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CLIMATE CHANGE AS THE DOMINANT CONTROL ON THE LAST GLACIAL-HOLOCENE $\delta^{13}C$ VARIATIONS OF SEDIMENTARY ORGANIC CARBON IN THE LAN-YANG PLAIN, NORTHEASTERN TAIWAN

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ABSTRACT

This paper presents records of $\delta^{13}C$ of bulk sedimentary organic matter from two cores retrieved from the Lan-Yang Plain in northeastern Taiwan. The two cores, each 250 meters in length, drilled at Chu-An and Wu-Chieh, yielded very similar carbon isotope profiles. Except for one single sample in the uppermost section of Wu-Chieh Core, both cores exhibit quite stable depleted $\delta^{13}C$ values of –23‰ ~ -26 ‰ throughout the upper 4/5 sections, indicative of the dominance of C_3 plants growing under warm and humid conditions. As confirmed by calibrated radiocarbon dates, these intervals were deposited over the past 15 kyrs. The lowermost parts of both cores show a spiky pattern of $\delta^{13}C$ values (–14‰ ~ -25 ‰) in the last glacial intervals characterized by alternating dominance of C_4 and C_3 plants.

INTRODUCTION

$^{13}C/^{12}C$ ratios (hereafter denoted as $\delta^{13}C_{PDB}$) of organic matter in bulk sediments of estuary and the shallow, marginal sea reflect the source of organic matter of the catchment area and provenance (Bird *et al.*, 1992). The ultimate source of organic matter is almost exclusively plants and most significant among various factors contributing to the $\delta^{13}C$ values of sedimentary organic matter is the type of vegetation contemporaneous to continental soils (Victoria *et al.*, 1995; Bird and Pousai, 1997; Hatté *et al.*, 1998; Yeh and Wang, 2001) along with phytoplankton in the water bodies of the depositional site (Popp *et al.*, 1997).

During photosynthesis, plants take in preferentially ^{12}C and consequently cause isotopic fractionation between plant biomass and the CO_2 source. The isotopic fractionation depends on the type of vegetation and on the plant environment (O'Leary, 1981; Lajtha and Marshall, 1994; and, see a recent comprehensive review of Yeh and Wang, 2001). Plants show a wide spread of $\delta^{13}C_{PDB}$ values from –8 to – 38 ‰. This wide range is mainly attributed to the difference in the photosynthetic pathways such as C_3, C_4 and CAM (Bender, 1971; Deines, 1980; Farquhar *et al.*, 1989; O'Leary *et al.*, 1981; 1992), and secondarily to plant genes and environmental conditions (such as light intensity, partial pressure of atmospheric CO_2, humidity, and temperature) under which carbon fixation took place (e.g., Körner *et al.*, 1991; Stewart *et al.*, 1995; Kao *et al.*, 2000). According to the recent compilation by Yeh and Wang (2001), the $\delta^{13}C_{PDB}$ values of whole leaf samples of C_3 plants range from –22 to – 38 ‰ and differ distinctively from those of C_4 plants, which range from –8 to – 15 ‰. Bridging over the value ranges of C_3 and C_4 plants, the $\delta^{13}C_{PDB}$ values of leaf samples of CAM plants spread between –13 and –30 ‰. The values of various tissues, including the stem, shoot and root of a plant, are, in principle, within the same range of those of leaves, although the wood and litter tend to show slightly heavier $\delta^{13}C$ values (e.g., Martinelli *et al.*, 1998). A survey of the published data of various tissues of plants has led Yeh and Wang (2001) to conclude that the values of leaves are close to that of the whole plants.

The $\delta^{13}C_{PDB}$ values of organic carbon in the surface soils faithfully reflect the vegetation types in a variety of biomes (Victoria *et al.*, 1995; McClaran and McPherson, 1995; Yeh *et al.*, 1995). For example, along a transect through tropical/subtropical biomes in northern Australia, the soil of the forest (exclusively C_3 plants) has an average $\delta^{13}C$ value of –28 ‰ while that of C_4-dominanted tropical grasslands has an average $\delta^{13}C$ value of –15.5 ‰ (Bird and Pousai, 1997). The $\delta^{13}C$ values of river sediments from the transect region reflect the $\delta^{13}C$ values of soils in the region also (Bird and Pousai, 1997). Although degradation of organic matter is differential among various organic species and therefore can modify the original $\delta^{13}C_{PDB}$ value of bulk organic matter, while the isotopic signals might be only slightly altered, and especially under conditions when organic matter is buried rapidly and has not been subjected to significant diagenetic alteration in young-aged sediments, such as in the present case of this study.

To interpret the past $\delta^{13}C$ variations in sedimentary cores, we need to have a good reference of $\delta^{13}C$ variations of local biota and sediments. Fortunately, for the vegetation and lake sediments of northeastern Taiwan, Yeh and his colleagues (Yeh *et al.*, 1995; Yeh and Kao, 1996; Kao *et al.*, 2000; Wang and Yeh, 2003) have done a series of seminal isotopic analyses in recent years. The $\delta^{13}C$ values of leaves of vascular plants in coniferous-hardwood subalpine forest in the Yuen-Yang Lake (Fig. 1) area range between -28.6 - -33.5 ‰ (Kao *et al.*, 2000) while the associated bryophytes in the same forest yielded $\delta^{13}C$ values of -26.7 to -30.7 ‰ (Yeh and Kao, 1996). Measurements of carbon isotope ratios of bulk sediments from soils in the same area and core-tops of two sedimentary cores taken from the Yuen-Yang Lake show a limited range of ~-28.5 to -27.5 ‰ (Yeh *et al.*, 1995). Meanwhile, the $\delta^{13}C$ values of the bulk sediments of the past ~4000 years of the lake sediments range between -30.5 and -26 ‰ (Yeh *et al.*, 1995). These results suggest that the $\delta^{13}C$ values of soil and lake sediments faithfully reflect that of the surrounding vegetation in the mountainous areas of the upper reach of the Lan-Yang River. Wang and Yeh (2003) reported that marine benthic macroalgae off the northeastern corner of Taiwan yielded $\delta^{13}C$ values of -23.8 to – -11.7 ‰. In the absence of direct measurement of $\delta^{13}C$ values of marine phytoplankton of the coastal waters off northeastern Taiwan, we adopt the generally cited $\delta^{13}C$ values of ~-20 ‰ of the subtropical ocean (Rau *et al.*, 1982) as a reference.

MATERIALS AND METHODS

The studied sediment samples were collected from two cores drilled at Chu-An (竹安) and Wu-Chieh (五結) in the Lan-Yang Plain (蘭陽平原) in northeastern Taiwan (Fig. 1). The

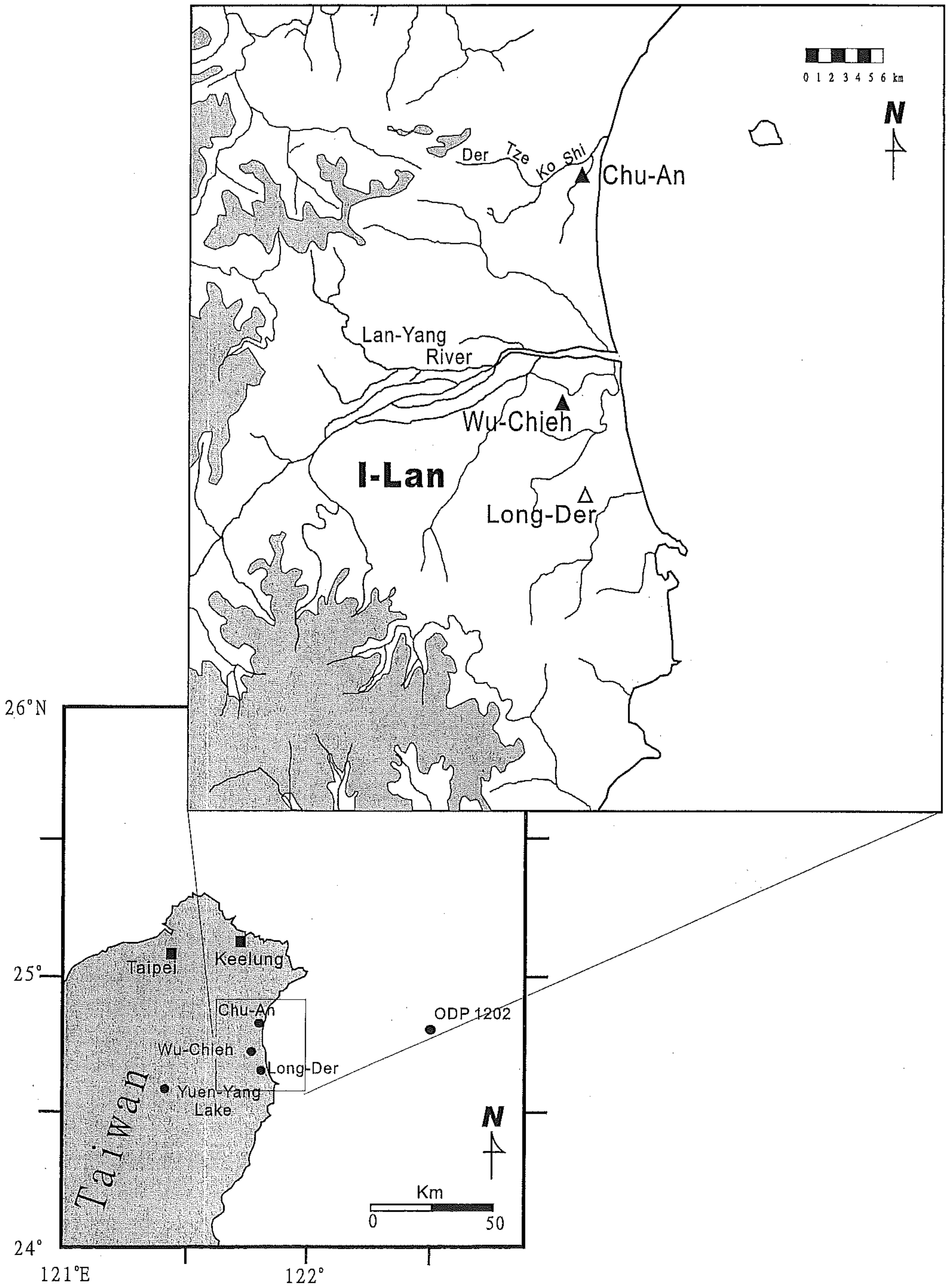

Figure 1. Location map showing site locations of Wu-Chieh Core and Chu-An Core in northeastern Taiwan. The small-scale map shows also locations of other sites mentioned in the text.

Wu-Chieh Core is located in the lower reach area of Lan-Yang River (蘭陽溪) with a distance of about 4 km to the coast whereas the Chu-An Core is on the shore line in the vicinity of river mouth of a small creek, the Der-Tze-Ko Chi (得子口溪). The drilled sequences are both 250 m in length, composed mainly of shaly beds intercalated with silty and sandy layers (Fig. 2). Sedimentary facies analyses suggest that the deposition environments changed from the estuary/ flood plain through an offshore phase and then eventually to a flood plain condition (Fig. 2).

Fine-sediment samples were collected roughly every 8 meters from the shaly intervals of both sequences. Each sediment sample was first mechanically ground to a fine powder in an agate mortar with a pestle. Around 4 mg of the powder sediment was reacted with 2N HCl to remove carbonates. The HCl treatment may remove some labile carbon, but our experiments with different concentrations of HCl under varying temperatures have demonstrated that the treatment does not appreciably affect the measured δ^{13}C values (see also Bird *et al.*, 1994). The sediments were then rinsed with de-ionized water and filtered via a Whatman GF/A filtering paper in a vacuum system. The filtered sediments were then dried in an oven and then removed from the filter and stored in a glass vial. About 150 mg of decarbonized sediment was mixed with CuO pellets, copper and silver foil and then combusted in a quartz tube at 860°C for four hours. The resultant CO_2 was purified through an ethanol-dry ice trap and a liquid nitrogen trap. The isotopic ratio of the carbon was measured with a Finnigan Delta Plus isotope ratio mass spectrometer housed in the Department of Geosciences, National Taiwan University. The results are reported in the conventional δ notation with reference to PDB standard. The uncertainty (one standard deviation) associated with an individual analysis is less than 0.05 ‰.

Wood, tree root, plant debries and mollusca shells were picked from these two cores for Carbon-14 dating. The dating materials were analyzed by the University of Waikato and Beta Analytic Radiocarbon Dating Laboratories.

RESULTS AND DISCUSSION

The results of isotopic analysis of organic carbon in the bulk sediments are listed in Table 1. δ^{13}C values with respect to depth in two sequences are shown in Fig. 2. The ^{14}C ages younger than 20,265 years BP (Table 2) were converted to calendar ages using CALIB rev.4. 4 (available at http://www.calib.org/). The regional ^{14}C reservoir age (ΔR = deviation from the average global reservoir age of 400 years) of shell materials is 35±23 years (Hideshima *et al.*, 2001). The converted calendar ages are those occupying the largest area under probability distribution of 2-sigma (95.4%) and listed in Table 2. For conventional radiocarbon ages older than 20,265 yrBP, the dates were converted to calendar ages using the polynomial equation of Bard et al (1998): $[\text{cal BP}] = -3.0126 \times 10^{-6} \times [^{14}\text{C age BP}]^2 + 1.2896 \times [^{14}\text{C age BP}] - 1005$. The δ^{13}C values of the dated plant fragments are shown on the plot as solid dots for reference. Eight out from the ten dated samples show very similar δ^{13}C values to that of the contemporary sedimentary bulk organic matter. The only discrepancies are in the intervals deposited during low sea-level stands where the δ^{13}C values are variable and fluctuating (Fig. 2). This similarity suggests that the δ^{13}C value of bulk sediments is indeed a good proxy of vegetation of the provenance.

The δ^{13}C values of bulk sediments span virtually the range between those of C_3 and C_4 vegetation, from –26 ‰ to -14 ‰. Except for one single point on the top of Wu-Chieh Core (9.76 m with a double-checked δ^{13}C value of ~18 ‰), the upper 4/5 sections of both cores

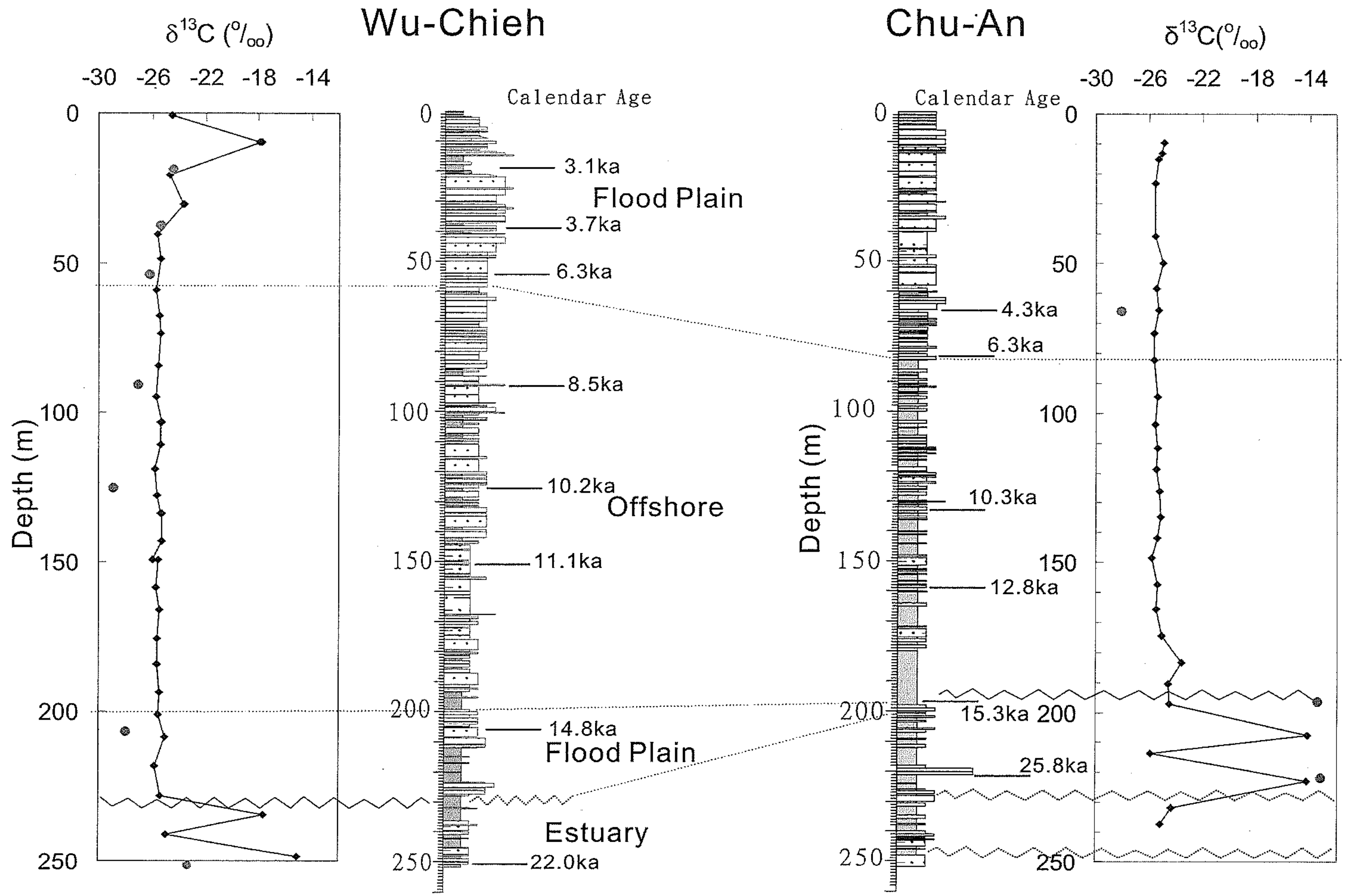

Figure 2. Lithology columns of the Wu-Chien Core and Chu-An cores and downcore variation in $\delta^{13}C_{org}$ of bulk sediments. Lines connected with the solid diamond symbol represent profiles of $\delta^{13}C_{org}$ of bulk sediments while the discrete solid dots represent the $\delta^{13}C_{org}$ values of dated materials. Facies interpretation and carbon-14 ages of dated intervals are indicated. The zig-zag lines represent disconformities recognized from facies analyses.

Table 1. $\delta^{13}C$ values of bulk sedimentary carbon of the Wu-Chieh and Chu-An Cores.

Wu-Chieh Core		**Chu-An Core**	
Depth (m)	$\delta^{13}C$	Depth (m)	$\delta^{13}C$
0.80	-24.6	9.53	-24.9
9.76	-17.9	13.54	-25.1
9.76	-17.8	15.32	-25.3
20.77	-24.7	23.36	-25.6
30.45	-23.7	41.05	-25.6
30.45	-23.7	49.79	-25.0
40.53	-25.6	58.39	-25.4
48.63	-25.4	65.47	-25.3
59.09	-25.8	73.26	-25.7
67.60	-25.5	82.32	-25.7
73.45	-25.4	94.56	-25.4
84.24	-25.5	103.69	-25.5
94.59	-25.7	111.70	-25.4
103.15	-25.3	118.71	-25.5
103.15	-25.4	118.71	-25.5
110.74	-25.4	126.29	-25.2
110.74	-25.4	134.55	-25.1
118.73	-25.8	141.85	-25.4
127.75	-25.6	148.48	-25.8
133.79	-25.4	157.50	-25.4
133.79	-25.3	165.51	-25.5
142.86	-25.3	174.30	-25.1
149.30	-26.0	183.31	-23.6
149.30	-25.6	190.30	-24.6
158.78	-25.7	197.30	-24.5
165.87	-25.5	207.41	-14.3
175.63	-25.6	213.71	-25.9
184.23	-25.6	222.70	-14.3
193.53	-25.5	231.70	-24.3
201.13	-25.5	237.38	-25.2
208.57	-25.1	237.38	-25.2
218.13	-25.8		
227.98	-25.4		
234.54	-17.6		
240.93	-24.9		
248.37	-15.1		

Table 2. Carbon-14 dating results (the Wu-Chieh core and Chu-An core samples)

Core Site	Depth (m)	Material	14C age (yrBP)	$\delta^{13}C$	Calender yrBP (max, min)	2 sigma % area
Wu-Chieh	19.1	wood	2800±70	-24.5	3095 (3093-3098)	0.588
Wu-Chieh	37.7	root	3530±110	-25.4	3721 (3551-4091)	0.980
Wu-Chieh	53.7	wood	5510±40	-26.2	6313 (6270-6356)	0.638
Wu-Chieh	90.55	wood	7750±40	-27.1	8509 (8425-8592)	1.000
Wu-Chieh	125.14	wood	9090±270	-28.9	10177 (9542-10811)	0.952
Wu-Chieh	151.2	shell	10120±40	+0.1	11067 (10934-11199)	0.498
Wu-Chieh	206.6	wood	12410±50	-28.0	14769 (14136-15402)	1.000
Wu-Chieh	250.9	Plant material	18540±80	-23.4	22036 (21326-22746)	1.000
Chu-An	65.9	wood	3900±40	-28.1	4325 (4229-4422)	0.962
Chu-An	81.8	shell	5770±60	-0.5	6275 (5981-6273)	1.000
Chu-An	133.4	shell	9620±70	-0.7	10321 (9965-10677)	0.938
Chu-An	159.7	shell	11250±80	+0.7	12799 (12589-13009)	0.836
Chu-An	196.3	Wood	12960±50	-13.5	15289 (14564-16010)	1.000
Chu-An	221.6	Wood	21900±90	-13.2	25792	

show relatively small range of variations in $\delta^{13}C$ between -26 ‰ and -24 ‰. Only in the lower 1/5 sections, both cores recorded strong fluctuation of $\delta^{13}C$ values, swinging between –25 and –15 ‰ (Fig. 2).

The single, heavy $\delta^{13}C$ value of ~18 ‰ at 9.76 m in Wu-Chieh Core (Fig. 2) might have resulted from agricultural activities in the near-by area as implied by a sudden dominance of pollens of Gramineae in the top section of the same core (Tseng, 2001). The same time interval is also marked by an increase of pollens of *Alnus* in Long-Der Core(龍德井)located in the southern part of Lan-Yang Plain (Lin *et al.*, 2002). *Alnus* is a characteristic pioneering species of secondary forest in the low land area of northeastern Taiwan. The increase of the *Alnus* might imply 'slash and burn' activities of early colonizers (Lin *et al.*, 2002).

The relatively negative $\delta^{13}C$ values of ~25 ‰ in the upper sections are indicative of mainly C_3-plant remains with minor amounts of marine phytoplankton and tropical grass (C_4 plant). In contrast, the heavier $\delta^{13}C$ values of ~15 ‰ in the lowermost sections imply the dominance of tropical grass. It has been reported that the higher water-use efficiency of C_4 plants enables them to outcompete C_3 plants in dry tropical environments (Schulze *et al.*, 1996). On the other hand, C_4 plants also are more advantageous than C_3 plants under the lower atmospheric partial pressure of CO_2. We need to differentiate which of the two factors, local humidity or global atmospheric CO_2 concentration, would be the main factor causing the occurrence of C_4 plants in this area during the last glacial age. For the following four reasons, we prefer to interpret the dominance of C_4 plants as a response of vegetation to local aridity and moderate cooling:

(1) The $\delta^{13}C$ profiles do not match the variation pattern of CO_2 concentration recorded in the ice core. The concentration of CO_2 increased continuously from 180 ppm of the Last Glacial Maximum and reached to ~265 ppm at about 10 ka, and then eventually culminated to pre-industrial concentration of 280 ppm in the end of Holocene (Smith *et al.*, 1999). In contrast, the $\delta^{13}C_{org}$ values in our cores remain to be stable and constant ever since 15 ka (Fig. 3). Furthermore, Feng and Epstein (1995) predicted that the $\delta^{13}C$ of C_3 plants would decrease by about 0.02 ‰ per 1 ppm increase in CO_2 concentration. Therefore the increase of CO_2 concentration from the last glacial stage to the Recent would cause only ~2 ‰ decrease in $\delta^{13}C$.

(2) The $\delta^{13}C$ values show rapid fluctuation between –25 and –15 ‰ during the last glacial stage, yet no comparable fluctuations in CO_2 concentration were observed from ice cores.

(3) Pollen records of both cores show a significant increase of *Artemisia* and Cyperaceae in sediments older than 15 ka (below the disconformity in Figs. 2 and 3). These C_4 plants are supposedly adapted to dry and hot climates (Tseng, 2001).

(4) Sea surface temperatures (SSTs) of the southern Okinawa Trough during the last glacial stage was as low as 21°C, a drop of ~6°C from the modern temperature, while the SSTs during the deglaciation interval show a continuous rising trend from 14 ka (22°C) to 8 ka and then remained to be stable at about 26.5°C (Prof. Meixun Zhao and Chi-Yue Huang of National Cheng Kung University, personal communication, 2003). When the SSTs in the near-by marginal sea show a significant rise during the deglaciation interval, the $\delta^{13}C$ of bulk sediments in Lan-Yang Plain reached already quite depleted and stable values. This suggests strongly that the vegetation shift from C_4 to C_3 plants had been mainly a response to changes in humidity rather than to the temperature rise.

Briefly, we believe that the episodic appearance of heavier $\delta^{13}C$ values in the lower sections indicates brief occurrence of arid conditions in the northeastern Taiwan during the last glacial

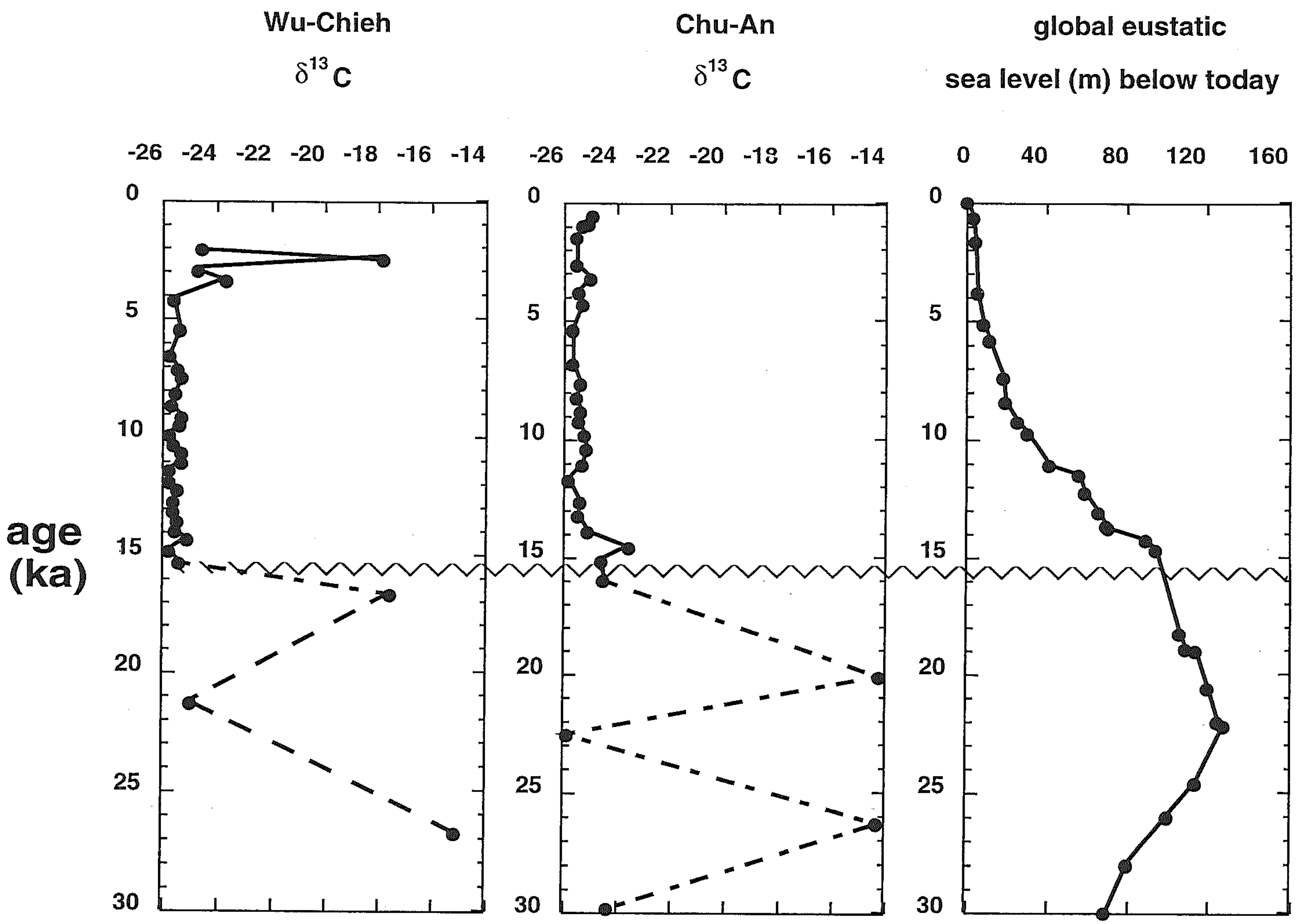

Figure 3. Time-series of $\delta^{13}C_{org}$ of bulk sediments and global eustatic sea-level change in the past 30,000 years. The composite sea-level curve was constructed using data presented in Fairbanks (1989), Bard *et al.*, (1990) and Lambeck *et al.*, (2002). The zig-zag lines represent diastems recognized from facies analyses. Interpretation of sedimentary facies are also indicated.

stage, and such regional climatic fluctuations have exerted a strong control on the relative abundance of C_3 and C_4 plants in northeastern Taiwan.

The boundary that marks the dramatic change in the $\delta^{13}C$ profile, namely, at approximately a sub-depth of 225 m at the Wu-Chieh Core and a sub-depth 200 m at the Chu-An Core (Fig. 2), coincides exactly with the regional disconformity that separates the postglacial-aged sediments from the glacial-aged deposits. This disconfomity marks a shift of the depositional facies from the estuary/flood plain to shore face and offshore environments (Fig. 3). This interpretation has been confirmed by the existence of calcareous nannofossils in the sections above the disconformity (Rong-Chang Wu of CPC, personal communication, 2000). The age of the bottom of the shore face/offshore sequence is dated to be ~ 15 ka (calendar age, Table 2), a time coinciding with the end of a major sea level rise during the last deglaciation (Fairbanks, 1989; Bard *et al.*, 1990; Lambeck *et al.*, 2002, see Fig. 3). On the other hand, although the upper sections of these two cores (top 80 meters of the Chu-An Core, 60 m of the Wu-Chieh Core) shifted again to deposits of flood plain sedimentation, the $\delta^{13}C$ values of bulk sedimentary organic matter remained the same. This suggests that the $\delta^{13}C$ of bulk sediments has been governed mainly by climate instead of depositional environment.

In summary, the $\delta^{13}C$ profiles indicate that for the last 15 kyrs, the northeastern Taiwan has enjoyed a relatively stable environment characterized by C_3-dominated vegetation. The climatic conditions have been warm and humid, comparable to today's climate. On the other hand, prior to 15 ka, the Lan-Yang Plain witnessed frequent sea-level falls and rises and experienced alternations of humid and arid conditions during the last glacial stage.

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