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Serial reverse and strike slip on imbricate faults: The Coastal Range of east Taiwan

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ABSTRACT

Holocene marine chronologies for three segments of the Coastal Range of east Taiwan indicate that there has been broadly uniform uplift of about 3–5 mm/yr during the past 8000 yr. Previous reports have cited local Holocene uplift rates as high as 14 mm/yr, and geodetic measurements indicate uplift of as much as 20 mm/yr. Furthermore, the seismic record reflects contraction of 26–54 mm/yr, whereas the Luzon volcanic arc is here being subducted beneath Eurasia at an average rate of 68 mm/yr. We attribute the discrepancies in both uplift and contractional measurements to distributed deformation between upthrust imbricate slices of an accreted sediment prism, the vertical component being taken up by serial reverse slip on the thrusts that bound the slices and the horizontal component being taken up by serial strike slip along the thrusts.

INTRODUCTION

The amount of long-term tectonic slip on extensional coasts can be determined by combining apparently incompatible uplift sequences for different parts of individual fault segments or adjacent fault segments (Stewart and Vita-Finzi, 1996). This present study extends the approach to a compressional setting in an attempt to link the evidence of plate kinematics and estimates of seismic moment.

We studied the shoreline that borders the Coastal Range of Taiwan (Fig. 1), where part of the Luzon volcanic arc has been in oblique collision with the Eurasian continent for the past 4 m.y. (Hsu, 1990). Although the direction of principal stress indicated by microseismicity off east Taiwan is in good agreement with the accepted tectonic pattern (e.g., Yu and Tsai, 1982), there is disagreement over how and at what rate the convergence is being taken up. In contrast, clear Wadati-Benioff zones are indicated by seismicity northeast of Taiwan, where the Philippine Sea plate is being subducted northward along the Ryukyu Trench, and south of Taiwan, where the southern part of the Luzon arc is being subducted eastward (Pezzopane and Wesnousky, 1989).

The seismic moment tensors of the eight largest shallow earthquakes that occurred between 1963 and 1989, earthquakes that are considered to be consistent with those of the preceding 175 yr, represent 26–54 mm/yr of contraction at an azimuth of about 290° (Pezzopane and Wesnousky, 1989), compared with the 68 mm/yr at 310° predicted by plate tectonic models (Seno, 1977). As elsewhere, the shortfall has been attributed to an unrepresentative seismic record, errors in the estimated rates of plate convergence, or aseismic deformation. Nevertheless, contrary to Brune (1968), seismic moment release pertaining to major events is not necessarily a good measure of crustal deformation. This notion is

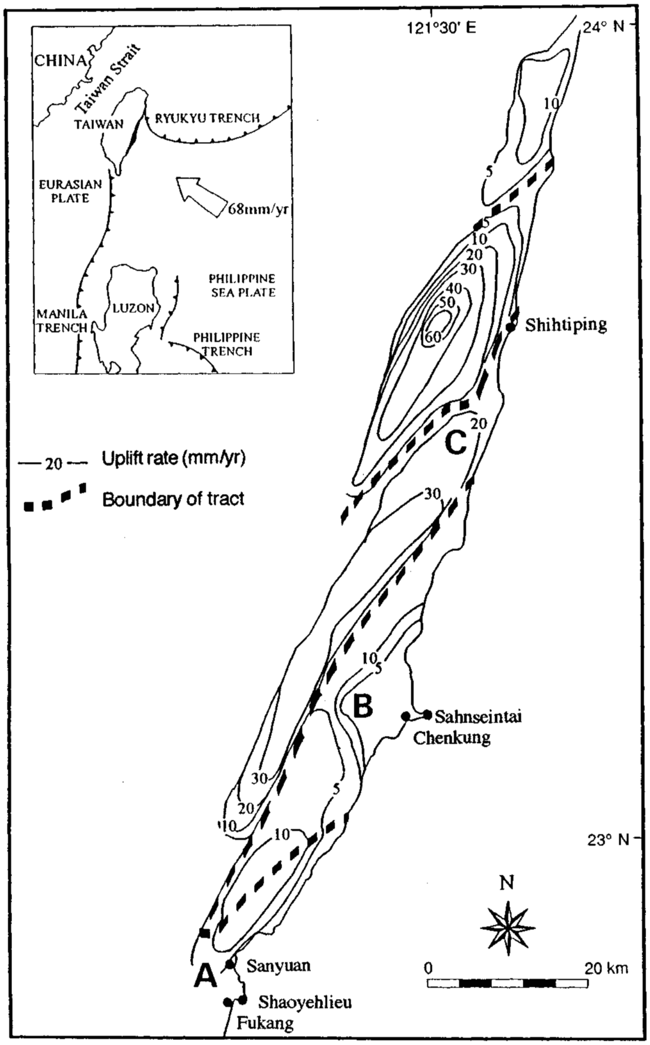

Figure 1. Major tectonic tracts (heavy broken lines) of Coastal Range (after Lin, 1991). Coastal uplift data for tracts A, B, and C are presented in Table 1 and Figure 2. Contours show uplift (in mm/yr) between geodetic surveys of 1914–1921 and 1976–1979 (Chen, 1984) replotted with ARC/INFO (Lin, 1991). Inset shows tectonic setting of Taiwan.

explored by using evidence for shoreline displacement during the past 8000 yr to show that shortening is broadly distributed, even without taking into account the seismically active zone that extends at least 150 km off the east coast of Taiwan (Pezzopane and Wesnousky, 1989).

COASTAL UPLIFT

The Coastal Range is an accretionary wedge composed of island-arc volcanic rocks surmounted by a thick cover of detritus derived from the mountains to the west (Hsu, 1956; Chi et al., 1981; Lundberg and Dorsey, 1990). The wedge is cut by a series of major, en echelon, southeast-verging thrusts (Ho, 1982), most of which are from the Pleistocene in age (post-NN19, according to Chi et al., 1981). Lin (1991) suggested that these thrusts define a series of distinctive morphological units (Fig. 1), although he showed that many of the differences between them stem from variations in lithology and exposure rather than tectonic history. We propose that they are the surface expression of imbricate faults within the accretionary wedge.

Rapid Holocene uplift has been documented on the east coast of Taiwan since Lin (1969) described a series of marine terraces rising to more than 80 m. Numerous studies of uplift using ^{14}C and U-series dating of corals and molluscs have been stimulated by the presence of extensive reefs and terraces (see review by Lin, 1991). By using ^{14}C ages on driftwood and archaeological data as well as some of the ^{14}C ages on coral reported by Liew et al. (1993) and incorporated in Table 1 here, Chen et al. (1991) concluded that the average uplift rate has been 14 mm/yr in the southern part of the Coastal Range and 5–9 mm/yr in the northern part. Konishi et al. (1968) estimated an average rate of 6–9 mm/yr at Hualien (lat ~24°N) and Peng et al. (1977) obtained a Holocene average of 5.0 ± 0.4 mm/yr for the Coastal Range. The most thorough survey, by Liew et al. (1993), yielded Holocene rates from 2.5–3.0 to more than 8 mm/yr for a 65 km length of coast north of Chenkung.

Our study pursues the question of differential uplift further by considering tracts of coast between major thrusts to be analogous to normal fault segments on extensional coasts (Stewart and Vita-Finzi, 1996), so that they are adequately documented by a single section only if its uplift record is reasonably complete. Accordingly, whereas tract C (Fig. 1) is represented by the sequence at Shihtiping and tract B by that at Sahnseintai, tract A requires data from Shaoyehlieu, Fukang, and Sanyuan. The age/height values used here (Fig. 2) are based on published conventional ^{14}C and U-series dates supplemented by seven first-order ^{14}C dates on shells from fossil intertidal platforms (Table 1; calibration to calendar dates follows that of Stuiver and Reimer, 1993). Sea-level correction is based on the theoretical curve for continental shorelines calculated by W. R. Peltier (1997, personal commun.), which yields a transgression at about 5000 yr B.P. of 1.3 m in the north and 1.1 m in the south of the Coastal Range. The timing agrees well with the sea-level maximum of 2.4 m at 4700 yr B.P. in the Taiwan Strait reported by Chen and Liu (1996). Corrected elevations were rounded up or down to the nearest 1 m to avoid artificial precision.

If analyzed by least squares, the plots for B and C yield curves that do not meet the origin. This could stem from our failure to allow for apparent sample age produced by an oceanic reservoir effect; however, because it does not arise in curve A, a more plausible explanation is that, as in the Zagros Mountains of Iran (Vita-Finzi, 1982), tracts B and C have been tectonically quiescent for the past 700–800 yr. The uplift rates determined by least squares are 3.1 mm/yr for A, 3 mm/yr for B, and 5 mm/yr for C; the averages are 3.1, 2.5, and 4.2 mm/yr, respectively.

TABLE 1. ^{14}C AND U-SERIES AGES USED FOR CALCULATING HOLOCENE COASTAL UPLIFT

Elevation (m)		Corr. elev.* (m)	Calibrated age † (yr B.P.)	Source §
Shaoyehlieu (121° 11' 27"E, 22° 47'53" N)				
15		15	3390 ± 210	a (454)
7.7		8	2820 ± 180	a (450)
Fukang (121°08'E,22°49'N)				
20	c	24	7530 ± 260	b
9	c	9	2080 ± 200	b
3	c	3	655 ± 100	b
3.3	c	3	1080 ± 70	c
1.87	c	1	2950 ± 60	c
Sanyuan (121°11'05"E, 22°49'11"W)				
1.0		1	280 ±180	a (455)
Sahnseintai (121°24'07"E, 23°07'28"N)				
14	c	14	5980 ± 125 #	d
13.5	c	14	5850 ± 150 #	d
7	c	7	3040 ± 195 #	d
4.5		5	1750 ± 180	a (446)
4.2		4	2350 ± 180	a (447)
3.5		4	2000 ± 150	a (443)
2.4	c	2	1520 ± 50	d
2.3	c	2	1400 ± 300 *t*	d
2.3	c	2	1300 ± 300 *t*	d
1	c	1	1080 ± 185	d
Shihtiping (121°30'04"E, 23°29'36"N)				
21	c	20	5100 ± 600 *t*	d
19	c	18	4300 ± 350 *t*	d
14	c	14	3435 ± 120	d
14	c	14	3670 ± 145	d
14		14	3590 ± 130	d
14	c	14	3890 ± 160	d
5.5	c	6	1800 ± 300 *t*	d
5		5	2450 ± 170	a (464)
1.7	c	2	1295 ± 35	d
1.7	c	2	1700 ± 350 *t*	d
1.8		2	780 ± 130	a (465)

* Elevation corrected by interpolating between sea-level curves for 22°N, 121°E and 25°N, 122°E by W. R. Peltier (July 1997, personal commun.; see Fig. 2) rounded up or down to nearest 1.0 m; 1 m subtracted from elevations in Liew et al. (1993) as they are given there above MSL.

† Ages determined by ^{14}C unless Th/U (*t*) is specified, on shell (species listed in Lin, 1991) unless coral (c) is specified. UCL- dates by first-order ^{14}C method (Vita-Finzi 1992). Age calibration following Stuiver & Reimer (1993), with range expressed as ± value using the higher of the two error limits.

§ Source: a = this study (UCL-); b = Peng et al. (1977); c = Lin (1989); d = Liew et al. (1993) and sources therein.

After subtraction of age-correction factor in Liew et al. (1993) of 540 yr. In the absence of isotopic data, correction for fractionation could not be removed, but it is unlikely to exceed the standard error.

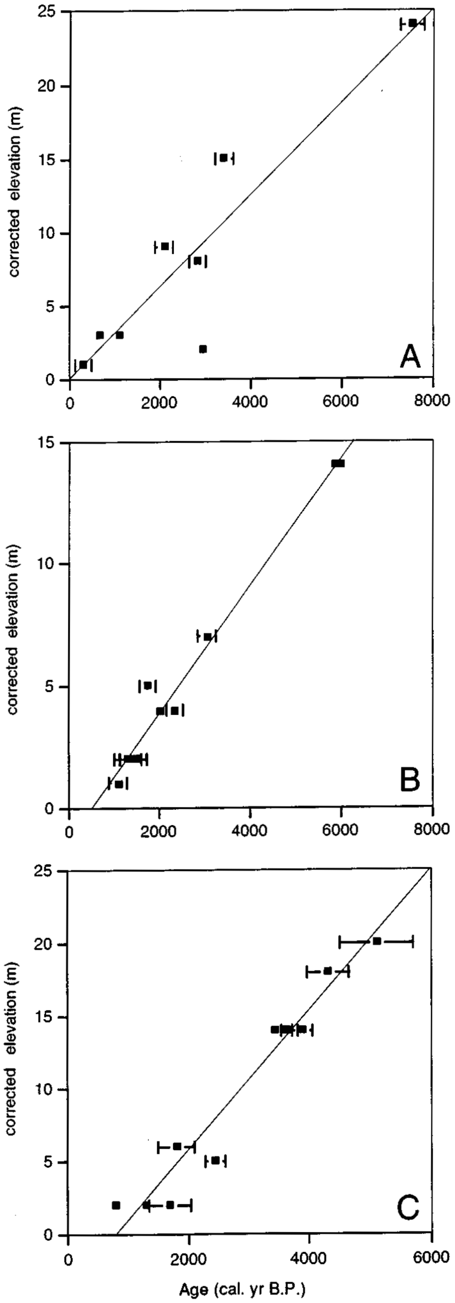

Figure 2. Age vs. height plots for (A) Shaoyehlieu, Fukang, and Sanyuan, (B) Sahnseintai, and (C) Shihtiping (see Fig. 1 and Table 1). Elevations have been corrected for sea-level change after W. R. Peltier (1997, personal commun.). ^{14}C ages are calibrated after Stuiver and Reimer (1993). Graphs fitted by least squares.

DISCUSSION

A stepped series of benches indicative of spasmodic uplift can be seen at Shihtiping (15, 6, 4.5, 3.5, 1.5, and High Water; the 3.5 m level is the best developed) and Shihyushan, 8 km north of Chenkung (at least five notches between about 30 and 43 m). Others were described by Liew et al. (1993), who concluded that there had been coseismic vertical displacements of a few meters. Bonilla (1977) reported uplift of 0.6 m at Hualien after the earthquake of 22 October 1951. Thus there are times when a tract of coast has a seismicity hiatus, which leads to a misleadingly low uplift rate, and others when the same tract undergoes a phase of rapid emergence (cf. Vita-Finzi, 1996).

In addition, the coast is subject to warping, whether as a consequence of localized uplift, or because, as suggested by Biq (1965), sinistral displacement on the fault that bounds the Coastal Range to the west leads to transcurrent buckling.

Although there is some slight northward increase in uplift rate, it is trivial when compared with the errors inherent in the data and in no way matches the variability found by earlier paleoshore studies or the geodetic evidence for localized uplift of as much as 35 mm/yr (Liu and Yu, 1989). This uniformity is not caused by the swamping of the signal by the sea-level correction (cf. Vita-Finzi, 1996), because this is of little significance for the past 8000 yr, within which the bulk of the ages fall; instead, as in extensional settings (Stewart and Vita-Finzi, 1996), the uniformity is primarily the result of smoothing of the short-term record.

Our suggestion that the Coastal Range is cut by imbricate faults generated within the accretionary wedge conforms with Biq's (1971) observation that the one documented example of coseismic uplift on the coast, at Hualien in 1951, occurred on an eastward-dipping thrust. Taking this angle as 45°, the observed Holocene uplift rate amounts to shortening normal to the coast at 3–5 mm/yr. The corresponding rate parallel to the azimuth of plate slip (310°; Seno et al., 1987) is 68 mm/yr. The uplift rate is an order of magnitude too low only if all the deformation is concentrated at the coast. The conclusion that uplift is distributed across strike, partly on reverse faults, some of which could be blind and others low-angle thrusts, is in agreement with the geodetic evidence. The mechanism is akin to serial folding in the sense that movement occurs on several structures across strike, but not synchronously. In Figure 1, contours display the elevation change between two geodetic surveys, one during the period 1914–1921 and the other during the period 1976–1979. Note that uplift is distributed across the entire Coastal Range. The seismic record represents 26–54 mm/yr of shortening (Pezzopane and Wesnousky, 1989), but substantial aseismic deformation is known in the Longitudinal Valley west of the Coastal Range (Yu and Chen, 1994), and may occur within the Coastal Range.

It is possible that additional shortening is taken up by strike-slip movement not merely between the Coastal Range and the rest of Taiwan, but also within the Coastal Range. Focal-plane solutions in the central and northern Coastal Range (Lee, 1983; Yeh et al., 1991) indicate reverse faulting with a strike-slip component. No difference in the elevation of marine terraces has been observed on opposite sides of the major thrusts where they cut the coast (Liew et al., 1993), whereas triangulation data spanning the period 1914–1979 indicate counterclockwise rotation (Biq, 1984), consistent with sinistral "bookshelf" deformation driven by oblique convergence.

In sum, deformation of the Coastal Range may be distributed across strike by serial faulting on reverse imbricate faults and along strike by serial strike-slip displacement between imbricate thrust sheets: a paperback version of the bookshelf model.

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