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Late Holocene fluvial aggradation and bedrock incision in an active mountain belt, Li-wu River, eastern Taiwan

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ABSTRACT

Although over long term an orogen that has been actively deforming would maintain a theoretical steady state with erosion balancing rock uplift, the short-term evolution of the orogen is strongly dictated by climatic forcing and other environmental perturbations such as seismic or rainfall events. The data from the Li-wu River in eastern Taiwan shows that the response of these short-term environmental changes can be quick and drastic. Based on radiocarbon dates of fill terraces, the river had aggraded during ca. 4-2 ka, starting at the river mouth and transferring to the upstream direction, with the maximum thickness of deposition of 350 m. The subsequent incision cut locally through bedrock (marble/schist) where the channel had shifted laterally away from its original position during or after the aggradation. The rate of this bedrock incision is up to > 10 mm/yr (and likely > 20 mm/yr). Even considering only the net incision of bedrock since the time before the aggradation, the rate obtained in the upper part of the river is much higher than the long-term rock uplift rate of 3-6 mm/yr. The observed aggradation corresponds to a relatively cool and dry climate recorded by palynological data. This suggests that lowering of tree line and enhancing of periglacial processes in the upper part of the catchment may have played important roles upon the excessive supply of the sediments that caused the aggradation. Alternatively, the aggradation may be simply triggered by some seismic or rainfall events. In any cases, given the capability of the river to incise bedrock, episodic deposition that temporarily retards or stops the incision is likely to be a norm for the river, such that over long term the incision and rock uplift can be mutually balanced.

Keywords: Landscape evolution; Liwu River; Climate change; Fill terrace; Bedrock incision

INTRODUCTION

Provided by steep valley walls, narrow bedrock channels, and lack of significant modern sediment storage, studies of mountain-river evolution commonly put emphasis on erosion processes. Proposing river's boundary shear stress, or rate of energy expenditure, a primary agent leads to the stream-power hypothesis for formulating fluvial incision into bedrock (e.g., Howard et al., 1994; Whipple and Tucker, 1999). Assuming that fluvial incision rates define regional erosion rates (e.g., Tucker and Slingerland, 1996; Willett, 1999) and that the erosion checks rock uplift (e.g., Synder et al., 2000; Kirby and Whipple, 2001) further facilitates modeling the evolution of mountain landscapes under various conditions.

On the other hand, it is known that many variables in river systems, such as channel transport capacity and sediment supply from hillslopes, are subject to the dynamic forcing of climate and other irregularly varying controls (e.g., hazardous earthquakes or rainfalls). These controls would affect the rate of bedrock erosion, by changing either the stream power or amounts of abrasion tools for erosion (Sklar and Dietrich, 1998). To an extent, the long-term erosion trend of mountain rivers may temporarily reverse, as shown by the occurrence of flights of fill terraces in many active orogenic belts (e.g., Bull, 1991; Porter et al., 1992; Lavé and Avouac, 2000; Pratt et al., 2004). Although commonly ignored, the degree and frequency of these short-term unsteady geomorphic processes determine how well, over given time and spatial scales, the known mountain evolution models can apply to the real landscapes.

To predict or evaluate short-term landscape evolution is, however, difficult. This is due, in part, to the insufficient knowledge about the nature of the external forcing operating on this time span (such as intensity and frequency of heavy rainfall in given climate conditions). Also, different catchments (or parts of the catchments) may have different sensitivity and adjustability to given environmental perturbations.

The resulting response of landscape (timing and extent) thus may vary from place to place (e.g., Schumm, 1973). To improve the understanding about this dynamic system relies directly on field observations about landscape histories, in association with independently derived paleo-environmental data (such as paleo-climate and paleo-seismic data).

In this paper, we present the late Holocene history of the Li-wu River in eastern Taiwan. The river drains one of the most active mountain belts in the world. High relief and steep valleys manifest the long-term incision trend of the river in response to rock uplift. Fission-track data suggest denudation rates of 3-6 mm/yr (Liu, 1982; Willett, et al., 2003). Repeated surveys yielded ongoing bedrock incision rates of several millimeters per year (Hartshorn et al., 2002). Still, the river had aggraded, as recorded by a series of fill terraces up to four hundred meters in height. Lin (1957) studied these terraces when aerial photographs and detailed topographic maps were not available. We re-investigated these terraces and dated them by the radiocarbon method. A great portion of our data was collected during 1987-1990, when the river basin was under numerous constructions by the power company (Liu, 1989; Chi, 1995). Still, some key outcrops were revealed recently. Combining all these data allows us to re-interpret the river history.

Lin (1957) pointed out that the source of the gravels that constitute the fill terraces is different from the modern channel. To substantiate this point, which may be important for understanding the genesis of the terraces, we counted gravels of different lithological types at multiple sites of the modern channel and terraces. We also estimated the river incision rates since the abandonment of the terraces, which includes incision cutting into the fill sediments and the bedrock underneath. We further assessed the rates of incision that cuts purely through bedrock. These rates were compared to the long-term and current erosion rates. Finally, we discussed the origin of these terraces and their environmental bearings by taking into account the known paleo-climate records in Taiwan.

REGIONAL SETTING

General. The Li-wu River (basin area 620 km^2) is one of the major transverse rivers draining the eastern slope of the Central Range, Taiwan (Fig. 1). The Taiwan orogen results from the active collision between the Chinese continental margin and the Luzon volcanic arc starting at about 5 Ma (Fig. 1) (Chai, 1972; Bowin et al., 1978; Teng, 1990). The Central Range, 3000s m-high and forming the backbone of the orogen (Fig. 1), is composed of metamorphosed pre-Tertiary continental basement and its Cenozoic sedimentary cover. The range has been rapidly exhumed, with ziron and apatite fission-track ages of commonly < 3 Ma, or equivalent to denudation rates of 3-6 mm/yr (Liu, 1982; Willett, et al., 2003). This high rate of erosion is believed to have been balanced by rock uplift, with the height of the range reaching a dynamic steady-state condition (Willett et al., 2001).

The Central Range is non-glaciated, under a tropical-subtropical monsoon climate and receives annual rainfall of 2000-3000 mm, much of which is brought about by tropical typhoons. The range shows clear vertical zoning of vegetation. To date, temperate to tropical forests typically grow below 3000 m in elevation, above which alpine scrub and bamboo grassland dominate.

The main divide of the Central Range bounding the Li-wu catchment is higher than the divide to the north and to the south. The highest peak of the catchment (the Nan-hu Mountain), located in the north, is 3700s m high above the sea level (Fig. 2). This peak is drained by the south-flowing Tai-sai River (drainage area 180 km^2), the largest tributary of the Li-wu River. It joins the trunk stream, or the Ta-tzu-chi-li River (drainage area 250 km^2), at Tien-hsiang (Fig. 2). Between the main-stem Tai-sai and Ta-tzu-chi-li rivers, there are two major tributaries: the Wa-hel River (joining the Ta-tzu-chi-li River near Tien-hsiang) and the Hsiao-wa-hel River (tributary of the Tai-sai River) (Fig. 2). Some morphometric elements of these rivers are summarized in Table 1.

The rocks underlying the Li-wu catchment include: (1) low-grade meta-sedimentary rock (slate, argillite, phillite, meta-sandstone, and meta-conglomerate) exposed around the main divide of the Central Range, (2) a mixture of schist complex (black, green and siliceous schists) in the middle part of the basin, and (3) thick marble and some gneiss in the lower catchment (Fig. 3). The major foliation and rock boundaries trend NE, or oblique to most of the major river valleys. The densely foliated slate and schists are believed to be the least resistant rock formation in the river basin. Hartshorn et al. (2002) reported a value of tensile strength of 5.3 MPa for the schists by using the Brazilian tension splitting method. The meta-sandstone and meta-conglomerate are perhaps the most resistant. They are, however, generally thin (few meters in thickness) and have limited effects on the regional river morphology. In contrast, the thick marble in the lower part of the river basin, exhibiting a tensile strength of 9-10 MPa (Sklar and Dietrich, 2001), forms the several-hundred-meter-high Ta-ro-ko Gorge (Figs. 2 and 3).

Ongoing erosion. To understand the ongoing bedrock erosion rates in the Li-wu River, Hartshorn et al. (2002) conducted detailed surveys at a site about 1.5 km downstream of Tien-hsiang. They obtained incision rates of 2-6 mm near the base of the channel (0.5-1 m above the low-flow line) during a year of no great floods. In contrast, a super-typhoon resulted in erosion of commonly 10-30 mm, and locally up to 180 mm where a joint-bound block was plucked away. Most of this erosion, however, took place at higher channel levels (2-4 m above the low-flow line). Prorating the erosion for the return period of the typhoon (about 20 years) yields incision rates of 0.3-1.7 mm/yr for the rock surface near the base of the channel.

Combining the data from both the normal and super-typhoon years yields ongoing bedrock incision rates of 2-8 mm/yr, which may be considered matching well with the long-term denudation rates derived from fission-track data.

METHODS

We mapped river terraces from aerial photographs and plotted them onto 1-to-25,000 scale topographic maps issued by Ministry of the Interior. The elevation of the terrace surfaces was determined from these maps and referenced to the elevation of the modern channel defined on the maps. As the maps have a contour interval of 10 m, the determined height of the terraces would have an uncertainty of 10 m (i.e. terraces with heights < 10 m are not differentiated in this study). Modern channel longitudinal profiles and valley cross sections also are based on these maps.

We then examined the stratigraphy of terrace deposits and underlying bedrock configuration in the field. Plant fragments within the terrace deposits were sought for radiocarbon dating. All the radiocarbon ages are calibrated by using the program of CALIB REV4.4.2 (Stuiver and Reimer, 1993), and expressed as 1σ ranges. The thickness of the deposits and height of any targets (e.g., bedrock surface and carbon samples) relative to local datum (e.g., channel level) were measured by hand leveling, altimeter or laser rangefinder.

To understand the temporal change in source of the sediments, we counted gravels of different lithological types at multiple sites of the modern channel and terraces (proceeded on the spring and early summer of 2003). Only cobble-sized gravels were counted; they were randomly collected on channel bars or outcrops to a number of at least 100 at each site.

RESULTS AND INTERPRETATION

Terrace distribution and constitution. River terraces (and terrace remnants), including an abandoned alluvial fan emanating from the river mouth, are developed (or preserved) mainly along the trunk stream downstream from Tien-hsiang and along the Tai-sai River (Figs. 2, 4, and 5). These terraces consist of multiple steps and show complex sequences. The number of the steps varies from river reach to reach. Even at similar levels above the modern channel, strath-typed terrace (with < 10 m-thick sediment cover) and fill-typed terrace (with > 20 m thick sediments) alternate along the river (Fig. 6). Most of these terraces, up to 420 m high above the modern channel, develop fresh soil horizons. Lateritic soil was reported only on terrace remnants > 150s m high above the modern channel near the river mouth (Figs. 4a and 6) (Lin, 1957).

The sediments constituting the fill-typed terraces in the Li-wu River generally thicken to the upstream direction. At the river mouth, the maximal thickness of the sediments exposed (i.e. at the proximal part of the alluvial fan) is 40-50 m. The thickness of the deposits is up to 180 m at Pu-lo-wan (Fig. 4, Section II), 240 m near Tien-hsiang (Fig. 5, Section IV), and reaches the maximum of 280 m at His-pao (Fig. 5, Section V). These sediments are composed mainly of pebble-cobble-sized gravels with thin sandy layers. They are generally sorted and stratified, similar to those exposed on the modern channel that show the influence of water flood or hyperconcentrated flow. However, there are significant parts of the gravels in the terraces that are disorganized and poorly sorted. They consist commonly of angular to sub-angular clasts with abundant fine-grained matrix, and are likely to be of debris-flow origin.

The observed thick fill sediments, except those near and downstream of the river mouth, are all underlain by bedrock. Depositional terraces with no bedrock underneath are all < 40 m in height, and occur only in the upper parts of the Tai-sai and Ta-tzu-chi-li rivers. Unlike the bedrock that forms strath terraces, the bedrock underlying the thick fill sediments is rarely observed as flat surfaces. Instead, the boundaries between the sediments and bedrock in these terraces are irregular or steeply inclined. At some places, the bedrock underlying the terraces is bounded on both the upstream and downstream sides by thick fill sediments, suggesting the existence of bedrock valleys buried in the terraces. We recognized such paleo-valleys at six sites (Figs. 4 and 5). The rivers that created these paleo-valleys can be inferred from the distribution of the valley-fill sediments, supplemented by paleo-current data revealed by gravel imbrication (Liu, 1989). The paleo-valleys near the river mouth, at Pu-lo-wan and Ho-liu were apparently eroded by the trunk stream (Fig. 4). The paleo-valley east of Tien-hsiang and that underneath the divide separating the Tai-sai and Ta-tzu-chi-li rivers are likely to have been occupied by the Tai-sai and Wa-hel rivers, respectively (Fig. 5a). The paleo-valley near the junction of the Tai-sai and Hsiao-wa-hel rivers (Fig. 5b) was apparently created by the Hsiao-wa-hel River.

The widths of our observed paleo-valleys are comparable to those of the adjacent valleys occupied by the modern channel, except for the one near the river mouth, which appears to be narrower (Fig. 4a). The base of the paleo-valley near the river mouth is still buried by the modern fluvial sediments (Fig. 4a, Section I). The base of the paleo-valley at Pu-lo-wan is about 20 m high above the modern channel (Fig. 4b, Section II). They are all 35-40 m high for the paleo-valleys at Ho-liu, east of Tien-hsiang, and near the junction of the Tai-sai and Hsiao-wa-hel rivers (Figs. 4c and 5). The base of the paleo-valley created by the Wa-hel River is 10-15 m high at the side facing the modern Wa-hel River, but is 40-50 m high at the side connecting to the modern Ta-tzu-chi-li River (Fig. 5a). This contrast in high is apparently caused by the greater incision of the Ta-tzu-chi-li River than the Wa-hel River since the formation of the paleo-valley, resulting in a significant knickpoint in the downstream-most part of the Wa-hel River (downstream of Site 14 in Fig. 5a).

Most of our observed paleo-valleys have been reported by Lin (1957). By using gold mining data back to 1920s, Lin (1957) confirmed that fluvial gravel is at least 250 m thick at the center of the terrace remnant east of Tien-hsiang, although bedrock crops out on the side of the modern channel to at least 200 m in height.

The preservation of these paleo-valleys requires that the channels had shifted or jumped laterally before or during the subsequent incision. At Pu-lo-wan, this could have occurred as meander cutoff, as shown by the map-view shape of the paleo-valley (Fig. 4b). The aggradation of the sediments that buried the valley could have narrowed the meander neck and facilitated the cutoff. Around the Tien-hsiang area, the distribution of the fill sediments shows that the drainage divides that had separated the Tai-sai and Wa-hel rivers from the Ta-tzu-chi-li River were entirely inundated by the aggraded sediments (Fig. 5a). Consequently, a wide floodplain developed around the downstream-most parts of both the Tai-sai and Wa-hel rivers, which allowed the two rivers, having flowed parallel to the Ta-tzu-chi-li River, to shift freely and take shorter courses to join the Ta-tzu-chi-li River (Fig. 5a). For the other paleo-valleys to be preserved, either the river had significantly trimmed bedrock laterally during or after the aggradation (Fig. 7), or there have existed wide valleys created long before the formation of the observed paleo-valleys (see discussion below).

Terrace chronology and river-incision rate. River terraces capped by lateritic soil in Taiwan are believed to have been abandoned no later than about 30 ka, according to available radiocarbon dates (Liu, 1990; Hsieh and Knuepfer, 2002; Ota, et al., 2002). This constrains the formation time of the reported lateritic terraces near the mouth of the Li-wu River. For the non-lateritic terraces in the river, they are likely to be Holocene in age. We obtained six radiocarbon dates from five terraces (Table 2), all of which are derived from wood fragments within muddy debris-flow deposits. Two dates, < 200 yr.BP and 153-418 cal.yr.BP (1σ range), are sampled from the lower-level (<30 m high) depositional terraces in the upper parts of the Ta-tzu-chi-li and Tai-sai rivers (Table 2; Fig. 2). The date of 2470-2710 cal.yr.BP and 2348-2486 cal.yr.BP are obtained from, respectively, the terrace at the junction of the Tai-sai and Hsiao-wa-hel rivers (Section VI; Fig. 5) and underneath the divide between the Tai-sai and Ta-tzu-chi-li rivers (Section IV; Fig. 5). Both are dated at the lower parts of the thick fill sequences. The rest two dates, 3273-3549 cal.yr.BP and 3570-3810 cal.yr.BP, are from sediments (at the same stratigraphic position) filling the paleo-valley near the river mouth (Section I; Fig. 4).

All the dates yield extremely high rates of river sedimentation and subsequent incision. The development of the terraces of few tens of meters in height (aggradation followed by incision) would have taken only few hundred years in the upper parts of both the Ta-tzu-chi-li and Tai-sai rivers. At the junction of the Tai-sai and Hsiao-wa-hel rivers, the rivers has aggraded by at least 150 m (calculated from the dated sample to the local top of the terrace remnant) and subsequently downcut by more than 200 m since 2.5-2.7 ka (Fig. 5, Section VI). As the downcutting must have occurred after 2.5-2.7 ka, the river incision since then proceeded at a rate of > 70 mm/yr. Similarly, based on the dates and the height of the terrace remnant, a downcutting rate of > 100 mm/yr is obtained near the junction of the Tai-sai and Ta-tzu-chi-li rivers (Fig. 5, Section IV), and of > 10 mm/yr near the river mouth (Fig. 4, Section I).

The calculated incision rates since the abandonment of the terraces are for rivers cutting mainly into unconsolidated sediments deposited previously. However, where the paleo-valleys are preserved, a considerable portion of bedrock next to the valleys must have been cut at the same pace as cutting of the sediments in the upstream and downstream directions (Fig. 7). The heights of the bedrock ridges between the paleo-valleys and the modern rivers next to them are about 20 m near the river mouth (Section I), 150 m at Pu-lo-wan (Section II), 100 m at Ho-liu (Section III) (Fig. 4), and 70 m at the junction of the Tai-sai and Hsiao-wa-hel rivers (Section VI; Fig. 5) (the heights of the bedrock separating the modern Tai-sai and Wa-hel rivers from their paleo-valleys are unclear, due to the almost orthogonal intersecting of the modern- and paleo-valleys; Fig. 5a). Given that the filling of the paleo-valley near the junction of the Tai-sai and Hsiao-wa-hel rivers ended after 2.5-2.7 ka, and assuming that the entire 70 m high bedrock exposed here was cut after then, we obtained a bedrock incision rate of > 26 mm/yr at this local river reach (Section VI; Fig. 5).

The incision that abandoned the terraces has eventually cut through the sediments and carved entirely into bedrock, as shown by the preserved paleo-valleys with bases higher than the modern channel. These abandoned valley bases must have been created prior to the dates derived from the sediments filling the valleys. The 35-40 m-high base of the paleo-valley near the junction of the Tai-sai and Hsiao-wa-hel rivers thus yields an incision rate of < 14 mm/yr since the formation of the valley. Underneath the divide between the Tai-sai and Ta-tzu-chi-li rivers, the 10-15 m-high paleo-valley base (created by the Wa-hel River) facing the Wa-hel River yields an incision rate of < 6 mm/yr. At the other side of the same paleo-valley facing the Ta-tzu-chi-li River, the 40-50 m high relief between the paleo-valley base and the modern channel yields an incision rate of < 20 mm/yr. The base of the paleo-valley near the river mouth is lower than the modern channel, indicating that nearly no net incision has occurred in the past ~4 ky.

Terrace correlation and river history. Although multiple steps of fill-typed terraces are developed, no evidence shows that the thick sedimentary sequences filling the paleo-valleys had been truncated and re-deposited. If these multiple steps of terraces had resulted from repeated river aggradation and incision, the true river sedimentation and downcutting rates would have been much higher than what we have calculated. We considered this to be unlikely and propose that there is only one major aggradation-incision cycle after the formation of the observed paleo-valleys.

We smoothly connected the terrace treads and the tops of the terrace remnants that are underlain by the locally thickest sediments, including the abandoned alluvial fan at the river mouth. The resulting river long-profile consists of a steeper, upper part (average gradient 0.060) and a gentler, lower part (average gradient 0.034), with the inflection point (or zone) located at the Ta-ro-ko Gorge (Fig. 6). The upper part of the profile is roughly parallel to the modern Tai-sai River Valley, and the lower part converges downstream toward the modern trunk-stream river (Fig. 6). We regard this correlation to be reasonable, if not unique. It follows that most of the terraces lower than this correlated profile are cut terraces, resulting from sporadic lateral erosion on the long-term incision. This suitably explains why the strath- and fill-typed terraces alternate along the river, because the lateral erosion could have cut into the previously aggraded sediments at some places (forming fill-cut terraces) but cut into bedrock at other places. Aggradation of up to 30 m thick sediments had re-occurred within the recent few hundreds of years, according to the dates. This aggradation, however, is only restricted in the upper Ta-tzu-chi-li and Tai-sai rivers. The following incision has not yet reached bedrock underneath these aggraded sediments.

Our correlation suggests that during the major aggradation episode, the 30s km-long Li-wu River from the river mouth to much of the Tai-sai River had entirely been inundated by alluvium. The aggradation must have extended to the Ta-tzu-chi-li and other rivers, but the evidence for this is poorly preserved (still, >80 m think sediments are locally preserved as terraces remnants in the Wa-hel River two kilometers upstream of the junction with the Ta-tzu-chi-li River; Fig. 2). According to the dating data, this aggradation, beginning prior to 3.5 ka, started at the river mouth and transferred to the upstream direction. The aggradation at the upper part of the Tai-sai River ended after 2.5 ka. Given that the observed bases of the paleo-valleys in the Tai-sai River are 35-40 m high above the modern channel, the maximum thickness of the sediments deposited during the aggradation is about 350 m.

We estimated the volume of the aggraded sediments by using the correlated river long-profile and the heights of the paleo-valley bottoms. We linearly extended the correlated river profile in the Tai-sai River to the upstream direction and used the gradient of this long-profile to restore the extent of the aggraded sediments in the Ta-tzu-chi-li, Wa-hel, and Hsiao-wa-hel rivers. The base of these sediments is assumed 40 m high above the modern channel for these three rivers. For the first order approximation, we assigned the average width of all the valleys that contained these sediments to be 250 m, which is about the average width of the modern major valleys upstream from the Ta-ro-ko Gorge (measured at elevations about 150 m high above the channel). The resulting volume of the aggraded sediments is about 3.5 km^3 (not including the volume of the alluvial fan at the river mouth, which is 0.3 km^3). Two third of this volume are equally distributed in the main-stem Ta-tzu-chi-li and Tai-sai rivers, 5% and 6%, respectively, in the Wa-hel and Hsiao-wa-hel rivers. Assuming that all these sediments were accumulated in two thousand years (from 4 ka to 2 ka), we obtained an annual deposition rate of 0.0018 km^3/yr, or equivalent to a denudation rate of 2.9 mm/yr for the catchment.

Gravel count. We grouped the counted gravels made up of slate, argillite, black-schist and meta-sandstone as “black-typed” gravel, in comparison with the “green-typed” gravel of green-schist and siliceous-schist origins. These two groups of gravels constitute most of the gravels counted (> 70%) (Table 3). All the gravels counted in the modern river are water-laden deposits on exposed channel bars. The black- and green-typed gravels are roughly equal in percentage in the modern Tai-sai River and the trunk stream downstream from Tien-hsiang (Sites 1-12; Fig. 8). The black-typed gravels, however, are two-to-three folds more than the green-typed gravels in the modern Ta-tzu-chi-li River (Sites 13) and the Wa-hel River (Site 14) (Fig. 8). This indicates that at least during the survey period (spring and early summer of 2003), the Tai-sai River contributes to most of the gravel load in the trunk stream downstream from the junction of the Tai-sai and Ta-tzu-chi-li rivers.

The gravels counted from the terraces are mainly hyperconcentrated- and/or debris-flow deposits (Table 3). Unlike those on the modern channel, these gravels are dominantly black-typed (Table 3; Fig. 8). The ratio of the black- to green-typed gravels is generally > 4 at the middle and higher stratigraphic positions of the fill sequences. This ratio even exceeds 40 at Pu-lo-wan (Table 3; Fig. 8), although the nearest black-typed rock (black schists) crops out 7 km in the upstream direction (Figs. 3 and 6). The ratio of the black- to green-typed gravels appears to be smaller at the lower stratigraphic positions of the fill sequences (2.8 near the bottom of the paleo-valley at Ho-liu, and 1.8 at the beds 20 m above the base of the paleo-Hsiao-wa-hel valley) (Fig. 8). These data are consistent with the observation by Lin (1957). By examining mining data, Lin (1957) reported that the sediments within the terrace remnant east of Tien-hsiang are composed mainly of slate- and black-schist-typed gravels, with significant amounts of marble- and green-schist-typed gravels occurring only in the lowest part of the sequence. These facts, together with the more common occurrence of debris-flow deposits in the terraces, suggest that the source and transport history of the sediments during the river aggradation are different from the present.

DISCUSSION AND IMPLICATIONS

River incision rate. We have calculated river incision rates from three aspects: (1) since the abandonment of the terraces (including downcutting into sediments and bedrock), which is generally > 100 mm/yr in the Tai-sai River; (2) from the paleo-valley bottom to the modern channel, which is < 20 mm/yr upstream of the Ta-ro-ko Gorge and nearly none around the river mouth; (3) through bedrock where the channel had significantly shifted laterally before or during the incision, which is > 26 mm/yr at the junction of the Tai-sai and Hsiao-wa-hel rivers. Our correlated terraces are roughly constant in height above the modern channel upstream of the Ta-ro-ko Gorge and lower to the downstream direction from the gorge (Fig. 6). Assuming that the incision took place synchronously along the river (which is, in fact, likely to be earlier in the upper-stream reach [Bull, 1991]), the obtained incision rates (the first type) would be roughly uniform upstream of the Ta-ro-ko Gorge and decrease from there to the river mouth. Our observed paleo-valleys upstream of the Ta-ro-ko Gorge also have bases higher than their counterparts in the downstream reaches. As the deposition that filled these valleys is likely to have started earlier in the downstream reach (i.e. the incision that created the paleo-valleys had ended later in the upstream reach), the resulting incision rates of the second type would be higher upstream than downstream of the Ta-ro-ko Gorge. The incision rates of the third type, constrained by those of the first and the second types, should be similar in pattern with the incision rate of these two types, although the heights of the bedrock separating the paleo-valleys and the modern channels vary randomly along the river. Given that these heights are about 150 m at Pu-lo-wan, 100 m at Ho-liu, and assuming that the bedrock was incised later than 2.5 ka, we obtained incision rates of > 40 mm/yr at both sites.

The extremely high rate of incision since the abandonment of the terraces (the first type) should mainly reflect the low resistance of the aggradated sediments to erosion.

The incision rate calculated from the base of the paleo-valley to the modern channel (the second type) is closer to the long-term rock uplift rate of 3-6 mm/yr. This is especially for the river reaches downstream of the Ta-ro-ko Gorge (at Pu-lo-wan and around the river mouth). For river reaches upstream of the Ta-ro-ko Gorge, the obtained incision rates, < 20 mm/yr, may still be considered higher than the rock uplift rate. We believe that this greater incision (second type) upstream of the Ta-ro-ko Gorge is likely to reflect the greater long-term rock uplift of the region, compared with its counterpart to the downstream direction. Note, however, that even within a distance of only several hundred meters apart, our obtained incision rate (second type) is much higher in the Ta-tzu-chi-li River than in the Wa-hel River. The incision of the Wa-hel River, with a significant knickpoint joining the Ta-tzu-chi-li River, is apparently not directly controlled by rock uplift, although our obtained incison rate here, < 6 mm/yr, may be considered well matching with the long-term rock uplift rate. We believe this match to be coincidental. More likely, our data suggest that > 4 ky is required for the bedrock incision of the upper part of the Li-wu River to be regarded as approaching rock uplift.

The high rate of incision cutting purely through bedrock next to the preserved paleo-valleys (the third type), on the order of 10s mm/yr, may be rather unexpected. This raises a concern about whether the modern valleys abut to the observed paleo-valleys could be inherited from valleys created during the earlier aggradation-incision cycle. Figure 9 depicts this speculation by using the valley topography at Ho-liu as an example. As shown in the figure, a valley with the base H_0 (in meter) higher than the modern channel was presumably created at T_0 (in ka) (Fig. 9a). The river aggraded after T_0 and to a level of >100 m above the modern channel (Fig. 9b). The river then re-incised, while shifting laterally off the original valley, to form the observed paleo-valley. Assume that this incision cut to a level of

100 m above the modern channel at T_a (Fig. 9c), and to the base of the paleo-valley, 35 m high above the modern channel, at T_b (Fig. 9d). The aggradation resumed after T_b and to a level of 350 m above the modern channel (Fig. 9e). The incision started again and presumably reoccupied the level of H_0 at 2 ka before reaching the modern level (Figs. 9f and 9g).

According to Figure 9, the long-term bedrock incision rate (R_0) since T_0 can be formulated as:

$$R_0 = H_0/T_0 \tag{1}$$

The rate of bedrock incision (R_1) cutting from 100 m above the modern channel to the base of the paleo-valley (Figs. 9c and 9d) is:

$$R_1 = 65/(T_a - T_b) \tag{2}$$

In addition, the most recent bedrock incision rate (R_2) since 2 ka (Figs. 9f and 9g) is:

$$R_2 = H_0/2000 \tag{3}$$

Assuming that the long-term rock uplift at this river reach is suitably balanced by the bedrock incision since T_0, or R_0 = 3 mm/yr (lower bound), and given $T_0 > T_a > T_b > 2$ ka, we obtained:

$$R_1 > 65/(T_0 - 2000) \tag{4}$$

and

$$R_2 = 0.0015T_0 \tag{5}$$

Further assuming $R_1 = R_2$, and solving equations 4 and 5, we obtained $T_0 > 7.7$ ka and $R_2 > 11.5$ mm/yr. This rate is the minimum for any ever short-term bedrock incision at the site (e.g., if $R_2 < 11.5$ mm/yr, $T_0 < 7.7$ ka, we obtain $R_1 \gg 11.5$ mm/yr, and vice versa). The increase in long-term rock uplift rate also will increase these short-term bedrock incision rates (for example, if R_0 = 6 mm/yr, we obtained $T_0 > 5.8$ ka and $R_1 = R_2 > 17.4$ mm/yr). In addition, the calculated bedrock incision rates are affected by the rates of the valley aggradation and the subsequent incision into the aggraded sediments (i.e. T_a and T_b). To obtain $R_1 = R_2 = 11.5$ mm/yr requires $T_a = T_0$ and $T_b = 2$ ka, which is unrealistic. For the best approximation, $R_0 = 5$ mm/yr and $H_0 > 35$ m (as in Fig. 9), we obtained $T_0 > 7$ ka and $R_2 > 17.5$ mm/yr, if the modern valley around Ho-liu did have some degrees of inheritance from any pre-existing valley.

In summary, the local bedrock incision rate (the third type) of > 10 mm/yr holds, even considering the possibility of inheritance of the modern valley. This high rate of incision demonstrates the capability of the river to incise moderately resistant bedrock like marble and schist. This incision is unlike river capture or knickpoint migration associated with base-level fall. Rather, it behaves similar to the incision cutting through an actively growing anticline that brings bedrock to alluvium-covered river channels (e.g., Molnar et al., 1994; Lavé and Avouac, 2000; Hsieh and Knuepfer, 2002). Our data imply that such incision can be so efficient that it more than arrests tectonic uplift but keeps the same pace with degradation of fluvial sediments on both sides of the bedrock reaches. Not surprisingly, none of an actively growing structure of this kind has been able to long block the flow of the channel cutting through it.

Our obtained short-term bedrock incision rates (the third type) are much higher than the ongoing bedrock incision rates of 2-8 mm/yr surveyed at the site 1 km upstream of Ho-liu (Hartshorn et al., 2002). Consider that the survey site is now ~390 m above the sea level, the increase in riverbed elevation due to rock uplift (say, 6 mm/yr for 2 ky) during the deposition of the river has a negligible effect on the slope of the channel. It is also unlikely that the river’s annual discharge or flood frequency was much lower recently than in the past few thousands of years. We thus attribute the apparent discrepancy between the ongoing and millennium-averaged incision rates to the difference in bedload sediment supply. Note that when the channel cut through the bedrock next to the observed paleo-valleys, it cut into sediments in the rest parts of the river that aggraded previously. During this time, the supply of bedload sediments onto the local bedrock reaches next to the paleo-valleys must have been greater than the time when the aggraded sediments along the river were entirely removed. Greater supply of bedload sediments would facilitate bedrock incision by providing more abrasion tools (Sklar and Dietrich, 1998; 2000). This suitably explains the reason why the bedrock incision in the past few thousands of years had been faster than at present.

The Ta-tzu-chi-li River has been incised faster than the Wa-hel River in the past few thousands of years. A significant knickpoint also exists in the Hsiao-wa-hel River near the junction with the Tai-sai River, suggesting the more rapid incision of the Tai-sai River. Both features cannot be explained simply by the contrast in stream power between the two rivers joining together (in fact, given the greater slope and narrower channels, the stream power of the downstream-most parts of both the Wa-hel and Hsiao-wa-hel rivers are comparable with that of the Ta-tzu-chi-li and Tai-sai rivers). We suspected that these contrasts in incision capability also reflect the difference in supply of bedload sediments. This is supported by the fact that the volumes of the sediments that had been stored in the Ta-tzu-chi-li and Tai-sai rivers during the aggradation are several folds greater than those in the Wa-hel and Hsiao-wa-hel rivers.

Origins of river aggradation. With high relief and great annual rainfall, mountain rivers like the Li-wu may be considered as usually having sufficient power for not only conveying sediments but also eroding bedrock. This notion led Lin (1957) to attribute the observed hundreds-meter-high river aggradation in the Li-wu River to landslide damming that had elevated the local base level to reduce the river transport capacity. Lin (1957) also used the landslide dams created during the 1951 Hua-lien earthquake (M_L=7.4) as modern analogues. The rock fall during this earthquake resulted in several nature dams in the Li-wu River; the highest one, located in the Ta-ro-ko Gorge, has a height of 73 m.

We, however, argue that landslide damming would not be the major cause for the observed river aggradation. The nature dams generated during the 1951 earthquake, in fact, survived for only several months (Lin, 1957). We believe that building a long-lasting, hundreds-meter-high nature dam in the Li-wu River requires enormous deep-seated landslides. It is unlikely that such landslides occurring only few thousand years ago, if any, do not leave any observable sliding surface or scarp on the upper slope of the valley. In addition, the most probable site for the damming, as proposed by Lin (1957), would be in the Ta-ro-ko Gorge. The aggradation, however, occurred off the gorge and extended out of the mountain front as an alluvial fan. The formation of this alluvial fan also predates the aggradation in the upper part of the river, such that it could not have originated from outbreak of the dam that abruptly increased sediment load to the downstream direction, if any.

We propose that, like in many other active mountain belts, the observed river aggradation in the Li-wu River could have resulted from basin-wide increase in sediment supply. Our correlated river longitudinal profile is generally steeper than the modern river profile. This steepening far exceeds the differential tectonic movement inferred from the downstream lowering of the paleo-valley bases. This steepening, which promoted the river transport capacity, thus is likely to reflect the adjustment of the river to excessive supply of sediments (Bennett and Bridge, 1995; Alves and Cardoso, 1999). Aggradation triggered by surplus supply of sediments typically begins in the downstream reach, where river long-term has a stronger tendency to maintain at a constant level (i.e. closer to the aggradation condition) (Bull, 1991). This is consistent with our dating data.

The results of our gravel count show that the black-typed gravels had overwhelmed the green-typed ones during the river aggradation, but they are about equal in percentage currently. Consider that many of the black-typed gravels counted in the terraces are from angular to sub-angular debris-flow deposits, unlike those counted on the modern river that are of water-laden origin. Apparently, it is the massive placing of the black-typed gravels that had caused the higher ratio of the black- to green-typed gravels during the river aggradation. A great portion of the black-typed gravels (slate-, argillite-, and meta-sandstone-typed) must have come from the upper catchment of the Li-wu River (Fig. 3). This implies that in this high mountain region, landslides and debris flows must have been more common or extensive during the aggradation of the river than at present. How these debris flows had transported the angular/sub-angular gravel to the downstream reach (e.g., to Pu-lo-wan) remains unclear. Nonetheless, paleo-debris flows with even greater volumes have been reported traveling for > 40 km along the currently fluvial dominated rivers in the Himalaya mountains (Pratt et al., 2004).

Our estimation of the volume of the sediments stored in the river during the aggradation period is about 3.5 km^3, or equivalent to a denudation rate of 2.9 mm/yr if the duration of 2 ky for the aggradation is assumed. If this aggradation was entirely caused by landslide damming (say, at the river mouth), we would conclude that the denudation of the mountain during then was about the lower bound of the long-term average of 3-6 mm/yr. This, however, may contradict the results of our gravel count suggesting the greater or more common landslides and debris flows during the aggradation. More likely, the vast erosion of the mountain that had caused the deposition of the river far exceeded the long-term average, and the majority of the sediments being eroded had been transported out of the river basin.

We compared the river history of the Li-wu with the paleo-climate data derived from the Chi-tsai Lake, an alpine lake in central Taiwan (Fig. 10). Based on palynological studies, the sediments in this lake provide the most complete and reliable middle-to-late Holocene climate record in Taiwan (Liew and Huang, 1994). Also, located at the main divide of the Central Range (2800s m in elevation), the lake may be considered having undergone similar paleo-climate conditions with the upper Li-wu catchment.

It is shown that the aggradation of the Li-wu River, beginning before 3.5 ka and ending after 2.5 ka, corresponds to a relatively cool and dry climate (Fig. 10). This correlation leads us to consider that the inferred more extensive mass wasting processes in the upper catchment during the aggradation may have been, in part, caused by lowering of the tree line under the combined cooler and drier conditions. The cooler climate would also enhance periglacial processes in the high mountain regions, which may have increased production rates of debris on hillslopes (e.g., Bull, 1991). In addition, we suspect that in order to trigger more extensive landslides and debris flows, the magnitude and/or frequency of heavy rainfalls (or tropical typhoons) might have been greater during the aggradation of the river. The drier climate during this period then implies that the precipitation between the rainfall events were significantly lower than the normal condition. In other words, a rigorous climate might have occurred, as rainfall was so concentrated that it occurred only as a few catastrophic events. The drier condition between the events would minimize the river incision, which could have facilitated the aggradation during the next rainfall event.

The possibility for great earthquakes to trigger the excessive supply of sediments cannot be excluded, of course. We however do not have paleo-seismic data for comparison. Neither had the 1951 Hua-lien earthquake, although creating some nature dams, significantly increased the supply of sediments in the Li-wu River.

CONCLUSION

Whereas much emphasis has been paid about equilibrium of landscape with erosion balancing rock uplift, the fluctuation of the Li-wu River between 300s m aggradation and > 10 mm/yr bedrock incision during the late Holocene provides an example of how disequilibrium can occur in an actively uplifting mountain. The observed aggradation of the Li-wu River may correspond to a relatively cool and dry climate documented by palynological data. This may be different from the common notion that excessive supply of sediments, or greater erosion of mountains, should correlate to a wetter climate. Apparently, factors such as weathering, vegetation, and magnitude/frequency of heavy rainfalls that control the erosion rate may be too complex to be linked simply to annually or centennially averaged precipitation (and temperature) recorded by the paleo-climate proxies. Further field evidence, including more geomorphic and paleo-climate records together with monitoring of ongoing processes, is thus required to clarify this complexity and improve our understanding about the nature of climatic forcing upon landscape evolution.

Our obtained bedrock incision rate of > 10 mm/yr (and likely > 20 mm/yr) highlights the capability of the river to incise bedrock with a pace far exceeding the long-term rock uplift. Like the aggradation, this incision is probably also climate-driven, and particularly, may be facilitated by the abundant supply of bedload sediments acting as abrasion tools when the sediments deposited previously were re-transported after the aggradation. Given such efficiency in incision, one may wonder how the bedrock incision over long time can balance rock uplift. Apparently, although not all preserved as geomorphic evidence such as fill terraces, episodic deposition that temporarily retarded or stopped the incision must play an important role. Notice that the climate change that may have triggered the observed aggradation of the Li-wu River is subtle, compared to the known change in monsoon intensity or other climate systems during the early Holocene and during the deglacial-post glacial transition (e.g., Sirocko et al., 1993). We believe that the Li-wu River, and perhaps also other mountain rivers in Taiwan, is sensitive to environmental perturbations, even though these perturbations, such as seismic or super-rainfall events, may not be indicative of certain climate changes. The resulting dynamic fluctuation of river between incision and deposition is therefore a norm, rather than an exception.

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TABLE 1

MORPHOMETRIC ELEMENTS OF LI-WU AND ITS MAJOR TRIBUTARIES[a]

River	Drainage area (km^2)	Bain Relief (m)	Mean gradient of main-stem channel[b]
Trunk-stream Li-wu	621.2	3742	0.048
Ta-tzu-chi-li	249.4	3170	0.066
Tai-sai	183.1	3300	0.102
Wa-hel	57.2	2950	0.128
Hsiao-wa-hel	56.3	3050	0.133

[a] all based on 1-to-25,000-scale topographic maps.

[b] upstream limit defined at the place above which the angle of the V-shaped contours outlining the channel exceeds 90 degrees.

Table 2 RADIOCARBON DATES IN THE LI-WU RIVER

Location (Figs. 2, 4, and 5)	Sample height[a] (m)	Terrace height (m)	^{14}C age[b] (yr. BP)	Calibrated age (1σ)[c] (cal. yr. BP)
Upper Ta-tzu-chi-li R.	4	15	<200	--
Upper Tai-sai R.	3	20-25	250±35	153-418
Section VI	50	350-400	2480±40	2470-2710
Section IV	100	250-300	2400±40	2348-2486
Section I	20	40-60	3200±80	3273-3549
Section I	20	40-60	3410±60	3570-3810

[a] above modern channel

[b] by National Taiwan University ^{14}C dating laboratory

[c] using program of CALIB REV4.4.2 (Stuiver and Reimer, 1993)

TABLE 3

COUNTS OF LITHOLOGICAL TYPES OF GRAVEL IN THE LI-WU RIVER

Site No. (Figs. 4 and 5)	Percentage of total count (%)					Number of count
	Black typed (slate/argillite/ black schist/ meta-sandstone)	Green typed (green schist/ siliceous schist)	Marble	Gneiss	Undifferentiated Quartzite/meta-conglomerate	
Modern river						
1	39.3	29.6	23.0	6.6	1.5	196
2	38.9	35.2	15.6	5.2	5.2	270
3	43.4	37.8	11.6	3.6	3.6	251
4	38.9	35.0	15.6	7.3	3.1	163
5	51.2	41.1	4.4	0	3.2	248
6	40.4	41.8	17.0	0	0.8	141
7	46.8	44.9	5.4	0	2.8	316
8	50.1	40.1	6.6	0	3.6	137
9	43.7	50.3	4.6	0	1.3	151
10	55.3	36.6	4.9	0	3.3	123
11	42.9	51.6	0.0	0	5.0	219
12	50.7	43.1	1.3	0	4.9	225
13	62.3	23.9	10.7	0	3.1	159
14	62.1	29.0	5.5	0	4.1	145
Terrace						
A^a	67.5	22.5	1.7	0	8.3	150
B_1^a	74.6	1.8	12.5	0	11.1	114
B_2^a	80.0	1.5	6.9	0	11.6	195
C^a	63.6	23.1	8.3	0	5.0	121
D^a	68.4	10.7	8.5	0	12.4	117
E^a	80.0	13.4	5.0	0	1.6	151
F	66.4	15.6	12.3	0	5.7	122
G	58.1	33.0	8.8	0	0	112

[a] mainly from hyperconcentrated-flow and/or debris-flow deposits.

Figure captions

Figure 1. (a) Tectonic setting of Taiwan. Open arrow with rate shows the current movement of the Philippine Sea plate relative to the Chinese continental margin based on GPS measurements (Yu et al., 1997). (b) Morpho-tectonic framework of Taiwan. Central Range: metamorphosed pre-Tertiary continental basement and its Cenozoic sedimentary cover. Western Foothills: Oligocene to Pleistocene foreland fault-and-thrust belt. Longitudinal Valley: collision suture, which separates the Central Range from the Miocene to Pleistocene Coastal Range of Luzon arc (Philippine Sea plate) origins. Summarized from Ho (1986a).

Figure 2. Drainage system, distribution of river terraces, and sites of radiocarbon dates in the Li-wu River. For location see Figure 1.

Figure 3. Geological map of the Li-wu River basin (outlined by bold line) and its surrounding area. For location see Figure 1. Summarized from Ho (1986b).

Figure 4. Distribution and cross sections of river terraces along the trunk-stream Li-wu River downstream from Ho-liu. For location see Figure 2. Sites of gravel count, radiocarbon dates, and measured paleo-current directions (rose diagrams) are also shown. Note the existence of paleo-valleys buried in the terraces at (a) near the river mouth, (b) Pu-lo-wan, and (c) Ho-liu.

Figure 5. Distribution and cross sections of river terraces around Tien-hsiang and along the Tai-sai River. For location see Fig. 2. Note the existence of buried paleo-valleys at (a) underneath the divide between the Ta-tzu-chi-li and Tai-sai rivers (created by the Wa-hel River), and underneath the terrace remnant between Tien-hsiang and Ho-liu (created by the Tai-sai River), and (b) near the junction between the Tai-sai and Hsiao-wa-hel rivers (created by the Hsiao-wa-hel River). Legend and other notes as in Figure 4.

Figure 6. Longitudinal profiles of the terraces along the Tai-sai and the trunk-stream

Li-wu rivers. Terraces, represented by medium points of terrace treads or highest points of alluvium remnants, are projected to middle line of the valley defined by the terraces and modern floodplains. Elevations of terraces and modern channel (also projected to the middle-valley line) are determined from 10-meter-contoured, 1: 25,000 topographic maps. Heights of paleo-valley bases are surveyed by laser rangefinder or hand leveling.

Figure 7. Cartoons showing preservation of a buried paleo-valley next to the modern channel. (a) River incision created a V-shaped valley. (b) Deposition occurred that fill the valley while trimming bedrock laterally to widen the valley. (c) Incision resumed but took place off the axis of the origin valley (perhaps with minor lateral erosion to the direction opposite to the origin valley). (d) Continuous incision forms a fill terrace that contains the origin valley. Note the shifting of active channels from right-hand side to left-hand side of the figure.

Figure 8. Ratio of black- to green-typed gravels counted on the modern channel and in fill terraces. Numbers and letters refer to counting sites (see Figs. 4 and 5). For detail counting results see Table 3. Note the change of scale above ratio of 5.

Figure 9. Cartoons showing speculated multiple cycles of river incision and aggradation at Ho-liu. Elevation is referenced to the modern channel. Legend and other notes as in Figure 7. See text for calculation of bedrock incision rate based on this river history.

Figure 10. Correlation of palynological data from the Chi-tsai Lake (central Taiwan) with the aggradation of the Li-wu River (shaded). Open squares are radiocarbon dates of this study. Relative mean precipitation is shown by abundance of spore, and relative mean temperature, by abundance of *Tsuga sp.* (cold taxa) and combination of *Alnus sp.* and *Cyclobalanopsis sp.* (warm taxa). Bold squares on the time axis are radiocarbon dates that constrain the chronology of the sequence.

Summarized from Liew and Huang (1994).

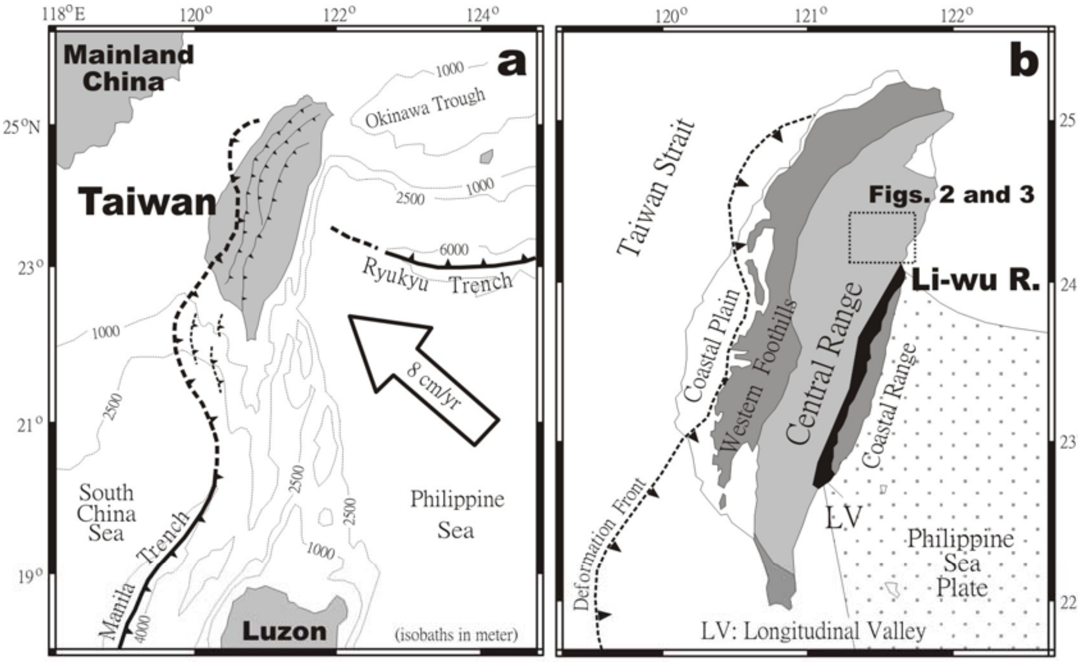

118°E
120°
122°
124°
25°N
23°
21°
19°
a
Mainland China
Taiwan
Okinawa Trough
1000
2500
6000
Ryukyu Trench
8 cm/yr
South China Sea
Manila Trench
4000
Philippine Sea
Luzon
(isobaths in meter)
b
121°
25°
24°
22°
Taiwan Strait
Figs. 2 and 3
Li-wu R.
Coastal Plain
Western Foothills
Central Range
Coastal Range
Deformation Front
LV
Philippine Sea Plate
LV: Longitudinal Valley

Figure 1

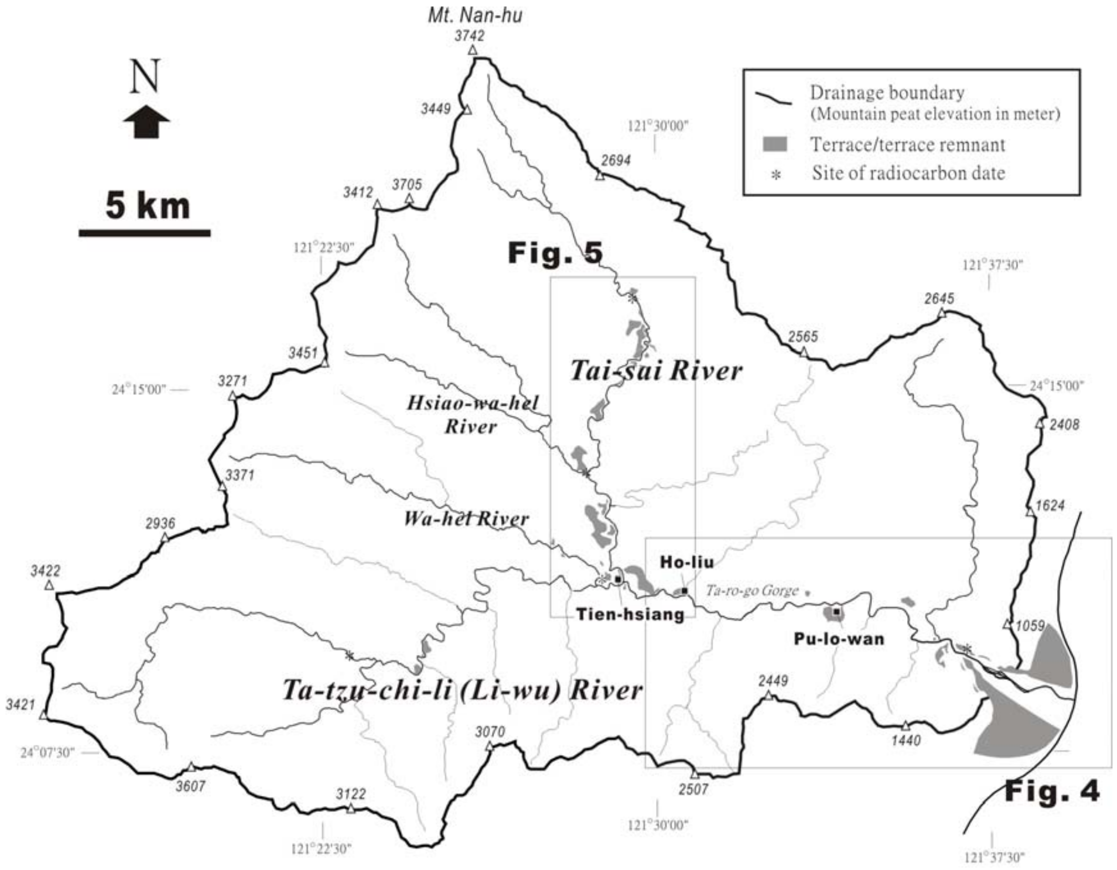

Mt. Nan-hu
3742
N
5 km
3449
2694
121°30'00"
Drainage boundary
(Mountain peat elevation in meter)
Terrace/terrace remnant
* Site of radiocarbon date
3412
3705
121°22'30"
Fig. 5
121°37'30"
2645
2565
Tai-sai River
3451
3271
24°15'00"
24°15'00"
Hsiao-wa-hel River
2408
1624
3371
Wa-hel River
2936
3422
Ho-liu
Ta-ro-go Gorge
Tien-hsiang
Pu-lo-wan
1059
Ta-tzu-chi-li (Li-wu) River
2449
3421
24°07'30"
3070
1440
3607
3122
2507
Fig. 4
121°22'30"
121°30'00"
121°37'30"

Figure 2

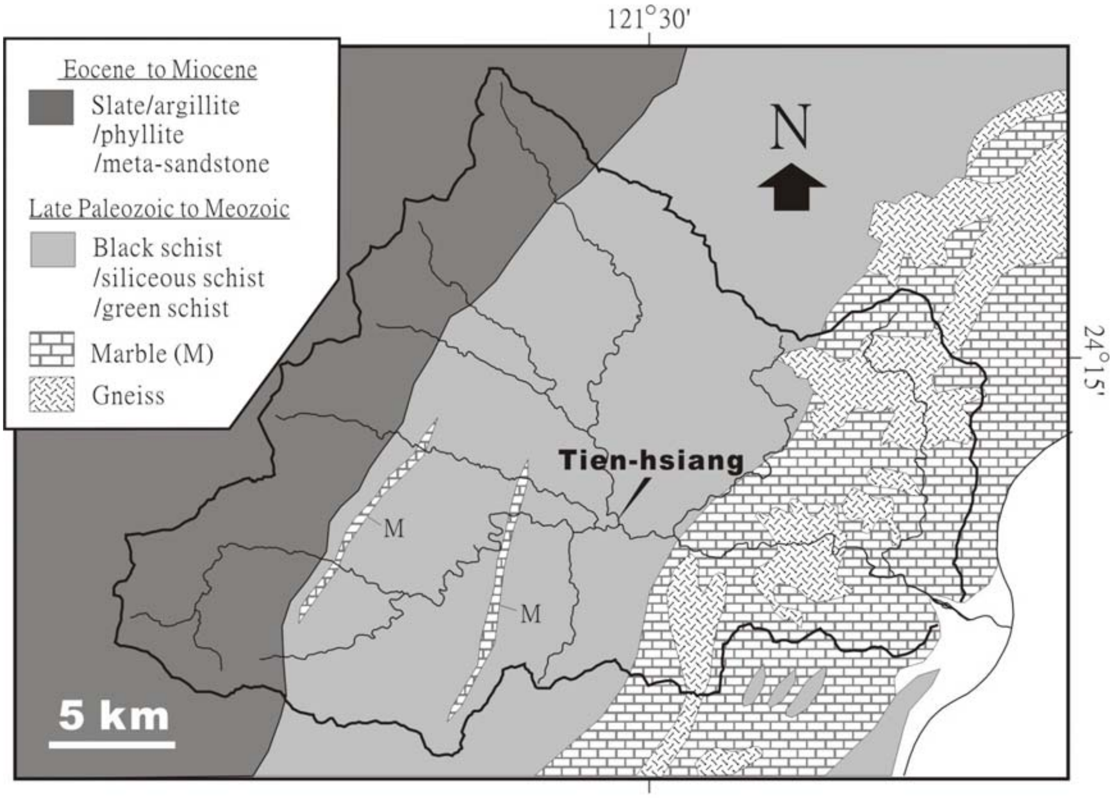

121°30'
Eocene to Miocene
Slate/argillite
/phyllite
/meta-sandstone
Late Paleozoic to Meozoic
Black schist
/siliceous schist
/green schist
Marble (M)
Gneiss
N
24°15'
Tien-hsiang
M
M
5 km

Figure 3

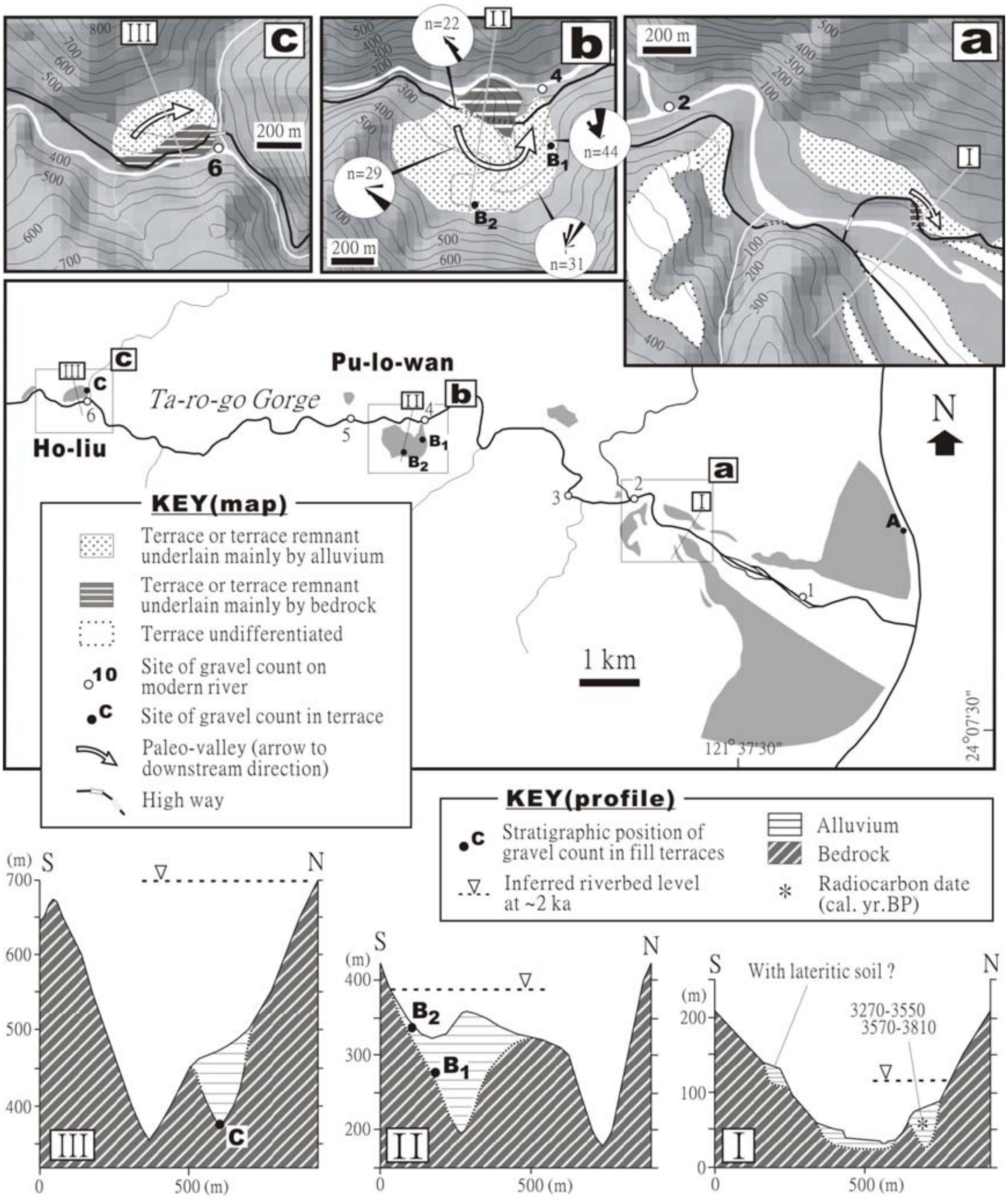
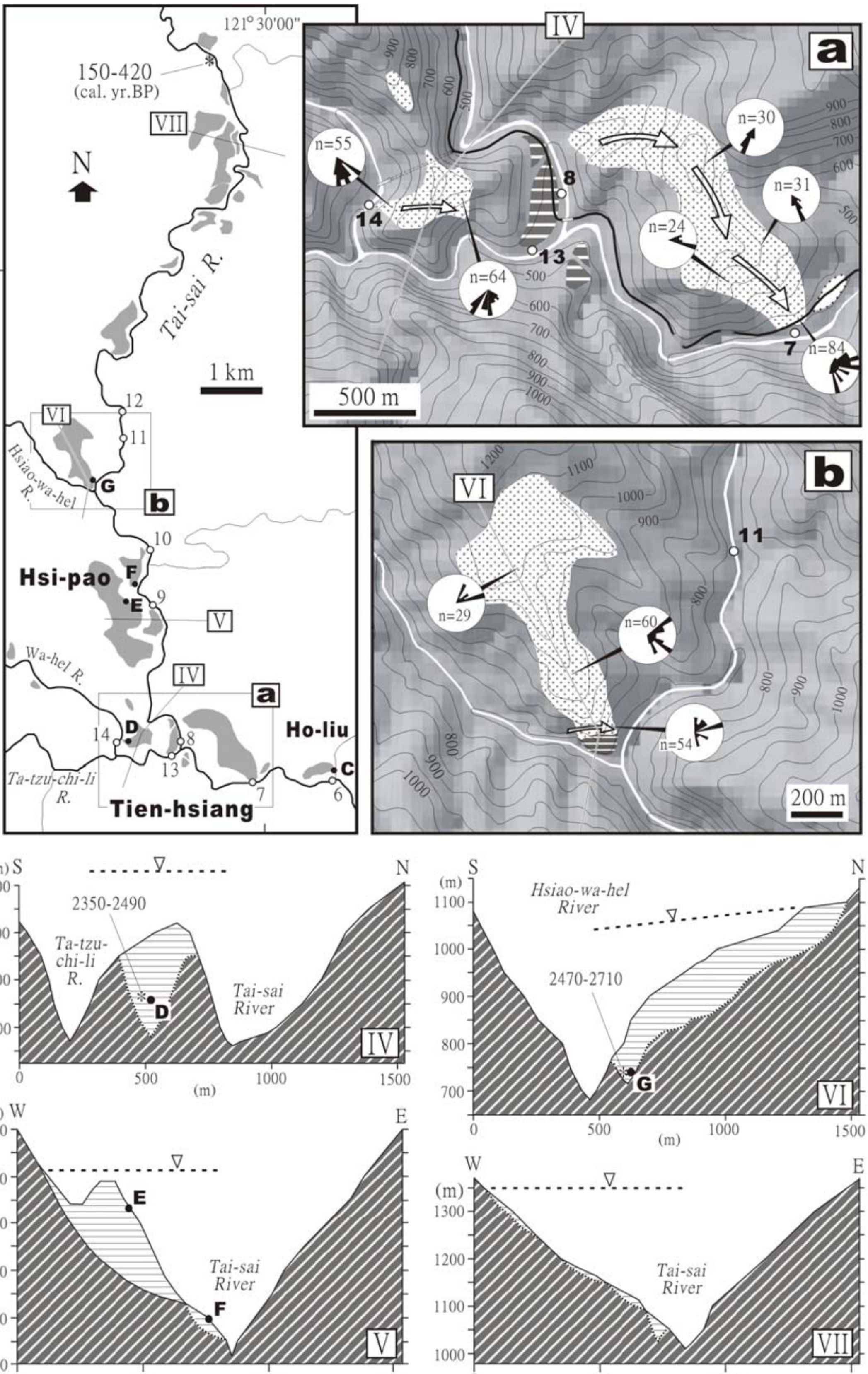

c
III
200 m
6
b
II
n=22
n=29
n=44
n=31
4
B1
B2
200 m
a
200 m
2
I
Pu-lo-wan
Ta-ro-go Gorge
Ho-liu
5
3
1
A
N
1 km
121°37'30"
24°07'30"
KEY(map)
Terrace or terrace remnant underlain mainly by alluvium
Terrace or terrace remnant underlain mainly by bedrock
Terrace undifferentiated
Site of gravel count on modern river
Site of gravel count in terrace
Paleo-valley (arrow to downstream direction)
High way
KEY(profile)
Stratigraphic position of gravel count in fill terraces
Inferred riverbed level at ~2 ka
Alluvium
Bedrock
Radiocarbon date (cal. yr.BP)
S
N
(m)
700
600
500
400
200
300
100
0
500 (m)
With lateritic soil ?
3270-3550
3570-3810

Figure 4



121° 30'00"
150-420
(cal. yr.BP)
VII
N
24°15'00"
Tai-sai R.
1 km
12
VI
11
Hsiao-wa-hel R.
G
b
10
Hsi-pao
F
E
9
V
Wa-hel R.
IV
a
Ho-liu
14
D
8
13
C
7
6
Ta-tzu-chi-li R.
Tien-hsiang
IV
a
n=55
14
8
13
n=64
n=30
n=31
n=24
7
n=84
500 m
b
VI
n=29
11
n=60
n=54
200 m
(m) S
N
2350-2490
Ta-tzu-chi-li R.
D
Tai-sai River
IV
(m)
(m) S
N
Hsiao-wa-hel River
2470-2710
G
VI
(m)
(m) W
E
E
Tai-sai River
F
V
(m)
W
E
(m)
Tai-sai River
VII
(m)

Figure 5

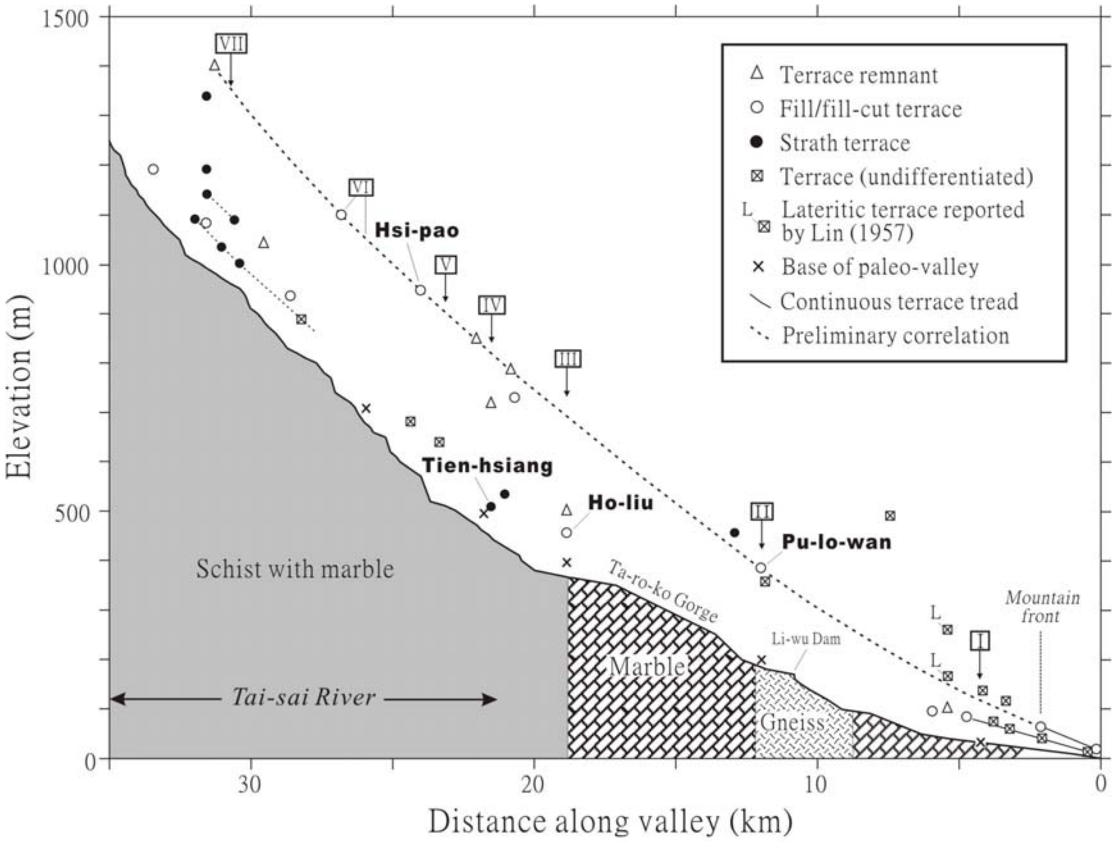

1500
1000
500
0
Elevation (m)
30
20
10
0
Distance along valley (km)
△ Terrace remnant
○ Fill/fill-cut terrace
● Strath terrace
⊠ Terrace (undifferentiated)
L ⊠ Lateritic terrace reported by Lin (1957)
× Base of paleo-valley
Continuous terrace tread
Preliminary correlation
VII
VI
V
IV
III
II
I
Hsi-pao
Tien-hsiang
Ho-liu
Pu-lo-wan
L
L
Mountain front
Schist with marble
Ta-ro-ko Gorge
Marble
Li-wu Dam
Gneiss
Tai-sai River

Figure 6

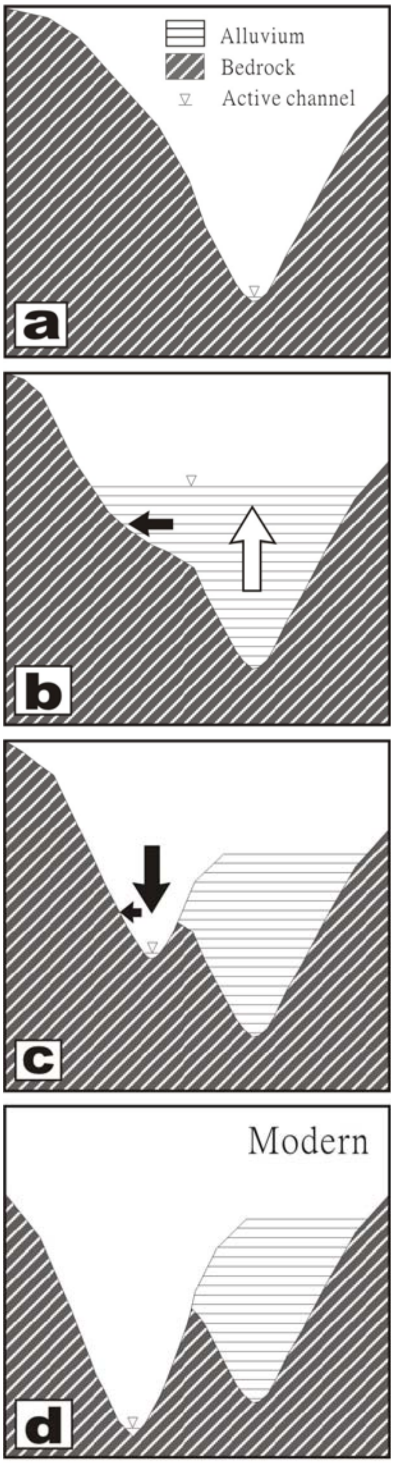


Figure 7

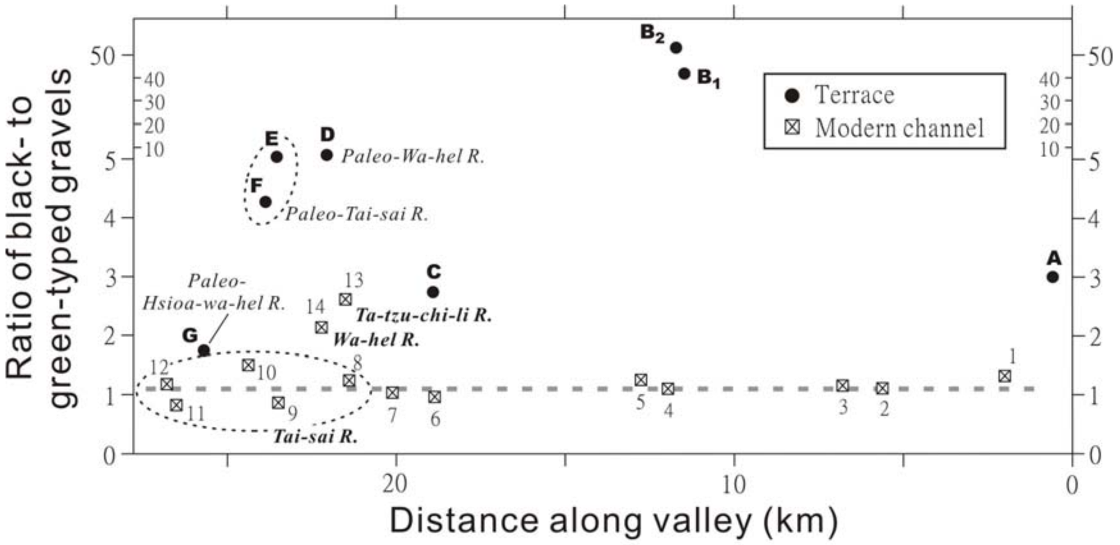

Ratio of black- to green-typed gravels
Distance along valley (km)
0
10
20
0
1
2
3
4
5
10
20
30
40
50
● Terrace
⊠ Modern channel
A
B2
B1
C
D
E
F
G
Paleo-Wa-hel R.
Paleo-Tai-sai R.
Paleo-Hsioa-wa-hel R.
Ta-tzu-chi-li R.
Wa-hel R.
Tai-sai R.
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Figure 8

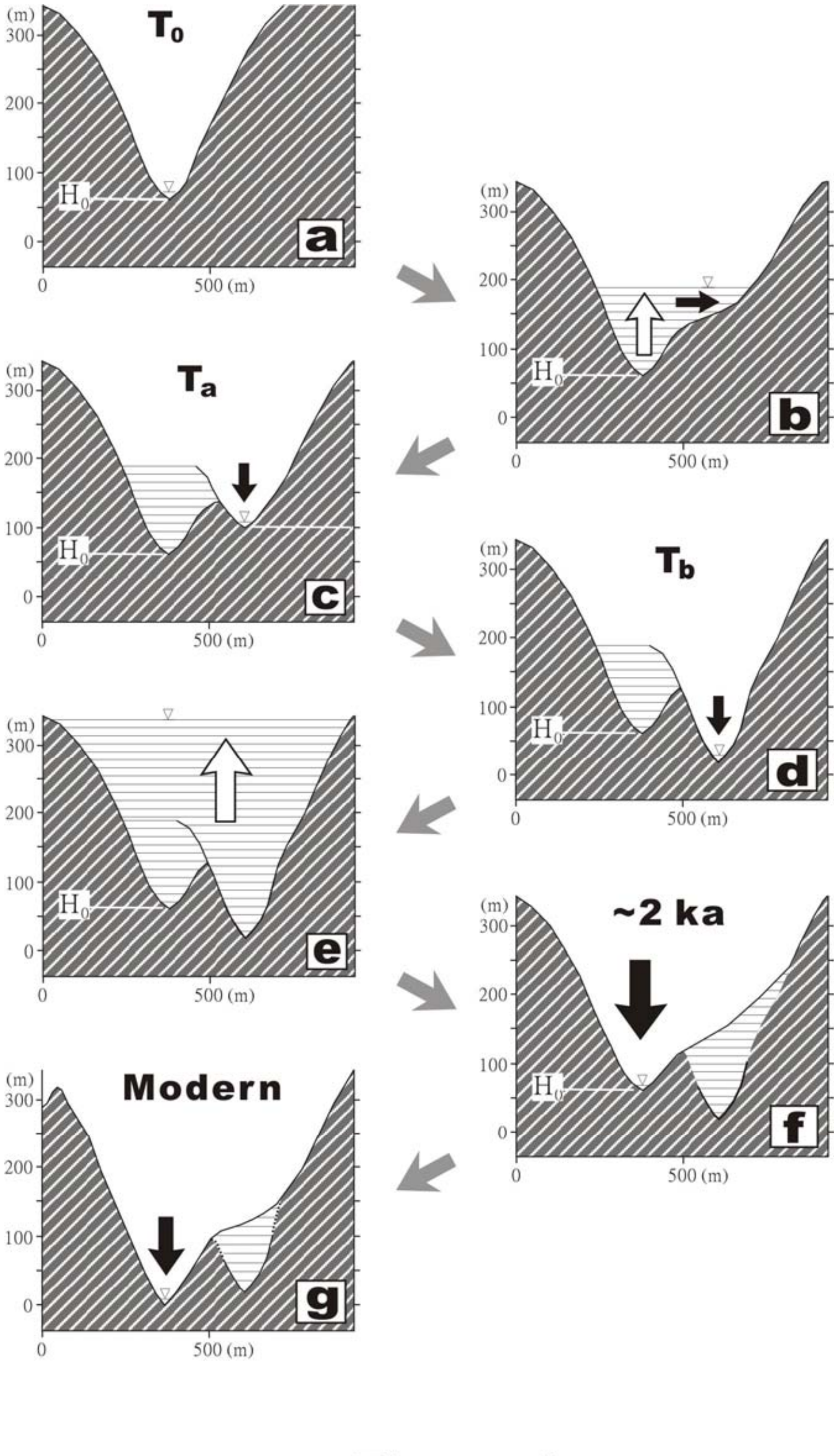
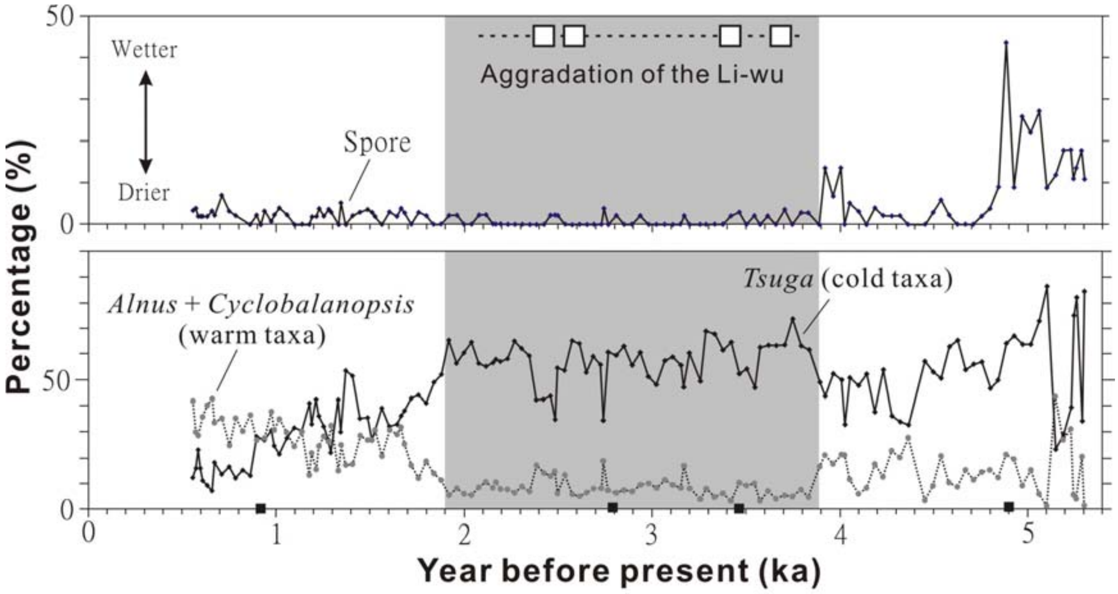


Figure 9



50
Wetter
Drier
0
Aggradation of the Li-wu
Spore
Percentage (%)
Alnus + Cyclobalanopsis
(warm taxa)
Tsuga (cold taxa)
50
0
0
1
2
3
4
5
Year before present (ka)

Figure 10