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Variations in Tectonic Activities of the Central and Southwestern Foothills, Taiwan, Inferred from River Hack Profiles

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ABSTRACT

A longitudinal profile of a river under static equilibrium shows no degradation or aggradation and can be ideally described as a straight line on a semi-logarithmic graph. This type of profile is called a "Hack profile". If a river runs across uprising active structure systems, its Hack profile becomes convex. Accumulated tectonic strain varies positively with the intensity of the upwarping in Hack-profile convexity. In this paper, we compare curvature changes in Hack profiles of a series of rivers running through faults in the central and southwestern Foothills of Taiwan. Longitudinal profiles of these rivers were derived from two versions of topographic maps (1904 and 1985) and recent DTM data (2000). Prior to comparisons, we calibrated the 1904 topographic map, named "Taiwan Bautu", by "offsetting" horizontal coordinates north and westward approximately 440 m and then "linear transforming" the elevation values. The Tungtzchiau fault of the central Foothills has remained inactive since 1935. Here relatively high uplift activity near the Wu River is indicated by significantly convex Hack profiles. This strain accumulation can be attributed to a lack of small magnitude earthquakes along the fault over the past 70 years. In the southwestern Foothills, relatively high uplift activity of similar intensity to the central Foothills is indicted near the Neocho River. Significant profiles with concave segments below the ideal graded profiles, at the lower reaches of rivers where continuous small magnitude strain release events have occurred, can only be found along the Sandieh, Neocho and Bazhang rivers in the southwestern Foothills. All these findings indicate that fault systems in the central Foothills tend to be locked and these faults could yield large earthquakes similar to the Chi-Chi event.

(Key words: Strain accumulation, Hack profile, Taiwan Bautu, Chi-Chi earthquake)

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1. INTRODUCTION

Landform development results from a dynamic equilibrium between crust uplifting and erosion. One of the natural processes of landform evolution is river erosion. The Davis cycle of erosion model presents that a river's longitudinal profile tends to be "graded" as the river approaches a mature state. Observations and theoretical analysis show that the time scale for river networks to reach equilibrium is long ($10^{3\sim6}$ years) even under relatively stable conditions (Pizzuto 1992). In a similar lithologic environment, the effects of tectonic activity on the course of a major river, can determine whether its profile reflects a youthful or mature stage. Many major rivers in Taiwan display such attributes, especially those near the Western Foothills. Taiwan is a highly uplifted orogenic belt with a high level of seismicity, formed by an arc-continent collision between the Eurasian plate and the Philippine Sea plate during the late Miocene (Ho 1988; Teng 1987, 1990). The Western Foothills consist of a series of subparallel thrust faults and related folds, which construct the western part of the fold and thrust belts of thin-skinned deformation (Suppe 1981, 1983). The mountain fronts of the central and south-western Foothills represent major active fault zones. Landform development in western Taiwan has been closely affected by the activities of these fault systems; and gross deviations from graded longitudinal profiles maybe the result of relatively recent events (Bull 1991).

Typically, tectonic deformation of the earth's surface takes place over thousands of years or longer. Although deformation is imperceptible to the human eye, it often can be measured by scientific instruments such as the global positioning system (GPS) and high-precision levelling surveys. River system analysis is the next most sensitive tool, as it is capable of adjusting to deformation over periods of decades to centuries (Keller and Pinter 1996). An idealized "graded" longitudinal profile of a river shows no degradation or aggradation and can be described by a simple logarithmic function. Such an ideal river profile plots as a straight line on a semi-logarithmic graph. The slope of this line is called the "Stream Length-gradient index (SL index)", or more commonly a "Hack profile" (Hack 1973). Hack profiling is a useful tectonic geomorphic index that allows detection of relative structure activities (Merritts and Vincent 1989; Rhea 1989; Marple and Talwani 1993; Brookfield 1998; Chen et al. 2003a; Chen 2004). Brookfield (1998) showed a series of convex Hack profiles for the great river systems of southern Asia caused by tectonic processes during the Cenozic India-Asia collision. Similar observations were made in for the South Carolina coastal plain. Marple and Talwani (1993) and Rhea (1989) point out that river anomalies observed within the South Carolina coastal plain express convex-upward longitudinal profiles and such features ought relate to an area of general uplift. Also, in the Mendocino triple junction region of northern California, Merritts and Vincent (1989) found that the Hack profile of rivers are convex in high uplift rate areas, and are almost straight and slightly concave in intermediate and low uplift rate areas. In Taiwan, Chen et al. (2003a) and Chen (2004) indicated that major rivers in the central Foothills show convex Hack profiles revealing early stage rivers adjusting to fault movement. In the south-western Foothills, the major rivers show slightly convex-concave Hack profiles indicating rivers in the later stage of adjustment to fault movement. In recent years, cartographic technology has developed rapidly and river longitudinal profiling can be easily and effectively derived from topographic maps and DTMs (Digital Terrain Model). Consequently, for large-scale and long-term surface deformation, Hack profiling, which provides information on both uplift and erosion, could be a very useful tool.

Sung et al. (2000) preliminarily analyzed SL index contour change for three major rivers in central Taiwan using two historical topographic maps. They summarized that variation of landform development reflects long-term crustal deformation better than geodetic measurements such as GPS. In this paper, the study area is extended to include the central to southwestern Foothills of Taiwan with Hack profiles of major rivers collected from three different topographic databases i.e., 1904, 1985, and 2000. We propose a comparison study of river morphology made amongst two historical topographic maps (1904 and 1985) and a more recent DTM study (2000). Calibration of the three topographic databases before comparisons is crucial so as not to confuse the results of tectonic activity with artefacts of the maps. The 1985 topographic map and the 2000 DTM use the same system of coordinate projection and ellipsoid. The "Taiwan Bautu" map is the most complete and accurate topographic map of 1904; however, there exists systematic errors in elevation as well as in the coordinate system when we compare it to the 1985 topographic map (Sung et al. 2000). Hsu (2002) previously proposed adequate transformations of high accuracy in coordinates for calibration of the "Taiwan Bautu"; however, we found that some systematic errors on a small to medium scale in the 1904 map still existed, especially in elevation. Nevertheless, the study of Sung et al. (2000) shows that the comparison study for a large area using whole Hack profiles is still feasible. In this study, we focus on variation in temporal changes for Hack profiles over the past century, and relate this variation to tectonic activities in central and southwestern Taiwan. We also hoped to attain better understanding of the longitudinal variations of morphotectonic features in the Western Foothills.

2. TOPOGRAPHIC MAPS AND DTM

The 1985 version of the topographic map is of a scale of 1/25000 and is published by the Department of Interior, ROC. Its accuracy is about 2.01 m in elevation and 11.23 m in coordinate system (Kuo 1998). The 2000 version of DTM is at a resolution of 20 m and was also published by the same department. Both the 1985 topographic map and the 2000 DTM use the Universal Transverse Mercator (zone 51) grid coordinate system and ellipsoid of GRS67. Due to rapid developments in survey technology, we believe that the 2000 DTM should have better accuracy both in elevation and in coordinate system than the 1985 topographic map. The 1904 map is at a scale of 1/20000 and was mapped by the Japanese Authority in Taiwan. It uses the longitude/latitude coordinate system and ellipsoid of Bessel 1841. The 1904 and 1985 maps cover most of the central and southwestern Foothills, but the 2000 DTM only covers a portion of the central Foothills along the surface rupture of the Chi-Chi earthquake.

According to studies by Sung et al. (2000), Hsu (2002), and Lin (2005), geomorphic information collected from the Taiwan Bautu is generally accountable for comparison study with the 1985 after calibrating for systematic errors due to different projections and ellipsoids. Thus, for calibrating systematic errors, we adopt the data transformation of Hsu (2002) to calibrate the ellipsoids and then select 23 first level triangulation stations as control points for coordinate calibration (Fig. 1). We find that space data for the Taiwan Bautu only needs to be offset about 440 m north and westward in an X-Y plane and a simple but perfect linear function in Z dimension for elevation transforming (Table 1). The linear transformation of the coordinates results in a root mean square (RMS) error of about 15 m (Table 1) (Sung 2000). Lin (2005) also proposes similar methodologies to transform exchanges of projection and geodetic datum between the two version of the maps with errors of between 12 ~ 25 m. In addition, because Hack profiling utilizes a semi-logarithmic graph with enhanced upstream profiling and condensed downstream profiling, the 23 control points distributed upstream of the rivers are adequate for estimating transformation parameters in this study. Thus, we think that this linear calibration is appropriate for large area qualitative analysis of Hack profile variation in the test sites of this paper.

Based on the three databases, we compare Hack profiles for rivers that cross major structures in the central and southwestern Foothills. These analyzed profiles are for the main channels of the river networks. Length data for the profiles is collected from the topographic maps of 1904 and 1985 versions, which are geocoded in the "Mapinfo" system; and elevation data is taken at crossings of the stream courses by contour lines. For the database of the 2000 DTM, river profiles are derived using "RiverTools" software. Temporal changes of Hack profiles over a period of 80 years (from 1904 to 1985) and 15 years (from 1985 to 2000) can be evaluated and we shall discuss these in detail in a later section.

3. THEORY AND METHODOLOGY

3.1 Curved Hack Profiles and the Ideal SL Index

A number of previous studies with respect to active crustal warping have provided useful information relating to river profile adjustments (Volkov et al. 1967; Burnett and Schumm 1983; Ouchi 1985; Snow and Slingerland 1990). The SL index has been commonly used to highlight gradient change of a stream's longitudinal profile. It reflects stream power or competence (Hack 1973). Usually, it is sensitive to changes in stream slope, and is applied to evaluate relationships between tectonic activity, rock resistance, and topography (Keller and Pinter 1996). The parameters measured are shown in Figs. 2a and b, and the equation is shown as below:

$$H = c - k' \times \log(L) \quad . \tag{1}$$

In Eq.(1), H is the altitude of the profile, and c is a constant. k' is called the SL index. The quantity L is the stream length measured from the drainage divide at the source of the longest stream in the drainage basin.

Most natural streams do not show only a single logarithmic profile that connects from riverhead to mouth throughout their length. The Hack profiles are usually "curved" and can be treated as a connected series of segments of various lengths. Because the SL index is sensitive to channel slope changes, in practice, the channel slope is averaged over a segment of the

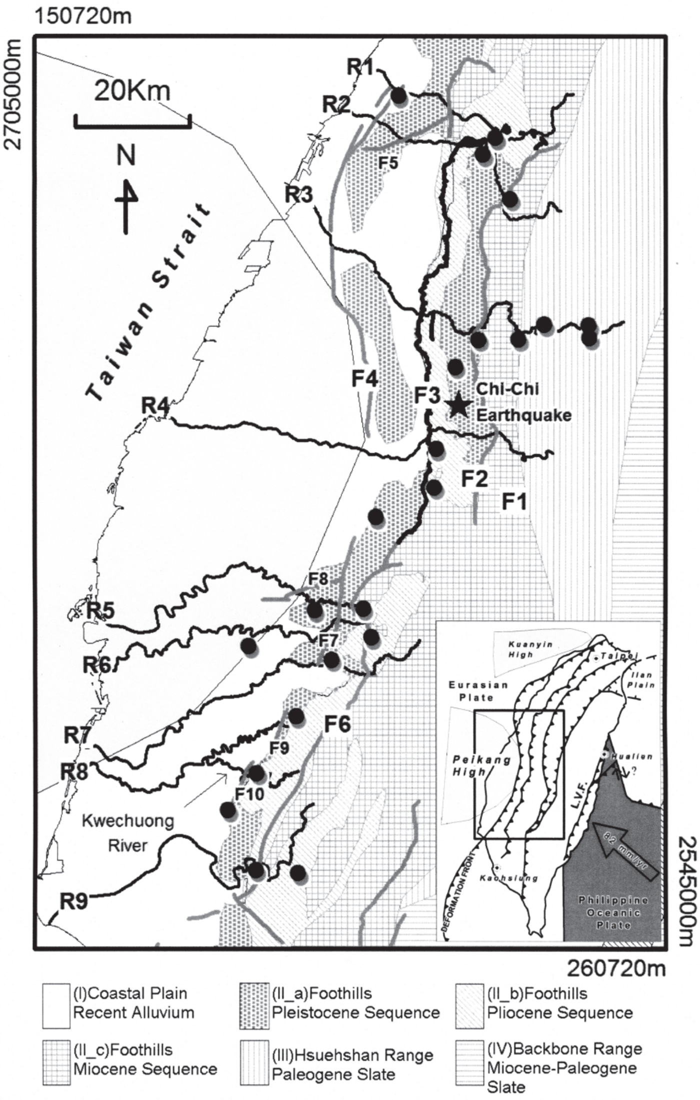

Fig. 1. The study area in this paper. The "central Foothills area" extends from the Daan River to the Chuoshue River, and the "southwestern foothills area" extends from the Sandieh River to the Zhengwun River. F1 is the Shuelikeng fault, F2 is the Shuangtung fault, F3 is the Chelungpu fault, F4 is the Changhwa fault, F5 is the Tungtzchiau fault, F6 is the Chuko fault, F7 is the Chiochongkeng fault, F8 is the Muchiliau fault, and F9 is the Liochia fault. The black heavy bold line is the surface rupture of the Chi-Chi earthquake. Thin lines are the 10 rivers analyzed in this paper. Map showing the distribution of 23 first level control points on the map of 1985 that was selected for calibrating the 1904 map. Solid black spots are the first level triangulation stations of 1985, and solid gray spots are the first level triangulation stations of 1904.

Table 1. Calibration parameters for the 1904 map. Values are generated using data from the 1985 map minus data from 1904. In a north-south direction, coordinate values of 1904 need to offset 436.9 ± 15.2 m northward; in an east-west direction, coordinate values need to offset 441.5 ± 13.4 m westward. The linear function for elevation values of the 1904 map ($E_{(1904)}$) for transformation to allow comparisons with elevation values of the 1985 map is: ($E_{(1985)}$) is $E_{(1985)} = 0.92 \times E_{(1904)} + 0.21$. RMS indicates the results of the calibration for 23 control points.

		Average Offset (m)	RMS Error (m) (Root Mean Square Error)
Horizontal Coordinate	W - E	-441.5	13.4
	N - S	436.9	15.2
Vertical Elevation		$E_{(1985)} = 0.92 \times E_{(1904)} + 0.21$ ($r^2 = 1$)	

reach step by step from river source to river mouth in order to smooth out local variations. Each segment expresses a small graded reach with a SL index value and a step SL index curve is constructed for the entire river (Fig. 2e). A segment is defined by use of linear fitting with its correlation coefficient to be at least 0.98. SL indices generated by linear fitting of Hack profiles might reflect small to medium scale geological features, such as lithology, folds and faults. The entire curved Hack profile might correspond to the long-term cumulative effect of tectonic activities (Hack 1973; Brookfield 1998; Chen et al. 2003a; Chen 2004). A straight line between river source and mouth can be considered as the graded situation of a natural stream in dynamic equilibrium (Fig. 2e). The slope of this line is called the graded gradient, *k*, and can represent the proxy of stream power for a river. Therefore, a large river has a greater *k* and a small river has a smaller *k*. Without the processes of internal activities, a curved Hack profile would gradually evolve into the “ideal” graded profile.

3.2 Tectonic Implications of Hack Profile Convexity Variation

As Figs. 2c and d show, the curvature of a Hack profile expresses an accumulation of both the internal and external processes of a river. If a river runs through a higher tectonically active area with uplift larger than denudation, such as an active fault zone, its Hack profile will remain convex reflecting the movement of the active structure. Under a compression tectonic regime, this convexity of the Hack profile varies positively with accumulated strain. Rapid surface strain accumulation reflects not only the highly active nature of a structure, but also the potential for earthquake occurrence. Consequently, theoretically the more intense the upwarping in the Hack profile, the higher the potential of an earthquake occurring. Therefore, convexity

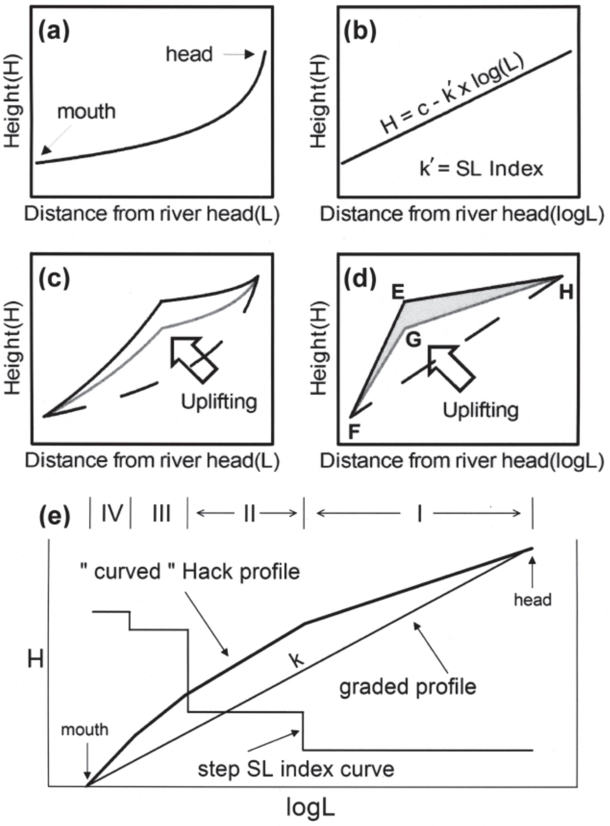

Fig. 2. Conceptual diagram of Hack profiles. Diagram (a) is a simulated graded profile in linear plot and diagram; (b) shows a straight line in semi-logarithmic plot. Diagram (c) is simulated profiles with uplifting in linear plot, and diagram (d) is a semi-logarithmic plot. The dashed profile is an origin-graded profile, and gray and black solid profiles express different degree of uplift caused by larger-scale tectonic activities. The black solid profile locks more strain energy than the gray solid profile. (e) The curved Hack profile can be divided into four graded segments (I, II, III, IV), each of which is linearly fitted and has its own SL index to construct the step SL index curve.

variation, derived from the comparison of Hack profiles of the same river at different times, can denote large-scale variation of surface strain accumulation and thus the potential of earthquake occurrence.

For conveniently comparing convexity variation between rivers, we need to define an index called the “Potential Index (PI)”. In Fig. 2d, PI is the ratio of area EFGH over area GFH. Area EFGH bounded beneath the black solid profile contains higher strain accumulation whilst that above the gray solid profile contains lower strain accumulation. In a semi-logarithmic plot, PI is convexity variation and implies variation in strain accumulation. In practice, the black solid and the gray solid profiles represent two profiles at different times. Area GFH i.e., that area between the gray solid profile and the dashed line (graded profile) is the initial state and is used to normalize the convexity variation. Under a given similar tectonic framework, it is easier to get larger variation of strain accumulation in a larger river (area EFGH) than a smaller one, so the normalizing step provides a measure by which the PI amongst rivers can be compared. If the Hack profile of a river generates "net upwarping" through time, the gray solid profile would express the historical profile and the black solid profile express the present profile and its PI value would be positive. Net upwarping might reflect stronger uplifting with relatively weaker denudation. By contrast, if the PI value is negative, we can then easily find a "net denudation" variation from the historical profile that contains higher strain potential (the black solid profile) down to the present profile that contains lower strain potential (the gray solid profile). Net erosion might reflect the result of weaker uplifting with relatively stronger denudation. According to the map's accuracy (Kuo 1998) and the transformation error (Sung 2000), the uncertainty of river profiles would be about 2 m in elevation and 11 ~ 26 m in the coordinate system. But for river profiles of 90 ~ 800 m high and 50 ~ 80 km long, uncertainty is relatively small. Furthermore, when we estimate the PI value, the normalization step averages uncertainty again. Thus, we assume that uncertainty from map accuracy and transformation can be ignored while qualitatively comparing river Hack profiles.

4. TECTONIC AND GEOLOGIC SETTING

The Taiwan mountain belt has been developing since about 5Ma as a result of an oblique collision between the Luzon island arc with the Chinese continental margin. It can be generally divided into several geologic terrains. The active Longitudinal Valley Fault (L.V.F.) separates two main geological provinces of Taiwan (Ho 1986; Tsai 1986). To the east, the Eastern Coastal Range comprises mainly volcanic and siliciclastic sequences of the accreted Luzon arc-trench system. Whereas the area to the west is comprised of the Longitudinal Valley, the Central Range, the Western Foothills (II_a, b, and c) and the Western Coastal Plain (I), which consist of metamorphic and sedimentary sequences of the deformed Chinese continental margin (Fig. 1). The Central Range can be further divided into its eastern and western flanks. The western flank contains the Hsuehshan Range (III) and Backbone Range (IV), underlain by a metamorphosed Cenozoic argillite-slate series. The pre-Tertiary basement crops out on the eastern flank. The Western Foothills (fold and thrust belt) are composed of shallow marine to shelf sediments from the Late Oligocene and the Miocene to the Early Pleistocene. Most of the folding and thrusting that took place is associated with east-dipping reverse faults that are considered to be still active (Bonilla 1975, 1977; Ho 1976; Suppe 1980; Chang 1994). Two major buried basement highs in western Taiwan have been revealed by subsurface studies: the Peikang High to the south and the Kuanyin High to the north. Drilling and seismic reflection data outlined the semicircular shape of the Peikang High and the presence of such a crustal high is likely to play an important role in the development of the frontal fold-and-thrust belts (Hung et al. 1999; Lacombe et al. 1999; Hu et al. 2001).

In the study area, there are nine major rivers running westwards through the mountain fronts of the central and southwestern Foothills. They are the Taan (R1), Dachia (R2), Wu (R3), Chuoshue (R4), Sandieh (R5), Neocho (R6), Bazhang (R7), Chishue (R8), and Zhengwun (R9) rivers. The Taan, Dachia, Wu, and Chuoshue rivers run across the Shuelikeng (F1), Shuangtung (F2), Chelungpu (F3), Changhwa (F4), and Tungtzchiau (F5) faults in the central Foothills. The Sandieh, Neocho, Bazhang, Chishue, and Zhengwun rivers run across the Chuko (F6), Chiochongkeng (F7), Meisan (F8), and Muchiliau (F9) faults in the southwestern Foothills (Fig. 1). Among these faults, the Chelungpu and Chuko faults, representing the major faults of the Foothills, show a hanging wall of late Miocene-Pliocene deformed strata overthrust upon a footwall of late Quaternary sequence and recent alluvium (Chang 1971; CPC 1982a, b; Chang et al. 1996).

During the past one hundred years, the study area has experienced coseismic surface rupturing a few times, in 1906 ($M_L = 7.1$), 1935 ($M_L = 7.1$), 1941 ($M_L = 7.1$) (Cheng et al. 1999), and the recent 1999 Chi-Chi earthquake. The Chi-Chi earthquake created a fault cliff up to 11 m high, the ground rupture extended more than 105 km and maximum PGA (Peak Ground Acceleration) was greater than 1G (CGS 1999). Although a higher ground deformation, surveyed by GPS during the period 1990 to 1995, appears in the southwestern Foothill (Yu et al. 1997), the crustal deformation pattern, caused by the Chi-Chi earthquake, appears unrelated to the velocity field. GPS data indicates that the Chelungpu fault was locked prior to the Chi-Chi earthquake. Sung et al. (2000) preliminarily used stream gradient change to detect long-term tectonic activity; their results showed good agreement with processes induced by the Chi-Chi event. Given the complexity of the tectonic setting framework and seismic history of the Western Foothills of Taiwan, long-term observation should provide a good tool for exploring long-term crustal deformation.

5. ANALYSIS AND DISCUSSION

For each river, we plot Hack profiles from databases at different times in order to compare convexity variation with time (Fig. 3).

5.1 The Central Foothills

The Daan and Dachia rivers show both their $PI_{1985-1904}$ values to be negative (-0.019 and -0.004), implying net denudation from 1904 to 1985. Therefore, there ought to be more denudation than uplift near the two rivers. A review of seismic history indicates that after the surface rupture of the 1935 earthquake ($M_L = 7.1$), activity along the Tungtzchiau fault (Fig. 1) remained inactive. Consequently, denudation would have become the dominant force in shaping the rivers' longitudinal profiles. Between the two rivers, net denudation of the Dachia River ($PI_{1985-1904} = -0.004$) appears to be smaller than the Daan River $PI_{1985-1904} = -0.019$). Given the similarity in geological and denudation conditions, other structure activity near the Dachia River is expected to have occurred to decrease the rate of net denudation. In other words, the smaller net denudation in the Dachia River suggests activity along the Shuangtung

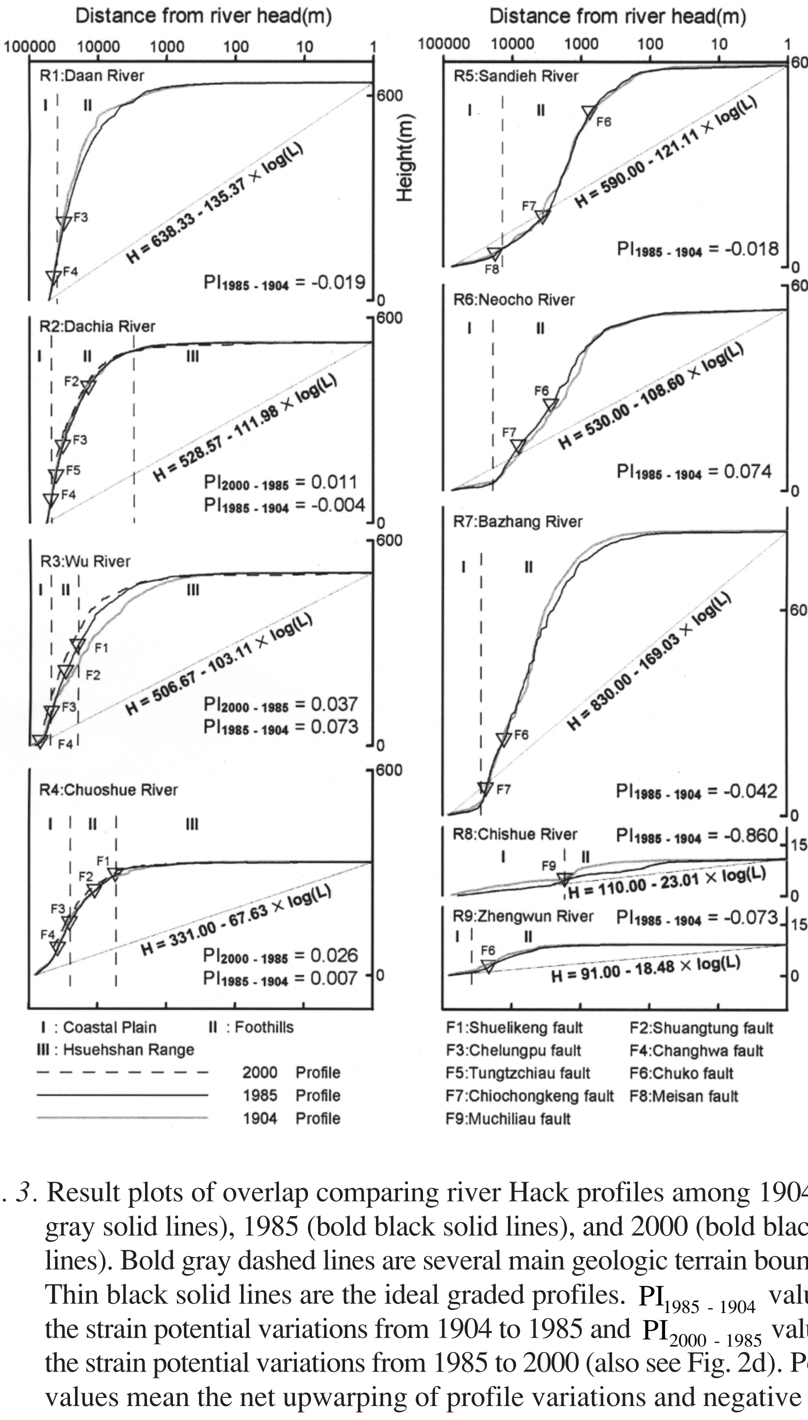

Fig. 3. Result plots of overlap comparing river Hack profiles among 1904 (bold gray solid lines), 1985 (bold black solid lines), and 2000 (bold black dash lines). Bold gray dashed lines are several main geologic terrain boundaries. Thin black solid lines are the ideal graded profiles. $PI_{1985-1904}$ values are the strain potential variations from 1904 to 1985 and $PI_{2000-1985}$ values are the strain potential variations from 1985 to 2000 (also see Fig. 2d). Positive values mean the net upwarping of profile variations and negative values mean the net erosion of profile variations. Four rivers in the left column are located in the central Foothills, and the other five rivers in the right column are located in the southwestern Foothill.

or the Chelungpu faults (Figs. 1, 3).

The positive $PI_{1985\ -\ 1904}$ values of the Wu and Chuoshue rivers imply uplift activity in the fault systems (F1, F2, F3, F4) of the central Foothills, especially near the Wu River ($PI_{1985\ -\ 1904}$ = 0.073). Due to limitations in the 2000 DTM database, there is only such data on the Dachia, Wu and Chuoshue rivers. Hack profiles of the three rivers exhibit strong net upwarping from 1985 to 2000. It is worth noting that the rate of upwarping for the period 1985 to 2000 is greater than that for 1904 to 1985. It is difficult here to ignore the influence of the 1999 Chi-Chi earthquake that contributed to a large part of the net upwarping. According to GPS geodetic measurements taken after the Chi-Chi earthquake, vertical displacement of the Chelungpu fault exhibits an average of 2 ~ 3 m in the southern block between the Wu and Chuoshue rivers and reaches a maximum slip of 7 ~ 8 m in the northern block between the Dachia and Wu rivers (CGS 1999; Ma et al. 1999). The $PI_{2000\ -\ 1985}$ value of the Wu River is also relatively high (= 0.037) and decreases toward the Chuoshue (= 0.026) and Dachia (= 0.011) rivers. From a long-term point of view, the area between the Wu and Chuoshue rivers has the highest activity potential in the central Foothills with the Dachia and Chuoshue rivers being interpreted as the northern and southern boundaries, respectively, due to their relatively lower PI values.

5.2 The South-Western Foothills

In this region, only the Neocho River has strong net upwarping ($PI_{1985\ -\ 1904}$ = 0.074). This is exhibited near the reaches of the Chuko and Chiochongkeng faults, and has an intensity similar to that of the Wu River in the central Foothills. Hack profiles of the Sandieh River at different times express a good balance between uplift and denudation. But in the reaches near the Chiochongkeng fault, temporal net denudation from 1904 to 1985 is evident and this is also reflected in its negative $PI_{1985\ -\ 1904}$ value (= -0.018). In the Bazhang River, a high negative $PI_{1985\ -\ 1904}$ value (= -0.042) is consistent with general net denudation from 1904 to 1985 in its upper reaches and is almost balanced in the reaches near the Chuko and Chiochongkeng faults. The highest negative $PI_{1985\ -\ 1904}$ value (= -0.860) is in the Chishue River. Almost the complete profile of the Chishue River shows strong net denudation from 1904 to 1985 except for light uplifting in the reaches near the Muchilliau fault. This shows the influence of the activity of the Muchilliau fault to be localized. The Zhengwun River is the southernmost river with light net denudation that runs across the south of the Chuko fault in this area. For the Chuko and the Chiochongkeng faults, which are the major active structures in the southwestern Foothills, the highest activity potential appears to be near the Neocho River. The Sandieh and Zhengwun rivers are interpreted as the northern and southern boundaries, respectively, due to their relative low PI values.

5.3 The Potential for Earthquake Occurrence

Brookfield (1998) proposed an evolution concept for change in a graded river profile by fault movement as shown in Fig. 4. As the displaced profile re-establishes its new graded state,

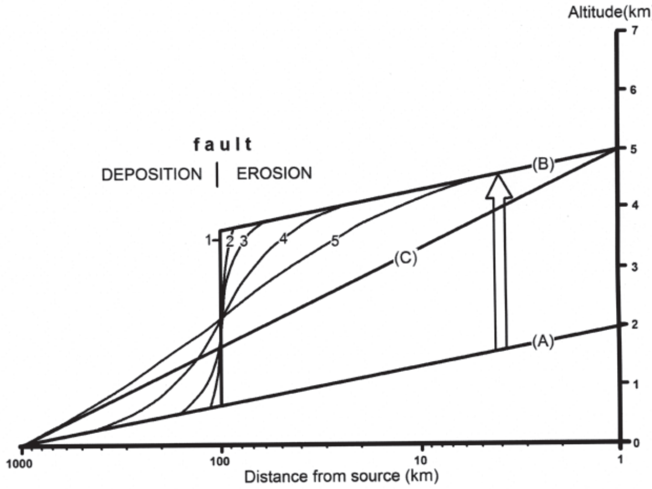

Fig. 4. Change in graded river profile by fault movement and the resulting adjustment. Graded river profile (A) is displaced to profile (B) by a sudden fault displacement. Erosion/deposition point is kept constant: in reality, it would migrate downwards and upstream, eroding earlier deposited sediment near the fault. Successive profiles 1 to 5 show a trend toward eventual new equilibrium profile (C). Reaction time is assumed to be instantaneous. Relaxation time to new dynamic equilibrium is unknown, but is exponential, with a half-life of probably millions of years for this size river (Adapted from Brookfield 1998).

the asymptotic decay curves clearly show a trend varying from a convex Hack profile to a convex-concave Hack profile due to weaker uplift with relatively stronger incision denudation. Moreover, it means that if a Hack profile remains convex, this could be due to stronger uplifting with relatively weaker denudation. In this paper, the major rivers in the central Foothills show convex Hack profiles (Fig. 3) revealing them to be in the early stages of this evolutionary concept (Fig. 4). However, the major rivers of the southwestern Foothills show slightly convex-concave shaped Hack profiles (Fig. 3) revealing them to be in the later stages (Fig. 4). The intersection of the reaches and graded gradient profiles of the Sandieh, Neocho and Bazhang rivers are all near the Chiochongkeng fault (Fig. 3). This implies that there should be frequent and continuous fault displacement gathering near the Chiochongkeng fault (Chen et al. 2003b).

Chen et al. (2003b) analysed earthquake time series data using the Cantor set model and concluded that temporal behavior of large magnitude earthquakes in the central and southwestern Foothills are similar, but earthquakes with smaller magnitude clustered more frequently and continuously in the southwestern Foothills than in the central Foothills, indicating that tectonic strain energy gathered and released more readily in the southwestern Foothills than in the central Foothills. Thus, we can further interpret that there should be more frequent and continuous seismic activities (regardless of the magnitude) occurring near the Chiochongkeng fault in the southwestern Foothills than the central Foothills. This also means that active faults in the central Foothills tend to "lock" strain energy more easily than in the southwestern Foothills.

Strain energy tends to accumulate in the central Foothills, which is captured in the convexity of the Hack profiles in the region. In contrast, strain energy tends to release more readily in the southwestern Foothills, which is reflected in the convex-concave shape of regional Hack profiles. Consequently, these results illustrate the effectiveness of detecting large-scale crustal deformation using long-term river Hack profile variations.

6. CONCLUSION

The use of Hack profiles appears to be an efficient method for detecting large-scale fault activity. By analysing the Hack profiles of a series rivers running through faults in different areas such as the central and southwestern Foothills of Taiwan, the total net accumulation of all internal and external processes of these rivers through time is recorded as curvature in their respective Hack profiles with the fundamental outcome being that the more intense the upwarping is of a Hack profile convexity, the more strain that has accumulated as a result of tectonic uplifting.

In this study, we first calibrate the 1904 "Taiwan Bautu" map to a more recent 1985 topographic map and 2000 DTM, which both use the Universal Transverse Mercator (zone 51) grid coordinate system and ellipsoid of GRS67. We compare Hack profiles of rivers derived from the three databases at different times (1904, 1985, and 2000) to disclose features of long-term crustal deformation. The results lead to the following conclusions:

(1) The Tungtzchiau fault became inactive after a 1935 earthquake ($M_L = 7.1$), and erosion became the predominate process rather than tectonic uplifting revealed in the reaches of the Daan and Dachia rivers that cut through the region.

(2) In the central Foothills, relative uplift is higher near the Wu River and decreases northwards and southwards. In the southwestern Foothills, relative uplift, of similar intensity, is higher near the Neocho River and this also decreases northwards and southwards.

(3) In the southwestern Foothills, significant concave segments at the lower reaches of rivers below that of ideal graded profiles can only be found in the Sandieh, Neocho and Bazhang rivers. By adopting the evolution concept of Brookfield (1998) and the earthquake time series analyzed by Chen et al. (2003b), our results show that fault systems in the southwestern Foothills tend to release strain more readily through small earthquakes whilst fault systems in the central Foothills tend to be locked. This also means that in terms of relative tectonic activity, the potential for large earthquakes in the central Foothills is higher than that in the southwestern Foothills.

(4) In the central Foothills, higher uplift in concert with a lack of small magnitude earthquakes implies that accumulated strain are to be expected, such as the Chi-Chi earthquake ($M_L = 7.3$) in 1999.

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