^{14}C WIGGLE-MATCHING OF THE B-TM TEPHRA, BAITOUSHAN VOLCANO, CHINA/NORTH KOREA

Shinya Yatsuzuka[1] • Mitsuru Okuno[1] • Toshio Nakamura[2] • Katsuhiko Kimura[3] • Yohei Setoma[4] • Tsuyoshi Miyamoto[5] • Kyu Han Kim[6] • Hiroshi Moriwaki[7] • Toshiro Nagase[8] • Xu Jin[9] • Bo Lu Jin[10] • Toshihiko Takahashi[11] • Hiromitsu Taniguchi[5]

ABSTRACT. We performed accelerator mass spectrometry (AMS) radiocarbon dating and wiggle-matching of 2 wood samples from charred trunks of trees (samples A and B) collected from an ignimbrite deposit on the northeastern slope of the Baitoushan Volcano on the border of China and North Korea. The obtained calendar years for the eruption are cal AD 945–960 for sample A and cal AD 859–884 and cal AD 935–963 for sample B in the 2-σ range. These results are unable to determine the precise eruption age. The reason for the difference in reported ages may be due to volcanic gas emission prior to the huge eruption.

INTRODUCTION

The Baitoushan-Tomakomai (B-Tm) tephra, which erupted from Baitoushan Volcano (also known as Paektusan and/or Changbaishan) on the border between present-day China and North Korea, reached the northeastern part of the Japanese Islands (Figure 1A; Machida et al. 1981, 1990; Machida and Arai 1983; Horn and Schmincke 2000; Guo et al. 2006). Machida (1992) proposed that the eruption influenced the fall of the Bo-hai Kingdom, which occupied the volcano and its adjacent areas in AD 926. To assess the chronological relationship of the eruption and the fate of the kingdom, various age determinations have been carried out. Fukusawa et al. (1998) reported the eruption age of B-Tm as AD 937–938 by counting non-glacial varves between the Towada-a (To-a) and B-Tm tephras that were intercalated in the cored sediment from Lake Ogawara, northeastern Japan (Figure 1A). This estimation assumed that the age of the To-a tephra is AD 915 as inferred from the ancient Japanese document "Fuso-Ryakuki" (Machida et al. 1981). Horn and Schmincke (2000) reported an eruption age of cal AD 945–984 with 2-σ probability using radiocarbon wiggle-matching of an upright tree in a fallout pumice on the southern slope (North Korean side). Nakamura et al. (2007) obtained a similar eruption age of cal AD 930–943 using a charred wood trunk in a lahar deposit at site C on the northern slope (Figure 1B). Thus, there is no agreement regarding the age of B-Tm. Nakagawa et al. (2004) found a pyroclastic deposit underlying the B-Tm tephra at site A on the northern slope (Figure 1B) and came up with an age estimate for the deposit. However, the age that they obtained is based on a single calibrated ^{14}C age for charcoal fragments. Therefore, we present here the results of ^{14}C wiggle-matching for charred wood trunks from sites A and B (Figure 1B), and discuss a detailed age determination for the B-Tm tephra.

[1]Department of Earth System Science, Faculty of Science, Fukuoka University, Fukuoka 814-0180, Japan. Corresponding authors. Email: sd093501@cis.fukuoka-u.ac.jp; okuno@fukuoka-u.ac.jp.
[2]Center for Chronological Research, Nagoya University, Nagoya 464-8602, Japan.
[3]Faculty of Symbiotic System Science, Fukushima University, Fukushima 960-1296, Japan.
[4]Kitakyushu Chamber of Commerce and Industry, Kitakyushu 802-8522, Japan.
[5]Center for Northeast Asian Studies, Tohoku University, Sendai 980-8576, Japan.
[6]Department of Science Education, Ewha Womans University, Seoul 120-750, South Korea.
[7]Faculty of Law, Economics and Humanities, Kagoshima University, Kagoshima 890-0065, Japan.
[8]Tohoku University Museum, Tohoku University, Sendai 980-8578, Japan.
[9]College of Geo-exploration Science and Technology, Jilin University, Changchun 130-026, China.
[10]Sixth Geological Survey, Jilin Province 133001, China.
[11]Wood works "Yui," Iwate 028-7301, Japan.

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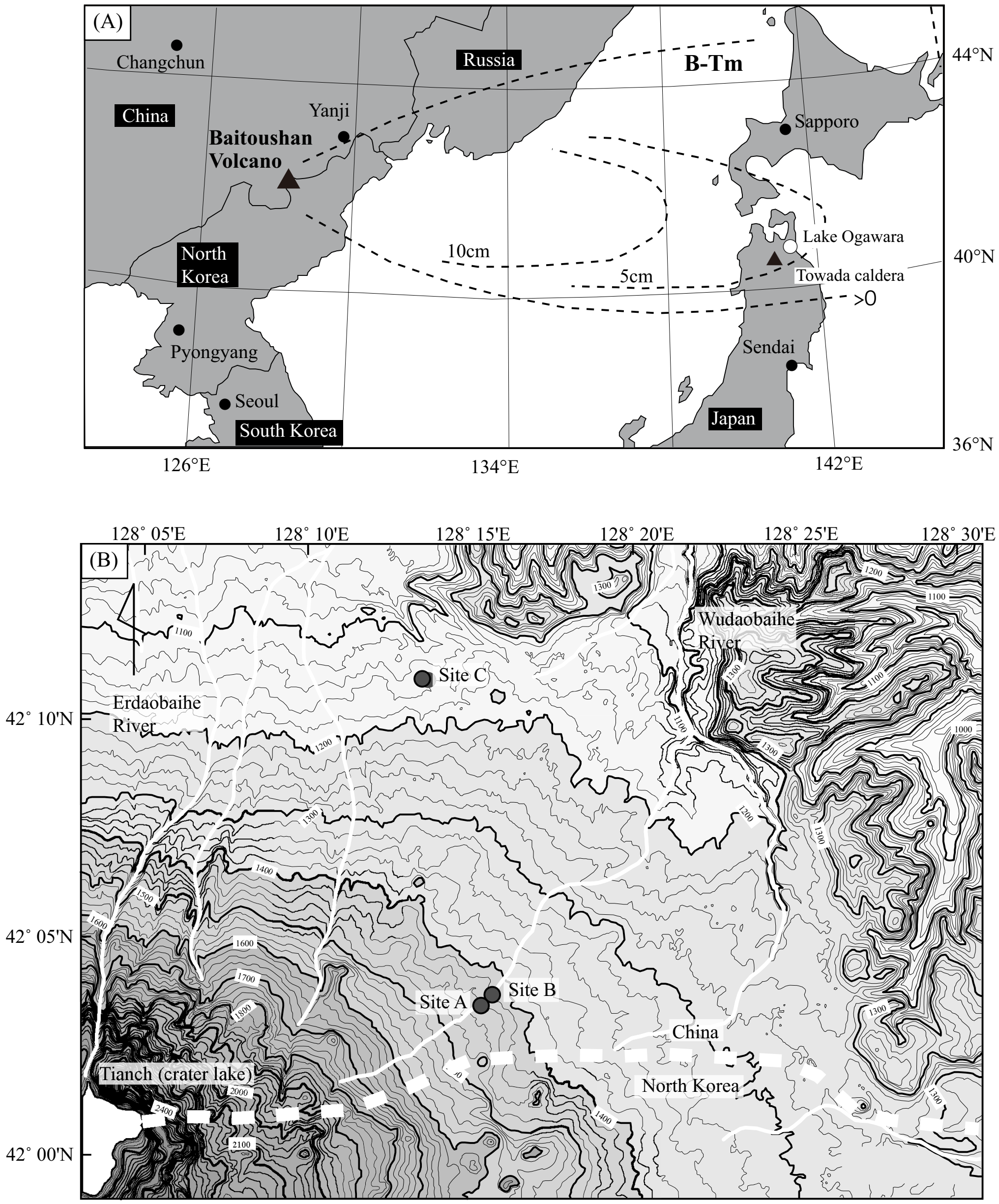

Figure 1 Index maps. (A) Distribution of the B-Tm tephra. Dashed lines with values indicate isopachs in cm (Machida and Arai 1983). (B) Topographic map of the northeast slope of Baitoushan Volcano. Filled circles indicate location of sampling and previously studied sites.

MATERIALS AND METHODS

Sample Location

Two wood samples from charred trunks of trees (samples A and B) were collected from sites A and B, respectively, on the northeastern slope of the Baitoushan Volcano (Figure 1B). Sample A (*Larix*) has 302 annual rings with bark and was collected near the contact of the pumice fall and ignimbrite deposits at site A (Figure 2A). Sample B (*Juniperus* sp.) has 59 annual rings with bark and was found in the lower horizon of the ignimbrite at site B (Figure 2B).

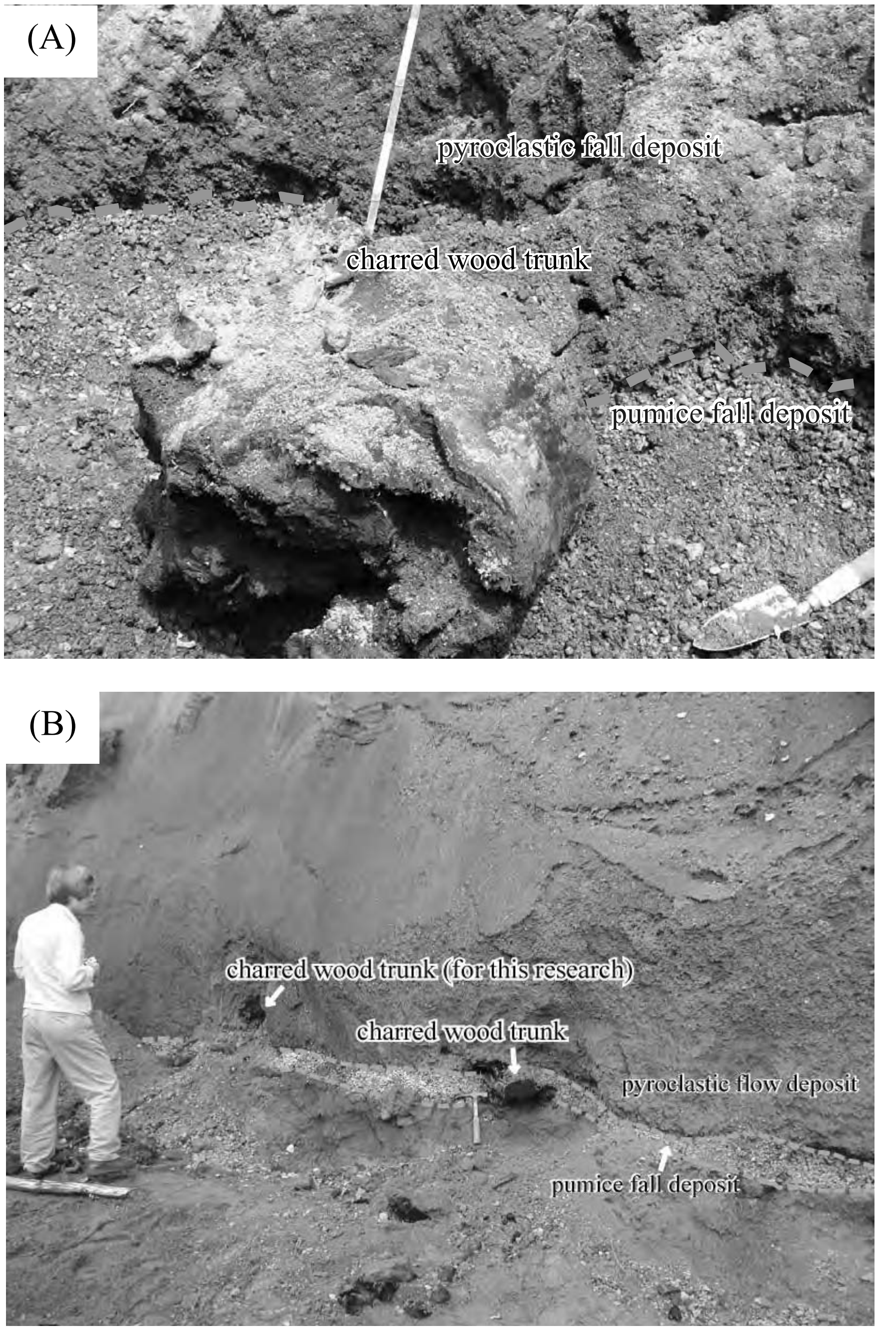

Figure 2 Photos showing occurrence of charred wood trunks: (A) sample A; (B) sample B.

Pretreatment and ^{14}C Measurement with AMS

Samples A and B were divided into annual rings for ^{14}C measurements at 10- and 2-yr intervals, respectively. Specimens of sample A can be measured using a 10-yr interval because it is suitable for wiggle-matching since it records a longer time. However, sample B has 2-yr intervals in order to represent a shorter time. The sliced annual rings were cleaned with acid-alkali-acid (AAA) treatments using 1.2N HCl and 1.2N NaOH, respectively, followed by distilled water washing and drying. About 3–4 mg of sample was sealed in a Vycor® tube together with CuO, then heated to 900 ºC for 6 hr. The graphite was reduced catalytically from the purified CO_2 on Fe powder with hydrogen gas in a sealed Vycor tube (Kitagawa et al. 1993). The ^{14}C measurement of pressed graphite was carried out with the HVEE accelerator mass spectrometry (AMS) system at Nagoya University (Nakamura et al. 2000). We used NIST HOx-II (SRM-4990C) as a ^{14}C standard. The ^{14}C errors include statistical uncertainties based on ^{14}C counting of sample standard and ^{14}C background targets. Machine errors were evaluated by the ^{14}C reproducibility of repeated measurements on standard targets, and errors in ^{14}C background removal calculations (Nakamura et al. 2007).

^{14}C Wiggle-Matching Analysis

Wiggle-matching analysis was performed with the computer program CALIB 5.0 (Stuiver and Reimer 1993) and Microsoft® Excel® software, based on Bayesian statistics (Nakamura et al. 2007). A probability distribution (p) on the calendar year axis was obtained by processing the calibration to conventional ^{14}C ages obtained from annual ring samples using CALIB 5.0 and the IntCal04 data set (Reimer et al. 2004). The obtained probability distribution (p) of each tree ring gives a numerical possibility $p_i(j)$ for a ^{14}C age, which corresponds to a certain calender year j, where the suffix i (i = 1 to n) is the annual ring count from the outermost ring, and $s(i)$ indicates the number of rings that can be separated from the outermost ring. The sum of $p_i(j)$ for all values of j is normalized. The overall probability P can be defined by multiplying $p_i(j)$ by changing the value of j as follows:

$$P = p_1(t-s(1)) \times p_2(t-s(2)) \times p_3(t-s(3)) \times \ldots \times p_1(t-s(i)) \times \ldots \times p_n(t-s(n)) \quad (1)$$

In Equation 1, t is a hypothetical age of the outermost ring. The maximum value of P gives the most probable age of the outermost ring. In this study, we did not measure the outermost ring of sample A. In such cases, the outermost ring is corrected for the most probable age. In addition, we check the best fit using a χ^2 test and calculating $F(t_s)$ and F_{crit} (Bronk Ramsey et al. 2001).

RESULTS AND DISCUSSION

The results of AMS ^{14}C dating in this study are shown in Tables 1 and 2. The conventional ^{14}C ages were calculated using the Libby half-life of 5568 yr. The calendar year range for sample A is from cal AD 945 to 960 at 95% confidence level and the best fit for the outermost ring is cal AD 953 (Figure 3A). The χ^2 test for sample A indicates cal AD 952 and has a best fit result of $F(t_s)<F_{crit}$. In contrast, the dates derived for sample B range from cal AD 859 to 884 and cal AD 935 to 963 at 95% confidence level, with the highest probability around cal AD 942 (Figure 3B). The χ^2 test for sample B results in an age of cal AD 942, but the agreement results in $F(t_s)>F_{crit}$, indicates that this determination is not precise. Figure 4 shows the results of ^{14}C wiggle-matching plotted on the IntCal04 calibration curve (Reimer et al. 2004). The ^{14}C dates for layers 8 and 10 of sample B were inconsistent with IntCal04. When both dates are omitted, the result of wiggle-matching is cal AD 942–969 (95% confidence level) with a best-fit date of cal AD 961. The χ^2 test for sample B excluding layers 8 and 10 gives a date of cal AD 961, and the agreement changes to $F(t_s)<F_{crit}$.

Table 1 AMS ^{14}C dating results of Sample A.

Sample A layer[a]	^{14}C age (BP)	Error ^{14}C age (±1 σ)	Lab code # (NUTA2-)
37	1123	29	10227
46	1089	29	10228
56	1143	28	10229
66	1149	29	10226
77	1161	29	10230
86	1162	29	10231
96	1205	29	10232
106	1232	29	10235
116	1191	29	10236
126	1185	29	10237
137	1166	29	10238
147	1206	28	10239
156	1226	28	10240
165	1200	28	10241
185	1289	28	10244

[a]Layers of annual rings were counted from the outermost ring.

Table 2 AMS ^{14}C dating results of Sample B.

Sample A layer[a]	^{14}C age (BP)	Error ^{14}C age (±1 σ)	Lab code # (NUTA2-)
2	1151	30	8273
4	1166	30	8274
6	1186	31	8275
8	1231	33	8276
10	1249	31	8277
12	1163	30	8282
14	1145	30	8283
16	1170	30	8284
18	1161	30	8285
20	1150	31	8286
22	1159	33	8290
24	1157	33	8291
26	1160	33	8292
28	1115	30	8293
30	1148	30	8294
32	1172	30	8297
34	1187	31	8298
36	1137	30	8299
38	1151	31	8300
40	1126	30	8301
42	1090	30	8302
44	1115	30	8303
46	1124	30	8307
48	1161	30	8308
50	1153	30	8309

[a]Layers of annual rings were counted from the outermost ring.

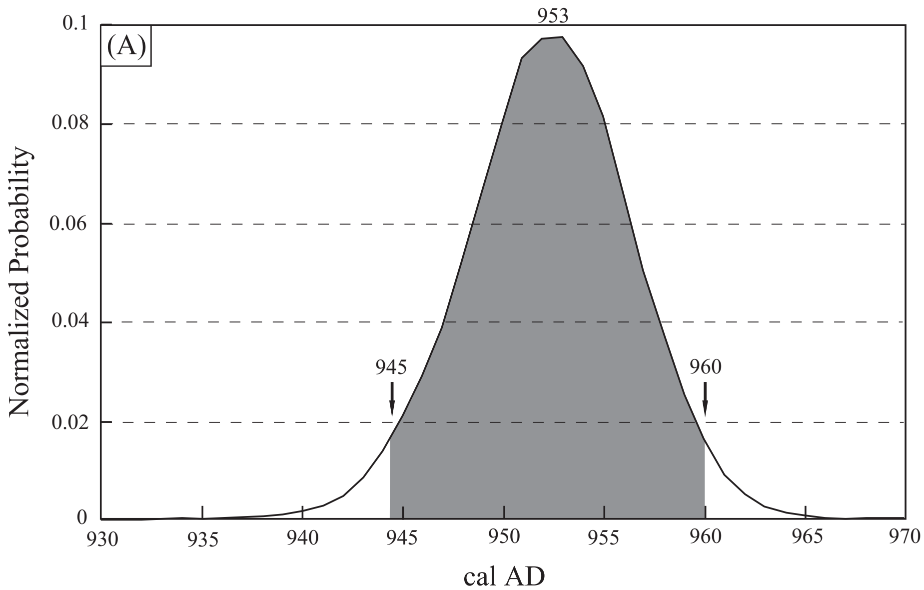

Figure 3 Probability distribution for ^{14}C wiggle-matching of charred wood trunks. Gray shadowed areas indicate calendar years at 95% confidence level: (A) sample A; (B) sample B.

On the basis of our results, there is little possibility that the huge eruption of Baitoushan Volcano occurred prior to the collapse of Bo-hai Kingdom (AD 926). Thus, it seems that the volcanic eruption did not cause the destruction of the kingdom. Furthermore, the result of sample A implies that the pyroclastic deposits at site A (Nakagawa et al. 2004) should belong to the B-Tm tephra at least chronologically. On the other hand, the ages derived for sample B indicate a small possibility that the eruption occurred during the 9th century AD (Figure 3B). Single calibration such as that done by Nakagawa et al. (2004) might show this low probability range. The reason for such a poor fit between sample B and IntCal04 may be attributed to the small amounts of tree rings used for the analyses. We estimated that sample B (omitting layers 8 and 10) is ~38 yr older than IntCal04, corresponding to

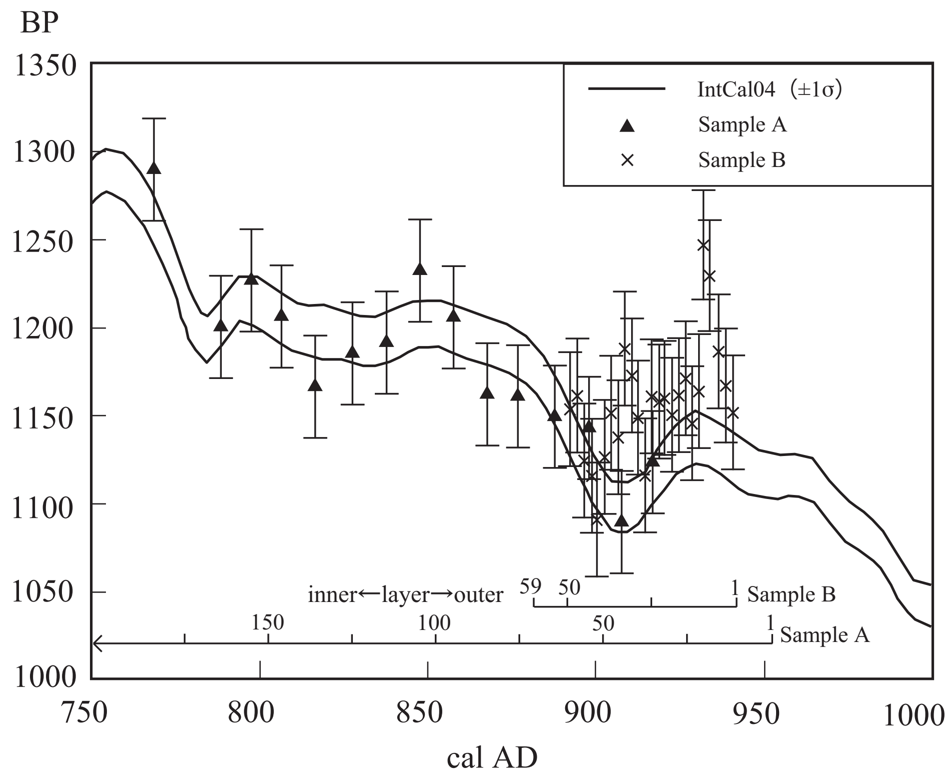

Figure 4 Plots on the IntCal04 calibration curve showing the results of ^{14}C wiggle-matching of charred wood trunks, samples A and B.

0.47% of contaminated dead carbon. ^{14}C depletion in the air CO_2 by emission of magma-derived CO_2 can be observed by studying carbon isotope anomalies in the local vegetation (e.g. Bruns et al. 1980). Pasquier-Cardin et al. (1999) reported that the magma-derived CO_2 emissions in Furnas caldera, Azores, led to apparent ^{14}C aging of up to 4400 yr. Thus, we infer that the time lag in sample B is a systematic shift due to volcanic gas emission prior to the eruption. Furthermore, poisonous components (SO_2 and H_2S) in volcanic gas cause widespread defoliation particularly on the leeward side of a volcano (e.g. Kamijo and Hashiba 2003). Age determination of volcanic eruptions using ^{14}C wiggle-matching assumes that the tree was killed by burial and heat from the pyroclastic deposits. If the systematic shift to older ages in sample B was caused by gas emission, it is also possible that some charred trees were already killed by poisonous gas before the eruption. To estimate these effects, we need to compare the ^{14}C wiggle-matching dates obtained from multiple samples *in situ*, with considerations of direction from source and geomorphology before the eruption.

CONCLUSION

To refine the chronology of the B-Tm eruption, we conducted ^{14}C wiggle-matching. The calibrated dates for sample A range from cal AD 945 to 960 at 95% confidence level and the best fit for the outermost ring is cal AD 953. The dates derived for sample B range from cal AD 859 to 884 and cal AD 935 to 963 at 95% confidence level, with the highest probability around cal AD 942. These results, including those from previous studies, are still unable to determine the precise eruption age. The reason for the difference of reported ages may be due to the effects of volcanic gas prior to the eruption.

Results of this study also suggest that the fall of the Bo-hai Kingdom (AD 926) possibly took place before the eruption of Baitoushan Volcano.

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