A late Mesozoic high plateau in eastern China: Evidence from basalt vesicular paleoaltimetry

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Eastern China is made of a number of large and small continental fragments throughout late Paleozoic and Mesozoic time, and is still the best natural laboratory for examining kinematic models of continent tectonics. The paleoelevation history of eastern China provides direct insight into the tectonic processes in China. Here we present basalt-vesicularity based estimates of the paleoaltimetry of the early Cretaceous basalts in northern East China, which indicate that the studied basalt units were at an elevation of more than 4 kilometers in late Mesozoic. Two vesicular basaltic rocks have been collected from bottom to top along the lava flow outcrop in eastern Inner Mongolia. After the digital precessing to the sample cross-sections, and taking advantage of the stereological conversion method to acquire the bubble size distributions, paleoelevation estimate was calculated for East China in the early Cretaceous. The results show that the elevation has been near 4700 ± 750 m when the lava flows were cooling, implying that there were highland regions in the northern part of the East China Plateau during the early Cretaceous. Combined with other geological evidence, we conclude that there was a high plateau with elevation near 5000 m above sea level in Eastern China during the late Mesozoic. This ancient high plateau in eastern China was most likely formed by the collision of the north and south China blocks.

early Cretaceous, east China Plateau, vesicular-basalt, paleoaltimetry, north and south China collision

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For the last three decades, numerous geological and paleomagnetic studies have shown that China was assembled from a number of large and small continental fragments throughout late Paleozoic and Mesozoic time. The tectonic configuration of eastern China is dominated by the North China Block (NCB) in the north and the South China Blocks (SCB) in the south (Figure 1(a)). The collision between the North and South China Blocks has played a central role in shaping the eastern Asian continent. One early tectonic model of the collision, based on paleomagnetic data and geologic evidence [1], envisions that in the latest Permian and Early Triassic the North and South China Blocks started colliding near the eastern end of what is now the

Qinling mountain belt (Figure 1(a)). After the initial contact in the east, suturing migrated progressively westward during the Early Mesozoic as the two blocks scissored together, eliminated the intervening marginal sea, and completed docking by Late Jurassic time.

Since the main collision and suturing between the NCB and SCB, however, there has been significant tectonic activity in the region. To the north, the scissors-like closure of the United China Block (NCB, SCB, and Mongolia) and Siberia did not end until Juro-Cretaceous time [2,3]. To the east, the subduction of the Kula plate beneath the Asian continental margin and the opening of the Bohai sea began in the Juro-Cretaceous [4]. To the west, the collision between India and Asia commenced in the Eocene, and continued to the present [5]. Besides causing large-scale intracontinental

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Figure 1 (a) Sampling localities in Inner Mongolia; (b) details of lava fields of the early Cretaceous Daote Nuoer Formation (shaded areas). Square box in (a) shows the location of (b). The dashed lines in (a) are the ancient plateau range delineated by Zhang et al. [6]. Our sampling location is ~200 km north of the boundary.

deformation and the most extensive region of the elevated topography in the world, the forceful collision and uplift of India and Asia appear also to be responsible for the today's topographic trend of China, with high plateaus in the west and low lands towards the east.

Several recent studies, however, suggested that parts of eastern China in late Mesozoic were probably in a region of high plateau, with its scale and elevation similar to that of the today's Qinghai-Tibet Plateau [6]. Geologic records also suggest that east Asia reversed its topography from west-tilting in late Mesozoic to today's east-tilting, an event that has exerted profound influence on paleoclimate and continent-ocean interactions [7]. Interestingly, abnormal large-scale magmatism also occurred in eastern China in late Mesozoic. Many acidic volcanics and irruptive rocks among them are geochemically analogous to adakites. These rocks are characterized by HREE depletion and no obvious negative Eu anomaly, low Y contents but high La/Yb and Sr/Y ratios [6]. Compared with the typical adakites in the Pacific Ocean, these rocks are enriched in K_2O ($Na_2O/K_2O=0.9-1.3$), with high contents of Sr (0.705–0.709), and generally with $\epsilon_{Nd}<0$. These geochemical signatures indicate that the adakite (C-type adakite) is derived from a deep source and is a product of partial melting of the lower-crust granulite or femic amphibolite in a thickened crust (>50 km) resulted from underplating of basaltic magma [6]. If the thickened crust corresponding to an elevated region, based on the principle of isostatics, then the late Jurassic to early Cretaceous aged C-type adakite volcanism may indicate the formation of a high plateau in Eastern China. This hypothesis has been favored by several constraints provided by paleogeographic, paleontologic, and paleoclimatic studies [8–12]. On the other hand, there are conflicting views on this Paleoplateau of eastern China, mainly from the lack of

convincing evidence to show whether these igneous rocks which have high Sr contents but low Yb could be called adakites [13–15].

Measuring the paleoelevation of high plateaux is critical to understanding their geodynamic evolution and tectonic process. Over the past decades, several techniques have been developed for measuring rock uplift and exhumation, such as tectonogeomorphic studies of fluvial systems and drainage basins [16], thermochronologic studies like those using apatite fission track dating [17], or (U-Th)/He thermochronology [18,19], stratigraphic and chronologic studies of erosional sediments and their accumulation rates [20], enthalpy or paleo- pCO_2 estimates based on paleoflora [21–24], and oxygen and hydrogen isotope studies of meteoric water and its proxies [25–29].

In recent years, a direct technique was developed for measuring paleoelevation via paleoatmospheric pressure on the basis of the vesicularity of basaltic lava flows [30–33]. This method is based on the difference in internal pressure between bubbles at the top and base of lava flows. At the top of the flow, pressure is atmospheric, while at the bottom of the flow, pressure is atmospheric plus the hydrostatic pressure of the overlying flow. The modal size of the vesicle (bubble) population is larger at the top than at the bottom.

$$\text{Thus,} \quad P = \rho g H / (\alpha - 1), \quad (1)$$

where P is atmospheric pressure, ρ is the density of the lava, g is the acceleration of gravity, H is the thickness of the flow, and $\alpha=V_T/V_B$, V_T and V_B are modal vesicle volumes between the top and base. Because lava thickness can be measured in the field, and the vesicle sizes can be measured in the lab, a simple relation can be solved for atmospheric pressure, and using the standard atmosphere, elevation can be determined. Sahagian and colleagues have successfully

tested this method with recent flows on the slopes of Mauna Loa, Hawaii, with an error of ± 400 m [31].

If indeed there existed a high plateau in eastern China, it would have not only affected the landform environment and the paleogeography of eastern China in late Mesozoic, but also influenced the paleoclimate of East Asia and by enlarge the world at that time. Paleoelevation estimation for this possible ancient plateau in eastern China has been an important scientific subject, around which there are considerable discussions and disputes. The widely different views have arisen because each investigation has been based on a particular line of evidence which is indirect proxy for paleoelevation, such as adakites, palaeoclimate and palaeobiocoenosis, but lack of direct study for elevation estimate, such as basalt vesicularity. Fortunately, Mesozoic vesicular basaltic rocks are extensively distributed in Eastern China which could potentially provide estimates for paleoelevation and range of the ancient Eastern China Plateau. In this paper we present results from the first study of early Cretaceous vesicular basaltic rocks from in Ji Linguole town, Inner Mongolia, examine the question of the existence of the ancient high Plateau in eastern China, and discuss the possible cause for the formation of this high plateau.

1 Sampling site and methods

An appropriate vesicular basaltic rock sample and reasonable vesicular statistical method are the keys paleoelevation determination using with basaltic vesicularity method. For this study, basaltic samples were collected from a quarry located 5 km to the south of Jilin Guole town in Xi Ujinqin Qi ($44^{\circ}25'28''\text{N}$, $117^{\circ}04'38''\text{E}$, altitude 1074 m) of Inner Mongolia (Figure 1(b)). According to the regional geological survey, these lavas belong to the Daote Nuocer Formation with well defined contact relationship in the field. The age of the Daote Nuocer Formation is reported as late Jurassic. However, recent studies by Chen et al. [34] obtained isotope ages for the rhyolites of the Chaganuoer Formation which underlies the Daote Nuocer Formation, and the basaltic andesite in the Bulagenhada Formation which overlies the Daote Nuocer Formation in the adjacent area. According to Chen et al., the age of the Daote Nuocer Formation should be between 142 and 129 Ma, which is in the Early Cretaceous.

At the sampling site, lava flows could be identified by a brick red or purple red oxidation roof on the top of each flow (Figure 2(a)). We targeted thick flows (at least 3 m in thickness) and selected flows within it the size of bubbles

Figure 2 The outcrop of vesicular basalt (a) and cross-sections of Dao Tenuocer Formation vesicular basalt samples (b), (c) in Ji Linguole, Xi Ujinqin Qi, Inner Mongolia (the smallest calibration of ruler: mm). Because samples were collected from a newly explored quarry, the outcrop is very messy. Even so, the eruption rhythm of lava flow is very clear.

must have clearly differentiation in vertical sense and have not been influenced by the pulling and dragging of the lava flow. To avoid the influence of external atmospheric pressure, the rocks inside the red roof were not collected for this study.

The vesicular basaltic rocks samples have been collected from bottom to top along the lava flow outcrop. All the samples have been collected from the same eruption, and consist of purple gray basalts, with many vesicular, mainly consist of plagioclase, olivine and some vitreous composition. The phenocrysts of plagioclase are board strips, often with symmetric twin, approximately 0.15–0.4 mm long, content of about 40%. Olivines are fine automorphic crystals, grain diameter about 0.05–0.15 mm, content of about 10%. Vitreous are turbid and not transparent, without microcrystal. Note our sampling location is outside of the inferred ancient eastern plateau by Zhang et al. (see the dotted lines in Figure 1(a)).

Determining the top and bottom along the transaction of the samples is the first step of the lab work, then grinding and buffing with randomness. We selected two samples (xw01 and xw04), which are uninfluenced by the pulling and dragging and nearly null coalescence, for vesicular statistics (Figure 2(b),(c)).

It is important to exactly measure modal vesicle size for measuring paleoelevation through paleoatmospheric pressure. There are three main methods to estimate the distribution patterns of vesicular basaltic in 3 dimensional space [35]. The first method is injecting hand samples with plastic monomer which subsequently polymerized, and then dis-

solving away the basalt, leaving plastic casts of vesicles for measurement and counting [36,37]. The second and more efficient technique is to determine vesicle size distributions from 2D cross-sections of hand samples [38,39]. The most accurate method for measuring bubble size distributions is the third, a High Resolution X-Ray Computed Tomography (HRXCT) method [40], which conducts high resolution 3D scanning of the basalt with X-Ray, and then modeling and counting.

This paper uses the second method, with the following operation procedures: (1) cut samples into thin sections; (2) examine the polished surfaces (and a scale) with a scanner at 600 dpi; (3) use two image processing tools (Adobe Photoshop and Image J) to optimize the pictures, including the resolution improvement, de-noising, filtering, gray image segmentation and the vesicular area measurement; (4) calculate the vesicle sizes through pixel conversion; and (5) convert the bubble size distributions form 2D area to 3D volume based on the principles and applications of stereology. Finally, we estimate paleoelevation according to eq. (1) above and the method described by Sahagian et al. [33].

2 Reconstruction of size distribution of the vesicles and paleoelevation results

Figure 2(b), (c) shows scanning images of samples used for this study. A total of 564 and 710 stomas are detected in the cross-sections of sample xw01 and sample xw04, respectively. Figure 3 shows the frequency distribution of observed

Figure 3 Frequency distribution of observed 2D cross-section sizes.

2D cross-section sizes. The area of observed 2D cross-section on sample xw01 ranges from 0 to 2 mm², and for sample xw04, 0 to 7 mm². Several stomas areas, accounting for less than 1%, are relatively scattered, which are obviously bigger than the average area of all stomas on the cross-section (even several times bigger than the average area). These areas could have been merged by several normal stomas and were not used in this study to ensure the accuracy of counting.

When a random plane cuts a distribution of particles, it does not intersect each through its center, but rather, the set of intersections can be divided into a probability distribution according to cross-section size, this distribution does not represent that of the 3D particles, but is normally described by a finite number of discrete size classes [39]. So we must use a stereological 2D to 3D conversion techniques [38,40].

Many workers have used section size of rounds in 2D to calculate volume of the spheres in 3D [38,41,42]. The stereological approach can be stated below. Let's assume r is cross-section radius, R is the sphere radius, N_V is the number density of the largest particle size class in 3D volume, and N_A is the number density of observed largest 2D cross-section class. If there is a bubble within r radius, its number density can be calculated as

$$N_A(r) = 2 \int_{R=r}^{R_{\max}} N_V(R) \frac{r}{\sqrt{R^2 - r^2}} dR, \quad (2)$$

$N_V(R)$ is the number density of the particle size class within R radius in 3D volume [42].

If we put the rounds (obtained from the cross-section) into groups according to their sizes, such as n groups with the same group interval (Δ), then we can get the size range of the j group rounds through $(j-1)\Delta$ – $j\Delta$, and, its number density at cross-section is

$$N_A(j) = \int_{(j-1)\Delta}^{j\Delta} \int_r^{R_{\max}} \frac{2rN_V(R)}{\sqrt{R^2 - r^2}} dR dr. \quad (3)$$

Because $R_{\max} = r_{\max} = j\Delta$, and only if $R \geq r$, the rounds could be obtained from the cross-section. Thus, we have

$$\begin{aligned} N_A(j) &= \int_{(j-1)\Delta}^{j\Delta} \int_{(j-1)\Delta}^R \frac{2rN_V(R)}{\sqrt{R^2 - r^2}} dR dr \\ &+ \int_{j\Delta}^{n\Delta} \int_{(j-1)\Delta}^{j\Delta} \frac{2rN_V(R)}{\sqrt{R^2 - r^2}} dR dr \\ &= \int_{(j-1)\Delta}^{j\Delta} 2\sqrt{R^2 - (j-1)^2 \Delta^2} \cdot N_V(R) dR \\ &+ \int_{j\Delta}^{n\Delta} 2 \left[\sqrt{R^2 - (j-1)^2 \Delta^2} - \sqrt{R^2 - j^2 \Delta^2} \right] \cdot N_V(R) dR. \end{aligned} \quad (4)$$

If we change the rounds with bubbles for grouping, n groups, Δ is group interval, $(i-1)\Delta$ – $i\Delta$ is the size range of the i group bubble, and only if $i \geq j$, the j group cross-section

could be obtained from the bubbles, then, a generalized form of the above formulation can be written as

$$\begin{aligned} N_A(j) &= \int_{(j-1)\Delta}^{j\Delta} 2\sqrt{R^2 - (j-1)^2 \Delta^2} N_V(R) dR \\ &+ \sum_{i=j+1}^n \int_{(i-1)\Delta}^{i\Delta} 2 \left[\sqrt{R^2 - (j-1)^2 \Delta^2} - \sqrt{R^2 - j^2 \Delta^2} \right] \\ &\times N_V(R) dR, \end{aligned} \quad (5)$$

i.e.

$$\begin{aligned} N_A(j) &= 2\sqrt{R_{(i=j)}^2 - (j-1)^2 \Delta^2} \int_{(j-1)\Delta}^{j\Delta} N_V dR \\ &+ \sum_{i=j+1}^n 2 \left[\sqrt{R_i^2 - (j-1)^2 \Delta^2} - \sqrt{R_i^2 - j^2 \Delta^2} \right] \\ &\times \int_{(i-1)\Delta}^{i\Delta} N_V(R) dR. \end{aligned} \quad (6)$$

Because $\int_{(i-1)\Delta}^{i\Delta} N_V dR$ is the number density of the bubble size class in some volume of the i group ($N_V(i)$), so,

$$N_A(j) = 2\Delta \sum_{i=j}^n k_{ji} N_V(i), \quad (7)$$

in this formula:

$$\begin{aligned} k_{ji} &= \frac{1}{\Delta} \sqrt{R_{(i=j)}^2 - (j-1)^2 \Delta^2} \quad (i=j), \\ k_{ji} &= \frac{1}{\Delta} \left[\sqrt{R_i^2 - (j-1)^2 \Delta^2} - \sqrt{R_i^2 - j^2 \Delta^2} \right] \quad (i > j). \end{aligned} \quad (8)$$

The k_{ji} could be calculated directly once the method of grouping and the group interval have been determined, then through back eq. (7), the size distribution in 3D of the bubbles ($N_V(R)$) can be obtained via

$$N_V(i) = \frac{1}{2\Delta} \sum_{j=i}^n a_{ij} N_A(j), \quad (9)$$

where a_{ij} is the inverse matrix of k_{ji} .

According to the above methods, we have reconstructed bubble size distribution of the two samples (xw01, xw04). Firstly, we selected available area data which we obtained from the cross-sections, eliminated the discrete data that were obviously not harmonious. We then converted the available data to section round radius. Adopting Goldsmith-Cruz-Orive principle [43], we divided all the bubbles and section rounds into 15 groups with radius as standard, group interval $\Delta = R_{\max}/15 = r_{\max}/15$. The radius size range of the cross-section rounds could be represented as $(j-1)\Delta$ – $j\Delta$, and $(i-1)\Delta$ – $i\Delta$ (size range of the bubbles). Take the average size as a nominal size in each group, i.e. nominal radius size of the j group is $(j-1/2)\Delta$, $(i-1/2)\Delta$ the bubbles. Thus, the value of the coefficient k_{ji} obtained is

Table 3 Frequency distribution from cross-section (2D) and 3D commutation

Sample	Data from the cross-section (2D)				Goldsmith-Cruz-Orive commutation data (3D)				
	Group <i>j</i>	Section round radius	Group interval	Number density <i>N_{A(0)}</i>	Group <i>i</i>	Sphere radius	Group interval	Number density <i>N_{V(0)}</i>	Error
xw01	1	0.033862	0.000000–0.067724	0	1	0.033862	0.000000–0.067724	0	0.01
	2	0.101585	0.067724–0.135448	0	2	0.101585	0.067724–0.135448	0	0.03
	3	0.169309	0.135448–0.203172	0	3	0.169309	0.135448–0.203172	0	0.18
	4	0.237033	0.203172–0.270896	16	4	0.237033	0.203172–0.270896	0	0.46
	5	0.304756	0.270896–0.338620	104	5	0.304756	0.270896–0.338620	9	0.69
	6	0.372480	0.338620–0.406344	159	6	0.372480	0.338620–0.406344	224	0.70
	7	0.440204	0.406344–0.474068	137	7	0.440204	0.406344–0.474068	263	0.57
	8	0.507927	0.474068–0.541792	72	8	0.507927	0.474068–0.541792	125	0.38
	9	0.575651	0.541792–0.609516	39	9	0.575651	0.541792–0.609516	71	0.26
	10	0.643375	0.609516–0.677240	17	10	0.643375	0.609516–0.677240	25	0.17
	11	0.711098	0.677240–0.744964	10	11	0.711098	0.677240–0.744964	17	0.12
	12	0.778822	0.744964–0.812688	4	12	0.778822	0.744964–0.812688	5	0.07
	13	0.846546	0.812688–0.880412	2	13	0.846546	0.812688–0.880412	4	0.04
	14	0.914269	0.880412–0.948136	0	14	0.914269	0.880412–0.948136	0	0.04
	15	0.981993	0.948136–1.015860	3	15	0.981993	0.948136–1.015860	6	0.05
xw04	1	0.044865	0.00000–0.08976	0	1	0.044865	0.000000–0.091019	0	0.02
	2	0.134595	0.08976–0.17952	0	2	0.134595	0.091019–0.182038	0	0.07
	3	0.224325	0.17952–0.26928	12	3	0.224325	0.182038–0.273057	0	0.16
	4	0.314055	0.26928–0.35904	48	4	0.314055	0.273057–0.364076	0	0.24
	5	0.403785	0.35904–0.44880	124	5	0.403785	0.364076–0.455095	88	0.29
	6	0.493515	0.44880–0.53856	141	6	0.493515	0.455095–0.546114	161	0.26
	7	0.583245	0.53856–0.62832	113	7	0.583245	0.546114–0.637133	145	0.21
	8	0.672975	0.62832–0.71808	70	8	0.672975	0.637133–0.728152	72	0.16
	9	0.762705	0.71808–0.80784	50	9	0.762705	0.728152–0.819171	51	0.12
	10	0.852435	0.80784–0.89760	34	10	0.852435	0.819171–0.910190	16	0.10
	11	0.942165	0.89760–0.98736	36	11	0.942165	0.910190–1.001209	34	0.09
	12	1.031895	0.98736–1.07712	23	12	1.031895	1.001209–1.092228	16	0.07
	13	1.121625	1.07712–1.16688	19	13	1.121625	1.092228–1.183247	9	0.07
	14	1.211355	1.16688–1.25664	20	14	1.211355	1.183247–1.274266	17	0.06
	15	1.301085	1.25664–1.34640	13	15	1.301085	1.274266–1.365285	19	0.04

Figure 4 Histogram of frequency distribution from cross-section (2D) and derived 3D frequency distribution.

Another possible kind of error is caused by stereoscopic transformation. In our calculations, the transformation formulas is eq. (9), so that

$$\sigma^2[N_V(i)] = \frac{1}{4A^2} \sum_{j=i}^n (a_{ij})^2 \sigma^2[N_A(j)]. \quad (11)$$

Because

$$N_A(j) = \frac{N(j)}{A_T}, \quad (12)$$

where $N(j)$ is the cross section numbers of the j group, and A_T is the totally tested area. Then we can obtain

$$\sigma^2[N_A(j)] = \frac{\sigma^2[N(j)]}{A_T^2}, \quad (13)$$

where $N(j)$ is commonly subjected to Poisson probability, therefore,

$$\sigma^2[N_A(j)] = \overline{N_A(j)}. \quad (14)$$

Then,
$$\sigma^2[N_A(j)] = \frac{\overline{N(j)}}{A_T^2} = \frac{N_A(j)}{A_T}. \quad (15)$$

So, $\sigma[N_V(i)]$ can be found by integrating eq. (11), so that

$$\sigma[N_V(i)] = \frac{1}{2A_T A} \sum_{j=i}^n a_{ij} \sqrt{N(j)}. \quad (16)$$

Table 3 shows the error of each group, their sum is the experiment transformation error of the samples, i.e. 3.77% for sample xw01, 1.96% for sample xw04. Accordingly, the final error of paleoelevation is ± 620 m.

Error sources caused by hydrostatic pressure at the base of lava flow come from both density measurements and potential error resulting from unrecognized minor inflation or deflation after solidification of upper and lower parts of the flow. Generally, each centimeter of measurement error of inflation/deflation would lead to an error of ± 33 m in elevation, we assume an error term to account for 10 cm of inflation/deflation between samples xw01 and xw04. This 10 cm error assumption, which is admittedly very big, can lead an elevation uncertainty of ± 330 m for a typical 3 m flow.

3.2 Sea level pressure at the time of eruption

Error sources caused by sea level pressure at the time of eruption are due to changing weather conditions. Typically, the time scale of these variations is no longer than several days for synoptic systems. Taking a conservative approach, variations in barometric pressure (due to weather) at the time of eruption will lead to an uncertainty of about ± 150 m for a given flow [35]. Of course, this kind of circumstance should exclude a hurricane or other very low pressure system.

Using the larger errors above, the total error from the various contributions is thus estimated as

$\sqrt{210^2 + 620^2 + 330^2 + 150^2}$, or about ± 750 m.

4 Discussion and conclusion

The palaeogeomorphology of East China during the Late Mesozoic is a hot debated scientific problem, which directly influences the palaeogeography, palaeoclimate and paleontology of China and even that of the whole Asia. To date, various lines of investigation on East China have been taken from indirect proxy, such as petrology, palaeontology, and palaeoclimatology, but absence of analysis on paleoaltimeter, and this has led to controversy about the existence of East China plateau. Determining the absolute elevation in eastern China is necessary to understand how crustal processes contributed to creating the high topography of this part of China.

Our data indicate that the elevation of the sampling site in Inner Mongolai was near 5000 m above sea level when the lava flow was emplaced, implying that there used to be highland regions during early Cretaceous.

The implication of our data challenges the question about the boundary of the proposed eastern China plateau. Zhang et al. [44] have discussed the north boundary of the plateau in detail according to the distribution of the adakite rocks. They consider that the plateau boundary distributes along the Chifeng-Kaiyuan rift zone (Figure 1(a)), and the northern border of the plateau may have shifted to the south from late Jurassic to early Cretaceous. Our study area is located 200 km north of the plateau border suggested by Zhang et al. The 5000 m paleoelevation could suggest that our sampling area was part of the high plateau, or a separate high mountain 200 km north to the ancient high plateau border. Interestingly, there are reports that early Cretaceous sediments from Changtu area of Liaoning Province and Xin Licheng area of Jilin Province contain large sum of ice raft depositions [45]. Because the paleolatitudes for these areas as well as for our sampling site were in the middle latitude zone [46,47], these ice raft deposits should be formed in high altitude region. The existence of the early Cretaceous ice raft deposits in Liaoning and Jining and our high altitude paleoelevation data from Inner Mongolia suggest that the extent of the early Cretaceous high plateau in eastern China is much wider than what proposed by Zhang et al. [44].

As mentioned in the beginning, the collision between the NCB and SCB has played a central role in shaping up the eastern Asian continents. The amalgamation of the NCB and SCB took place in the Late Permian, with collision first occurring near the eastern end (in today's geographic coordinates: 30°N, 120°E) of the Qinling Fold Belt and diachronously suturing from east to west due to a clockwise rotation of about 67° of SCB relative to NCB [1]. By the Middle Jurassic, the Qinling Sea is almost completely closed. Consequently, North and South China were assem-

bled by Middle Jurassic time.

We argue that with the cessation of the NCB-SCB subduction and associated magmatism in late Mesozoic and the closure of the PaleoTethys ocean in easternmost China due to collision, East China continent underwent dramatically reorganization. In particular, areas north of the NCB-SCB boundary, i.e. the outlined area in Figure 1(a), were under direct impact of collisional and rotational suturing. As there was no material escaped eastward, crustal thickening and uplifting must have been prevailing since Jurassic, building up topography in the region. Despite the uncertainties involved in dating tectonic events and paleoelevation determination, it seems clear that both the cessation of NCB-SCB collision and the existence of high elevation plateau in eastern China occurred in late Mesozoic, suggesting some causal relationship.

To sum up, we conclude that there was a high plateau with elevation near 5000 m above sea level in Eastern China during the late Mesozoic. This vast ancient high plateau in eastern China was most likely a product of the collision of the North and South China blocks.

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