A Report on Tectonic Landforms along the Philippine Fault Zone in the Northern Luzon Philippines

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Takashi NAKATA, Akira SANGAWA and Shin-ichi HIRANO

Introduction

The Philippine fault zone has been regarded as one of the most prominent fault zone in the world, since reported by Allen (1962), where significant fault landforms of relatively recent movements are continuing about 1200 km from South Mindanao to Lingayen Gulf in Luzon.

The linear trace with small curvature of the fault suggests a history of horizontal displacement. In fact, Allen (1962) demonstrated from numerous geomorphic evidences that the component of the displacement along the fault zone was sinistral. This interpretation was seconded by the actual surface displacement along the fault associated with the earthquake occurred in the Ragay Gulf in 1973 (Allen 1974).

Purpose of this short paper is to clarify the nature of the fault zone based on detailed field investigation, and for this purpose a study area was set up in the northern part of the Luzon Island. The writers made efforts to confirm fault traces and clarify the mode and degree of their displacements through the investigation.

Method of investigation

The field survey was carried out from the 29th April to the 10th May 1977, towards the end of dry season, in order to avoid the obstruction of tropical vegetation and heavy rainfall.

Vertical aerial photographs on a scale of about 1:40,000, partly covering the study area, were useful to identify the outline of fault landforms. Fault traces were accurately plotted in the field on topographic maps on a scale of 1:50,000 published by authority of the board of technical surveys of the Philippines.

To learn deformation of alluvial fans and river terraces precisely, profiles across fault scarps and scarplets were surveyed by handlevel, tape-measure and altimeter. Amount of vertical displacement along fault was calculated from these profiles and horizontal displacement was measured directly in the field.

Previous works

Willis (1937) first recognized the existence of throughgoing fault zone in the Philippine Archipelago, named it "Philippine fault zone" and considered the zone to be dominantly transcurrent because of its similarity to the San Andreas fault in California. Further, Willis mentioned that this fault zone was left-lateral in sense from observation on a single set of horizontal symmetric slickensides.

On the contrary, Alvir (1926) had insisted on dextral movement along the faults in northern Luzon. Benioff (1959) and St. Amand (1959) suggested the probable existence of right-handed displacement along the fault zone based on the counter-clockwise rotation theory in the western Pacific.

However, many investigators have agreed on Willis's idea from geomorphological and geological aspects (Alvir, 1941; King and Mckee, 1949; Vening Meinesz, 1954; Biq, 1960; Allen, 1962, 1974).

Allen (1962), confirming the trend Willis had suggested (1937), found out many geomorphic evidences — fault line scarps, fault troughs and valleys, side-hill ridges, numerous fault sags and sag ponds, and consistent stream off-sets — of which showed the recent left-handed movement.

Rutland (1967) inferred that there had not been significant strike-slip movement since the Miocene by the geological investigation from Dingalan to Laur, in Northern Luzon. However, the earthquake in 1973 ($M=7.3$) on the projected trace of the fault zone in the Ragay Gulf, Southern Luzon was associated with surface displacement of 3.2 m in sinistral sense (Allen, 1974).

Fitch (1970, 1972) demonstrated applying mechanism solution for recent earthquakes that the sense of parallel slip along the western margin of the Philippine Sea, which induce the movement of Philippine Sea Plate, agrees with the sinistral displacement of the Philippine fault zone.

Outline of landforms

The tectonic landforms throughout the Philippine fault zone were briefly described by Allen (1962).

In the northern Luzon, the northeast side of the fault zone is uniformly higher, making an obvious topographic contrast between mountains — Cordillera Central and Central Sierra Madre — and the Central Valley.

These mountains — composed of sedimentary and metamorphic rocks of Oligocene ∼ Miocene, Neogene and undifferentiated igneous rocks, and locally of pre-Jurassic base complex (Bureau of Mines, 1963) — run at right angles to the fault and parallel to each other, interposing the longitudinal Cagayan Valley between them. Cordillera Central is generally 1000 m to 3000 m high and Central Sierra Madre is 1000 m to 2000 m high.

The Central Valley, about 60 km in width and 180 km in length between Manila and Lingayen Gulf, is the most extensive lowland in the Philippines and underlays thick Plio-Pleistocene sediments.

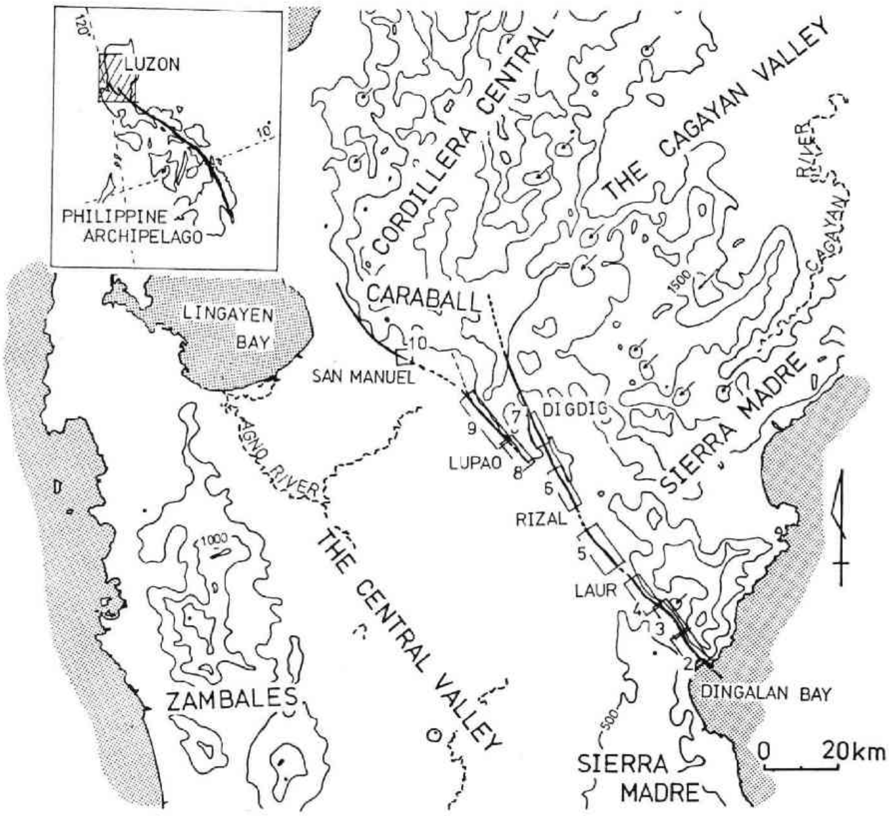

Fig. 1 Index map of the study area and its environs (Contour interval: 500 m, eliminating valleys less than 2.5 km across)
Arabian numericals mean the number of following figures. Solid lines are major fault trace of the Philippine fault after Allen (1962).

On both sides of the Central Valley, two parallel rows of comparatively low mountains, Zambales (1000 m to 2000 m high) and the extension of Sierra Madre (1000 m to 1500 m high) stretch in the N-S direction oblique to the fault.

The fault zone branches into two in the study area. One of them runs in the NW-SE direction across Sierra Madre between Dingalan Bay and Laur. Along the fault, the longitudinal Coronel River Basin is formed, being separated by a low divide from the coast of Dingalan Bay. In the north, the fault runs along the foot of Sierra Madre before it passes the town of Rizal. Then, trending to NNW along the Digdig river, it goes into Cordillera Central. Another branch is associated with evident fault topographies along the foot of Cordillera Central between Lupao and north of San Manuel, dividing the mountains from the Central Valley.

Alluvial fans and river terrace surfaces, continuously distributed and deformed along the fault, are depositional in most case and subdivided locally. They are tentatively divided into three groups, namely H, M and L surfaces in geomorphic aspects — height, continuation and degree of dissection on the surface and degree of weathering about the terrace deposits — in descending order. The flat surface of L surface is well-preserved and deposits are little weathered, while other surfaces are fairly dissected and composed of weathered (mostly reddishly weathered) gravel. They are not widely formed except the cases of the Digmara river fan and the Agno river fan.

The development of these fans is severely controlled by faulting. Between Gabaldon and Rizal, older fans are overlaid by younger fans in the downthrown side (SW side) of the fault, supposing considerable amounts of the vertical component of the faulting. From Umingan to San Quintin, fans of different ages are distributed in the same level, possibly causing the lateral displacement of fan heads by the dominant horizontal component of the fault movement.

1 Tectonic landforms along the fault between Dingalan Bay and Digdig river

1.1. Dingalan Bay to Gabaldon

The region, about 8∼9 km long, includes Dingalan Bay, Coronel river basin and lower divide between. It is mostly covered with ill-sorted boulder gravel of avalanche deposits from the mountains of the NE side (Rutland, 1967).

The fault zone consists of some parallel active breaks about 2 km wide and each is in extreme linearity trending to NNW (Photo 1, Fig. 11), along which several left-handed off-set streams are recognized, although none of which is sharply displaced. The northeastern part of the fault zone is characterized by several depressed troughs and sags (Allen, 1962; Rutland, 1967), among which the largest one is 400 m long, 50 m wide and 25 m deep (Fig. 2, Loc. ①; Photo 2, Fig. 12).

1.2. Gabaldon to Laur

This region consists of a large NW-SE elongated depression basin, bordered by fault scarps. In the south of the basin, between Gabaldon and north of Ligaya, it is bordered by concave edges, which converge to the northwest and to the southeast (Photo 3, Fig. 13). In the north of the basin, between north of Ligaya and Laur, both borders run nearly in parallel, and the basin is in transition to the Central Valley to the northwest.

Throughout the region, the main fault certainly passes along the northeastern fringe of the basin, which is far steeper than the opposite. Along the main fault, numerous fault scarps or scarplets are observed, which deformed alluvial fans and

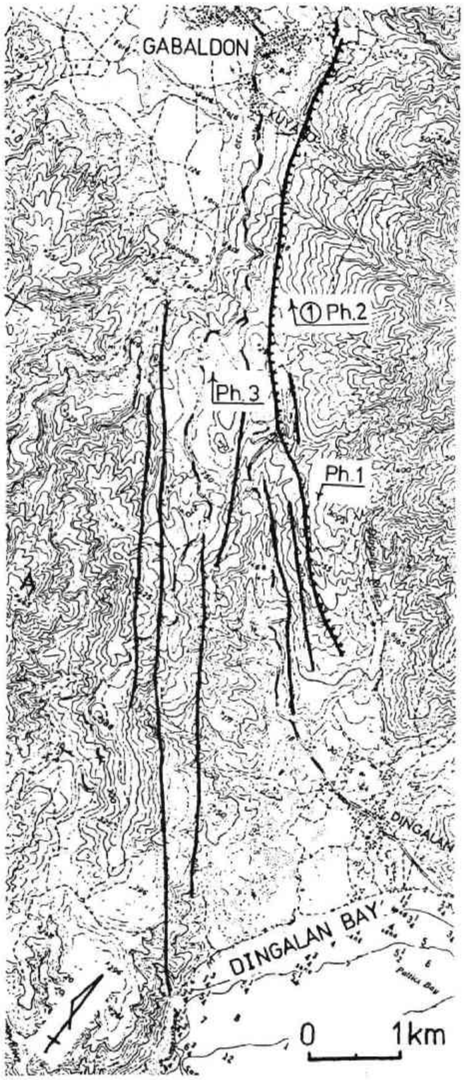

Fig. 2 Fault traces between Dingalan Bay and Gabaldon

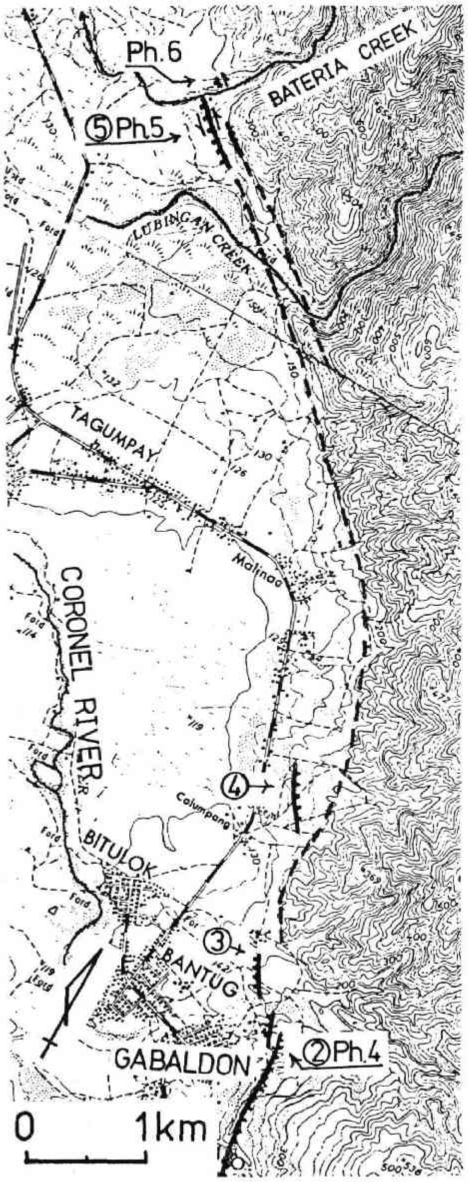

Fig. 3 Fault traces between Gabaldon and Bateria Creek

river terraces.

To the east of Gabaldon, an alluvial fan (correlated to L surface) is displaced by a scarplet facing to the east (Fig. 3, Loc. ②; Photo 4, Fig. 14), and a shallow

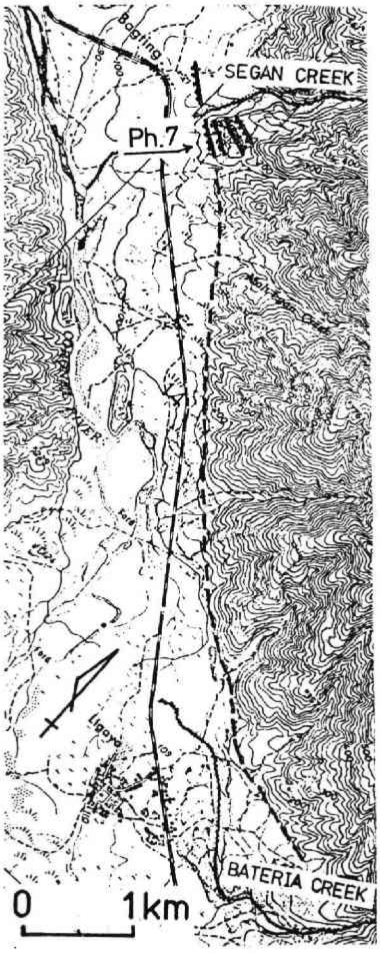

Fig. 4 Fault traces between Bateria Creek and Segan Creek

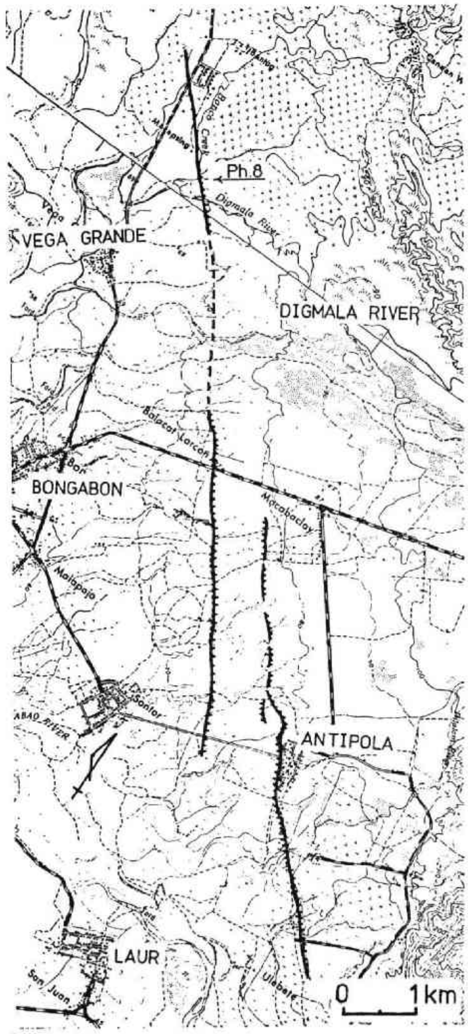

Fig. 5 Fault traces between Laur and to the south of Rizal

depression is observed on the downthrown side. The vertical displacements of the fan surface are measured 2.9～3.9 m. (Photo 4, Fig. 14). A parallel scarplet is recognized in the north, making a small horst landform.

To 500 m northwest from Loc. ③, some parallel scarplets dislocate an alluvial fan in the form of step faults whose vertical displacements are totalled 6～6.5 m.

To the north of Gabaldon, a break is found out on the fan (L), trending to NNW-SSE oblique to the mountain edge (Fig. 3, Loc. ④). The fan is downthrown to ENE, vertically 2.9 m in maximum.

About 5 km along the foot of the mountains between Loc. ④ (north of Gabaldon) and Lubingan Creek, the deformation on alluvial fans is not clearly recognized.

The river terraces and alluvial fans (L) at the debouchers of the Lubingan Creek and Bateria Creek into the plain are subdivided into L_1 and L_2 surfaces. Obvious scarplets cut these surfaces at right angles to the terrace cliffs (Fig. 3, Loc. ⑤; Photo 5, Fig. 15). Amounts of vertical displacements are $4.5 \sim 6.5$ (L_1) and $1.8 \sim 4.2$ (L_2). The erosional terrace cliff between L_1 and L_2 surface, is displaced horizontally 7.9 m in sinistral sense. The ratio between horizontal and vertical displacements after the formation of L_2 terrace are $4{:}1 \sim 2{:}1$. The scarplet diminishes at the right bank of the Bateria Creek.

Another break is recognized on the alluvial fan (L_2) about 80 m upstream, dislocating it vertically about 2 m (Photo 5, Fig. 15). On the right bank of the Bateria Creek, the northern extension of the break displaced some elevated stream channels and point-bars on L_2 surface vertically and horizontally (Photo 6, Fig. 16). Horizonal displacement is $1.2 \sim 1.6$ m in sinistral sense and vertical one is about 1 m, and their ratio after the formation of L_2 surface is $3{:}2 \sim 1{:}1$. This break cut the deposits of the surface.

About 6.5 km from Loc. ⑤ (Bateria Creek) to Loc. ⑥ (Segan Creek), obvious scarplets are not recognized on the fans.

An alluvial fan on the left bank of the Segan Creek is conspicuously interrupted by faulting. The terrace surface, covered by gravel a little weathered, belongs to M surface. Four faults run parallel at right angles to the Segan Creek within 200 m, two of which at the upstream are interposing a narrow depression zone—60 m wide and 5 m deep. The other two at the downstream clearly dislocate the fan 9 and 26 m vertically in steps (Photo 7, Fig. 17).

On the right bank of the Segan Creek, the NW extension of the above fault at the downstream is cutting the L_1 and L_2 surfaces, whose vertical displacements are over 5 m of L_1 surface and 1 m of L_2 surface respectively.

1.3. Laur to Rizal

Two parallel rows of scarplets in the NW-SE direction are observed on the Digmala river fan. One of which in the west was reported by Allen (1962) and named "Bongabon fault line" by Rutland (1967).

The scarplet at the upstream is about 6 km long, whose higher side is not fixed, and about 2.5 m in maximum relative height. It passes through the western side of Antipola, and a small bulge is observed to the north of this town.

The other one, running about 2 km east of Antipola, is about 9.5 km in length, and uniformly downthrown to NE vertically 3.7 m in maximum (Photo

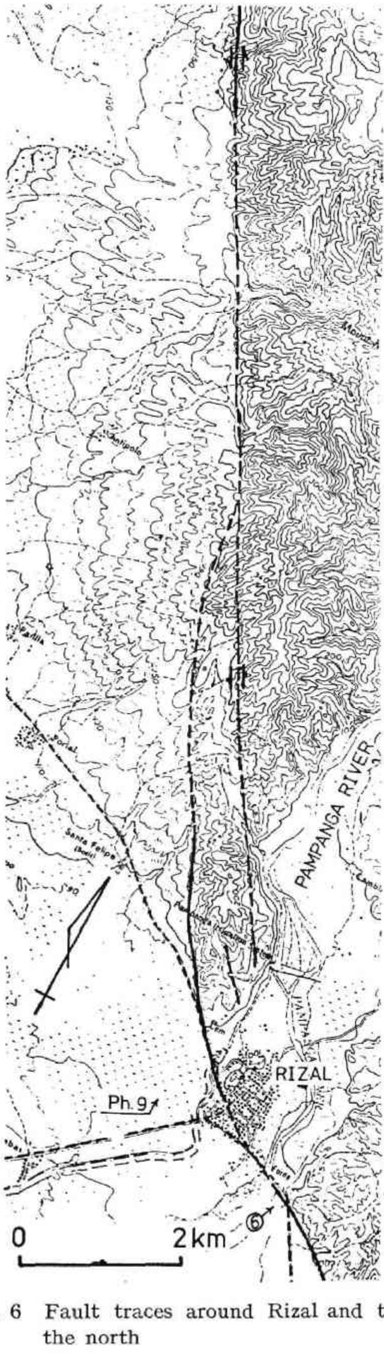

Fig. 6 Fault traces around Rizal and to the north

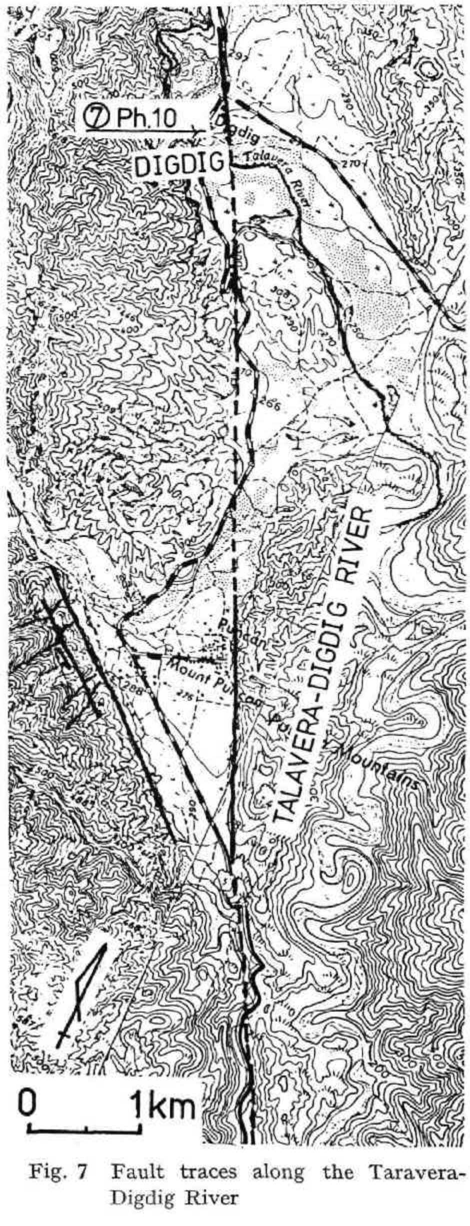

Fig. 7 Fault traces along the Taravera-Digdig River

8, Fig. 18). The downthrown side is mostly swampy.

Left-lateral off-set of stream channel is not clearly noticed along the scarplets.

1.4. Rizal and its surroundings

The Pampanga river, winding its stream through the mountains, makes a series of terrace surfaces well preserved around Rizal. Terrace surfaces are roughly classified into five, namely H_1, H_2, M_1, M_2 and L surfaces in descending order.

The fault, running through the town of Rizal in the NNW direction, displaces above mentioned surfaces on the right bank of the Pampanga (Photo 9, Fig. 19). The displacements amount over 85 m (H_1), over 45 m (H_2), over 20 m (M_1), over 10 m (M_2) and over 8 m (L) in maximum. Another fault is recognized in parallel to NNE.

On the left bank of the Pampanga, there is an inclined terrace surface (M_2) whose deposits, composed of weathered gravel bed 2.5 m thick, are inclined just in the same manner (N35°E, 17°S), probably deformed by the activity along the main fault (Loc. 6).

The fault zone continues to NNE, bordering the foot of the mountains, before entering Cordillera Central along the Talavera-Digdig river. Though detailed field survey has not been done in this region, fault landforms with linearity — especially many shutter-ridges — are recognized on the topographic map, showing the sinistral movement of the fault.

1.5. Along the Talavera-Digdig river valley

Along the fault, the longitudinal Talavera-Digdig valley was formed with steep walls which were sheared by numerous faults and joints.

In the north of Digdig, a terrace surface (L) is sharply cut on the very trace of the fault zone (Allen, 1962). The scarplet, facing to WSW, is over 3.5 m in height (Loc. ⑦; Photo 10, Fig. 20).

The linear valley along the fault is elongated to the north till it diminishes in Cordillera Central. Numerous sinistral off-sets of tributaries along the main fault were reported by Allen (1962), but they are not so clear.

2 Tectonic landforms along the fault around Umingan and San Manuel

2.1. East of Lupao

Another fault zone, bifurcated from the above described fault zone around the deboucher of the Talavera, is running along the boundary between hills (300~400 m high) and Caraball mountains (600~700 m high here).

Fig. 8 Fault traces to the east of Lupao

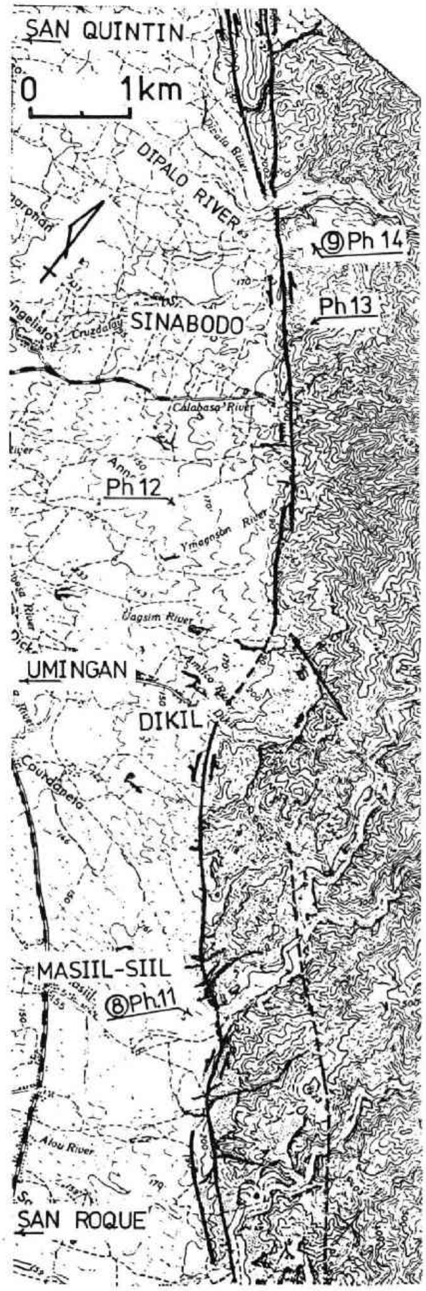

Fig. 9 Fault traces between San Roque and San Quintin

There are many parallel and oblique faults in the wide fault zone in this region, but they converge into one linear zone to the east of San Roque, clearly dividing Caraball (rises up to 1500 m in height here) from the Central Valley.

2.2. San Roque to San Quintin

Main fault passes through the foot of Caraball. A number of streams come down from the mountains across the fault zone and form confluent fans forward, which are roughly classified into M and L surfaces. These fans are dislocated just along the foot of Caraball.

To the northeast of San Roque, there are obvious stream off-sets and shutter-ridges, indicating the dominant sinistral sense of displacements. Here, the range of off-set is about 150 m in maximum.

Around Loc. ⑧, east of Masiil-siil, a river from the mountains forms terraces (L), which are subdivided into the upper (L_1) and the lower (L_2) surfaces. Oblique to the terrace cliffs, an obvious fault scarp is recognized, and it cuts both surfaces vertically and horizontally, the latter being much superior. The fault in terrace deposits is observed along the fault scarp (Photo 11, Fig. 21). The vertical displacements are about 5 m (L_1) and 1.5 m (L_2). The terrace cliff of L_1 surface is displaced 53.2 m in sinistral sense.

To NE of Masiil-siil, off-set streams are obviously recognized, showing left-lateral displacements 150 m in maximum.

To the northwest from Dikil, there are many shutter-ridges in sinistral sense of faulting (Photo 12, 13; Fig. 22, 23) and they become larger in scale to the north, the range of off-set being about 700 m in maximum. These ridges are constructed by sheared bedrocks which are generally covered with sub-angular boulder gravels.

To the east of San Quintin, interesting fault landforms are observed on the left bank of the Dipalo river (Loc. ⑨) where terrace surfaces are classified into L_1, L_2 and L_3 surfaces. Vertical and horizontal displacements of these micro-landforms are evidences for undoubted break of L_2 surface (Photo 14, Fig. 24). They were measured about 1 m vertically and 8.3 m horizontally in sinistral sense. The ratio of horizontal and vertical displacements after the formation of L_2 surface is calculated about 8:1. The terrace cliff of L_1 surface is displaced 20.5 m in sinistral sense.

To the north of San Quintin, the fault zone branches into two. One to NNW along the foot of Caraball and into Cordillera Central and the other to NW, directed to San Manuel. The latter is projecting a side-hill ridge whose west edge is sharply lined and probably more active than the former.

2.3. San Manuel and its surroundings

The Agno river, flowing its stream through Cordillera Central about 70 km long, makes wide fan surfaces into the Central Valley.

The fault appears in the west of the Agno river fans, passing through the town of San Manuel. The vertical displacements of these fan surfaces, downthrown to SSW, are over 38 m (M), 4.5 (L_1), 2.5 m (L_2) (Photo 15, 16; Fig. 25, 26).

The fault zone runs to NW along the foot of Cordillera Central, showing the linearity of landforms with some shutter-ridges and left-handed off-set streams.

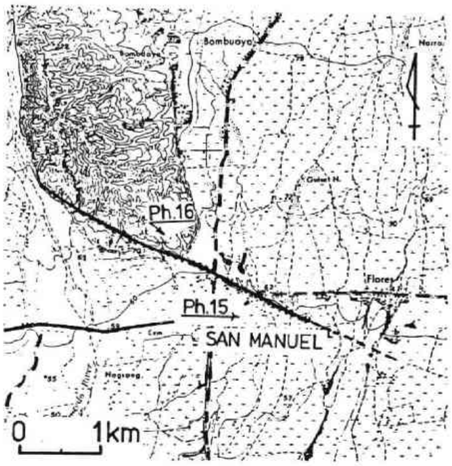

Fig. 10 Fault traces around San Manuel

Summary and conclusion

In the study area, the northern part of the Philippine fault zone, various fault landforms are evidently observed as mentioned above.

The region, from Dingalan Bay to Gabaldon, bears the fault landforms similar to Leyte, with some parallel breaks including a number of fault troughs in them. The fault landforms between Gabaldon and Rizal are characterized by the displacements on alluvial fans and river terraces along or near the foot of Sierra Madre. Left-lateral displacement together with vertical one is indicated by numerous breaks of terrace surfaces and cliffs, and change in sense of vertical displacement along the fault trace. Between San Roque and San Manuel fault displacements appear sharply just along the foot of Cordillera Central and landforms related to sinistral movements are distinctly recognized due to predominant horizontal activity of the fault in this section. Along the fault trace, diverging in the N-S direction from San Quintin (Allen, 1962), fault landforms are not clearly recognized.

Table 1 Vertical and horizontal displacements on the alluvial fans and river terraces

Location (Locality)	Vertical displacement		Sinistral displacement		Ratio of displacement sinistral vertical
	displacement (m) (upthrown side)	fan and terrace surface	displacement (m)	fan and terrace surface	
East of Gabaldon ②	2.9～3.9 (W)	L			
Northeast of Gabaldon ③	6～6.5 (E)	L			
North of Gabaldon ④	2.9 (W)	L			
Left bank of Bateria Creek ⑤	4.5～6.5 (E) 1.8～4.2 (E) 2 (E)	L_1 L_2 L_2	7.9	L_2	4:1～2:1
Right bank of Bateria Creek	1 (E)	L_2	1.2～1.6	L_2	3:2～1:1
Left bank of Segan Creek	5 (E) 5 (W) 9 (E) 26 (E)	M M M M			
Right bank of Segan Creek	over 5 (E) 1 (E)	L_1 L_2			
Laur to Rizal	2.5 (NE SW) 3.7 (NW)	L L			
Rizal	over 85 (E) over 45 (E) over 20 (E) over 10 (E) 8 (E)	H_1 H_2 M_1 M_2 L			
Digdig ⑦	over 35 (E)	L			
East of Masiil-sill ⑧	5 (E) 1.5 (E)	L_1 L_2	53.2	L_1	10:1
East of San Quintin ⑨	1 (E)	L_2	8.3 20.5	L_2 L_1	8:1
San Manuel	38 (NE) 4.5 (NE) 2.5 (NE)	M L_1 L_2			

The ratio of horizontal and vertical displacements is deduced from clear breaks on geomorphic surfaces in some localities (Table 1). Among them, along the fault traces between Masiil-siil and San Quintin, horizontal component of the movement far exceeds the vertical one. On the contrary, the ratio is nearly equal or the former excels a little the latter on the fault traces between Gabaldon and

Laur.

The maximum amount of stream off-set reaches 700 m, suggesting continuous sinistral displacement along the fault during late Quaternary. Continuous vertical displacement along the fault is typically recorded in multi-cyclic river terraces around Rizal.

Thus, ratio of horizontal and vertical displacements varies in places, although left-lateral displacement is consistently recognized throughout the fault zone. As plant fossil samples were collected from terrace deposits in some places for radiocarbon measurement, rate of displacement will be further discussed in future after dating of geomorphic surfaces.

Acknowledgement

The writers are deeply indebted to Professor K. Nishimura of Tohoku University, Japan for his continuous and valuable guide.

The writers are grateful to the staff of the Bureau of Mines, Philippines for their help and valuable suggestion. Thanks are also due to Mr. G.R. Balce of Tohoku University for his kind adivce and encouragement.

The writers would have never completed their work if it had not been for the grateful help of Mr. L. Estabillo and his family, who offered them a residence and supported them throughout their field investigation.

Mr. H. Mogi of Suiran high school, Japan, was kind enough to arrange for their investigation in Luzon.

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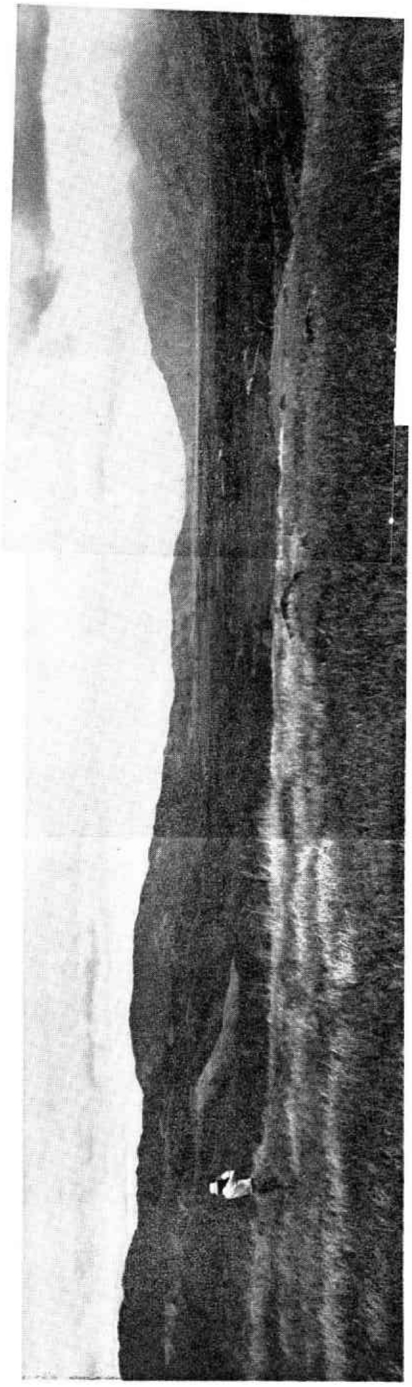
Plate I

Photo 1 & Fig. 11 Fault scarplet and depression to the north of Dingalan Bay

Photo 2 & Fig. 12 Fault sag to the south of Gabaldon (Loc. 1)

Plate II



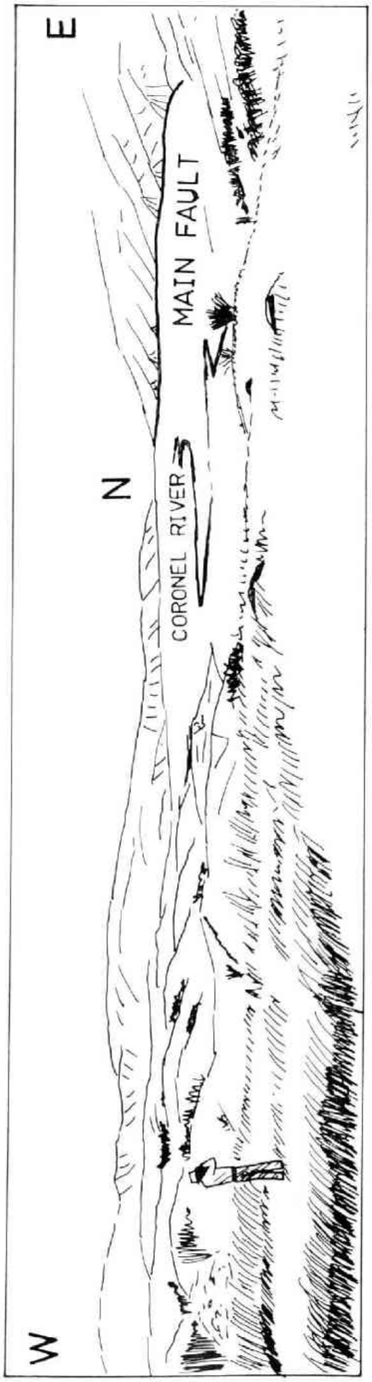


Photo 3 & Fig. 13 Large fault depression in the upper Coronel river basin

Plate III

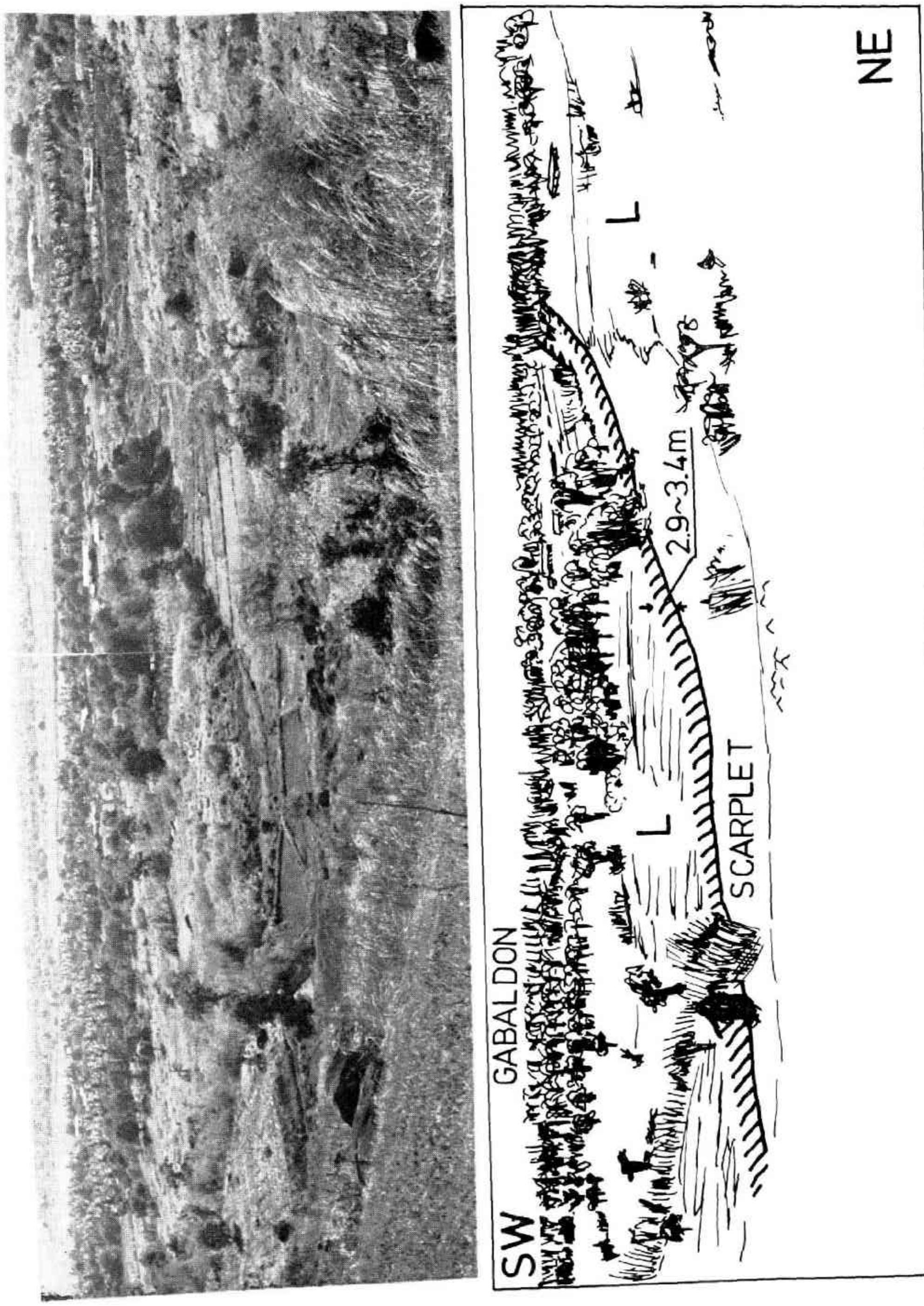


Photo 4 & Fig. 14 Fault scarplet to the east of Gabaldon (Loc. 2)

Plate IV

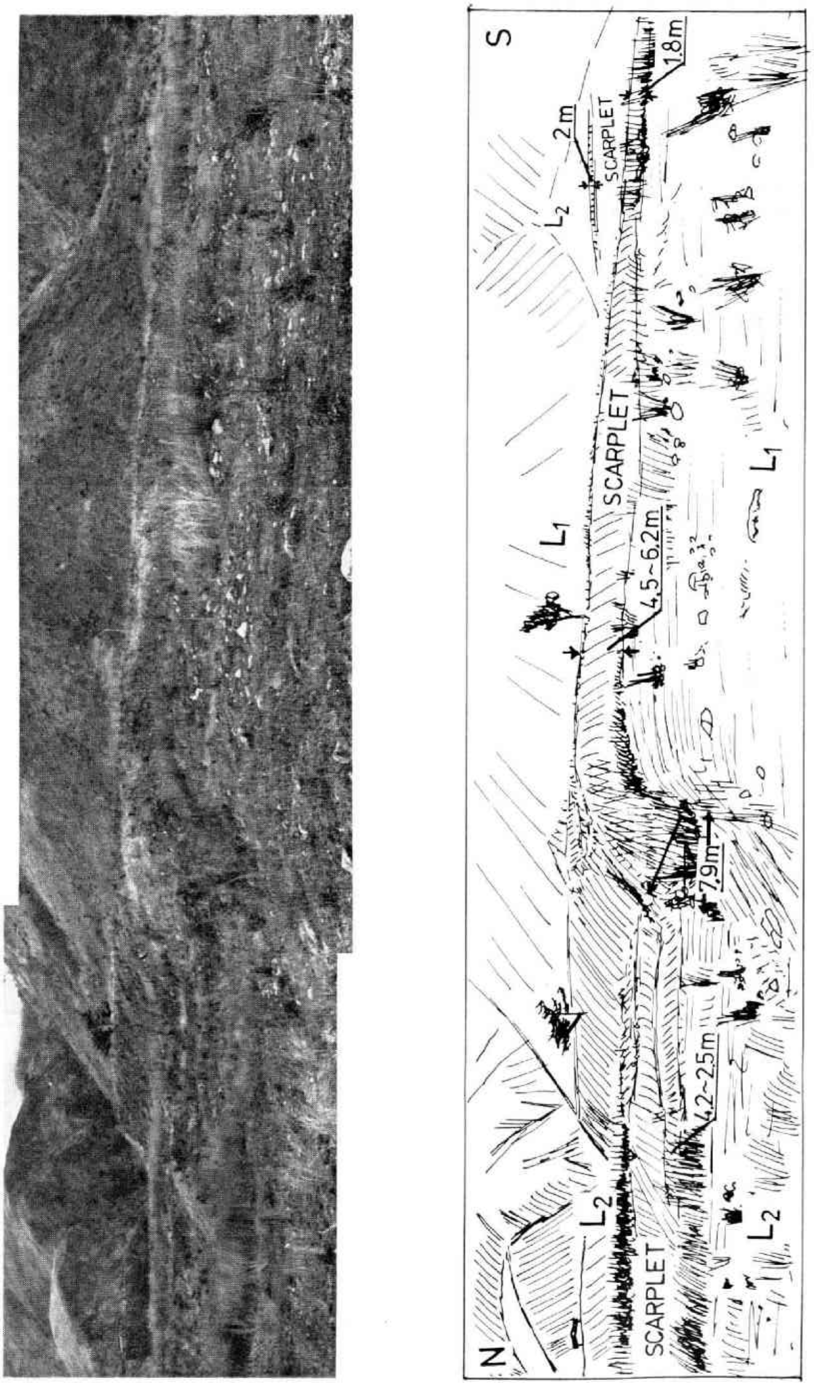


Photo 5 & Fig. 15 Displacement on the alluvial fan on the left bank of Bateria Creek (Loc. 5)

Plate V

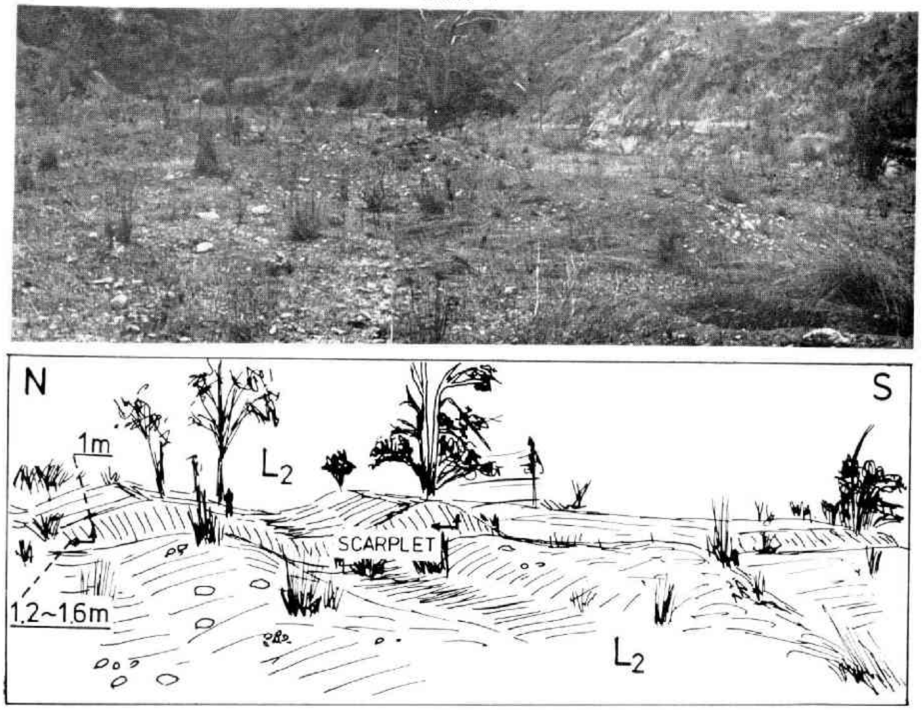


Photo 6 & Fig. 16 Left-lateral displacement of micro-fluvial landforms on the terrace on the right bank of Bateria Creek

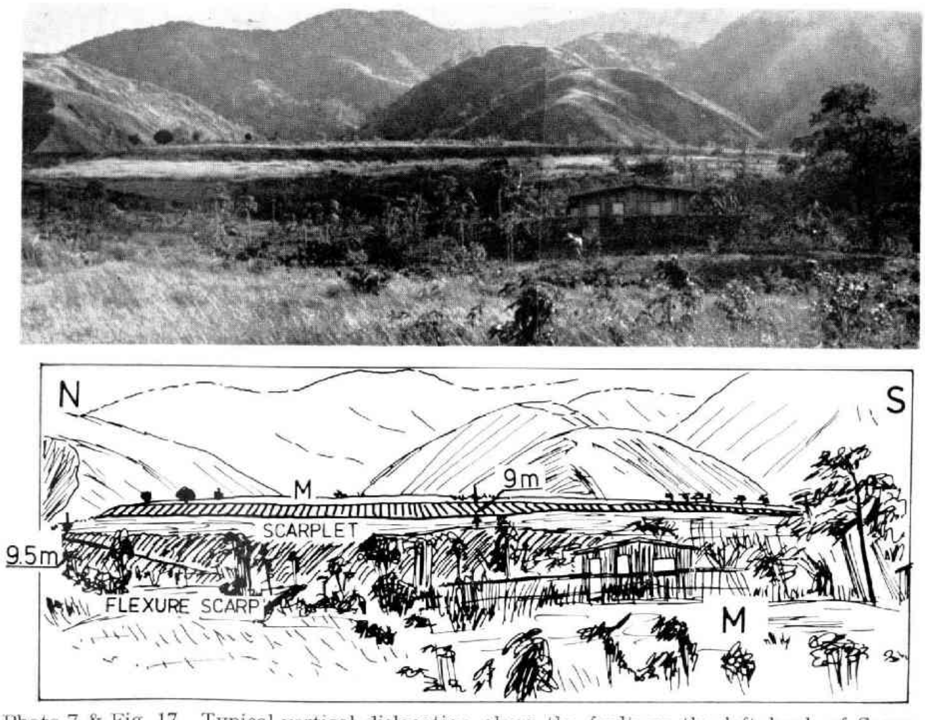
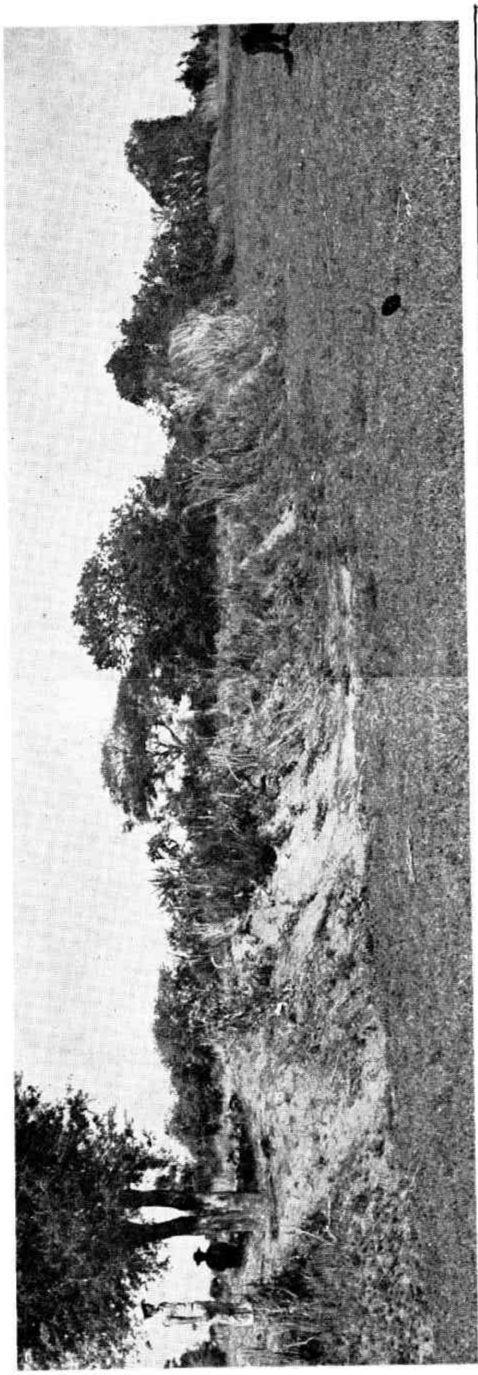


Photo 7 & Fig. 17 Typical vertical dislocation along the fault on the left bank of Segan Creek

Plate VI



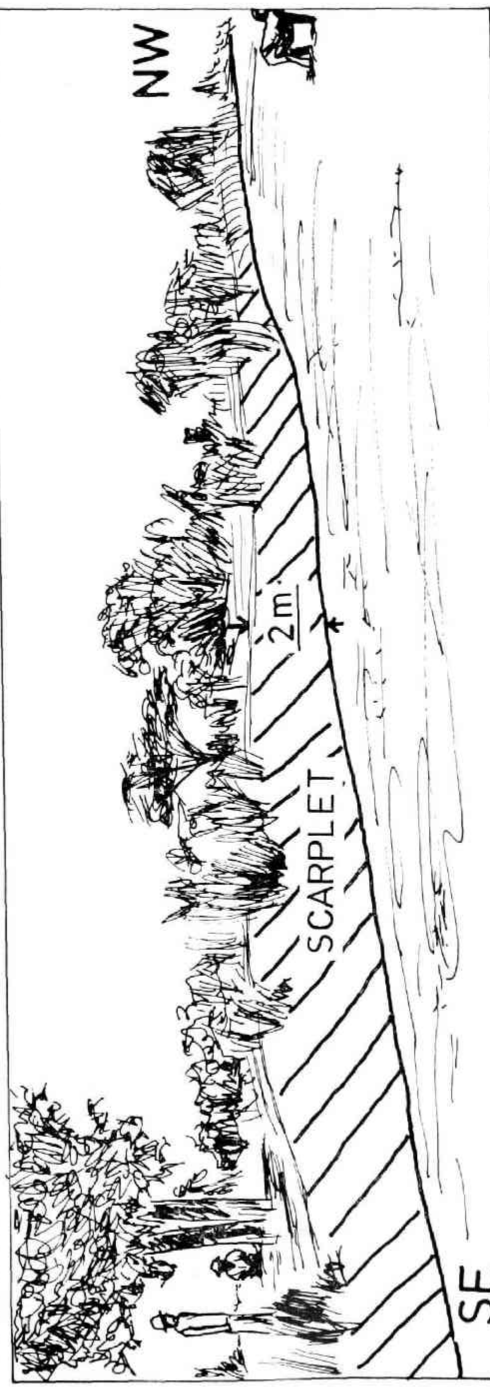


Photo 8 & Fig. 18 Eastward facing scarplet on the alluvial plain to the northeast of Vega Grande

Plate VII

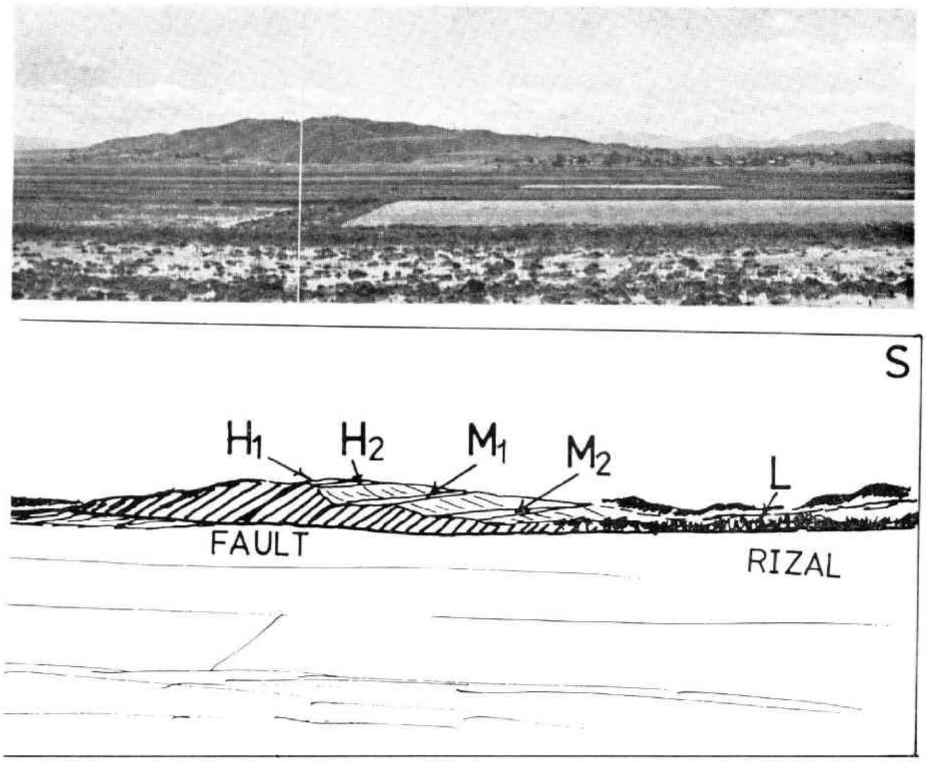


Photo 9 & Fig. 19 Continuous displacement of river terraces on the right bank of the Pampanga at Rizal

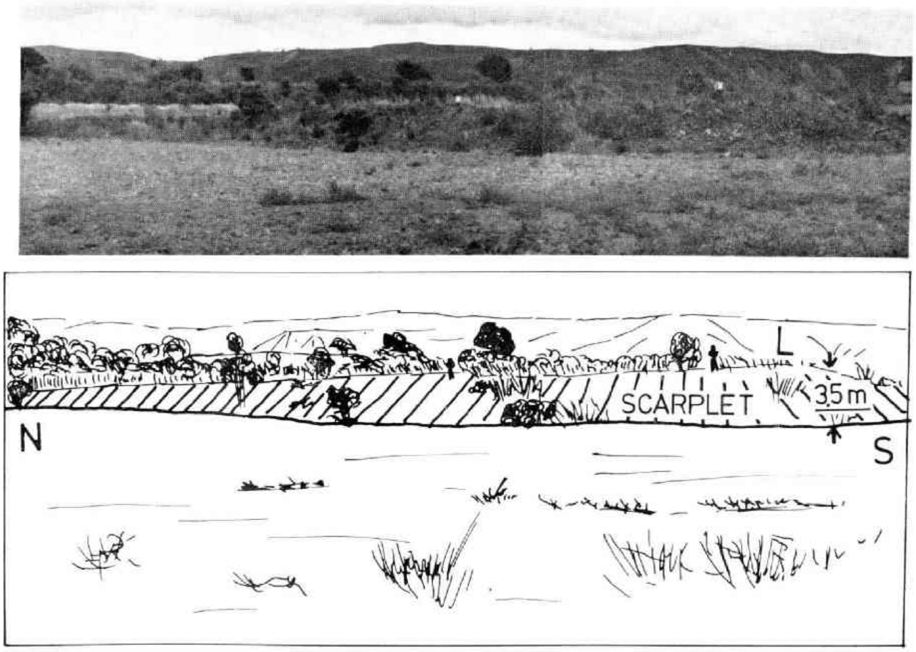


Photo 10 & Fig. 20 Fault escarpment along the main fault on the river terrace at Digdig

Plate VIII

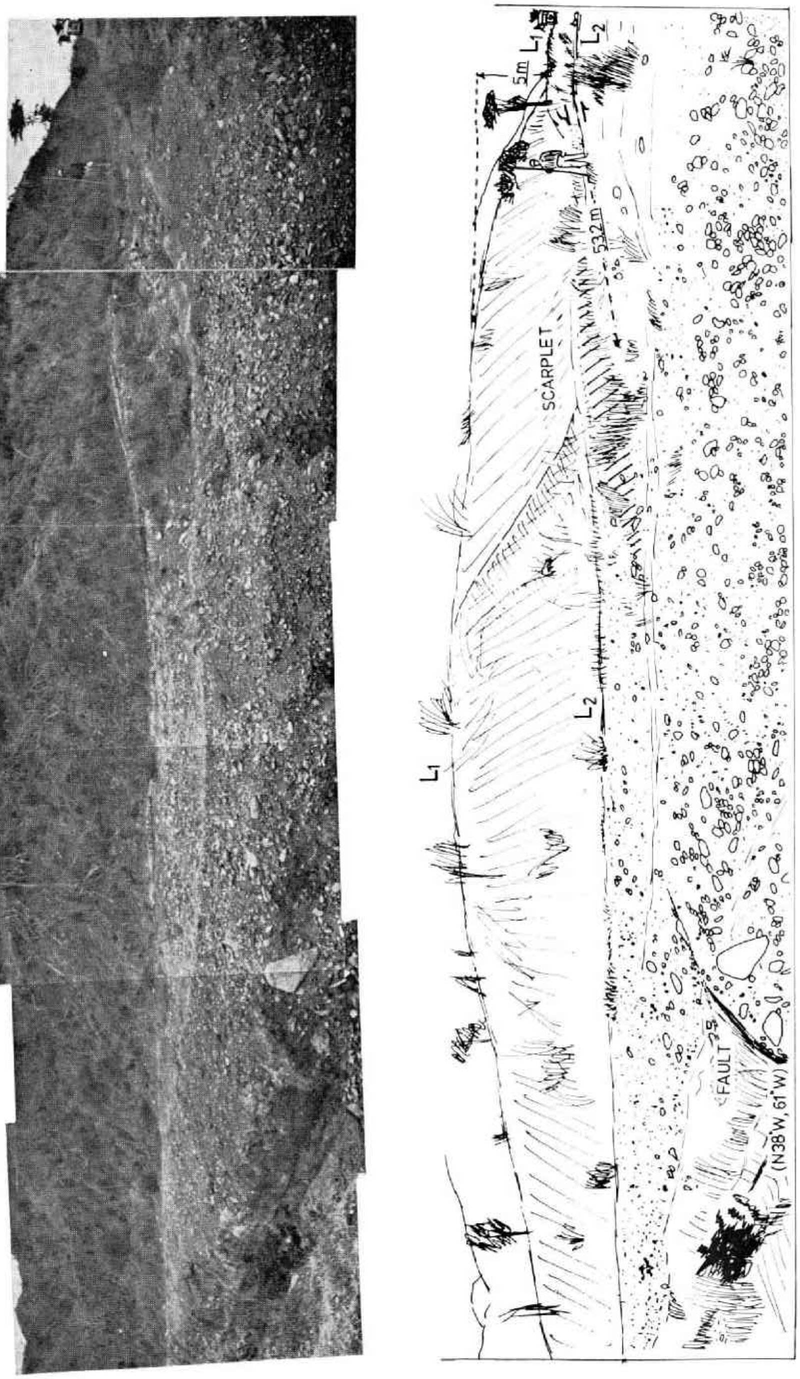
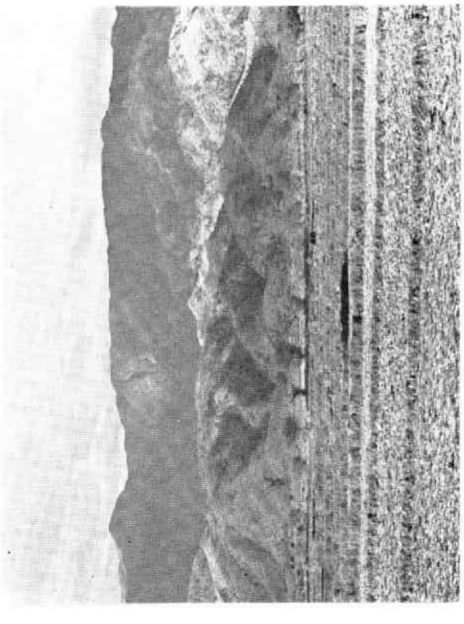


Photo 11 & Fig. 21 Fault scarplet and outcrop to the northeast of Masil-sil (Loc. 8)

Plate IX



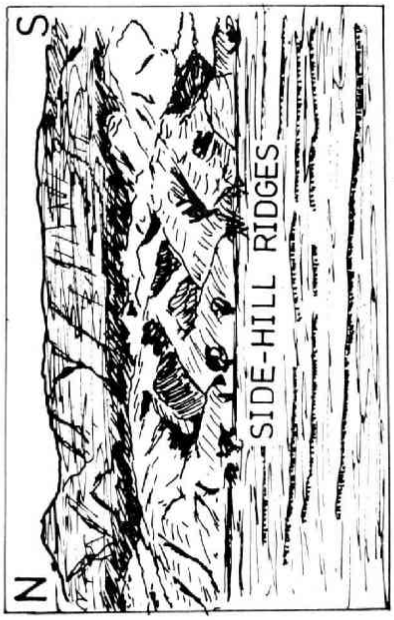
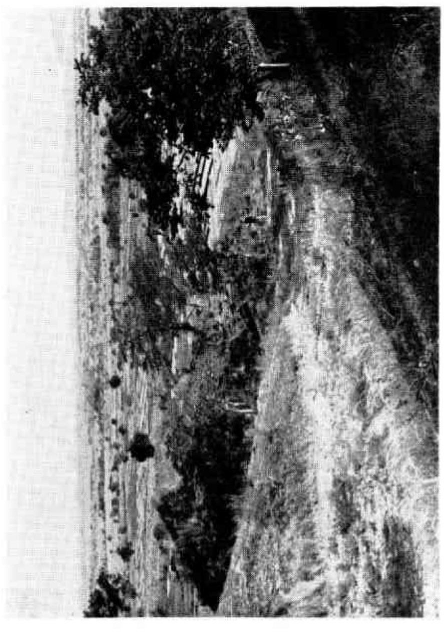


Photo 12 & Fig. 22 Typical side-hill ridges along the fault at the foot of Caraball



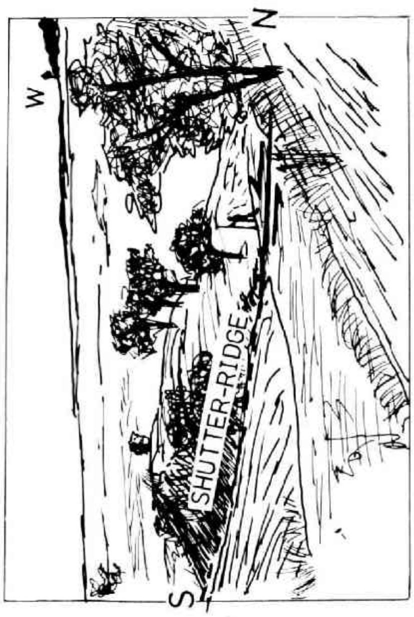
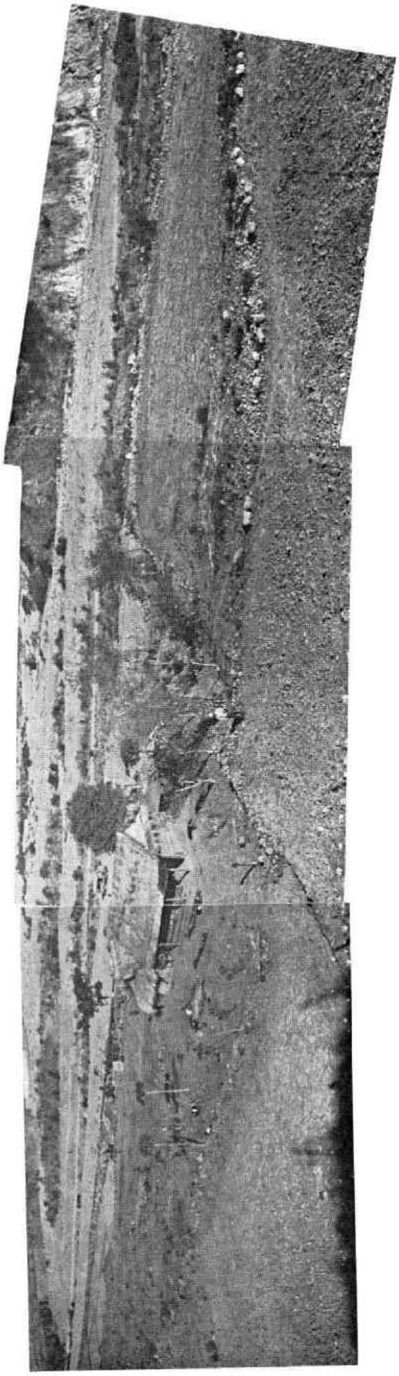


Photo 13 & Fig. 23 Shutter-ridge to the east of Sinabodo

Plate X



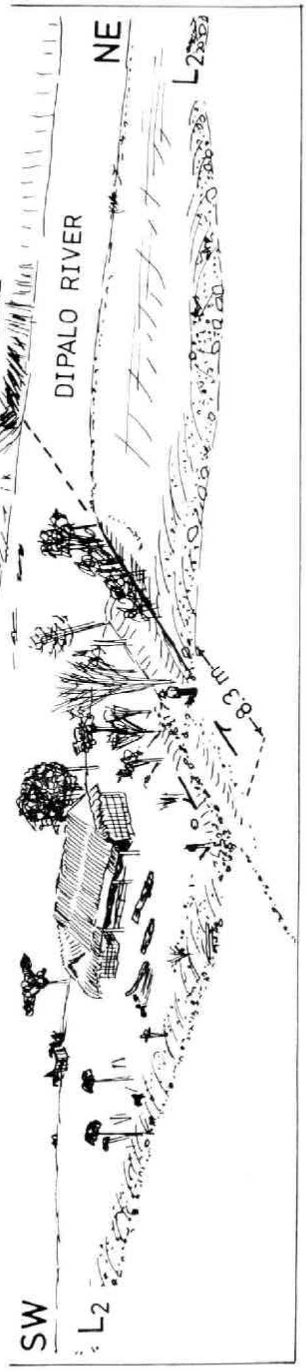
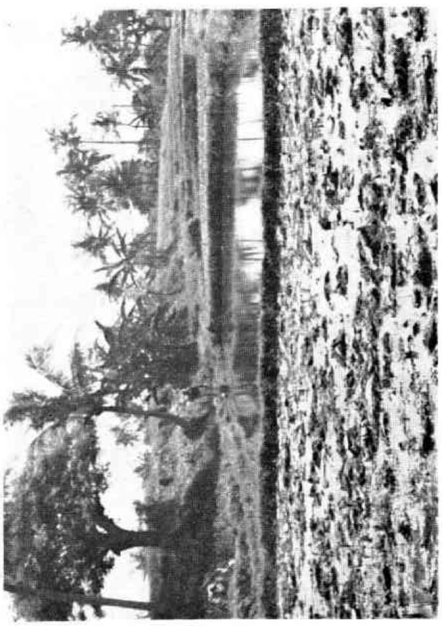


Photo 14 & Fig. 24 Remarkable sinistral displacement of river terrace on the left bank of the Dipalo (Loc. 9)

Plate XI



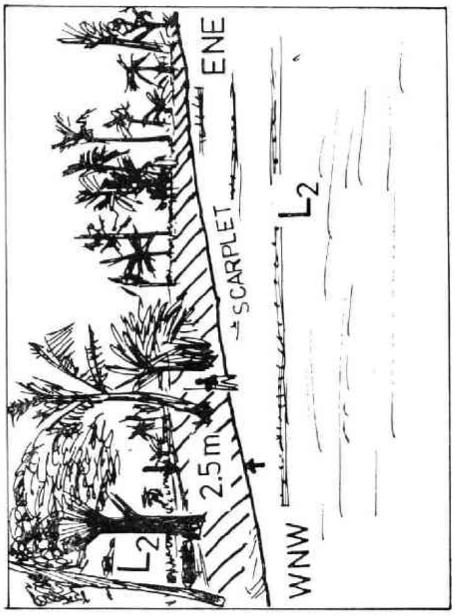


Photo 15 & Fig. 25 Fault scarplet to the east of San Manuel

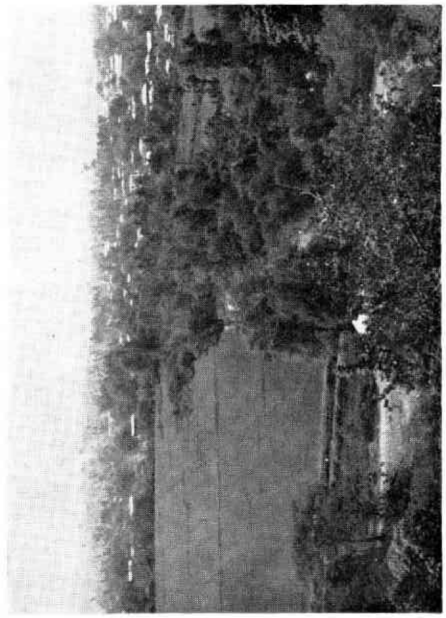


Photo 16 & Fig. 26 Faulted alluvial fan to the northwest of San Manuel