

# Impacts of environmental change and human activity on microbial ecosystems on the Tibetan Plateau, NW China

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## ABSTRACT

Microorganisms play important roles in maintaining ecosystem functions. It is poorly known, however, how microbial ecosystems respond to environmental changes and human activities. The purpose of this paper is to demonstrate that the microbial record in lake sediments and ice cores contains a wealth of paleoenvironmental and paleoclimatic information. Saline lakes on the Tibetan Plateau exhibit multiple environmental gradients and have accumulated thick sequences of sediments through time. Microbial abundance and species diversity vary considerably along environmental gradients across the plateau. Studies of lake sediments reveal that wet and warm climates are correlated with high bacterial abundance and diversity, whereas cold and dry climates result in low abundance and diversity. Recent human activities have enhanced sulfate reduction in lake sediments. Ice cores from the plateau reveal that bacterial abundance and diversity are positively correlated with dust particle concentration and temperature.

## INTRODUCTION

Recent research on biological responses to global climate change has focused on animals and plants and their interactions (Pounds et al., 2006; Whitfield et al., 2007). A limited number of studies have shown that, in soils and aquatic systems, microbial community structure, abundance, and activity respond to environmental changes, such as atmospheric CO<sub>2</sub> level, precipitation, temperature, and nitrogen deposition (Bowatte et al., 2008; Horz et al., 2004; W.X. Liu et al., 2009; Van der Gucht et al., 2007; Zak et al., 2000).

Lakes play important roles in the study of the response of microbial ecosystems to climate change and human activity. It has been suggested that the microbial record in lake sediments

is thought to be inappropriate for reconstruction of paleoenvironmental conditions because microorganisms continue to be active after deposition, and their measured abundance and diversity today may not reflect community structure and functions in the past. However, several studies have shown that certain groups of microorganisms preserved in lake sediments, such as phototrophs and aerobes, may be useful in reconstructing recent environmental changes (Coolen et al., 2004a, 2004b, 2006, 2008). These studies are limited to a few geographic locations, and the impacts of climate changes on microbial ecosystems are still poorly understood.

The goal of this paper is to demonstrate that the microbial record preserved in lake sediments and ice cores on the Tibetan Plateau can be a reliable indicator of past environmental change and human activity. We review and compile current literature on microbial response to environmental changes (elevation, water chemistry, mountain topography, UV radiation, salinity, and temperature/precipitation) and human activities (agriculture and eutrophication) recorded in lake sediments of the Tibetan Plateau. Data from ice core records are included to understand the response of microbes to dust storms and changes in temperature. We focus on the Tibetan Plateau because this region underwent dramatic environmental changes in recent geological history. The microbial response to these dramatic changes may be of global significance because understanding the microbial response to past environmental change is a key to predicting the impacts of future climate change on the biosphere.

## CLIMATE EVOLUTION OF THE TIBETAN PLATEAU

The Tibetan Plateau is the largest ( $2 \times 10^6$  km<sup>2</sup>) and highest plateau (average ~4500 meters above sea level [masl]) on Earth. This high elevation results from the Tertiary collision between the Eurasian continent and the India subcontinent. The plateau is bounded by deserts of the Tarim and Qaidam Basins to the north, the Himalayan, Karakoram, and Pamir mountain chains to its south and west, and the Tanggula Mountains on the east.

The Tibetan Plateau lies at a critical and sensitive junction of four climatic systems: the Westerlies, the East Asian Monsoon, the Siberian cold polar airflow, and the India monsoon (Fig. 1). Paleoclimate studies indicate that the last glacial period (late Pleistocene) was terminated by an abrupt warming event at 15 ka (Severinghaus and Brook, 1999). The subsequent transition to the Holocene was characterized by frequent fluctuations between warm and cold phases (Liu et al., 2008; Zhu et al., 2008; X.Q. Liu et al., 2009). The wet and warm climate in the early to mid-Holocene is recorded in lakes and loess deposits worldwide (Liu et al., 2008). The warm temperatures during this period accelerated evaporation and caused many

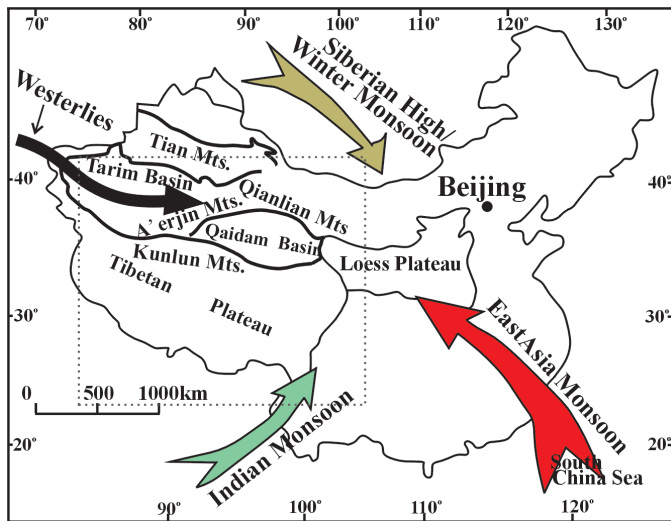


Figure 1. Major climatic systems on the Tibetan Plateau: the Westerlies, the East Asia Monsoon, the cold polar airflow from the Siberian high pressure, and the Indian monsoon. Dashed box shows the location of photo in Fig. 2.

lakes to evolve from open freshwater systems to saline lakes. During the late mid-Holocene to late Holocene, decreased solar insolation led to a cooler and drier climate. More recently, human activities and related regional climate changes have significantly changed the regional hydrology and ecosystem functions of the plateau (H. Wang et al., 2008).

Progressive desiccation since the Holocene has resulted in the formation of thousands of lakes of limited surface inflows and outflows (Fig. 2). The total lake area is  $4.5 \times 10^4 \text{ km}^2$ , and the lakes range in age from 2 to 8 Ma (Zheng and Yao, 2004; Zheng, 1995). Tibetan lakes exhibit multiple environmental gradients, including salinity (0.1 to 426.3 g/L), pH (5.4 to 9.8), and nutrient levels (Zheng, 1995). Because of the high elevation, UV radiation is intense, and changes in light conditions can be extreme

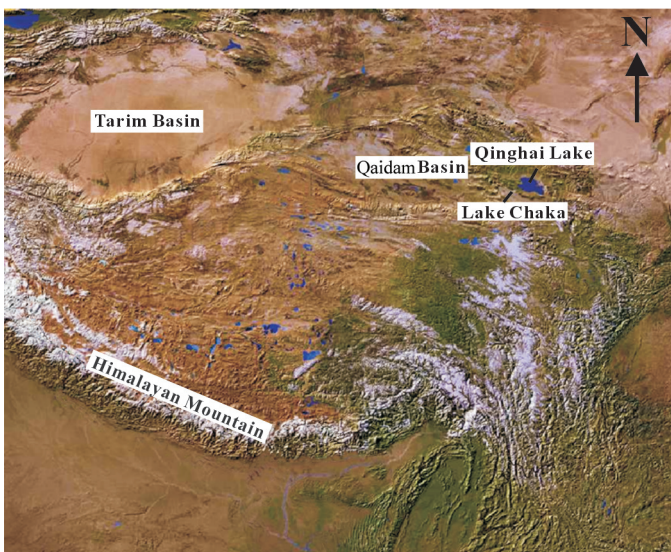


Figure 2. Topography of the Tibetan Plateau and distribution of lakes (in blue). The largest one is Qinghai Lake, with the longest dimension of 106 km.

between ice-covered and ice-free seasons. Many of these lakes have accumulated thick sequences of sediments that provide an archive of climatic change and vegetation succession. Ice core records provide another important means to investigate climatic and environmental changes in the Tibetan Plateau region (Yao et al., 2008, and references therein).

### MICROBIAL RESPONSE TO ENVIRONMENTAL GRADIENTS ON THE TIBETAN PLATEAU

High elevation does not limit the presence and distribution of microbes in lakes (Wu et al., 2006), and many “typical freshwater bacteria” present in low-elevation lakes (Hahn, 2006; Zwart et al., 2002) also occur in Tibetan lakes. Many members of marine benthic groups (MBG-B, -C, and -D archaea) and Miscellaneous Crenarchaeotic Group are present in Qinghai Lake (Jiang et al., 2008). These groups were previously believed to be exclusively present in deep-sea environments, and many are associated with methane gas hydrate deposits (Jiang et al., 2008, and references therein). Jiang et al. (2008) concluded that similar water chemistry between Qinghai Lake and seawater may be responsible for the occurrence of marine archaeal communities in Qinghai Lake. A subsequent study (Jiang et al., 2009) confirms this conclusion, showing that salinity, ionic ratios, and  $\text{Na}^+$  and  $\text{HCO}_3^-$  concentrations are important factors in shaping archaeal community composition. Hydrothermal activity, as suggested by water chemistry (Zheng, 1995), may be partially responsible for the presence of methanogenic and methanotrophic archaea in Tibetan lakes.

Tibetan lakes also harbor unique microbial communities. A total of 343 DNA sequences were compiled from published sources for Tibetan freshwater lakes, 74% of which could not be affiliated with any typical freshwater clusters (Hahn, 2006; Zwart et al., 2002). These sequences are unique to Tibetan lakes and are hereafter defined as “typical Tibetan freshwater bacteria.” They share certain characteristics with those from glacier ice or tundra soils in the Arctic or Antarctic (Y. Liu et al., 2009). The presence of these bacteria may be explained by a combination of geographic isolation and unique environmental conditions on the Tibetan Plateau.

Although elevation does not limit the presence of microbes in lakes, surface topography does control microbial diversity, likely by influencing precipitation patterns. For example, bacterial diversity in multiple lakes on the windward side of the Himalayan Region (Sommaruga and Casamayor, 2009) is higher than that in many lakes on the leeward side (Wu et al., 2006). We hypothesize that the moisture source may be responsible for the observed difference. On the windward side, the moisture source is the Indian monsoon, and favorable climatic and environmental factors (higher temperature, wetter climatic conditions, higher vegetation density and productivity) may lead to a higher diversity of bacteria in lake waters. As moist air rises over the mountains, it condenses and forms precipitation. We suggest that by the time the air moves over the mountains, most microorganisms have been removed by condensation-related particle fall-out, thus accounting for a lower diversity on the leeward side. This hypothesis is consistent with the observations of Yao et al. (2008), who reported that bacterial diversity during the monsoon season was greater than during the non-monsoon season.

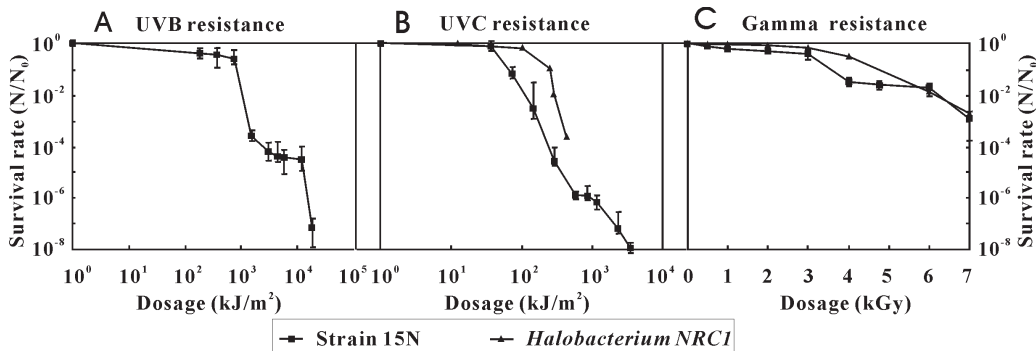


Figure 3. Survival rate of a halophilic bacterium 15N upon exposure to ultraviolet light (A) and comparison of the survival rate between 15N (solid squares) and *Halobacterium* NRC-1 (solid triangles) (B and C). (A) Ultraviolet-B (UVB) (312 nm) radiation. (B) Ultraviolet-C (UVC) (254 nm) radiation. (C)  $^{60}\text{Co}$  gamma radiation. N—number of viable cells after radiation;  $N_0$ —the initial number of viable cells in unirradiated sample. Error bars represent standard errors from duplicate experiments (from Dong, 2008).

Bacterial isolates obtained from Tibetan lakes are either phylogenetically or physiologically unique. Phylogenetically, many of them belong to the “typical Tibetan freshwater bacteria.” Physiologically, isolates exhibit various pigments and higher tolerance to salinity and UV radiation than those from other freshwater lakes, indicating local adaptation of the microbes. Y. Liu et al. (2009) reported that bacterial isolates from Lake Puma Yumco (5030 masl) and glacial melt water (6350 m on the East Rongbuk Glacier, Mount Everest) exhibit a variety of colors.

Despite the phylogenetic similarity of some isolates to common bacteria, they nonetheless possess unique pigments. The ability of these isolates to resist the intense UV radiation present at high elevations suggests that the pigments may provide some protection (Dong, 2008; Dong and Yu, 2007; Jiang et al., 2006). Indeed, a *Bacillus* isolate exhibits a similar level of UV and gamma radiation resistance as *Halobacterium* NRC-1 (Fig. 3), an archaeon known to be extremely resistant to UV and gamma radiation (Baliga et al., 2004; Kottmann et al., 2005).

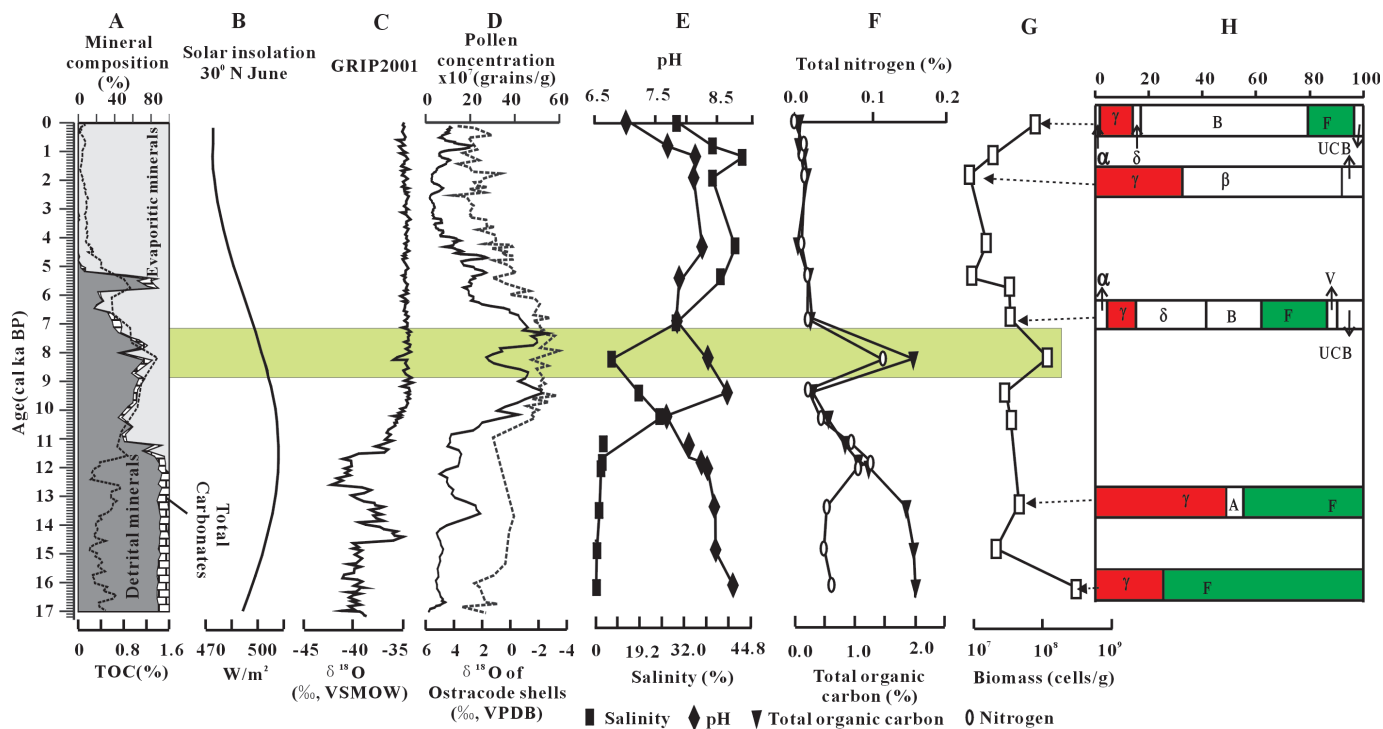


Figure 4. Correlation between paleoclimate indicators and bacteria abundance and diversity recorded in the sediments of Lake Chaka on the Tibetan Plateau. (A) A 9-m (17,000 yr) sediment core with superimposed mineral composition and total organic carbon (TOC) content (Liu et al., 2008). The dark-shaded area near the bottom third of the core represents detrital minerals (quartz, clays, and feldspars), and the light-shaded area near the top represents evaporative minerals (halite and sulfates). (B) Solar insolation at 30°N. (C) The Greenland Ice Core Project (GRIP)  $\delta^{18}\text{O}$  record from Greenland (Johnsen et al., 2001). VSMOW—Vienna standard mean ocean water. (D) Solid and broken lines are pollen concentration (Shen et al., 2005) and  $\delta^{18}\text{O}$  of ostracod shells (Liu et al., 2007), respectively. VPDB—Vienna Pee Dee belemnite. (E) Salinity and pH as measured in pore water by the core. (F) TOC and total nitrogen (TN) contents as measured in bulk sediments. (G) Bacterial abundance as measured by phospholipid fatty acid. (H) Phylogenetic groups of bacteria at five depths:  $\alpha$ —*Alphaproteobacteria*;  $\beta$ —*Betaproteobacteria*;  $\delta$ —*Deltaproteobacteria*;  $\gamma$ —*Gammaproteobacteria*; A—*Actinobacteria*; B—*Bacteroidetes*; F—*Firmicutes*; V—*Verrucomicrobia*; UCB—unclassified bacteria. Figures E, F, G, and H are from Jiang et al. (2007). A wet/warm period at 9 to 7 ka (the gold bar on the diagram) is identified by high TOC/TN/pollen contents, a peak in detrital mineral content, low salinity, and high pH. Bacterial abundance and diversity are highest during this time period.



## MICROBIAL RESPONSE TO PAST ENVIRONMENTAL CHANGES AND HUMAN ACTIVITY

### Climate Change

Using a 9-m sediment core from Lake Chaka, an inland hypersaline lake on the Tibetan Plateau, Jiang et al. (2007) observed that archaeal communities systematically respond to salinity change: The *Crenarchaeota* are predominant in the bottom freshwater sediments of the core, but absent in the salt layers near the top; instead, the halophilic *Halobacteriales* of the *Euryarchaeota* are the most important group in the hypersaline sediments near the top of the core.

Two strategies may be operative for the microbial response to increased salinity—replacement of one taxa by another or gradual adaptation of the same taxa (Jiang et al., 2007). The bacterial community exhibits a similar response pattern as the archaeal community. In addition to the salinity response, the microbes show a response to precipitation and temperature. For example, high bacterial abundance and diversity are correlated with the wet and warm climate in the early to mid-Holocene (9–7 k.y. B.P.; shaded area in Fig. 4), suggesting that enhanced nutrient levels during this period may have stimulated microbial growth and diversification. The presence of DNA sequences of phototrophic organisms (belonging to the *Alphaproteobacteria* in Fig. 4) indicates enhanced productivity, consistent with high total organic carbon (TOC) and total nitrogen (TN) contents in the lake at this time (Fig. 4). The enhancement of sulfate-reducing activity (i.e., the *Deltaproteobacteria* in Fig. 4) indicates water column anoxia, further supporting enhanced weathering and increased nutrient supply to the lake.

### Human Activity

The impacts of combined human activity and climate change are observed in the sediments of Qinghai Lake. We focused on microbial diversity, functional genes, and lipid biomarkers for the top 50 cm of sediments corresponding to 1500 yr of deposition (Dong et al., 2006) (Fig. 5); TOC, TN, pollen concentration, and  $\delta^{13}\text{C}$  of organic matter (Shen et al., 2005) all indicate a high productivity in the lake ~1000 yr ago. High biomass and bacterial diversity characterizes this time period. Unlike the over- and underlying sediment layers, the 1000-year-old sediment contains the *Deltaproteobacteria* (largely sulfate-reducing bacteria) as a major group (Fig. 5) (Dong et al., 2006). Enhancement of sulfate-reducing activity is consistent with high productivity in the lake that led to eutrophication and anoxic conditions.

The 1000-year-old sediments display a greater number of species with an affiliation to phototrophic green, nonsulfur bacteria. Because the light flux in sediment is insignificant, the presence of phototrophic bacteria may correspond to a period when phototrophs were abundant at a certain depth in the water column (Ji et al., 2009), reflecting enhanced productivity. High microbial diversity and activity during this time period is also supported by microarray data, a technique that detects diversity and relative abundance of functional genes in environmental samples. The detected functional genes are mostly related to C, N, and S biogeochemical cycling.

The high productivity in Qinghai Lake at this time may be due to human settlement and climate changes in the region. According to the historical records, the Qinghai Lake region was the governing center of minority groups and was under the influence of the Han ethnic group. In the Han Dynasty, the

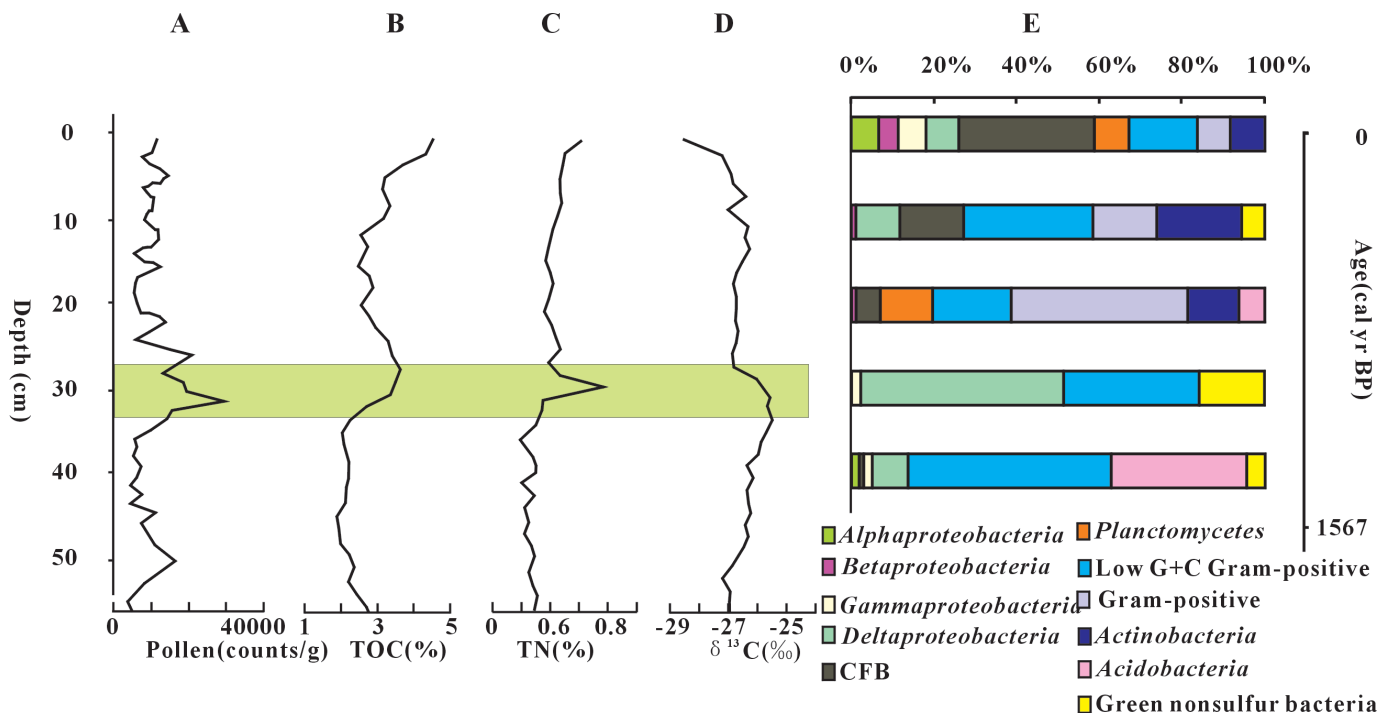


Figure 5. Correlation for a 50-cm sediment core from Qinghai Lake. High total organic carbon (TOC), total nitrogen (TN), pollen contents, and  $\delta^{13}\text{C}$  of organic matter suggest a period of enhanced primary productivity ~1000 years ago. This period corresponds to settlement of the Han ethnic group in the Xihai County near the Qinghai Lake region and a warm period that preceded the Little Ice Age. This enhanced productivity drove the lake to an anoxic condition, resulting in increased sulfate reduction activity (i.e., a large increase in *Deltaproteobacteria* on E). Figures A, B, C, and D are from Shen et al. (2005); the bacterial data are from Dong et al. (2006). CFB—*Cytophaga/Flavobacterium/Bacteroides*; G+C—Low C + C gram positive bacteria, a subgroup of *Firmicutes*.

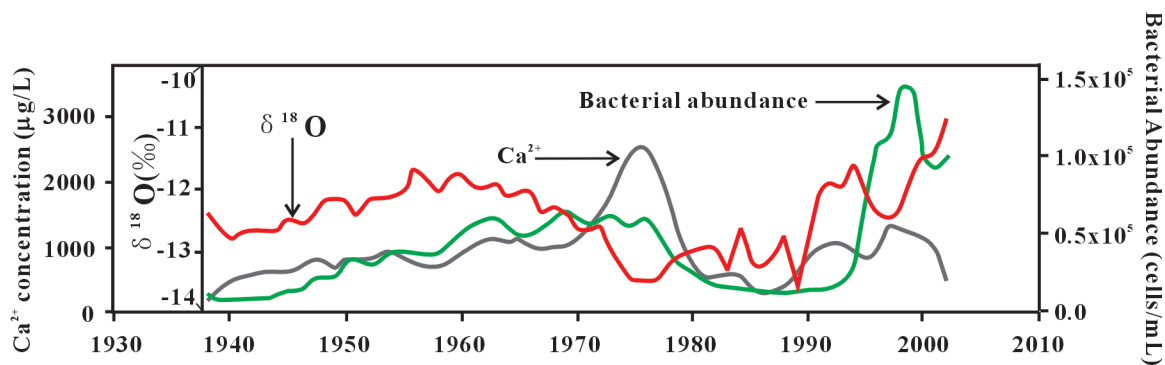


Figure 6. Annual variations of bacterial abundance,  $\text{Ca}^{2+}$  concentration (a proxy for dust particle concentration), and  $\delta^{18}\text{O}$  value of ice (a proxy for temperature) in an ice core from Mount Geladaindong (the summit of the Tanggula Mountains) from 1935 to 2004. The two prominent peaks of bacterial abundance in the middle 1970s and 1990s can be explained by a combination of dust and temperature effects. The highest  $\text{Ca}^{2+}$  concentration (in the middle 1970s) indicates the greatest dust transport of bacteria, but the lowest temperature does not support bacterial growth in ice; thus, the bacterial abundance is only the second highest. In the late 1990s, a combination of high dust content and warm temperature would have transported the greatest amount of bacteria and allowed the greatest amount of growth, thus accounting for the highest bacterial abundance. Data and interpretation are from Yao et al. (2008).

“Xihai County,” now called Sanjiaochen, was 20 km from the northeastern corner of Qinghai Lake (Shen et al., 2005). The development of this population center and related human activities may have resulted in increased nutrient loading into the lake, resulting in eutrophication and enhanced sulfate-reducing activity. This time also corresponds to a warm period that preceded the Little Ice Age. Thus, the combined effects of human activity and climate change may have been responsible for the enhanced primary productivity and sulfate reduction. The subsequent drop in productivity may be explained by a climatic shift to drier and colder conditions (Shen et al., 2005) and a related reduction in the local population.

### Dust Storms

Ice cores provide another record of the microbial response to past environmental change, especially dust storm activity. Past studies demonstrate that bacterial abundance is positively correlated with dust or clastic content (Chu et al., 2009; Xiang et al., 2004, 2005; Zhang et al., 2007). A recent study (Yao et al., 2008) found a positive correlation between bacteria abundance and  $\text{Ca}^{2+}$  concentration in ice cores, a proxy for dust particle concentration, but with certain exceptions (Fig. 6). The exceptions are ascribed to a temperature effect. Bacterial growth can occur before snow densification and transformation into ice (Yao et al., 2008). Strong dust storms and high temperatures therefore appear to provide favorable conditions for bacterial growth on ice sheets and glaciers.

### FUTURE PERSPECTIVES

The results summarized here demonstrate the potential of using the microbial record in lake sediments and ice cores for paleoenvironmental reconstruction. We hypothesize that vertical permeability of lake sediments and the rate of microbial evolution play important roles in determining the time frame over which the microbial record may be preserved in lake sediments and the degree to which this record can reflect past environmental changes. Favorable conditions for paleoenvironmental reconstruction are to be found where vertical mixing of sediments is limited, such as in clay-rich anoxic sediments, and microbial

evolution is slow. Future studies should focus on establishing the quantitative relationships between microbial records and environmental factors over longer time scales.

Anthropogenic lead, methane, ammonium, and organic compounds have been detected in ice cores of the Tibetan Plateau, and their concentrations have been increasing over the last several decades (X.P. Wang et al., 2008). It is unknown how these anthropogenic compounds impact the biosphere, especially with regard to microorganisms. Future endeavors should target specialized functional groups, such as phototrophs, aerobic methanotrophs, Pb-resistant organisms, and ammonia-oxidizing microorganisms. These functional traits may be more responsive to environmental changes (Green et al., 2008).

### CONCLUSIONS

Microbial abundance and diversity respond to environmental gradients in Tibetan lakes. Microbial records in lake sediments and ice cores contain a wealth of information about past climate changes and human activities. In lake sediments, wet and warm climates favor high bacterial abundance and diversity, whereas low bacterial abundance and diversity are correlated with dry and cold environments. Enhanced primary productivity and eutrophication as induced by human activity and warm/wet climates are recognized by elevated levels of sulfate reduction and  $\text{CO}_2$  fixation in lake sediments. Microbial records in ice cores provide a related record of dust storm activity and temperature variation.

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## LETTER

Dear Editor:

After reading Richard P. Palmer's "Letter" in the March issue of *GSA Today*\*, I had to check the cover to make sure I was reading *GSA Today* and not *USA Today*. Mr. Palmer is certainly entitled to his opinion, but his polemic tone, word choice ("Saint Gore," "data rigging," "prostitution") and obvious political bias renders his letter inappropriate for any scientific society's publication. There are more than enough outlets for the shrill opinion, such as blogs, newspapers, talk radio, or street demonstrations.

Perhaps worst of all, *GSA Today*'s publication of a "lifetime" geoscientist's diatribe lends a bit more credibility to the ideology-based criticisms of climate science. Those of us who work in the noisy classroom of science and public policy have enough trouble getting the students to pay attention. There is plenty of room for thoughtful opinion

and discourse, but disruptive shouting serves neither the science nor the students.

So please, *GSA Today*: Give scientific debate and opinion its rightful place, but do not follow the commercial media in giving "equal voice" to fake scientific challenges that are, in reality, angry and emotional yells.

**Rob McDowell**, Ph.D., P.G., Director, Environmental Policy Program, University of Georgia  
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