

## Research Article

# Middle-Late Pleistocene Paleo-Climature and Paleo-Altitude of the Centre of Tibetan Plateau Indicated by the Sporopollen Record of Well QZ-4

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### Abstract

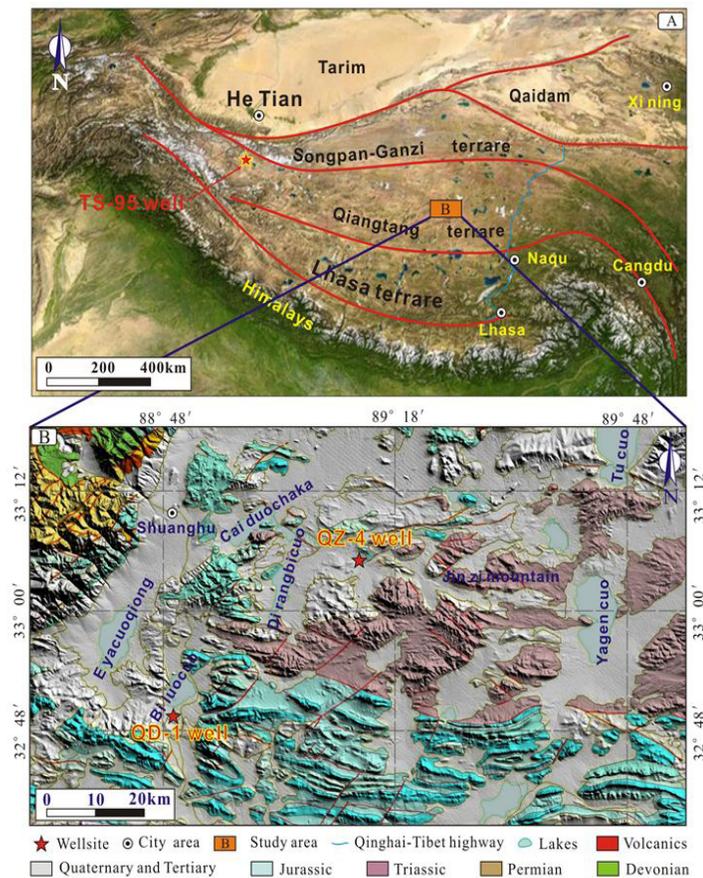
The core sample from well QZ-4 is an important climate archive for the central Tibetan Plateau in the middle-late Pleistocene. In this work, a detailed pollen analysis of it is carried out to provide a preliminary insight into the paleo-climate and paleo-altitude change in the central Tibetan Plateau. It can be concluded that the pollen assemblage can be obviously divided into two pollen zones, Pollen zone I (251.1-314 m in depth, 120.0-345.8 ka BP.) and Pollen zone II (200-251.1 m in depth, 105.4-120 ka BP.). The paleo-climate during pollen zone I deposition period was comparatively colder and wetter than it during the pollen zone II deposition period. After Gonghe Movement, the centre of Tibetan Plateau was uplifted about 300m (from 3500-3700m to 3800-4000m in elevation). The wind was changed from horizontal or downward direction to upward direction, in the study area. In the central of Tibetan Plateau, the climate change seems to be mainly driven by global climate change, and that tectonic uplift may have been a subordinate influence at the middle-late Pleistocene.

**Keywords:** Gonghe Movement; Mid-Pleistocene; Paleo-altitude; Palaeoclimate; Tibet Plateau

### Introduction

The Tibetan Plateau is not only the largest and highest mountain plateau on Earth, but it is also the site of the first successful terrestrial gas hydrate exploration in China [1]. In recent years, con-

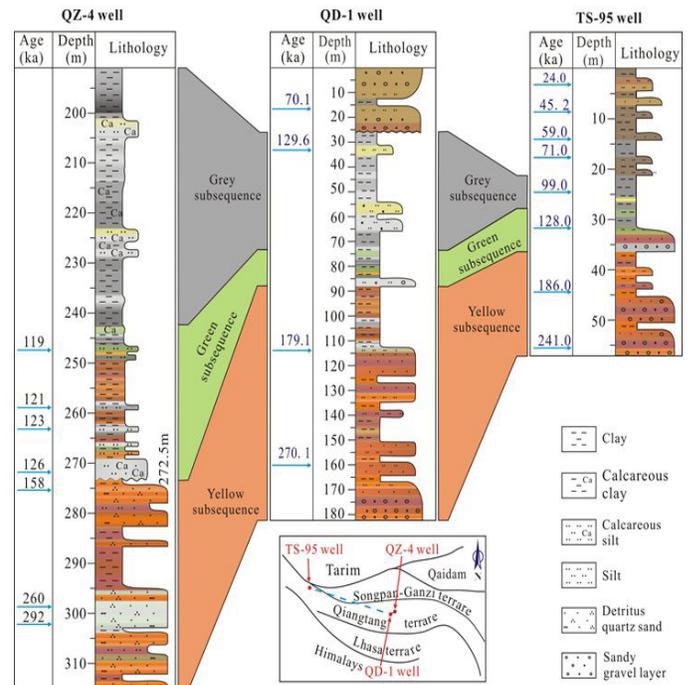
siderable attention has been focused on the study of the correlation between the uplift of the Tibetan Plateau and Quaternary climate evolution [2], which is not only beneficial to the study of global climate change, but it is also beneficial for the study of permafrost surveys and the exploration of gas hydrates in the Tibetan Plateau. However, the existing results come from the surrounding area [3,4], and little study in the central Tibetan Plateau has been reported (Figure 1).



**Figure 1 (a):** Map of the Tibet Plateau showing the location of the study area and well TS-95, (b) Map of the Shuanghu area showing the geomorphological features in the study area and the location of well QZ-4 and well QD-1.

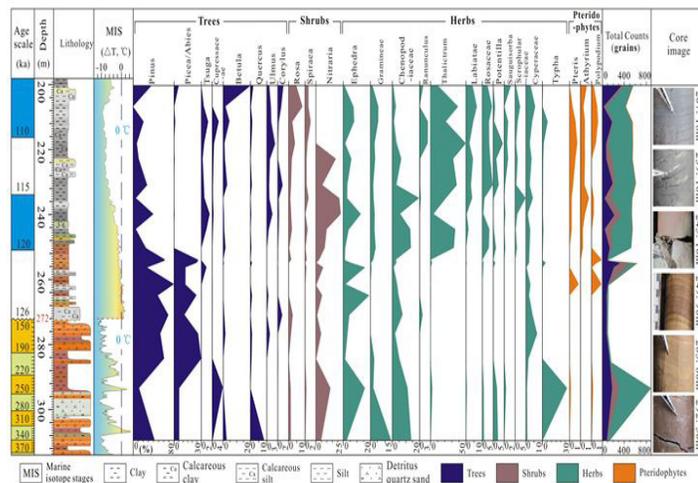
Previous studies have shown that, globally, the hottest period since the middle Pleistocene was at approximately 120 ka BP, which is recorded in the ice sheet above Lake Vostok in the southern hemisphere [5] and in Greenland [6] in the northern hemisphere. North Greenland Eemian Ice Drilling (NEEM) surface temperatures after the onset of the Eemian (126 ka) peaked at  $8 \pm 4$  °C above the mean of the past millennium [7]. In the central Tibetan Plateau, the Thermoluminescence (TL) dating of well QD-1 [7], the  $^{14}\text{C}$  and  $^{230}\text{Th}/^{234}\text{U}$  dating of well TS-95 [8,9] and the Electronic Spin Resonance (ESR) dating of well QZ-4 show that the transition section of the colour sequence in the three wells was deposited at approximately 120 ka (Figure 2). Furthermore, the last rapid uplift of the Tibetan Plateau started at 150 ka BP, which is referred to as the Gonghe Movement [10]. After the Gonghe Movement (Figure 3), the average elevation reached almost 4,000 m, at which the East Asian monsoon was apparently affected by the Tibetan Plateau [10,11]. The paleoclimate study based on the

cores of well QZ-4 will benefit the study of the correlation between climate changes in the central Tibetan Plateau and global climate change in the middle-late Pleistocene, which will contribute to the study of the correlation between the uplift of the Tibetan Plateau and Quaternary climate evolution.



**Figure 2:** The lithological association and the ESR, TL and  $^{14}\text{C}$  and  $^{230}\text{Th}/^{234}\text{U}$  dating results of this color sequence in well QZ-4, well QD-1 [7] and well TS-95 [8,9] with depth scale. The core images of this color sequence in well QZ-4.

In this work, the thickest Quaternary sedimentary formation in the central Tibetan Plateau was drilled in well QZ-4 (Figure 1), and the most complete core was collected. The cores are characterized by a colour sequence with three colour features: (1) the yellow subsequence (with dark yellowish-brown and brownish-red colour) at the depth from 272.48 m to 314 m, (2) the grey subsequence (with dark grey and whitish-grey colour) at the depth from 198 m to 240 m, and (3) the transition section (with light greyish-green colour) interbedded with the brown and grey clay at the depth from 240 m to 272.48 m, which is consistent with the colour sequences observed in wells QD-1 [7] and TS-95 [9], which are located in the central and north western Tibetan Plateau, respectively (Figure 2). The cores drilled in well QZ-4 are desirable archives for the study of climate change in the central Tibetan Plateau. In this paper, we present a detailed pollen analysis of the well QZ-4 in an effort to provide preliminary insight into the climate and the elevation change recorded in it.



**Figure 3:** Pollen and Spore percentage diagram for the well QZ-4 plotted against the depth and date. The data of the MIS curve are come from the website: [https://commons.wikimedia.org/wiki/File:Vostok\\_Petit\\_data.svg?uselang=zh-sg](https://commons.wikimedia.org/wiki/File:Vostok_Petit_data.svg?uselang=zh-sg)

### Sample and Methods

Well QZ-4 is located in the central Tibetan Plateau, approximately 50 km east of Shuanghu County at 89°14'E and 33°5'N, with an elevation of 4932 m. The surrounding area is a flat terrain, in which the maximum elevation difference is smaller than 50 m. The rivers in this area are seasonal rivers, which are formed during the rainy season and flow west into Dirangbicuo Lake and Caiduochaka Lake (Figure 1). The bedrock around the QZ-4 well is the Tumengela Formation, which is composed of quartz-lithic sandstone and was deposited in a deltaic floodplain environment in the Late Triassic. The total depth of this well is 314 m. The cores in the well were well collected at 190-314 m depth, partly collected at 0-110 m depth, and absent at 110-190 m depth. Basing on the core samples, core recovery, detritus and indicators of sedimentary environments (e.g., colour, lithologic characters, grain size, grain shape, particle roundness, sedimentary structures, and fossil assemblage) in the core samples, the stratigraphic sequence drilled in well QZ-4 can be subdivided into two sedimentary sequences:

The first sequence, at 0-198 m in depth, is a regressive depositional sequence, which consists of semi-deep lake facies, shallow lake facies, lake shore facies, meandering stream facies and flood plain from the deep to shallow layers in sequence. These facies are characterized by black grey clay and grey clay, light grey silty clay, light grey, yellow sand, and a yellow-brown sandy gravel layer, respectively.

The second sequence, at 198-314 m depth, consists of several transgressive-regressive depositional sequences, which consist of shallow lake facies, lake shore facies and semi-deep lake facies. In this sequence, the semi-deep lake facies are characterized by black

grey clay, grey clay, dark yellowish-brown clay and brownish-red clay, with horizontal bedding at depths of 198-199.9 m, 203.18-221.68 m, 227.18-240.8 m, 247.88-260.78 m and 281.33-293.98 m. The shallow lake facies are characterized by yellow-brown silty clay interlayered with thin light-grey silty clay, brown clay, and white grey clay at depths of 199.9-203.18 m, 221.68-227.18 m, 240.8-247.88 m, 260.78-278.31 m, 293.98-296.18 m and 302.4-313.0 m. The lake shore facies are characterized by yellow-brown sand interlayered with white grey sand and brown clay at depths of 278.31-281.33 m, 296.18-301.7 m and 313.0-314 m (Figure 2).

A total of 20 samples with 5 m intervals were collected from the well QZ-4 for palynological analysis. Samples weights of 200 g were used to prepare pollen residues for the upper 244m depth, and samples weights of 300 g were used to the lower depths. Samples were mostly prepared using standard techniques [12], involving alkali digestion, treatment with 10% cold HCl, 10% hot KOH, 46% hot HF, and Erdtman's acetolysis, staining with safranin, dehydration with tertiary butyl alcohol, and mounting in silicone oil. Prior to alkali digestion, moss polsters and soils were dispersed in distilled water and sieved (200 mm) to remove coarse detritus and sand. Lycopodium tablets were added to the samples to allow for estimation of pollen concentrations [13]. All samples have been studied under microscopes at Nanjing Institute of Geology and Palaeontology, Academic Sinica (Nanjing, China) and The Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences (Shijiazhuang, China). Leica microscope at a magnification of 400 was used for pollen identification and counting. More than 100 pollen grains were counted for each sample. Pollen abundance was expressed as percentages calculated using the total pollen sum.

### Results

Most of the studied samples yielded rich, well-preserved palynomorph assemblages, with the identified sporomorphs representing about 75 taxa, including arboreal taxa, e.g. *Pinus*, *Picea*, *Picea*, *Tsuga*, *Cupressaceae*, *Betula*, *Carpinus*, *Alnus*, *Juglans*, *Quercus*, *Fagus*, *Ailanthus*, *Ulmus*, *Tilia*, *Moraceae*, *Salix*, *Corylus*, *Ilex*, *Oleaceae*, as well as scrubby and herbaceous taxa, e.g. *Lonicera*, *Sambucus*, *Rosa*, *Spiraea*, *Rhododendron*, *Caragana*, *Reaumuria*, *Hippophae*, *Nitraria*, *Ephedra*, *Gramineae*, *Chenopodiaceae*, *Compositae*, *Chrysanthemum*, *Artemisia*, *Aster*, *Xanthium*, *Ranunculaceae*, *Ranunculus*, *Thalictrum*, *Polygonum*, *Rumex*, *Labiateae*, *Prunella*, *Euphorbia*, *Rosaceae*, *Potentilla*, *Sauguisorba*, *Papilionatae*, *Primula*, *Rubiaceae*, *Scrophulariaceae*, *Lythraceae*, *Cruciferae*, *Araliaceae*, *Geranium*, *Clerodendron*, *Gentiana*, *Solanaceae*, *Sedum*, *Umbelliferae*, *Saxifraga*, *Lilium*, *Arenaria*, *Macleaya*, *Urticaceae*, *Cyperaceae*, *Typha*, and some fern spores, including *Lycopodium*, *Sellaginella*, *Adiantaceae* *Pteris*, *Athyrium*, *Polypodiaceae*, *Polypodium*, *Lepisorus*, *Filicale*. Some algal remains (e.g. *Pediastrum*) were also detected. The total spore and pollen sum was used to calculate the percentage of various spore

and pollen taxa. As shown in (Figure 3), the pollen assemblage can obviously have divided into two pollen zones:

Pollen zone I (251.1-314 m in depth, 120.0-345.8 ka BP.) is characterised by single species and low pollen concentrations. The average pollen concentration is around 0.4 grain/g, except the sample at 295.0m in depth with 3.1 grain/g. In this pollen zone, the pollen species are particularly characterized by high abundance of tree, a few herb, shrubs and fern spores. The maximum proportion of tree pollen reaches 86.5%, with an average of 66.2%. The tree pollen principally includes *Pinus* (10.5-71.9%, av. 45.31%), *Picea* (5.6-29.0%, av. 17.4%) (Figure 3). *Tsuga*, *Cupressaceae*, *Betula*, *Quercus* etc. are occasionally seen in some samples. The average content of herb pollen is 19.2%. The herbs principally include *Ephedra* (0.9-18.9%, av. 7.0%), *Chenopodiaceae* (1.1-13.9%, av. 5.4%), *Cyperaceae* (0.2-6.8%, av. 2.1%) (Figure 3). *Gramineae*, *Artemisia*, *Labiatae*, *Rosaceae*, *Typha* etc. are occasionally seen in some samples, especially the *Typha* composes 25.9% of the total pollen sum at 295.0 m in depth. The maximum proportion of shrub pollen reaches 46.4%, with an average of 9.7%. The shrub principally includes *Nitraria* (0.5-12.7%, av. 4.2%) (Figure 3). *Lonicera*, *Rosa* etc. are occasionally seen in some samples, especially the *Lonicera* composes 38.8% of the total pollen sum at 256.9m in depth. The fern spores are sporadically present in a few samples. The maximum proportion of fern spores is smaller than 0.9%.

Pollen zone II (200-251.1m in depth, 105.4-120 ka BP.) is characterised by multiple species and high pollen concentrations. The average pollen concentration is around 2.8 grain/g. In this pollen zone, the pollen species are particularly characterized by a high abundance of herb, a few tree, shrubs and fern spores. The maximum proportion of herb pollen reaches 80.3%, with an average of 60.9%. The herb principally includes *Thalictrum* (4.2-50.5%, av. 28.8%), *Chenopodiaceae* (0.5-19.5%, av. 6.8%), *Ephedra* (0.7-12.9%, av. 4.7%), *Gramineae* (1.3-5.4%, av. 3.1%) (Figure 3). *Artemisia*, *Ranunculus*, *Labiatae*, *Rosaceae* etc. are occasionally seen in some samples. The maximum proportion of tree pollen reaches 61.9%, with an average of 24.5%. The trees principally are *Pinus* (0.5-35.6%, av. 16.11%) (Figure 3). *Picea*, *Tsuga*, *Cupressaceae*, *Betula*, *Quercus* etc. are occasionally seen in some samples. The maximum proportion of shrub pollen reaches 24.1%, with an average of 13.6%. The shrub principally includes *Nitraria* (0.5-21.4%, av. 9.0%), *Rosa* (0.4-8.6%, av. 2.9%) (Figure 3). *Lonicera*, *Spiraea*, *Hippophae*, *Reaumuria* etc. are occasionally seen in some samples. The maximum proportion of fern spores reaches 1.7%, with an average of 1.0%. The fern spores principally are *Athyrium* (0.2-0.8%, av. 0.4%), *Pteris*, *Polypodium*, *Lepisorus* etc. are sporadically present in a few samples.

## Discussion

### Ecologic Environment

The sporopollen assemblage of pollen zone I is characterized by high percentages of arboreal taxa, e.g. *Pinus*, *Picea* and *Abies*, and low percentages of scrubby and herbaceous taxa. However, the sporopollen assemblage of pollen zone II is characterized by high percentages of shrub species and herbaceous taxa, e.g. *Thalictrum*, *Rosaceae* and *Labiatae*, and low percentages of arboreal taxa (Figure 3).

Many studies of the representation of *Picea/Abies*-pollen in modern sporopollen assemblages indicate that such assemblages are highly indicative of autochthonous vegetation [14,15]. In pollen zone I, the average percentage of *Picea* and *Abies* is 17.4% (5.6-29.0%), which is suggesting that spruce and fir forests developed widely in the central of Tibetan Plateau. On the Tibetan Plateau today, *Picea* and *Abies* are the main representatives of sub-alpine dark coniferous forests and are principally distributed Gongga Mountain, Himalaya, Nyainqentanglha and Hengduan Mountains [14,16]. However, in the pollen zone II, *Picea* and *Abies* are occasionally seen in some samples, with average percentage of 0.8% (0-4.9%). The pollen zone II is mainly composed of shrub species and herbaceous taxa, such as *Labiatae* [16], *Thalictrum* [16] and *Rosaceae* (Yashiro, et al. 2010) which are the major herb species of alpine shrub meadow in Tibetan Plateau.

In brief, during pollen zone I deposition period, the zonal vegetation in the central of Tibetan Plateau should have been sub-alpine dark coniferous forests. However, it has been alpine shrub meadow during pollen zone II deposition period.

### Paleo-temperature Interpretation

The study of Cordova, et al. [17] shows that *Quercus-Ulmus-Poaceae* pollen assemblage zone and the development of a chernozem soil suggest cool-dry climate conditions. In well QZ-4, the *Quercus-Ulmus-Poaceae* pollen assemblage is observed in the pollen zone II, and the chernozem soil section is observed in this zone too (Figure 3). Meanwhile, it is known that *Pinus* prefers cool weather [18]. In the well QZ-4, the *Pinus* is observed in the both pollen zones. It is indicated that both the two pollen zones are deposited in the cool temperature regime.

On the other hand, *Chenopodiaceae*, *Cyperaceae* and *Lamiaceae* are suggesting dry and cold conditions [19]. In pollen zone II, *Chenopodiaceae*, *Cyperaceae* and *Lamiaceae* are richer than them in the pollen zone I. Meanwhile, the modern mean annual temperature is generally above 4 °C in the sub-alpine dark coniferous forests [14] and the is no higher than -1 °C in the alpine shrub

meadow in Tibetan Plateau [20]. Hence, it can be concluded that both pollen zone I and II are deposited in a cool climate environment. The climate is comparatively cooler during the pollen zone II depositional period than the pollen zone I depositional period. In the central of Tibetan Plateau, the temperature was slightly declined in the middle-late Pleistocene.

### Paleo-humidity Interpretation

The study of Ji, et al. [21] shows that the *Thalictrum* is normally in arid climates. In well QZ-4, *Thalictrum* is rich in pollen zone II (4.2-50.5%, av. 28.8%), but absent in the pollen zone I, which is indicating that regional climate is comparatively drier during the pollen zone II depositional period than the depositional period of pollen zone I.

*Ephedra* is typical desert plants and is often used as indicator of dry climate [22]. It is a perennial shrub and it is a very effective sand-binder. In Saudi Arabia, it is associated with sand dunes formation, especially the mobile, non-saline and low moisture content ones [23]. In the pollen zone I, the *Ephedra* principally is rich in the sand strata and absent in the clay strata. However, in pollen zone II, it is obviously richer in clay strata than sand strata (Figure 3). It is indicated that the *Ephedra* is principally associated with sand dunes formation in the pollen zone I. Nevertheless, in pollen zone II, the climate is so dry that the *Ephedra* is principally associated with the moisture. The regional climate is comparatively drier during the pollen zone II depositional period than the depositional period of pollen zone I.

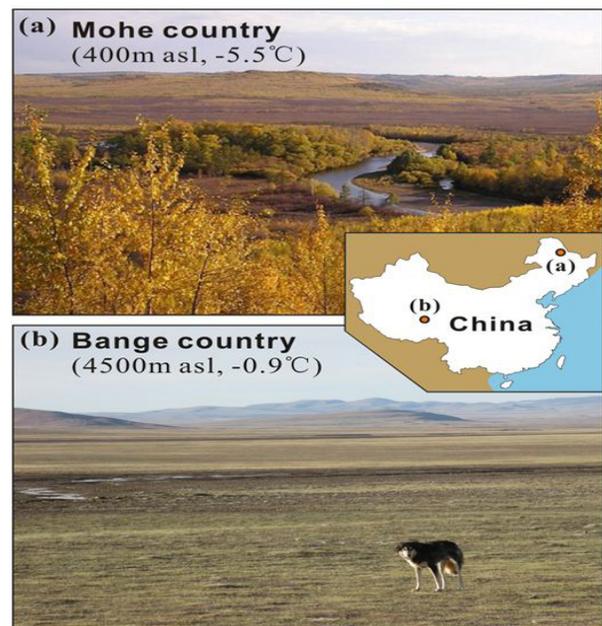
*Nitraria* is one of dominant species in desertified steppe and desert [24]. *Gramineae* is better represented in dry than in moist forest [25], and it is taken as dry climate [26]. *Chenopodiaceae* characterize dry environments [22,27]. *Rosaceae* and *Rosa* are suitable for cool-dry conditions [28]. The *Nitraria*, *Chenopodiaceae*, *Gramineae*, *Rosaceae* and *Rosa* are enriched in pollen zone II (Figure 3), which are indicated that regional climate is comparatively drier during the pollen zone II depositional period than the depositional period of pollen zone I. In brief, climate is comparatively drier during the pollen zone II depositional period than the depositional period of pollen zone I. In the central of Tibetan Plateau, the climate was dried in the middle-late Pleistocene.

### Paleo-altimetry Interpretation

Traditionally, air temperature decline with increasing elevation in free air (lapse rate) is considered the primary factor determining the position and composition of altitude-related vegetation zones [29]. The approaches basing on the correlation of temperature and altitude are applied to the reconstruction of paleo-altimetry [14], such as isotopes [30], atmospheric pressure, enthalpy,  $pCO_2$ , fossils, the  $\delta D$  of leaf-waxes and sporopollen assemblages. However, the practice shows that surface temperatures do not depend simply on elevation. For example, there is no trees grow-

ing in the area higher than 4500m in the central of Tibet, such as the mean annual temperature is about  $-0.9^{\circ}C$  in the Bange county where the elevation is about 4500m (Figure 4). However, multiple species of plant grow in the cold region such as the Mohe country in the Northeast of China. The mean annual temperature is at about  $-5.5^{\circ}C$  in Mohe country where the elevation is only about 400m (Figure 4). Song, et al. [29] suggested that palaeo-elevation can be deduced by enthalpy which is a combination of both temperature and humidity at a constant pressure. In fact, the air pressure is declining with increasing of elevation. The quantitative study of paleo-altimetry would be much more complex than existing research. Up to now, in the study area, there have been no quantitative temperature data (such as  $U^{k'_{37}}$  and TEX86), humidity data and air pressure data in middle-late Pleistocene. In present, the analogy analysis is likely more credible than quantitative estimation of palaeo-elevation which is based on the temperature, humidity and air pressure.

Fossil pollen is almost ubiquitous and this makes it attractive as the basis of a possible palaeoaltimeter. Based on their presumed Nearest Living Relatives, the climate and altitude can be studied through their taxonomic affinity and assumptions about past environmental tolerances [14,29,31]. In the eastern Tibetan Plateau, the distribution of modern pollen assemblages had been well study by [16,32,33], in the altitudinal transect from 1100 to 4500 m (Table 1). Based on previous work, the paleo-elevation of the pollen zone can be semi-quantitatively estimated by its pollen assemblages respectively (Figure 5).

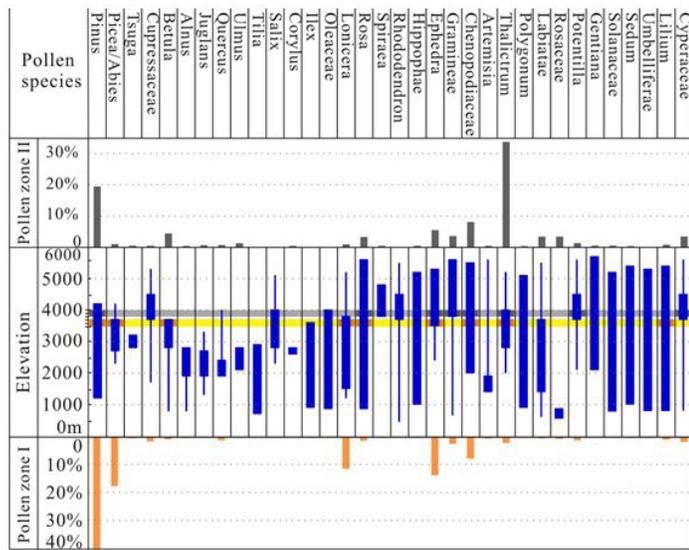


**Figure 4:** The vegetation distribution is not depend simply on elevation, such as the present vegetation landscape in Mohe country is obviously different from it in the Bange country.

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	Pollen/Spore	Content in Pollen zone II(%)	Content in Pollen zone I(%)	Credible upper limit (m)	Maximum reported (m)	Minimum reported (m)	Credible lower limit (m)	References
1	Pinus	19.54	38.63	4200	4200	1200	1200	[29]
2	Picea/Abies	0.97	16.76	3700	4200	2300	2700	[16,29]
3	Tsuga	0.52	0.22	3200	3200	2800	2800	[29]
4	Cupressaceae	0.48	1.32	4500	5300	1700	3700	[16,29]
5	Betula/Carpinus	4.41	0.62	3700	2800	780	2800	[16,29]
6	Alnus	0.38	0.18	2800	2800	780	1900	[29]
7	Juglans	0.66	0.13	2700	3300	1300	1900	[29]
8	Quercus	0.68	0.92	2400	4000	1900	1900	[16,29]
9	Ulmus	1.24	0.04	2800	2800	2100	2100	[29]
10	Tilia	0.02	0.00	2900	2900	700	700	[16,29]
11	Salix	0.05	0.09	4000	5100	2300	2800	[16,29]
12	Corylus	0.43	0.04	2800	2800	2600	2600	[29]
13	Ilex	0.00	0.13	3600	3600	900	900	[29]
14	Oleaceae	0.07	0.00	4000	4000	860	860	[29]
15	Lonicera	0.93	10.78	3800	5200	1200	1500	[29,34]
16	Rosa	3.28	1.10	5600	5600	860	860	[29]
17	Spiraea	0.43	0.09	4800	4800	3800	3800	[29]
18	Rhododendron	0.05	0.00	4500	5490	450	3700	[16,29]
19	Hippophae	0.48	0.13	5200	5200	1000	1000	[29]
20	Ephedra	5.47	13.07	5300	5300	2400	3500	[29,35,36]
21	Gramineae	3.57	2.11	5600	5600	650	3800	[29,37,38]
22	Chenopodiaceae	8.10	7.26	5500	5500	2000	2000	[29]
23	Artemisia	0.43	0.31	1900	5600	1400	1400	[29]
24	Thalictrum	33.88	1.85	4000	5200	2000	2800	[16,29]
25	Polygonum	0.36	0.00	5100	5100	900	900	[29]
26	Labiatae	3.37	0.26	3700	5500	600	1400	[29]
27	Rosaceae	3.39	0.44	860	860	560	560	[29]
28	Potentilla	1.29	0.92	4500	5600	2100	3700	[16,29]
29	Gentiana	0.50	0.04	5700	5700	2100	2100	[29]
30	Solanaceae	0.50	0.04	5200	5200	780	780	[29]
31	Sedum	0.34	0.18	5400	5400	1000	1000	[29]
32	Umbelliferae	0.00	0.13	5300	5300	800	800	[29]
33	Lilium	0.77	0.70	5400	5400	800	800	[29]
34	Cyperaceae	3.42	1.50	4500	5600	800	3700	[12,16,29]

**Table 1:** Modern altitudinal ranges of taxa and the percentage content of taxa in each pollen zone.



**Figure 5:** Plot of altitude ranges of presumed nearest living relatives of pollen taxa recovered from the eastern Tibetan Plateau. The pollen percentages of the pollen zone I and II is coloured with orange and grey respectively. The distribution belt of the pollen zone I and II is expressed with the yellow and grey horizontal bars respectively.

Pollen zone I is dominated by *Pinus* (38.6%, 1200-4200m), *Picea* and *Abies* (16.8%, 2700-3700m), *Ephedra* (13.1%, 2400-5300m), *Lonicera* (10.8%, 1200-5200m), *Chenopodiaceae* (7.3%, 2000-5500m), *Gramineae* (2.1%, 650-5600m), *Thalictrum* (1.9%, 2800-4000m), *Cyperaceae* (1.5%, 3700-4500m), *Cupressaceae* (1.3%, 3700-4500m), *Rosa* (1.1%, 860-5600m) and *Potentilla* (1.0%, 3700-4500m). It is showing that the pollen zone I was mainly came from the belt in the elevation of 3500-3700m. Meanwhile, the pollen zone II is dominated by *Thalictrum* (33.9%), *Pinus* (19.5%), *Chenopodiaceae* (8.1%), *Ephedra* (5.5%), *Betula* (4.4%), *Gramineae* (3.6%), *Labiatae* (3.4%), *Rosaceae* (3.4%), *Cyperaceae* (3.4%), *Potentilla* (1.2%), *Ulmus* (1.2%), *Lonicera* (1.0%) and *Rosa* (1.0%). It is showing that the pollen zone II was mainly came from the belt in the elevation of 3800-4000m.

In the eastern Tibetan Plateau, the subalpine dark coniferous forests are distributed in the belt range from 2800 to 3700 m above the sea level (asl) of Gongga Mountain [16]. The frigid dark coniferous forests are distributed in the belt range from 2800 to 3600 m asl of Gongga Mountain (Li et al., 2009). Mountain dark coniferous forests are mainly distributed in the northern slopes of some mountains at an elevation of about 3100-3500m asl in the southeast and 2800-3800m asl in the northwest of Tibetan Plateau [39]. As mention above, the pollen zone I is mainly deposited in the subalpine dark coniferous forests environment. Hence, it is reasonable that the pollen zone I was mainly came from the belt in the elevation from 3500 to 3700m.

The alpine shrub meadows are distributed at an elevation of about 3700-4000 m asl in Gongga Mountain [16], 3800-4800m asl in the southern slope of mid-Himalaya Mountains [40], above 3800 m in the eastern margin of the Tibetan Plateau [41]. As mention above, the pollen zone I is mainly deposited in the subalpine dark coniferous forests environment. Hence, it is reasonable that the pollen zone I was mainly came from the belt in the elevation of 3800-4000m.

The study of the Zhou, et al. [42] is shows that the elevation of the Plateau surface was raised about 300m, from 4270 to 4570m after the Gonghe Movement. Although the absolute altitude is inconsistency with our study, the rising height of the plateau surface is consistency with ours [42]. Meanwhile, our study is consistency with the paleo-elevation inferred from oxygen isotope of lacustrine deposits in the Kunlun Mountain Pass too. In the Pliocene period, the paleo-elevation was 3426 m from oxygen isotope of marlstone sample collected at 94°03'58"E and 35°38'18"N [43]. In the Pleistocene period, the paleo-elevation was 3773 m from oxygen isotope of marlstone sample collected at 94°05'24"E and 35°38'42"N [43]. The paleo-elevation was 3769 m from oxygen isotope of marlstone sample collected at 94°05'44"E and 35°38'51"N [43]. The elevation of Kunlun Mountain Pass was raised about 340m (from 3430 to 3770m) during the period from Pliocene to Pleistocene [43]. The modern elevation of Kunlun Mountain Pass is approximately 4780m asl. The modern elevation of the study area is approximately 4932m, which is approximately 150m higher than the Kunlun Mountain Pass. Hence, it is reasonable that the elevation of study area was raised about 300m (from 3500-3700m to 3800-4000m) during the middle-late Pleistocene.

### The wind direction interpretation

Usually, air temperature is declining with the increasing elevation. As shown above, the elevation of study area was raised about 300m (from 3500-3700m to 3800-4000m) during the middle-late Pleistocene. It seems to be contrary to the paleo-temperature interpretation that the climate is comparatively cooler during the pollen zone I depositional period than the pollen zone II depositional period. However, in the pollen zone I, part of the pollen (*Cupressaceae*, *Gramineae*, *Cyperaceae* and *Potentilla*) is come from higher altitude, but little is come from the lower altitude localities (Figure 5). It is indicated that the study area was located in the advection wind or down wind direction. In the pollen zone II, the pollen species are not only more numerous than them in Pollen zone I, but also the pollen assemblages in it are more complex. A little pollen (*Potentilla*) is coming from higher altitude localities, while a lot of pollen is come from the lower altitude localities (*Tsuga*, *Alnus*, *Juglans*, *Quercus*, *Ulmus*, *Salix*, *Artemisia*, *Rosaceae*) (Figure 5). It is indicated that the study area was located in the upwind direction. It can be concluded that the wind direc-

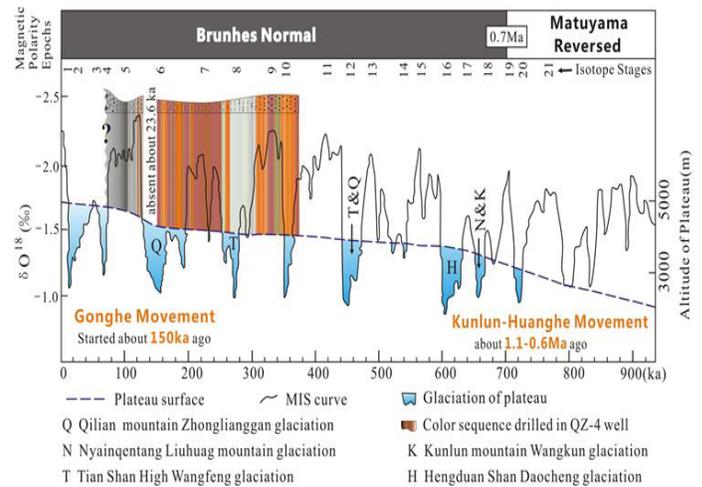
tion in the central of Tibetan Plateau was changed from horizontal or downward direction to upward direction at middle-late Pleistocene. During the pollen zone II depositional period, the pollen may be transported on to the high and relatively cold plateau from lower altitude warm temperate forests by upwelling wind (summer monsoon) [29], which may be resulted the characteristics that the climate is comparatively cooler during the pollen zone I depositional period than the pollen zone II depositional period.

### Influence of the Gonghe Movement

It is known that the hottest period since the middle-Pleistocene was at approximately 120 ka BP both in the southern hemisphere [44,45] and northern hemisphere [6]. Meanwhile the Gonghe movement was started at 150ka BP and persisted for about 50ka [10,11] (Figure 6). Hence, many studies regard the Plateau uplift as a possible driving force for the simultaneous enhancement of East Asian winter and summer monsoons as well as for the Mid-Pleistocene transition occurrence [46,47]. However, some authors suggest that the mid-Pliocene climate changes in East Asia are unlikely to be a response to Plateau uplift [48].

As shown above, the elevation of study area was raised about 300m (from 3500-3700m to 3800-4000m) during the middle-late Pleistocene. As the elevation increased, the temperature would be decreased about 1.8°C calculated with an air temperature gradient of 6K/km. However, the MIS (marine isotope stage) curve shows that the annual temperature raised about 8°C after the Gonghe movement (Figure 3). In the central of Tibetan Plateau, the temperature was slightly elevated in the middle-late Pleistocene. The climate change in the central of Tibetan Plateau was corresponding with the global climate change at the middle-late Pleistocene.

In another face, the paleo-climate during pollen zone I deposition period was comparatively wetter than it during the pollen zone II, which is shown that the barrier effect of Tibetan Plateau to moisture is stronger and stronger with the elevation increasing of Tibetan Plateau. Hence, it can be concluded that the climate change in the central of Tibetan Plateau at the middle-late Pleistocene documented by the well QZ-4 core seems to be mainly driven by global climate change, and that tectonic uplift may have been a subordinate influence.



**Figure 6:** The coupling relationship between the uplift of Tibet Plateau and Quaternary climate evolution (modified from reference Li J. [10]).

### Conclusions

The comprehensive paleo-climate and paleo-altimetry studies of the pollen samples from the well QZ-4, in the centre of Tibetan Plateau, lead to the following conclusions:

- I. In the well QZ-4, the pollen assemblage can obviously divided into two pollen zones. Pollen zone I (251.1-314 m in depth, 120.0-345.8 ka BP.) is characterised by single species and low pollen concentrations. Pollen zone II (200-251.1m in depth, 105.4-120 ka BP.) is characterised by multiple species and high pollen concentrations.
- II. The paleo-climate during pollen zone I was comparatively colder and wetter than it during the pollen zone II.
- III. The palaeo-elevation of pollen zone I is concentrated on the belt in the elevation from 3500 to 3700m. The palaeo-elevation of pollen zone II is mainly come from the belt in the elevation from 3800 to 4000m. The study area had been uplifted about 300m after the Gonghe Movement.
- IV. In the centre of Tibetan Plateau, the wind had changed

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from horizontal or downwelling wind to upwelling wind, in the middle-late Pleistocene.

V. In the central of Tibetan Plateau, the climate change seems to be mainly driven by global climate change, and that tectonic uplift may have been a subordinate influence in the middle-late Pleistocene.

## Highlights

I. The center of Tibetan Plateau uplifted about 300m after Gonghe movement.

II. Barrier effect of Tibetan Plateau to moisture was enhanced after Gonghe movement.

III. Wind changed from horizontal or downwelling to upwelling after Gonghe movement.

IV. Paleo-climate change in Tibetan Plateau is mainly driven by global climate change.

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