Letter Section

Marine deposits of late glacial times exposed by tectonic uplift on the east coast of Taiwan*

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ABSTRACT

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Marine sediments deposited some 14,000 years ago, when the sea level was between 80 and 100 m below the present sea level, have been found exposed at about 17 m in altitude near Tu-lan, on the east coast of Taiwan. This implies a minimum average uplift rate of 7.6 ± 0.9 mm/yr; similar values of tectonic uplift are not uncommon on the eastern Coastal Range of Taiwan. Such rates of tectonic uplift, among the highest reported in the literature, are of the same order as present-day maximum glacio-isostatic uplift rates.

Introduction

The most spectacular examples of late Quaternary regional crustal uplift are usually reported from formerly glaciated areas. In Fennoscandia, for example, the vertical displacement since the last glacial peak is estimated to have reached a maximum of 800–850 m (Mörner, 1979; i.e. an average rate of about 40 mm/yr). Even greater values probably occurred in northern Canada. However, uplift rates in these areas have been gradually decreasing since the ice domes melted and present-day values deduced from tide-gauge records are usually less than 10 mm/yr.

In areas where glacio-isostatic movements are predominant, the normal behaviour over a long

term is a cyclic up-and-down oscillatory pattern, with main periodicities of the order of 19, 23, 41 and 100 kyr, related to the effect of astronomic periodicities on climatic changes (Berger et al., 1990). Absolute vertical displacements between two similar climatic periods may, therefore, be quite small in these areas.

In regions remote from ice sheets, on the other hand, tectonic uplift rates are usually one order of magnitude less than the glacio-isostatic rates. Around the Pacific and Indian Oceans, for example, last Interglacial shorelines (dated 125 ± 10 kyr) are reported everywhere at elevations less than 400 m (Yonekura, 1983; Yoshikawa, 1987), corresponding to uplift rates less than 3.2 mm/yr, and most often much lower than this value.

In this paper we provide further evidence of tectonic uplift rates of the order of 6–10 mm/yr which have been active throughout the Holocene and in one case, since at least 14,000 years on the east coast of Taiwan. For Chinese names, the English transcription has been used.

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Fig. 1. Lithospheric plate structure in and around Taiwan (schematic). Main thrusts as thick lines, barbs on overriding side. In sections: oceanic crust hachured, continental crust with pattern of crosses, island-arc crust with pattern of overturned "v", lithospheric mantle left white (from Angelier et al., 1986).

The geodynamic context

The Taiwan region forms a transition between two opposite movements of the Philippine Sea plate (Fig. 1): underthrusting along the Ryukyu Islands, and overthrusting along the volcanic islands extending from the Batan Islands to central Luzon (Hsu, 1971; Angelier et al., 1986; Angelier, 1990). The eastern Coastal Range of Taiwan is an accreted prism of the Luzon arc, belonging to the Philippine Sea plate, which collided with the Eurasian plate margin. As shown by paleontologic (Chi et al., 1985; Huang and Lin, 1991), volcanologic (Yang et al., 1992) and paleomagnetic studies (Yang et al., 1983; Lee, 1989), intensive collision has occurred since the late Pliocene and has spread southwards.

Field data

Tu-lan (22°52'N, 121°13'E)

Fifteen kilometres northeast of T'ai-tung, above a pebble beach, a 35-m-high cliff consists of marine and river mouth deposits capping a Pliocene sedimentary basement (Fig. 2). Intercalated between a basal conglomerate and a layer of river mouth

deposits with cobbles, a well stratified layer of fossiliferous sand deposits appears in situ (Fig. 3). In the sand, the plagioclase/quartz rate is about 0.66, i.e. near that of the most feldspathic near-shore sands (Biq et al., 1985). The clay fraction is low and consists of several heterogeneous minerals: smectite, kaolinite (and/or chlorite) and traces of illite similar to that of marine clays. The shell fraction includes, in addition to undetermined oyster fragments, thin Lamellibranch and Gastropoda debris, some of which have been identified:

- *Anodontia edentula*, generally living on the shallow muddy sea floor;
- *Paphia undulata*, usually found in sheltered muddy bays;
- *Gafrarium tumidum*, very frequent on a sandy shallow sea floor;
- *Clypeomorus purpurascea*, living in the intertidal zone of rocky shores; and
- *Diodora suprapunicea*, which are shallow-dwelling epiphytal limpets.

The above sediments may have been transported in a water environment calm enough, and/or accumulated at a depositional rate rapid enough, to make the sedimentation of thin shell debris and mica grains possible (the average spring tidal range is 1.25 m in this area). As microfauna is totally

Fig. 2. Location map and simplified profile of the Tu-lan section (from Hsieh, 1990, modified); A=Piocene sedimentary basement; B=offshore to beach sandy deposits; C=river mouth deposits, nearshore to fluvial environment; S=position of dated samples.

Fig. 3. Detail of the Tu-lan outcrop. The samples dated at about 14,000 years were collected at the level of the observer's eye, at about +17 m. Above: river mouth deposits with cobbles. Below: the present-day pebble beach. (Photo P.A. Pirazzoli.)

absent, this could be the case of a beach sheltered from swells, or of a 10–15 m deep sea floor in an area affected by significant fluvial influx. These deposits probably do not belong to submerged

coastal bars, owing to: (1) the grain size (fine sands, median = 110 μm), (2) a limited sorting, (3) the absence of ripple structures, (4) the thickness of the deposits (about 10 m), and (5) the occurrence

on some quartz grains of a silicic film, which would have been dissolved by prolonged submersion; the last two arguments strongly support the beach interpretation. However, very few beaches in eastern Taiwan consist of such a fine sand; in the Tulan area, in particular, pebble beaches predominate and sandy beds similar to the studied one, exposed above the Pliocene basement in nearby outcrops, have been interpreted as shoreface deposits (Hsieh, 1990).

Two samples consisting of Lamellibranch debris (*Anodontia edentula* and *Paphia undulata*), collected from the cliff at about +17 m, were dated by AMS ^{14}C at $12,250 \pm 130$ yr B.P. (GifA-90218) and $12,170 \pm 160$ yr B.P. (GifA-91094) (assuming a reservoir age of 400 ± 140 years). A sample of Gastropoda shell debris (*Diodora suprapunicea*) collected from the same place gave $12,480 \pm 160$ yr B.P. (GifA-91087). These converging dates suggest that the ages of the shell debris samples are fairly representative of the age of the sands in which they are found. The ages fall beyond the calibration curves for marine samples proposed by Stuiver et al. (1986). According to the calibration of the ^{14}C time scale proposed by Bard et al. (1990a, 1992), using mass spectrometric U–Th ages from Barbados corals, the preceding ^{14}C dates correspond to the period between 13,800 and 14,400 years ago.

In the absence of a local relative sea-level curve, the sea-level position at that time can be estimated at about –100 m using planktonic and benthic ^{18}O data (Shackleton, 1987, fig. 5), or between –80 and –85 m using calibrated dates of corals from Barbados after correction for the local tectonic trend (Bard et al., 1990a,b); these are of course only first order estimations, since glacial-isostatic contributions have a significant spatial dependence on the geometry of the coastline even over distances of less than 100 km (Nakada et al., 1991). A tentative average uplift rate between 6.7 and 8.5 mm/yr (i.e. of 7.6 ± 0.9 mm/yr) can be deduced for the last $14,100 \pm 300$ years from the above data if the samples studied belong to a beach; this of course would only be a minimum rate in the case of submarine deposits.

According to Bard et al. (1990b), around 14,000 years ago the sea level was rising at a rate of about 37 mm/yr. Though this is probably an average

value, possibly including acceleration and deceleration periods, it is much faster than the local tectonic rate (Fig. 4). The sand deposits studied were, therefore, in any case submerged and may have been capped by further nearshore/offshore deposits, most of which seem, however, to have been eroded. The coastal environment changed from sheltered to moderately exposed near the mouth of a torrent, as shown by the colluvium with cobble layers which can be observed a few metres higher in the same section (Fig. 3). Concerning the depositional environment of these undated deposits, it should be noted that steep slopes, poorly consolidated rock, heavy rainfall, recurrent great earthquakes and strong uplift and erosion rates have caused frequent landslides in this coastal area and offshore slumpings, bringing from time to time huge masses of land sediments to the narrow coastal, nearshore and offshore zones.

Assuming that the uplift rate remained constant in time, the $14,100 \pm 300$ year old sediments were submerged at a maximum depth of about 30 m below the rising sea level, reaching the sea level again only in the Late Holocene (Fig. 4), since when they have emerged, whereas a steep pebble beach has developed on the present-day exposed shore (Fig. 3).

The Ch'eng-kung–Feng-pin area

As shown in a recent study which will be published elsewhere (Liew et al., 1993), the 65-km-long coastal sector between Ch'eng-kung and Feng-pin exhibits irregular average uplift rates, varying from 2.5 to over 8.0 mm/yr. The highest rates have been reported near Shih-yü-san (6 to 9 mm/yr during the last 9000 years) and between Ta-wan and Feng-pin (over 6 mm/yr during the last 2000 years).

Hua-lien

The occurrence of rapid late-Holocene uplift at Mei-lun near Hua-lien, at the northern end of the eastern Coastal Range, is known to have existed since the late 1960s, when Lin (1969) obtained dates of 3870 ± 260 yr B.P. (NTU-4) and 3100 ± 290 yr B.P. (NTU-13) from corals collected at unspecified elevations from raised reefs over-

Fig. 4. Estimated average uplift rate at Tu-lan, versus rates and levels of the post-glacial eustatic rise according to Bard et al. (1990a,b). After deposition some 14,000 years ago and submergence by the eustatic sea-level rise, the samples studied may have emerged only between 2000 and 3000 years ago.

lying a Pleistocene tableland surface reaching 46 m in altitude. Younger ages (1512 ± 45 yr B.P., NTU-159; 1052 ± 32 yr B.P., NTU-166) were obtained from coral and shell samples collected twenty years earlier by C.C. Lin from reef outcrops overlying the same tableland at elevations lower than +3 m (Hsu et al., 1973). Aware of these findings, Konishi et al. (1968) collected from an outcrop of reef-wall limestone, 25 m above sea level (for a photograph of these raised reefs, see Pirazzoli, 1991, p. 142), an aragonitic coral sample which was dated 2800 ± 115 yr B.P. by ^{14}C (N-407), and 4200 ± 370 yr B.P. by ^{230}Th . This corresponds to an average uplift rate since 4000–3000 yr B.P. estimated between 6.0 and 9.7 mm/yr (Konishi

et al., 1968). Repeated levellings between 1984 and 1987 (Liu and Yu, 1990) have shown uneven uplifts in the Hua-lien area ranging from 20 to 100 mm. Most of the vertical displacements have taken place in 1986, probably related to two large earthquakes which occurred in this region.

Conclusions

Though uplift trends can be quite variable along the east coast of Taiwan, rates of the order of 6 to 9 mm/yr are not uncommon. These values are among the highest rates, over the time scale of several thousand years, reported in the literature from tectonically active areas and appear to be of

the same order as the maximum present-day uplift rates in former ice-sheet areas. At such rates, remnants of last Interglacial shorelines would have occurred, if preserved, at altitudes between 750 and 1100 m.

At Tu-lan, marine sediments about 14,000 years old are now exposed well above the present sea level. It is the first time, to our knowledge, that sea deposits of late glacial times are found emerged outside areas of glacio-isostatic uplift.

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