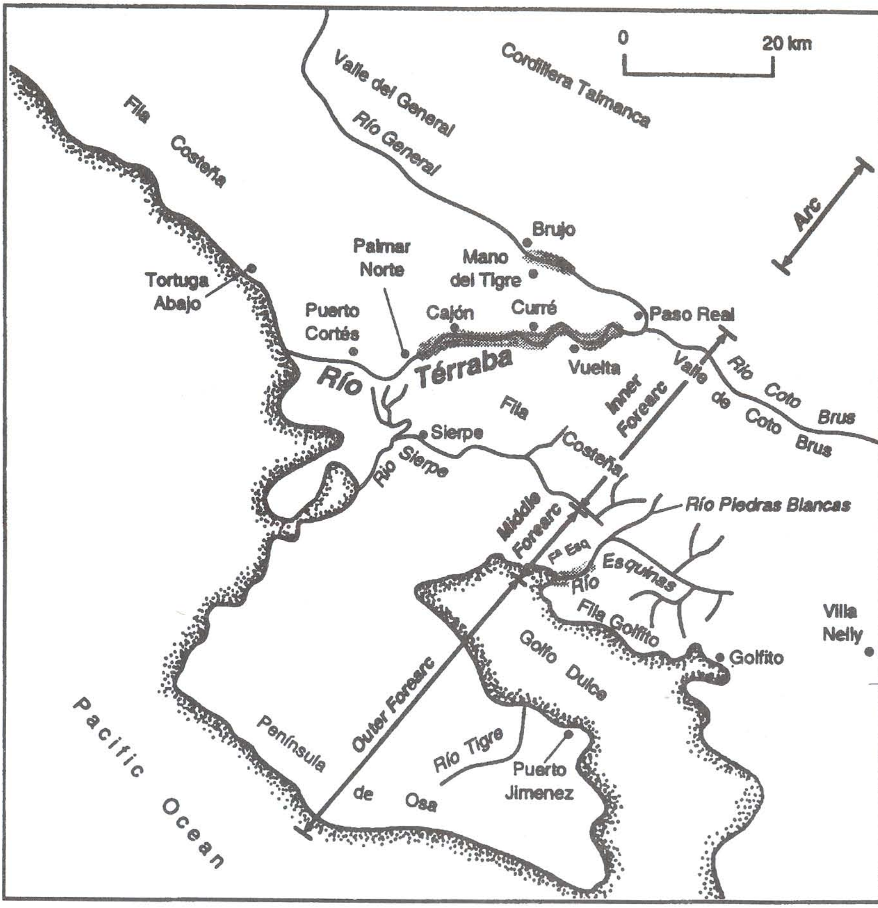

Figure 2. Map showing the locations of the study areas in southern Costa Rica. The labeled arrows show the locations of the dormant volcanic arc and the outer, middle, and inner forearc regions. The forearc regions trend approximately northwest parallel to the coast and the Middle America Trench.

geomorphology, and relative physiographic position within the forearc are used to subdivide the region into three distinctive regions referred to as the outer, middle, and inner forearc regions (Fig. 2). Río Térraba is situated in the inner forearc region.

A field-based soil chronosequence was established to ensure accurate correlation of tectonically deformed fluvial landforms. Reconstruction of fluvial terraces allows assessment of fluvial adjustments through time to tectonism where the river traverses major tectonic features within the canyon and along the southwest flanks of the Fila Costeña. Although clast-size data for the Pleistocene and Holocene fluvial deposits suggest little change in the hydrology of Río Térraba in the past 35 ky, terrace remnants and sedimentology document changes in clast composition, sinuosity, gradient, knickpoint migration, and channel location. In general, terraces diverge upstream but the greatest divergence occurs in the canyon region. Differences in clast composition reflect changes in source areas related to volcanism in the lower reaches of Río General. Substantial drainage reorganization is also indicated by lithologies contained in distal region deposits that correspond to source area materials not currently accessed by the underfit stream systems associated with the deposits. A major oblique slip fault (Falla Longitudinal de Costa Rica) is thought to be responsible for lateral displacement of the trunk stream.

Holocene (Qt3 and Qt4) and Pleistocene (Qt1 and Qt2) fluvial terraces are mapped along Río Térraba and range in height above base level (abl) from 2 m to more than 120 m and are distinguishable by characteristic soil properties (Table 1), clast composition, and topographic position. Radiocarbon dating, archaeological materials, and comparison of relative degree of pedogenic development to a dated soil chronosequence on Peninsula de Osa 40 km to the south provide age control. Clast size (b-axis) is consistent (up to 35-cm b-axis) on all terraces and an overall downstream decrease in grain size is observed. The active floodplain (**Qt5**) has two distinct levels representing seasonal discharge, is <4 m abl, and plutonic clasts are dominant. Terrace **Qt4** (youngest) remnants are preserved 1 to 8 m abl, and the deposits has weakly developed soil that has a pale (10YR hue) Bw-Cox horizon, a dominance of plutonic clasts (47%), and similar abundances of volcanic (28%) and sedimentary clasts (25%). Qt4 has the smallest amount of deformation of all of the terraces (<2 m across active faults). In the delta region Qt4 merges with the Qt5 floodplain. **Qt3** remnants are preserved 7 to 10 m abl and show up to 5 m of warping (measured from the Qt4 datum) where the river crosses major faults. The soil developed on Qt3 has a reddened (7.5-8.75YR hue) cumulic Bt horizon that is more than 1.8 m thick. Qt3 deposits have equal abundances (38%) of volcanic and plutonic clasts. Terrace **Qt2** remnants are up to 40 m abl and soils developed on Qt2 deposits have well-developed, reddened (5YR hue) Bt horizons more than 3 m thick. Volcanic clasts are dominant in Qt2 although the content of plutonic clasts is greater than in Qt1 deposits. Terrace **Qt1** (oldest) ranges from 30-to 120+m abl and is tilted, warped into broad folds, and faulted by northwest trending high-angle reverse faults in the region northwest of Palmar Norte. A well-developed soil with a red (2.5YR hue) Bt horizon that is greater than 3 m thick is formed on Qt1 and volcanic clasts are dominant (50 to 60%). Other Río Térraba fluvial deposits of presumed early Pleistocene or latest Pliocene age are >200 m abl in isolated exposures along the south flank of the Fila Costeña.

A generalized longitudinal profile and gradients of Río General/Río Térraba (Fig. 3) shows changes from the headwater region, through the Fila Costeña, and from the Fila Costeña to the Pacific Ocean. Most of the relief and slope of the Río General/Río Térraba system (ave gradient 0.0224 m/m) is contained in the upper 20 km, where the river loses nearly 75% of its relief (>2800 m drop in elevation). From the confluence of Río General and Río Coto Brus the average gradient of Río Térraba is 0.0014 m/m, however, the reach within the Fila Costeña is steeper (0.002 m/m) than the reaches immediately upstream and downstream. The gradient decreases by an order of magnitude to 0.00038 m/m (averaged to the ocean) after the river leaves the canyon.

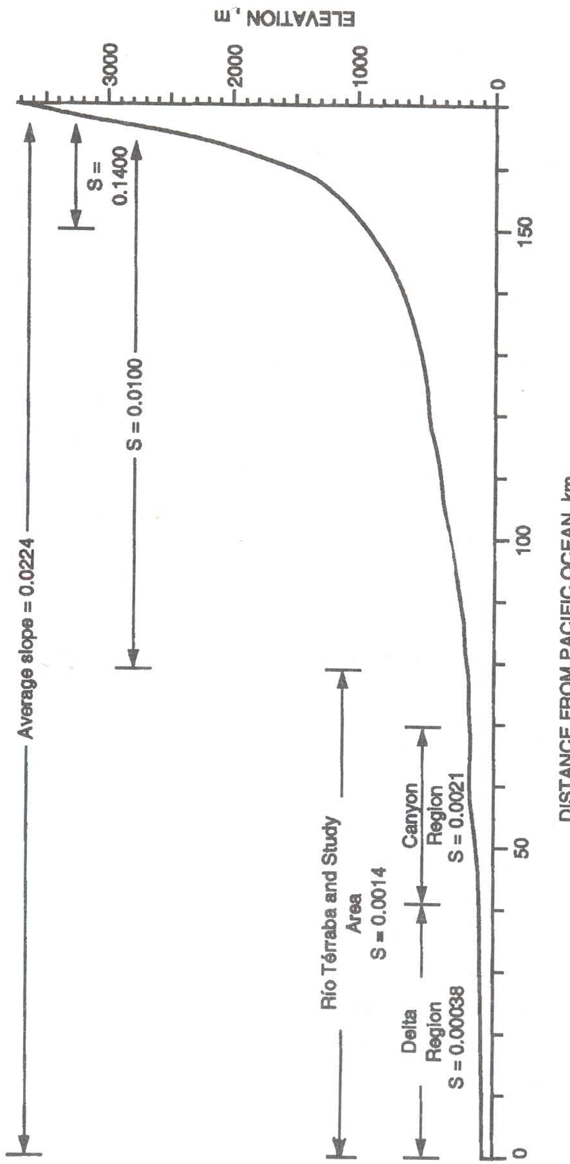

Figure 3. Longitudinal Profile showing the slope (S) of Rio General/Rio Terraba from headwaters of Rio General to the Pacific Ocean.

Changes in river gradient are associated with changes in bedrock lithology and depositional bars at tributary confluences, and are greatest (up to 0.004) where major fault systems cross the river. Variations in stream gradient show the influence of lithology on fluvial geomorphology and the apparent inability of Río Térraba to maintain an equilibrium profile through the actively uplifting Fila Costeña. From Palmar Norte to the coast, the Holocene terraces form the broad delta plain to the south of the river. North of the river, the delta plain is narrow as the river follows a course close to the mountain front and fluvial terrace remnants are found at elevations ranging from 15 m to over 250 m along the mountain front from Palmar Norte to Tortuga Abajo.

Prominent changes in sinuosity occurred in the canyon region during late Pleistocene and Holocene. Paleochannel positions reconstructed from the terrace sequence at Vuelta Campana allow assessment of changes through time in meander amplitude, wavelength, and radius of curvature (r_m) (Fig. 4, Table 2). A general compressing or tightening of meanders has occurred upstream of the Changüena Fault, suggesting long-term influence by the fault. At the fault, r_m shows a general decrease through time. Upstream from the fault, meander amplitude exhibits alternating decreases and increases through time similar to the trends observed at the fault and wavelength shows a general decrease.

An abandoned meander preserved near Palmar Norte at the Palmar Fault (Fig. 5) offers the opportunity to assess changes in meander morphometry since abandonment post-Qt3 time. In general, meander amplitude decreases both upstream and downstream from the fault. Meander wavelength and radius of curvature both increase upstream and downstream from the fault. From upstream to downstream, the inferred position of the river during Qt3 time shows that meander amplitude, meander wavelength increased, and r_m decreased (Fig. 5, Table 2). Meander decompression appears to have occurred since Qt3 time here in contrast with the reach at Vuelta Campana where meander compression through time is observed.

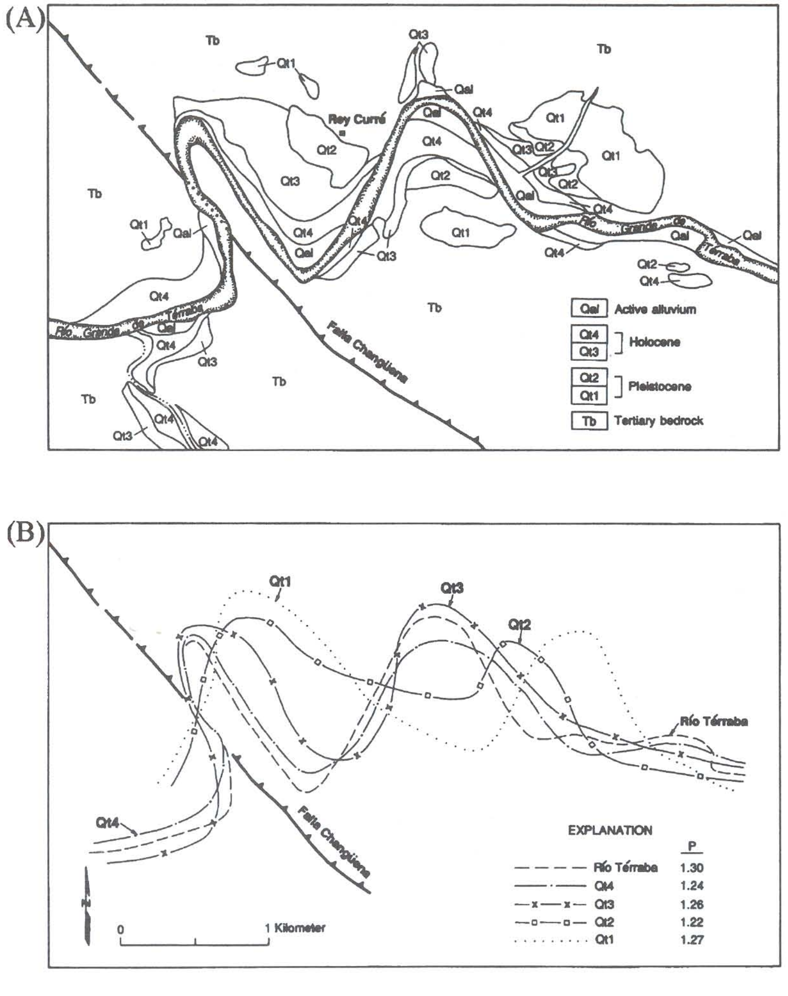

Figure 4. Quaternary geologic map (A) and plots of paleochannels (B) for Rio Terraba at Vuelta Campana in the vicinity of Falla Changuena

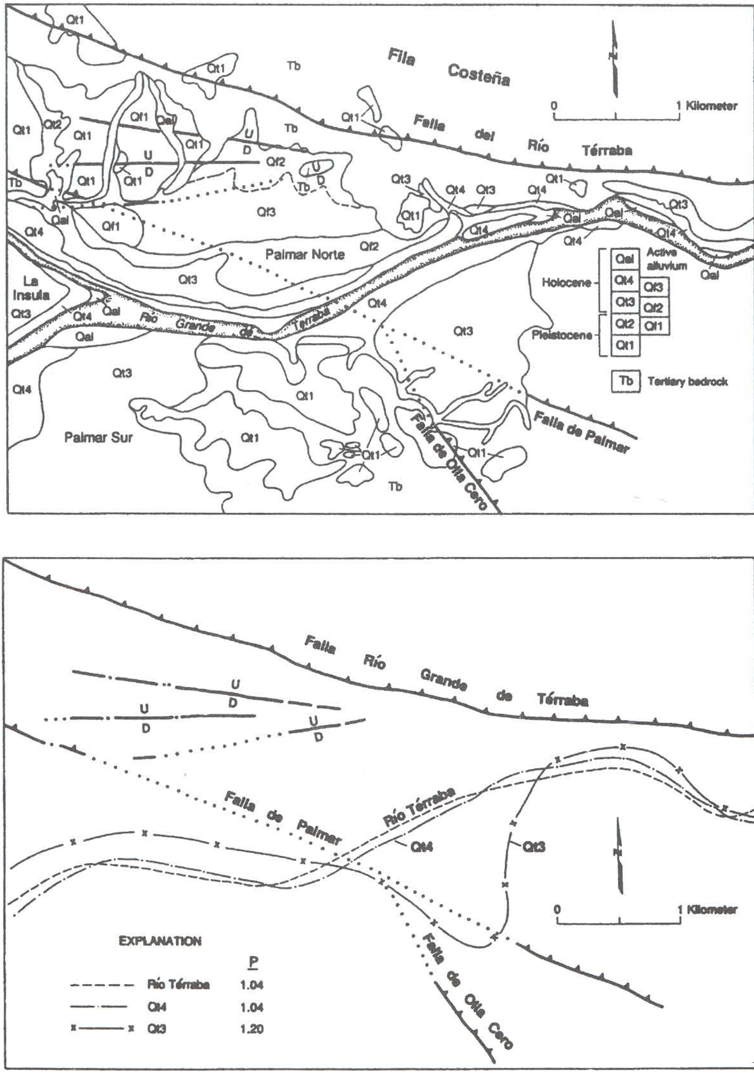

Figure 5. Quaternary geologic map (A) and plots of paleochannels (B) for Rio Terraba near Palmar Norte at Falla de Palmar.

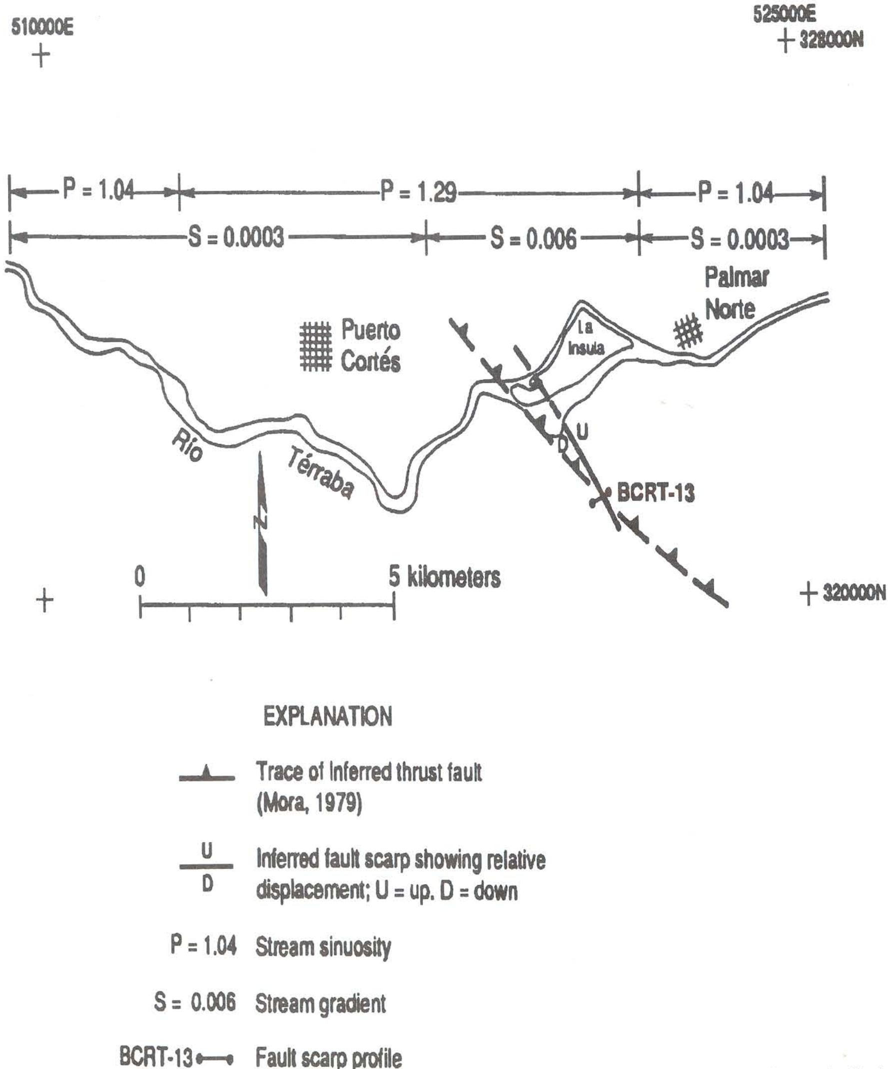

Figure 6. Map showing changes in stream morphometry for Rio Terraba where it crosses a strand of the Falla Longitudinal.

Table 1. Summary of soil properties for soils developed on sand beach ridges and fluvial deposits in the study region

Beach Ridge or Fluvial Terrace	Height Above Base Level (m)	^{14}C and Estimated Ages (ka)	Characteristic Horizon	Maximum Horizon Thickness (m)	Maximum Horizon Reddening (Hue)	Maximum Structure†	Clay Films§
Osa Peninsula Beach Ridges							
BR-8	1 - 2	<1.0	--	--	--	--	--
BR-7	1 - 2	<1.0**	Cox	0.8	10 YR	Massive - Sg	n.o.
BR-6	3 - 5	2.0**	Bw - Cox	0.4 - 0.6	10 YR	Massive	n.o.
BR-5	5 - 6	2.2	Bw	0.3	10 YR	Weak Sbk	1 n
BR-4	6 - 8	2.4**	Bw	0.4 - 0.6	10 YR	Weak Sbk	2-3 n-mk
BR-3	14 - 20	3.0 - 6.0	Bt	0.6	8.75 YR	Moderate Sbk	1 n-mk
BR-2	18 - 23	10 - 20	Bt	1.6	7.5 YR	Strong Sbk	3-4 mk
BR-1	25	<30	Bt	2.0	2.5 YR - 5 YR	Strong Sbk	4 mk
Osa Peninsula - Río Tigre Fluvial Terraces							
Active	0 - 1	--	Cu - Cox	1.5	10 YR	Massive-Sg	n.o.
Qt4	2 - 3	<2.5	Bw - Cox	0.6	10 YR	Strong sbk	n.o.
Qt3	5 - 6	6.3**	Bt	1.25	7.5 YR	Strong Sbk	3-4 k
Qt2	15 - 40+	6 - 20	Bt	1.6+	5 YR - 6.75 YR	Strong Sbk	4 k
Qt1	20 - 100+	<35	Bt	3.4+	2.5 YR	Strong Sbk	3-4 k
Rio Térraba Fluvial Terraces							
Qt5	0 - 4	<0.5	Cu	3.0+	10 YR	Massive - Sg	n.o.
Qt4	1 - 8	<2.0	Bw - Cox	1.0+	10 YR	Massive - Weak Sbk	n.o.
Qt3	5 - 10	4.0 - 6.0	Bt	1.8+	7.5 YR - 8.75 YR	Moderate - Strong Sbk	2-3 n-mk
Qt2	20 - 40	10 - 15	Bt	3.0+	5 YR	Strong Sbk	3 mk
Qt1	30 - 250+	<35	Bt	3.0+	2.5 YR	Strong Sbk	4 mk-k

Soil-horizon nomenclature, and soil-structure and clay-film notation follows Soil Survey Staff (1975) and Birkeland (1984). Soil hues are Munsell soil colors.

*Parent materials - Beach ridge deposits: fine- to medium-grained, moderately-well sorted, lithic-rich sand; fluvial deposits: poorly- to moderately-sorted, fine sand to medium gravels consisting of sedimentary clastics and ophiolite clasts

†Sbk = subangular blocky; Sg = single grain

§Frequency and thickness: 1 = few; 2 = common; 3 = many; 4 = continuous; n = thin; mk = moderately thick; k = thick; n.o. = not observed

**Radiocarbon dates

*Parent material: poorly- to moderately-sorted, fine-to coarse-grained sands, silts, and clays, imbricated pebbles, gravels cobbles, and boulders up to 40 cm b-axis diameter.

Table 2. Morphometry of abandoned meanders along Rio Terraba at Vuelta Campana and near Palmar Norte

(a) Near Vuelta Campana at Falla Changüena[*]

	At Fault			Upstream from Fault		
Channel	A[†] (m)	λ[§] (m)	r_m[**] (m)	A (m)	λ (m)	r_m (m)
Active	1270	830	75	975	1610	250
Qt4	1120	1075	85	830	1805	365
Qt3	1320	1120	175	1025	1805	250
Qt2	1075	2000	250	585	1950	180
Qt1	1270	2200	210	925	1950	240

(b) Palmar Norte at Falla de Palmar[*]

	At Fault			Upstream from Fault		
Channel	A[†] (m)	λ[§] (m)	r_m[**] (m)	A (m)	λ (m)	r_m (m)
Active	460	4000	2200	530	2500	1880
Qt4	530	4100	2200	700	2500	1880
Qt3	1350	2000	265	1175	1900	765
Qt2	–	–	–	–	–	–
Qt1	–	–	–	–	–	–

[*]Meander properties determined from inferred position of paleochannel based on fluvial terrace remnants
[†]Meander amplitude in meters
[§]Meander wavelength in meters
[**]Radius of curvature in meters
- No data for Qt1 and Qt2 remnants for abandoned meander at Palmar Norte

Where the Longitudinal Fault crosses the river, changes in sinuosity and stream slope are observed for 2 km upstream and 2 km downstream (Fig. 6). Over the 4-km-long reach channel pattern differs markedly from reaches upstream and downstream of the fault scarp. In this reach, the river has (1) a meandering pattern, (2) a gradient that increases by 20 times from 0.0003 m/m to 0.0060 m/m (extends 2 km upstream of the fault trace), (3) stream sinuosity that increases from 1.04 to 1.29 and is coincident with the start of the steepened reach and extending about 6 km downstream, (4) diverging terraces, and (5) increased incision in the immediate vicinity of the fault trace. Knickpoints in this reach and 3.5 km upstream may be related to displacement on the Longitudinal Fault or one of its splays or geomorphic adjustments to changes in discharge and sediment load. Alternative explanations such as constant slip faults and sea-level induced knickpoints require either unrealistic assumptions or extreme rates of migration.

Qt1 terrace remnants in the delta region indicate that the lower Río Térraba has remained near its present position since the latest Pleistocene, although other evidence suggests that the course of Río Térraba may have changed throughout the Pleistocene. Approximately 30 to 35 km of northwest translation of an ancestral Río Térraba channel by the Longitudinal Fault is proposed as an explanation for the apparent beheaded streams (Río Esquinas and Río Sierpe) which are grossly underfit and contain elevated fluvial terraces with deposits associated with distant source areas. This study has demonstrated that despite the power of the Río General/Río Térraba river system and high rates of weathering in the tropics, the high rates of tectonic activity have had a profound influence on the fluvial geomorphology and geomorphic evolution of the system.