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Pumice layers in marine terraces: implications for tectonic uplift rates on the east and northeast coasts of Taiwan over the last hundreds of years

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Abstract

Two very rare pumice-rich layers were recently found at two sites in Taiwan, more precisely in the lowermost marine terrace of the Sanhsientai area on the southeast coast, and in that of the Yenliao area, on the northeast coast. The pumice-rich layer in the former is about 15 cm in thickness and is composed of 60–70% gray to dark gray, subangular to angular pumice fragments with barnacle shell fragments. The layer in the latter, on the other hand, is about 10 cm in thickness and is composed of 40–50% light gray to gray, subrounded to subangular pumice fragments with a few carbonized wood fragments. Despite their different occurrences, both pumice fragments very closely resemble each other in terms of major and trace as well as isotopic compositions and, therefore, may be considered to have come from the same source, the Luzon or Philippine arcs. ^{14}C-dating gives the layers an equal age ranging from around 420 to 402 cal. yr BP. Based on the age and altitude of the marine terraces in the Sanhsientai and Yenliao areas, however, the uplift rates are 10.9 and 5.4 mm/yr, respectively. The results strongly indicate that, firstly, the uplift rates may have accelerated in the last thousands of years during the Holocene in the Sanhsientai–Chengkung area and that, secondly, the northern coastal area of Taiwan likely suffered from a spasmodic uplift in the very latest Holocene.

1. Introduction

Taiwan is located within the complexity of the oblique collision zone of the Eurasian continental plate and the Philippine oceanic plate (Fig. 1). Presently, the Philippine Sea plate is moving towards WNW at about 70 mm/yr (Seno and Maruyama, 1984), and it is believed the mountain-building process is still in progress (Tsai et al., 1981; Yu and Chen, 1994). A dominant collision zone frequently inducing folding and fault thrusting in the area may exist in central Taiwan. At the latitude of southern Taiwan, the Philippine Sea plate is riding up over the continental shelf of the South China Sea. Farther south in Taiwan, an oceanic part of the Eurasian plate is subducting beneath the Philippine Sea plate along the Manila trench, which results in the bulldozing of shelf sediments both upward and westwardly. Such active movements over the last 5 million years have been creating the island of Taiwan (Ho, 1986; Teng, 1987, 1990). Therefore, rapid crustal movements and widely distributed active structures make up the geological characteristics of this young tectonic entity (Peng et al., 1977; Chen, 1984; Yu et al., 1997, 1999; Chang et al., 1998).

Since Taiwan is in such an active orogenic zone, rapid tectonic uplift rates have been reported for different time periods: 5.9–7.5 mm/yr for the last 1 Ma, 2.5–8 mm/yr for the last thousands of years and 0–35 mm/yr for the 1984–1987 leveling measurements in Taiwan, especially in the Coastal Range and along the east coast (Table 1; Peng et al., 1977; Liu and Yu, 1990; Lundberg and Dorsey, 1990; Wang and Burnett, 1990; Chen et al., 1991; Liew et al., 1990, 1993).

Pumice, which is a light, porous volcanic rock with many trapped gas bubbles, commonly forms during explosive eruptions (Whitham and Sparks, 1986). These

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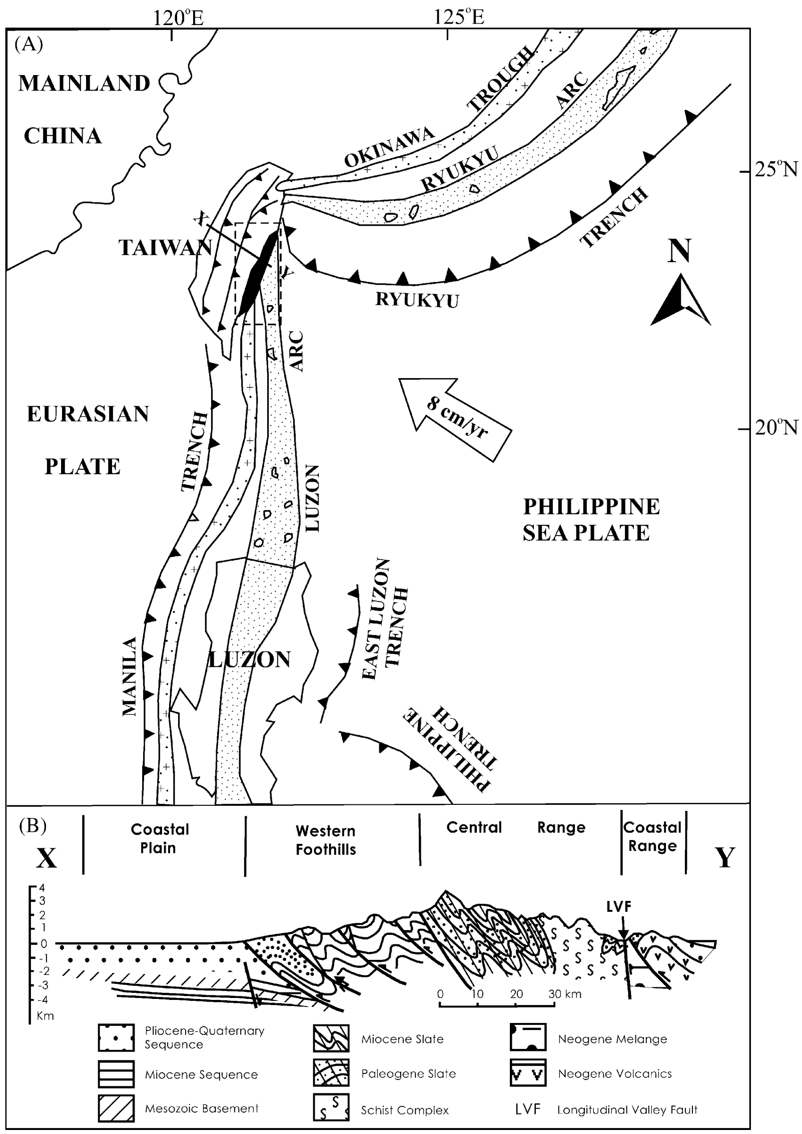

Fig. 1. (A) Tectonics in the vicinity of Taiwan (modified from Ho, 1986). (B) Schematic cross-section of the Taiwan collision zone (modified from Teng, 1990).

Table 1
Published uplift rates in the Taiwan area

Region	Uplift rate (mm/yr)	Duration	Method	References
Northern Coastal Range	7.5	~1.0 Ma	Stratigraphic calculations	Lundberg and Dorsey (1990)
Southern Coastal Range	5.9	~1.0 Ma	Stratigraphic calculations	Lundberg and Dorsey (1990)
Hengchun Peninsula	3.5 ± 0.3–3.3 ± 0.4	(Holocene) 10 Ka	Uranium-series and ^{14}C dating on fossil corals	Wang and Burnett (1990)
East Coastal range	5.3 ± 0.8–4.7 ± 1.0	(Holocene) 10 Ka	Uranium-series and ^{14}C dated on the fossil corals	Wang and Burnett (1990)
Lanyu and Lutao	2.2 ± 0.2–1.6 ± 0.4	(Holocene) 10 Ka	Uranium-series and ^{14}C dating on fossil corals	Wang and Burnett (1990)
Southern Taiwan	5.3	Long-term	Uplifted corals	Peng et al. (1977)
Eastern Coast of Taiwan	5.0	Long-term	Uplifted corals	Peng et al. (1977)
Eastern Coast of Taiwan	2.5–3.0 to over 8	Holocene	Elevated shorelines	Liew et al. (1993)
Northern Coastal Range	5–9	<5000 yr	Uplifted corals	Chen et al. (1991)
Southern Coastal range	14	<5000 yr	Uplifted corals	Chen et al. (1991)
Eastern Coast of Taiwan	0–35	1984–1987	Leveling	Liu and Yu (1990)
Southern Longitudinal Valley	30	1984–1987	Leveling	Liu and Yu (1990)

rocks usually float on the water surface for a while before eventually sinking onto the sea floor, and the time required for them to absorb enough water to sink depends on such physical properties as pumice size, initial density, the size distribution of vesicles and the connectedness of the vesicles (Whitham and Sparks, 1986). This means that a pumice layer in a sedimentary sequence is a good time marker for the purposes of dating and correlation. Aside from this, a pumice layer can be used both to estimate the uplift rate of the last hundreds of years and to determine the centennial-scale uplift rates of an entire area. As well, a pumice layer can also serve to trace its source. For these reasons, in this paper, we investigated and report on the two pumice layers found in the lowermost marine terrace of the Sanhsientai area, on the southeastern coast, and in that of the Yenliao area, on the northeastern coast of Taiwan.

2. Occurrences and leveling measurements

2.1. Sanhsientai area

Four distinct marine terraces have been identified in the Chengkung–Sanhsientai area at altitudes of 65–70, 20–45, 7–20 m and slightly less than 6 m on the southeast coast of Taiwan (Liew et al., 1990). Most of the basement rocks from the marine terraces in this area are the Pliocene sedimentary strata. The pumice-rich layer, however, is exposed in the lowermost marine terrace of the area (Fig. 2A). It is about 15 cm in thickness and intercalates with beach sands. Precise leveling measurements indicate the altitude of this marine terrace is around 5.51 m (Fig. 2B and C). Volcanic breccias, however, crop out as basement rocks in the terrace and occur as huge blocks slumped from

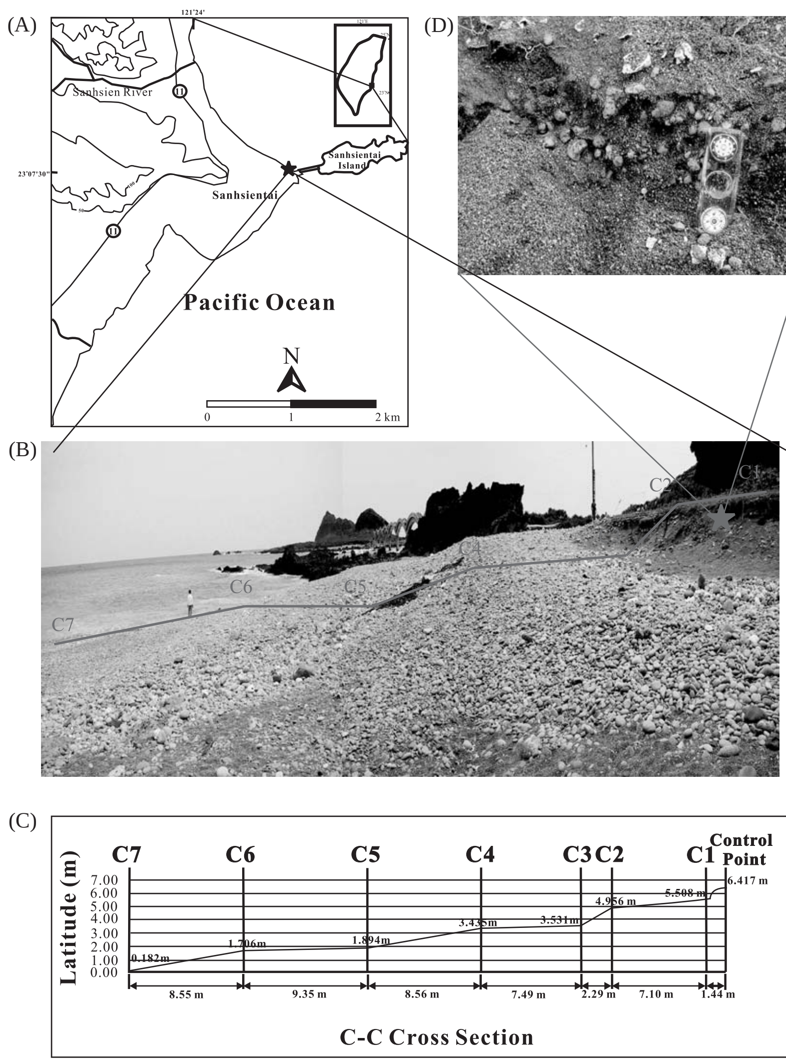

Fig. 2. (A) Map showing the location of the marine terrace in the Sanhsientai area, the southeast coast of Taiwan. (B) Photograph indicating the measuring points of latitude in the cross-section of the Sanhsientai marine terrace using the precise leveling method. (C) Results of latitude in the cross-section of the marine terrace in the Sanhsientai area. (D) Occurrence of the pumice-rich layer in the Sanhsientai marine terrace.

the Tuluanshan Formation in the form of volcanic debris avalanche in the sedimentary strata, namely the Paliwan Formation (Song et al., 1994).

This pumice-rich layer is massive and is dominantly composed of 60–70% gray to dark gray, subangular to angular and homogeneous pumice fragments with barnacle shell fragments that are mixed with coarse beach sands (Fig. 2D). It is overlaid by well-sorted beach sands, suggesting that the pumice fragments were deposited on the normal beach environment. The grain-sizes of the pumice fragments are fairly constant, ranging from 2 to 5 cm in diameter. Plagioclase and augite with a few hypersthene comprise the principal constituents of the phenocrysts, which account for less than 10% of the total mineral contents. The groundmass predominantly consists of vesicle-rich glasses.

2.2. Yenliao area

At least three terraces have developed in the Yenliao area on the Tertiary sedimentary strata on the northeast coast of Taiwan (Peng et al., 1977). The pumice-rich layer is found in the lowermost marine terrace, which located behind a barrier (Fig. 3A and B). About 10 cm in thickness and intercalating with well-sorted beach sands suggest that they deposited on the normal beach environment. This marine terrace has an altitude of around 3.05 m, as determined by precise leveling measurements (Fig. 3C).

The pumice-rich layer in the Yenliao area is also massive but, unlike that in Sanhsientai, it is composed of 40–50% gray to dark gray with sporadic white pumice fragments (Fig. 3D). The gray pumice is angular to subangular, whereas the white is subrounded to rounded

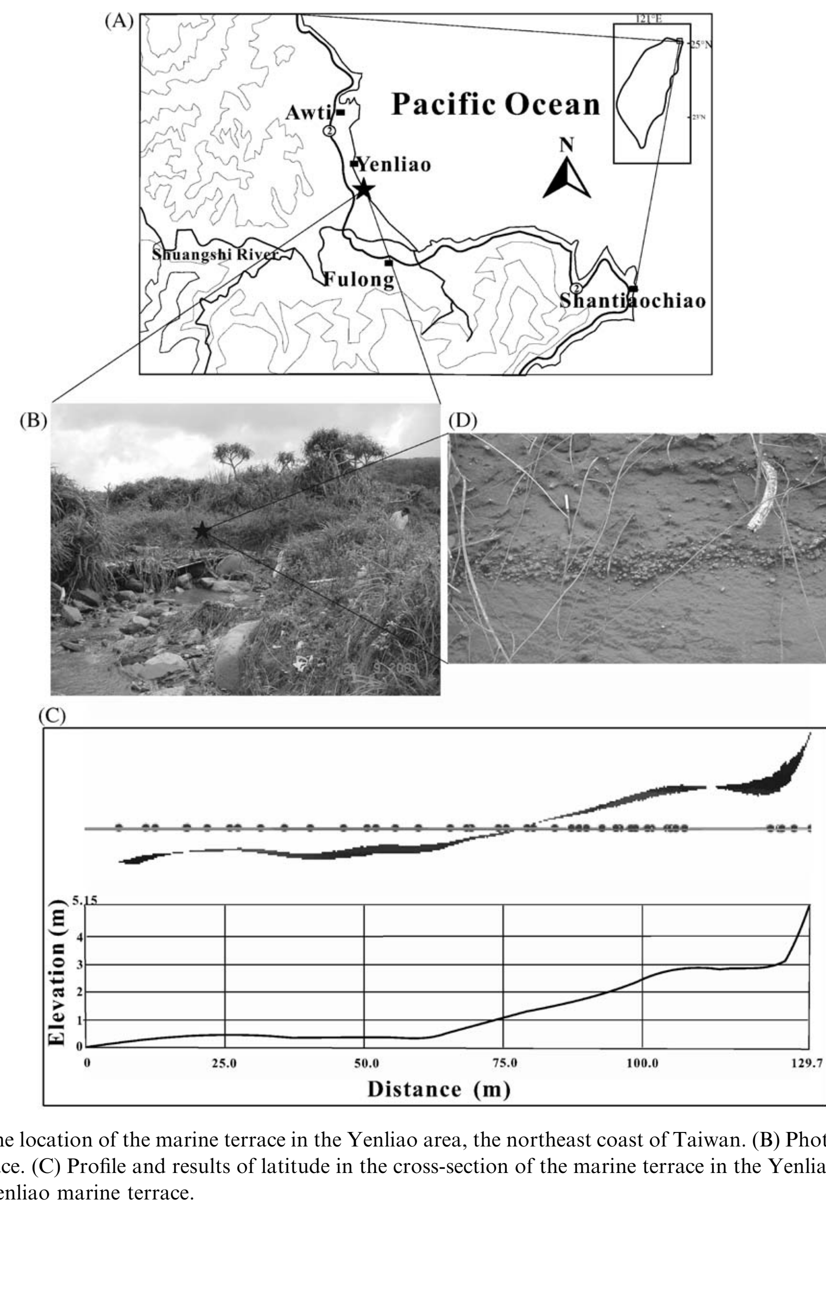

Fig. 3. (A) Map showing the location of the marine terrace in the Yenliao area, the northeast coast of Taiwan. (B) Photograph indicating the locality of the Yenliao marine terrace. (C) Profile and results of latitude in the cross-section of the marine terrace in the Yenliao area. (D) Occurrence of the pumice-rich layer in the Yenliao marine terrace.

in shape. The grain-sizes of the gray pumice fragments are quite similar to each other in the area and range from 2 to 3 cm in diameter. By contrast, the white pumice fragments are variable in size—ranging from less than 1 cm to over 8 cm in diameter. The characteristics of being rounded in shape, variable in terms of width size and few in abundance infer that the white ones may be epiclastic volcanic fragments, like those typically found on current day coastal beaches in Taiwan.

Plagioclase and augite with rare hypersthene are the principal constituents of the phenocrysts in the gray pumice, which constitute less than 10% of the total mineral contents. The groundmass is vitrophyric with abundant vesicles. Conversely, the white, on the other hand, is phenocryst-free but vesicle-rich glassy pumice.

3. Geochemistry of pumice

We sampled three gray pumice fragments from each pumice-rich layer in the lowermost marine terraces of the Sanhsientai and Yenliao areas and two white ones from the Yenliao area, for a total of 8 samples. These samples were used to analyze the major and trace elements as well as the isotopic compositions. Chemical analyses were carried out with X-ray fluorescence spectrometry (XRFS) for major elements using a Rigaku RIX-2000 Spectrometer at the Department of Geosciences, National Taiwan University. Analytical errors were about 1–3% (Lee et al., 1997). Trace elements and REE were determined by inductively coupled plasma-mass spectrometry (ICP-MS) using a Perkin Elmer Elan-6000 Spectrometer at the Guangzhou Institute of Geochemistry, Chinese Academy of Science, and this showed good stability within a $\sim 5\%$ variation (Liu et al., 1996). Sr isotopic analyses were conducted using conventional cation exchange chromatography and mass spectrometric procedures on the MAT 262 for Sr at the Institute of Geosciences, Academia Sinica. Details as to the isotopic analyses can be found in Chen et al. (1990). The $^{87}Sr/^{86}Sr$ ratio was corrected for mass fractionation by normalizing to 0.1194. The $^{87}Sr/^{86}Sr$ ratio for the NBS987 standard was 0.710310 with a long-term reproducibility of $2\sigma = \pm 0.000028$.

The composition and abundance of the major and trace elements are given in Table 2. The gray and white pumice fragments have a very narrow range of SiO_2 content from 59.75% to 60.77% and 71.45% to 72.82%, respectively. The gray ones fall into the anadesitic range ($52\% < SiO_2 < 63\%$), but the white ones are within the rhyolitic ($>63\%$). Other diagnostic oxides also show similar concordance within a narrow range of SiO_2 e.g., Al_2O_3, Fe_2O_3, CaO, Na_2O, and K_2O (Table 2). In the plots of K_2O and K_2O+Na_2O vs. SiO_2 (Fig. 4), the gray pumices fall in the field of the shoshonitic (high-K) rock series of the New Guinea Highlands (Mackenzie and Chappell, 1972), while the white ones are classified as belonging to the low-K rock series. Although these two kinds of pumice, i.e. gray and white, are readily distinguishable from the plots of K_2O and K_2O+Na_2O vs. SiO_2 (Fig. 4) the major-element compositions of the gray pumices from the Sanhsientai and Yenliao areas are almost perfectly identical (Table 2 and Fig. 4).

The trace-element contents of the gray pumices fall in a very narrow range and are virtually the same in both areas, especially with respect to the elements of Cr, Ni, Rb, Sr, Y, Zr, Nb, Ba, Hf, Ta, Pb, Th, U and REE. Obviously, these contents differ significantly from those of the white pumices. To illustrate this, chondrite-normalized REE patterns of the gray pumices are very enriched in light REE (LREE) and show a little Eu-negative anomaly (Fig. 5). This contrasts with an only moderate enrichment in LREE and just a little Eu-negative anomaly in the case of the white pumices (Fig. 5).

The primodial-mantle normalized abundance patterns of incompatible-trace elements (Fig. 6) clearly represent the characteristics of enrichment of the LIL elements (Cs, K, Rb, Ba, and Th) relative to the HFS elements (Ta, Nb, Zr, Ti and Y) in all pumice compositions. These characteristics are common to subduction-related volcanic rocks. Significant differences, nevertheless, are evident between the gray and white pumices: the former are more enriched in LIL elements and phosphorous than the latter. However, the contents, chondrite-normalized REE and primodial-mantle normalized abundance patterns of the gray pumices from the Sanhsientai and Yenliao areas are almost identical.

The isotopic results of Sr are presented in Table 2. The Sr isotopic ratios of pumice from the Sanhsientai area are in the range of 0.70390–0.70384. The Sr isotopic ratios of the gray pumice from the Yenliao area are in the range of 0.70382–0.70396, while the white ones are in the range of 0.70446–0.70453. Therefore, the Sr isotopic ratios suggest that the gray pumice from the Sanhsientai and Yenliao marine terraces may very well have come from the same source.

4. Discussion

4.1. Ages of the pumice layers

Many barnacle shells are found in the pumice-rich layer of the Sanhsientai marine terrace, and they occur either intercalated with or overlaid on the pumice-rich layer (Fig. 2). Unfortunately, X-ray diffraction (XRD) determined that calcite is the dominant phase of these shells, a strong indicator that they may have suffered from late buried changes. However, although no carbonized wood was found in the Sanhsientai marine terrace, only carbonized wood, but no barnacle shell,

Table 2
Geochemical data of the pumices from the Sanhsientai and Yenliao marine terraces

	SST1	SST2	SST3	FL-1a	FL-1b	FL-2a	FL-2b	FL-2c
SiO_2	59.75	60.20	60.32	72.82	71.45	60.71	60.61	60.77
TiO_2	0.58	0.59	0.58	0.18	0.26	0.57	0.57	0.59
Al_2O_3	15.86	16.11	16.13	12.36	12.88	16.19	16.03	15.52
Fe_2O_3	5.41	5.35	5.21	3.00	3.41	5.03	5.17	5.43
MnO	0.17	0.17	0.17	0.11	0.12	0.16	0.16	0.17
MgO	2.34	1.87	1.77	0.00	0.01	1.52	1.80	2.01
CaO	3.84	3.52	3.51	2.18	2.30	3.24	3.65	3.59
Na_2O	4.51	4.65	4.62	4.45	4.44	4.70	4.57	4.49
K_2O	4.26	4.43	4.45	1.03	1.24	4.34	4.25	4.19
P_2O_5	0.21	0.22	0.22	0.03	0.05	0.22	0.22	0.22
Total	96.93	97.11	96.99	96.16	96.16	96.67	97.03	96.97
Sc	10.01	10.14	10.11	11.69	11.9	7.157	12.14	12.8
V	69.7	73.54	72.3	0.588	1.332	52.98	81.42	78.35
Cr	16.76	23.81	22.39	0.506	0.434	10.4	23.11	23.7
Co	9.825	9.428	10.16	0.648	0.607	6.958	10.81	10.91
Ni	12.71	7.628	10.77	0.231	0.268	5.599	9.377	11.04
Ga	17.41	16.8	17.49	14.94	15.21	17.22	17.38	17.23
Ge	1.735	1.696	1.796	2.038	2.028	1.778	1.767	1.81
Rb	94.8	97.56	95.9	30.05	30.48	101.7	90.84	89.37
Sr	465.7	395.9	470.4	106.7	102.4	404.1	494.5	467.3
Y	34.2	34.57	33.94	47.24	47.77	35.03	34.35	35.45
Zr	245.4	254.9	247.5	150.2	149.7	267	238.7	236.3
Nb	9.945	10.15	10.18	3.267	3.313	11.22	9.977	9.563
Cs	1.917	1.941	1.894	1.932	1.973	2.186	1.824	1.803
Ba	1477.6	1469.2	1510.5	236.9	238.6	1541.1	1451.3	1414.7
La	73.7	74.22	74.62	11.81	11.82	77.18	72.88	71.83
Ce	133.5	133.4	133.6	26.44	26.61	140.8	130	129
Pr	15.9	16.08	15.9	3.795	3.865	16.59	15.61	15.64
Nd	56.23	57.37	56.34	17.04	17.39	58.3	55.83	55.7
Sm	9.037	9.155	8.952	4.587	4.642	9.353	9.035	9.088
Eu	1.886	1.848	1.896	1.129	1.129	1.93	1.969	1.935
Gd	6.678	6.776	6.653	5.822	5.862	6.813	6.893	7.15
Tb	1.002	1.006	1.011	1.065	1.088	1.026	1.014	1.06
Dy	5.48	5.545	5.434	6.906	7.015	5.644	5.49	5.718
Ho	1.101	1.095	1.085	1.523	1.518	1.145	1.101	1.127
Er	3.202	3.219	3.16	4.435	4.542	3.279	3.167	3.349
Tm	0.516	0.521	0.499	0.729	0.743	0.525	0.51	0.524
Yb	3.481	3.551	3.537	5.083	5.136	3.67	3.48	3.572
Lu	0.579	0.586	0.577	0.834	0.828	0.608	0.565	0.6
Hf	6.225	6.338	6.205	4.37	4.373	6.782	6.017	6.03
Ta	0.508	0.538	0.523	0.26	0.271	0.596	0.519	0.508
Pb	16.48	16.84	16.54	5.894	5.787	18.89	16.19	16.14
Th	18.6	19.28	19.12	3.634	3.665	20.85	18.19	18.13
U	4.995	5.17	5.149	0.837	0.841	5.376	4.829	4.866
$^{87}Sr/^{86}Sr$	0.703900 ± 16	0.703838 ± 17	0.703840 ± 16	0.704534 ± 15	0.704463 ± 16	0.703960 ± 15	0.703822 ± 14	0.703843 ± 16

SST-x: samples of gray pumice from the Sanhsientai area; FL-1x: samples of white pumice from the Yenliao area; and FL-2x: samples of gray pumice from the Yenliao area.

Table 3
^{14}C ages of the pumice-rich layers in the Yenliao areas of Taiwan

Sample No.	Locality	Materials	Laboratory No.	^{14}C Age (yr BP)[a]	Calibrated Age (cal. yr BP)[b]
YL-01	Yenliao	Carbonized wood	NTU-3647	220 ± 50	420–402

[a] All conventional ages were calculated using the ^{14}C half-life of 5568 yr and were corrected for mass fractionation of carbon isotopes by normalizing the $\delta^{13}C$ values of the samples to 25% relative to PDB, an international standard.

[b] Age data were calibrated following Stuiver and Reimer (1993). We assumed a standard reservoir correction ($R = 0$) and an error multiplier of one ($k = 1$). The calibrated age ranges represent two standard deviations under phase assumptions.

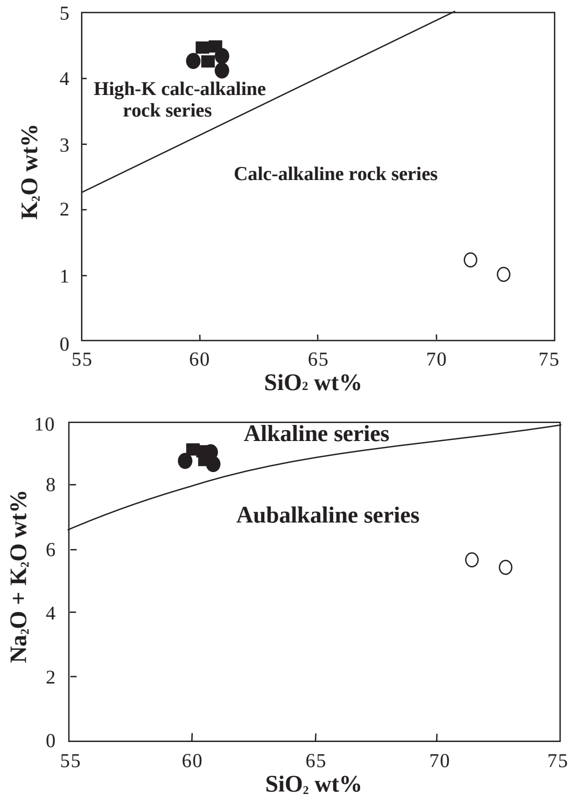

Fig. 4. Variation diagram of K_2O and K_2O+Na_2O vs. SiO_2. Solid squares for the pumice samples from the Sanhsientai marine terrace; solid circles for the gray pumice from the Yenliao marine terrace; open circles for the white pumice from the Yenliao marine terrace. Boundary line of K_2O vs. SiO_2 after White et al. (1979).

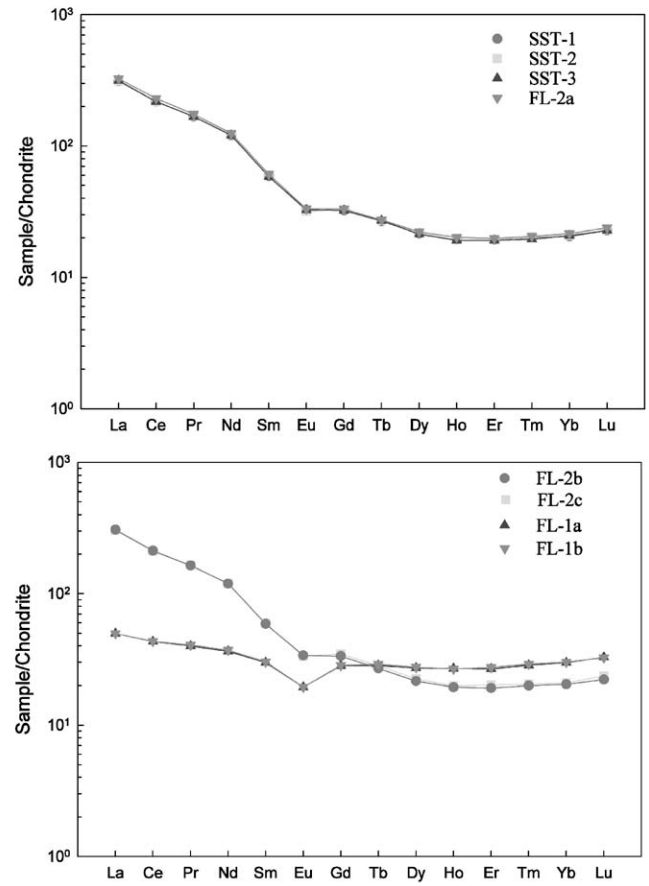

Fig. 5. Chondrite normalized REE patterns for the pumices from the Sanhsientai and Yenliao marine terraces. Sample numbers such as SST-x from the Sanhsientai area; FL-2x from the Yenliao gray pumice; and FL-1x from the Yenliao white pumice.

was noted in the Yenliao marine terrace. This study, therefore, then sampled one carbonized wood fragment from the Yenliao area for radiogenic ^{14}C dating. Radiocarbon measurements were performed by CO_2 β-counting in the ^{14}C laboratory of the Department of Geosciences, National Taiwan University. The age results of ^{14}C dating, listed in Table 3, indicate the carbonized wood fragment from the Yenliao terrace has an age ranging from 420 to 402 cal. yr BP.

Pumice is a violently erupted product, which occurs either in a subaerial or submarine environment. It can float on the sea surface for sometime but eventually sinks to the sea bottom after absorbing enough water (Whitham and Sparks, 1986). Laboratory experiments have indicated that pumice can remain afloat for over one- and- a-half years on the water. Hot pumice, however, often sinks immediately on immersion in water despite having a lower density than water (Whitham and Sparks, 1986). The pumice-rich layers occur in the lowermost marine terraces of both areas and their chemical compositions are almost replicates (Figs. 4–6, and Table 2), which is strong support for the proposition that they were, in all likelihood, deposited by the same eruption. It follows, therefore, that the deposited time of the pumice-rich layers in both areas may actually range from 420 to 402 cal. yr BP.

4.2. Uplift rates on the east and northeast coasts of Taiwan

Calculating the uplift rates in one place, i.e. in a marine terrace, is based on altitude and time. In other words, the rates are determined by the length of time it took for the terrace to uplift to that altitude. The formula used in this research for the calculations is $H_n - H_d - W_d/\text{Age}$, where H_n, H_d and W_d are, respectively, the terrace height at present, the height of deposition at high tide, and the difference in sea level between the time of deposition and now. Associated with well-sorted beach sands and no storm berm nearby indicate that the pumice-rich layer deposited on the normal beach condition. Therefore, the height of deposition employed in this research is the maximum height at high tide for the last tens of years (Central Weather Bureau, 2000), meaning that the calculated uplift rates may actually be on the low side. In that there has been almost no change in sea level over the last hundreds of years (Fairbridge, 1976; Gibb, 1986), the formula can be re-written as $H_n - H_d/\mathrm{Age}$. Based on this re-written formula and on data for age and altitude of the marine terraces in the Sanhsientai and Yenliao areas, the uplift rates in these areas are 10.9 and 5.4 mm/yr (Table 4), respectively.

As stated earlier, Taiwan is located in an active orogenic belt, and its rapid tectonic uplift rates have been reported for different time periods (Table 1). The reported average uplift rates in the Sanhsientai–Chengkung area on different time scales were about 3.5 mm/yr for the Holocene compared with over 30 mm/yr for the last 20 yr (Liu and Yu, 1990; Liew et al., 1993). This study provides data for the uplift rates on the scale of hundred years in the Sanhsientai area. The results clearly indicate that the average uplift rate in the last hundreds of years has been about 10.9 mm/yr. This strongly infers that the uplift rate may have accelerated in the last thousands of years in the Sanhsientai–Chengkung area. The same apparent increase in uplift rate towards the present is known in many places of the world, which suggests a probably change in the convergence rate between two plates (Ota, 1986).

The maximum rate of uplift in the northern coastal area of Taiwan was as low as about 2 mm/yr from about 1500 to 5500 BP, but was 5.3 mm/yr from 5500 to 8500 BP (Peng et al., 1977). Compare this with the uplift rate in the last hundreds of years, which has been as high as about 5.4 mm/yr. The striking contrast is a good indicator that the northern coastal area of Taiwan suffered from a spasmodic uplift during the very latest Holocene.

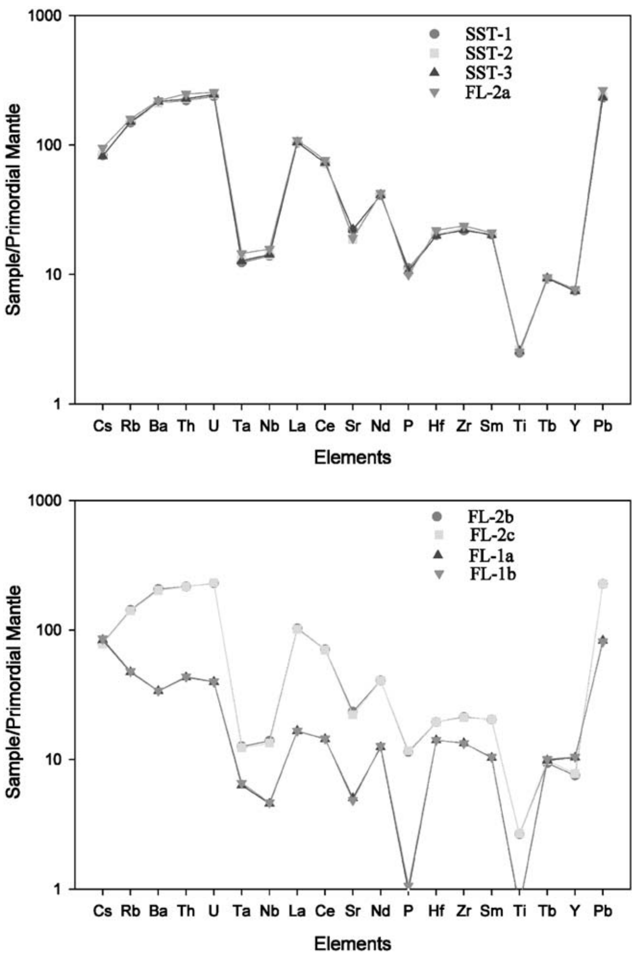

Fig. 6. Primodial-mantle normalized incompatible-trace element diagram for the pumices from the Sanhsientai and Yenliao marine terraces. Sample numbers are the same as those in Fig. 5.

4.3. Source of pumice

Pumice, a common product of an explosive volcanic eruption and an important component of many pyroclastic deposits and volcanogenic sediments (Whitham and Sparks, 1986), is formed by the fragmentation of frothy magma and is transported by pyroclastic or epiclastic processes as part of either submarine or subaerial activities (Fisher and Schmincke, 1984). The characteristics of pumice geochemistry, i.e. enrichment of LIL elements relative to HFS elements (Fig. 6) indicate that pumice fragments in marine terraces are, by and large, products of subduction-related volcanic eruptions (Gill, 1981; Thorpe, 1982). However, the volcanic rocks found and investigated in the northern volcanic zone and the eastern volcanic zone of Taiwan (Chen, 1978; Chen and Lin, 1979; Chen and Kato, 1989; Juang and Chen, 1989; Wang et al., 1999), definitively are products of arc volcanism, and most of them are older than 0.2 Ma. It is however, most peculiar that no historical active volcanoes have ever been reported in Taiwan, with the exception of four submarine eruptions in the offshore of eastern Taiwan (Kuno, 1962). Hence, the source of the pumice fragments could not have been volcanism in and around Taiwan. Further evidence of this is that the geochemical characteristics do not support the claim that those pumices came from

Table 4
Uplift rates of the marine terraces in the Sanhsientai and the Yenliao areas of Taiwan

Locality	H_n (cm)	H_d (cm)[a]	Age (yr BP)[b]	Uplift rate (mm)
Sanhsientai	551	105	411	10.9
Yenliao	305	85	411	5.4

[a] H_d is the maximum height of high tide for the last tens of years (Central Weather Bureau, 2000).
[b] Average calibrated ages of carbonized wood from the Yenliao pumice layer.

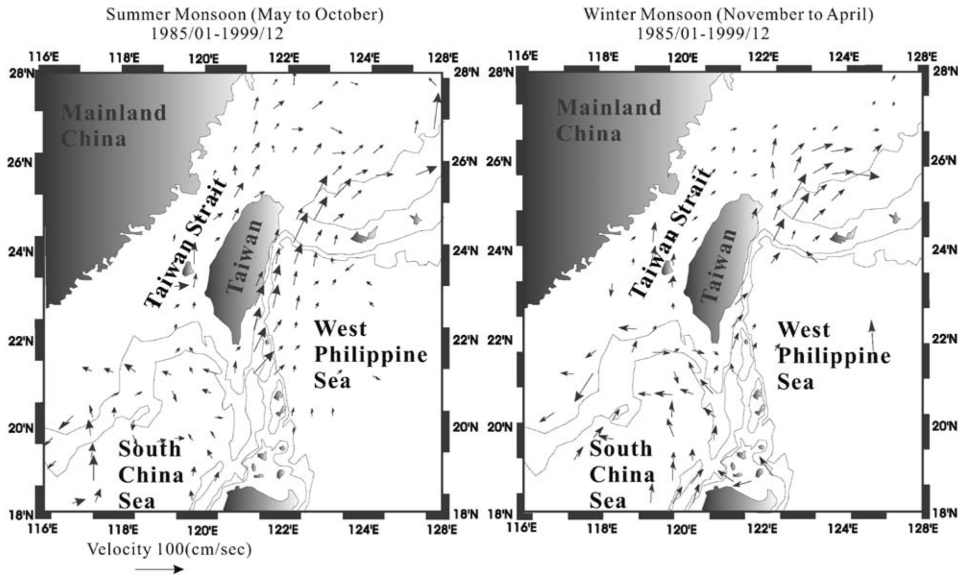

Fig. 7. Seasonal patterns of sea surface circulation and current velocity around Taiwan in the summer and winter monsoons (after National Center for Ocean Research (NCOR), 2000).

volcanoes in and around Taiwan, either, especially in light of the low- to medium-K (Taiwan volcanic rocks) vs. high-K (pumice) rock series (Chen, 1978; Chen and Lin, 1979; Chen and Kato, 1989; Juang and Chen, 1989; Wang et al., 1999).

The occurrence of the pumice-rich layers in the marine terraces of the east and northeast coasts of Taiwan undoubtedly point to the fact that the pumice fragments were transported by ocean currents and deposited in beach environments shortly after a volcanic eruption. The pumice fragments in the Sanhsientai area are larger, more angular and homogeneous than those in the Yenliao area. Of great significance is that the main circulation of the sea surface current (Kuroshio Current) around eastern and northeastern Taiwan is from south to north all year long (Fig. 7). This evidence makes it fully reasonable to conclude that the pumice fragments must have come from the south, or more specifically, the Luzon or Philippine arcs.

5. Conclusions

A pumice-rich layer is a good time marker for use in correlations in a sedimentary sequence. One pumice-rich layer was found in the lowermost marine terrace of the Sanhsientai area on the southeast coast, and another in the Yenliao area on the northeast coast of Taiwan. Petrological and geochemical studies indicate that these two pumice-rich layers have almost identical characteristics and must be of the same origin, more precisely from the Luzon or Philippine arcs. Combining the age and altitude of the two marine terraces in the Sanhsientai and Yenliao areas, the uplift rate on the southeast coast has been 10.9 mm/yr, while that on the northeast coast has been 5.4 mm/yr in the last hundreds of years. These results in conjunction with published data covering different time periods of uplift rate reveal, with little doubt, that on the southeast coast, the uplift rate may very well have accelerated during the Holocene, while the northern coastal area most probably suffered from a spasmodic uplift during the same period.

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