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23. We thank H. A. Scheraga and F. W. McLafferty (Cornell University) for the RNase A samples, and acknowledge the U.S. Department of Energy, through internal Exploratory Research of the Molecular Research Center under contract DE-AC06-76RLO 1830, the National Science Foundation Instrumentation and Instrument Development Program (DIR 8908096), and the NIH Office of Human Genome Research (GM 42940), for support of this research. Pacific Northwest Laboratory is operated by Battelle Memorial Institute.

16 November 1989; accepted 14 February 1990

Holocene Mean Uplift Rates Across an Active Plate-Collision Boundary in Taiwan

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Samples of Holocene fossil coral from uplifted reefs of three tectonically distinct, yet geographically proximal regions of Taiwan have been dated by uranium-series and ^{14}C isotopes. Applying corrections for altitude change caused by sea level fluctuations enables evaluation of long-term average Holocene uplift rates for three areas across an active convergent margin: (i) the Hengchun Peninsula of the Eurasian tectonic plate; (ii) the Eastern Coastal Range of Taiwan, a plate boundary; and (iii) two offshore islands, Lanyu and Lutao, both situated on the leading edge of the adjoining Philippine Plate. The data indicate that while all three areas have experienced uplift through the Holocene, plate collision has caused significantly higher uplift rates in the region directly along the plate boundary.

TECTONICALLY, TAIWAN IS OF GREAT interest because a major plate boundary, separating the Eurasian and Philippine tectonic plates, runs through its eastern section. Geophysical studies have shown that eastern Taiwan is seismically and geodetically active as a result of ongoing collision (*1*, *2*). To some degree, collision also seems to be taking place to the west, as the Eurasian Plate is subducted and the accretionary wedge is pushed by the Philippine Plate. Geodetic surveys and tidal observations spanning several years have shown that the modern uplift rate of eastern Taiwan is as high as 35 mm/year, among the highest known in the world (*3*). Although uplift rates are known to be high, few studies have attempted to assess how these rates vary across a convergent margin, and whether uplift is temporally constant or intermittent. To address these questions, we examined long-term (thousands of years) uplift rates on both sides of the Taiwan collision boundary, as well as in the boundary zone itself.

The distribution of raised coral reef terraces in Taiwan is such that we were able to evaluate uplift rates for different parts of the collisional boundary by collecting samples from three locations (Fig. 1): (i) the Eastern Coastal Range (the northern extension of the Luzon Arc and in the boundary zone between the Eurasian and Philippine tectonic plates), (ii) the Hengchun Peninsula (on the main island of Taiwan, lying directly on the accretionary wedge overlying the Eurasian Plate), and (iii) two islands off the southeastern coast of Taiwan, Lanyu and Lutao (both on the Philippine plate). Our sample set allowed us to evaluate relative uplift from three close, yet tectonically distinctive settings, that is, the leading edges of two large tectonic plates and their zone of active collision.

In an earlier study, Peng *et al.* (*4*) summarized 34 radiocarbon ages of uplifted Holocene corals sampled at elevations up to 25 m above present sea level from the Hengchun Peninsula and Eastern Coastal Range of Taiwan. That study showed that average long-term uplift rates are 5.3 mm/year for southern Taiwan and 5.0 mm/year for the Eastern Coastal area. Our additional data and sampling points allow a more complete assessment of the long-term geodetic changes along the plate boundary as well as in those areas more removed from the collision zone during the Holocene.

Because fossil corals are suitable for both uranium-series and ^{14}C dating, and are known to grow within a limited depth range, they are ideal samples for neotectonic studies. Coral segments, mostly of the *Faviicae* and *Porticae* species, were trimmed to remove the outer, somewhat weathered crust and were ultrasonically cleaned to ensure that no terrestrial contaminating materials remained (*5*). All samples were analyzed by x-ray diffraction, and only those containing less than approximately 2% calcite, a recrystallized product of the original aragonite, were used for isotopic analysis (*6*). The height of each sample was deter-

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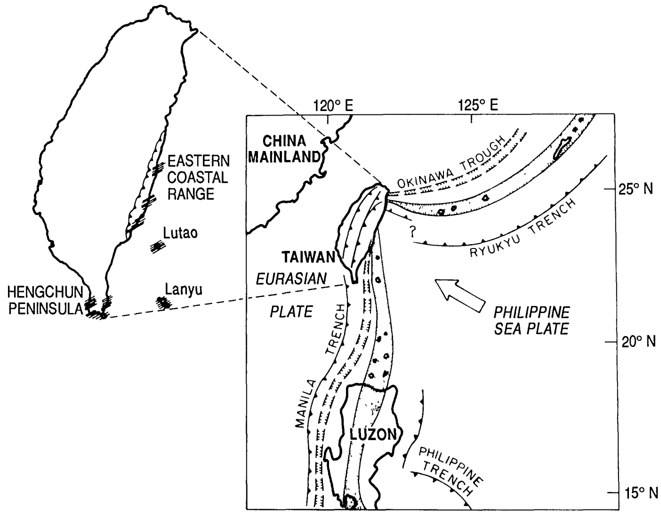
Fig. 1. A map showing the major tectonic elements of the Taiwan region (*1*). The eastern part of Taiwan is part of the current collision zone of the Eurasian and Philippine Sea tectonic plates. Areas where fossil corals were collected from raised terraces are shown by the stripped patterns and include the Hengchun Peninsula (on the Eurasian Plate), the Eastern Coastal Area (an active plate boundary), and two offshore islands, Lanyu and Lutao (on the Philippine tectonic plate).



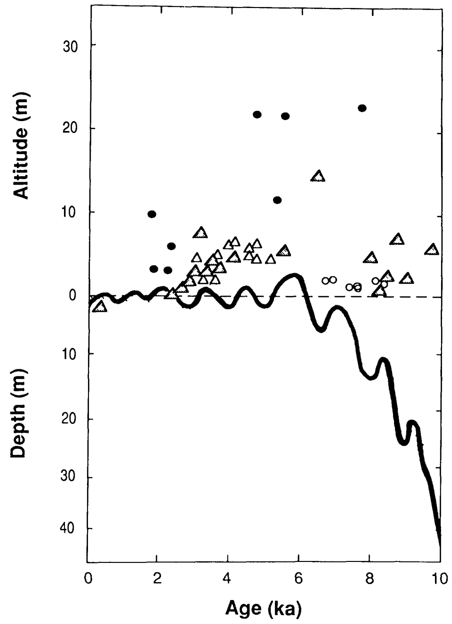


Fig. 2. Uranium-series ages versus uncorrected altitudes of coral reef samples together with a generalized eustatic sea level curve (dotted line) (*14*) and a more detailed curve based on data from the East China Sea region (solid line) (*15*). The horizontal dashed line represents present-day sea level. ●, Eastern Costal Range; ▲, Hengchun Peninsula; △, Lanyu; ○, Lutao. Abbreviation: ka, thousand years ago.

mined by a leveling survey relative to present mean sea level.

A total of 49 analyses were performed for activities of uranium and thorium isotopes (*7*). In addition, 17 samples were also dated by ^{14}C techniques, and similar ages were obtained for 13 samples analyzed by both methods (*8*). Concentrations of uranium for all samples are similar to modern corals (*9*). Measured ^{230}Th activities are apparently free of contamination effects as indicated by the low ^{232}Th contents found in our samples (*10*). The $^{234}U/^{238}U$ activity ratios, corrected for the decay of ^{234}U, are close to that found in modern seawater, that is, there is ~14% excess ^{234}U activity relative to ^{238}U.

We used the radioisotopic dates (t) of the raised coral reefs, their present altitude (A) relative to mean sea level, and estimates of past sea level (E) relative to present, to estimate a "minimum uplift height" ($A + E$) for each sample locality as a function of time. Because depositional depths of corals vary by species from about 3 m to as great as about 20 m (for stony corals) (*11*), we did not attempt to estimate the exact depth of our coral samples relative to past sea level. Initial depths for all coral samples were assumed to be zero, and thus calculated uplifts are considered "minimum."

Accurate correction for eustatic sea level change (E) is critical because the time scale under consideration (approximately the last 10,000 years) represents a period of large sea level variation as the last major continental ice sheets retreated to their present positions. It is now generally recognized that sea level fluctuations were not globally uniform because of the deformation of the earth's surface and its geoid by shifting ice and water loads (*12*).

We examined several sea level curves (*13*) and decided to use two curves that serve to bracket most reasonable possibilities for the Taiwan coastal region (Fig. 2). We applied corrections based on a generalized "world-wide eustatic" curve (*14*) and a more detailed curve based on data collected from the East China Sea region (*15*). The eastern China curve is based on several dozen radiocarbon ages compiled from beach rock, coral reefs, chenier ridges, and other materials located close to our study area. Both in terms of its temporal resolution and proximity to the sampled coral terraces, it must be considered the more reliable curve for sea level corrections.

When sample altitudes for sea level change since coral formation are corrected by either curve, plots of minimum uplift versus age produce well-defined trends (Fig. 3). Linear least-square fits to the data give slopes (mean uplift rate) of 4.7 to 5.3 mm/year for the Eastern Coastal Range, 3.3 to 3.5 mm/year for Hengchun Peninsula, and 1.6 to 2.2 mm/year for the Lanyu-Lutao coral terraces (*16*). The lower value of each uplift range is based on altitude data corrected by the East China Sea curve. The depth intercepts of our plots should represent the average original growth depth of the analyzed corals. Values range from about −1 to −7 m, reasonable results for the species analyzed.

In addition to uplift, shortening and active faulting of tectonic plates may occur along a convergent margin. The relative importance of each process depends on the local and regional geology. Our data show that while all three sites across the Taiwan margin show significant uplift, the average rate in the Eastern Coastal Range is at least two times as fast as that in the Lanyu-Lutao area. If we include previously published data (*4*), the minimum uplift for the Hengchun Peninsula increases slightly to 4.2 mm/year, whereas the rate for the Eastern Coastal Range remains the same. The relative uplift rate relation (Eastern Coastal Range > Hengchun Peninsula > Lanyu-Lutao area) holds in either case and with either sea level curve used for altitude correction.

A significantly higher uplift rate for the Eastern Coastal Area is consistent with geodetic and geomorphological studies that indicate that rates are (or have been) higher in that area compared to elsewhere in Taiwan (*7*). As a long-term average, the rate is considered high, comparable to the 4 to 5 mm/year values determined for the Himalayas (*4*). Furthermore, the distribution of data in the uplift versus age plot (Fig. 3) indicates that uplift has been active and fairly uniform for at least the last several thousand years.

The relatively low uplift rate of the offshore islands (Philippine Plate) is expected for the more stable, precollision environment that characterizes that area. Our estimated uplift rates for this area are close to rates previously estimated for Northern Taiwan, located about the same distance away from the plate boundary (*4*). In northeastern Taiwan, subduction of the Philippine Plate beneath the Ryukyu Arc is marked by an east-west planar seismic zone about 50 kilometers wide centered near Hualien at 24°N (*1, 2*). The Lanyu-Lutao rates are also similar to the <1- to 2-mm/year values previously determined for the Ryukyu Is-

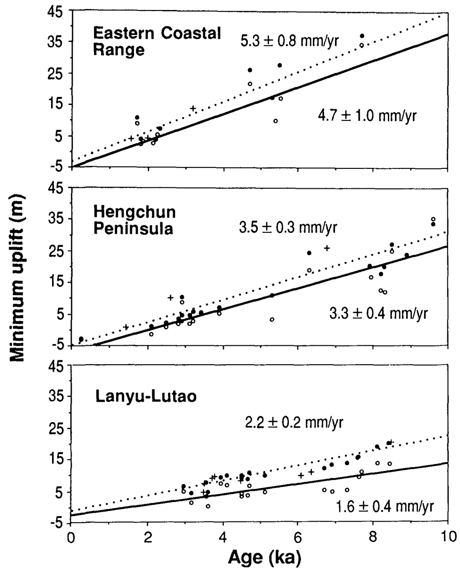


Fig. 3. Plots of minimum uplift versus sample age for the three study areas. The enclosed circles and dashed regression lines are for data points with altitudes corrected by the generalized sea level curve (*14*), whereas the open circles and solid regression lines are corrected according to the East China Sea curve (*15*). The slopes of these lines represent average uplift rates. Based on the errors shown (standard error of the regression), there is no significant difference in results with the use of either sea level curve for altitude correction. Crosses represent ^{14}C ages with altitudes corrected by the generalized sea level curve. Abbreviations: ka, thousand years ago; yr, year.

lands, northeast of Taiwan (*17*). The moderately high uplift rate indicated for the southern peninsular area may be related to the recently proposed eastward-plunging subduction zone in southern Taiwan, centered at about 22°N (*18*). The uplift rates are in accord with the seismically based interpretation that subduction is important in the southern part of the country, although its effects are perhaps less evident during the Holocene.

Our analysis of the distribution and age of elevated coral samples across an active convergent margin in Taiwan has shown that uplift has persisted at a reasonably uniform rate through the Holocene. Comparison to other collisional boundaries must await similar investigations across other zones of tectonic convergence.

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6. In all, 14 samples were analyzed in Tallahassee [Florida State University (FSU)] and 43 samples were analyzed in Taipei [Institute of Earth Sciences (IES)] including 12 replicates of samples run at FSU. A regression of calculated ^{230}Th ages based on uranium-series measurements of these replicates showed that, on average, the IES ages equaled 95% of the FSU ages [$(\Sigma dev^2/\{n-2\})^{1/2}$ = 960 years]. Both laboratories used temperature-controlled ion-exchange and rotating-disc electrodeposition procedures [W. J. McCabe, R. G. Ditchburn, N. E. Whitehead, *Inst. Nuclear Sci. (New Zealand) Rep. INS-R-262* (1979), p. 29; R. G. Ditchburn and W. J. McCabe, *ibid. INS-R-325* (1984), p. 10; W. C. Burnett, K. B. Baker, P. Chin, W. J. McCabe, R. G. Ditchburn, *Mar. Geol.* **80**, 215 (1988)].
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30 October 1989; accepted 15 February 1990

Indication of Increasing Solar Ultraviolet-B Radiation Flux in Alpine Regions

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Measurements at the Jungfraujoch High Mountain Station (Swiss Alps, 47°N, 3576 meters above sea level) indicate that there has been a slight increase of about 1 percent per year in the flux of solar ultraviolet-B radiation (290 to 330 nanometers) since 1981. A Robertson-Berger detector was used to measure solar erythemal radiation. The increase can be related to a long-term ozone depletion.

With depletion of stratospheric ozone (O_3), the flux of solar ultraviolet-B radiation (UVB) (290 to 330 nm) reaching the earth's surface should increase. Such an increase could have various consequences; in particular, it could increase the risk of skin cancer (*1–3*). In the Northern Hemisphere, a slight O_3 depletion of approximately 3% from 1969 to 1986 has been reported (*4*), in contrast to a considerable O_3 depletion over Antarctica in October (*5*). Earlier studies have not detected an increase in the UVB flux corresponding to the O_3 depletion in the Northern Hemisphere, however (*6–8*). Detection of a slight long-term increase is not easy, because the flux of UVB reaching the earth is influenced by numerous atmospheric conditions, apart from O_3 content. Changes in aerosol concentration, in cloudiness, and in the reflectivity of the earth's surface due to varying snow cover affect the flux of UVB. In addition, there is a strong natural seasonal variation of the O_3 content in mid-latitudes (*9*). All these effects lead to a large variability in the flux of UVB at the earth's surface; this variability can mask a tendency toward a slight increase.

In order to minimize the effects of these masking parameters and to identify long-term effects of decreasing O_3 concentrations

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