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EXPRESS LETTER

Controlling factors in stalagmite oxygen isotopic composition and the paleoprecipitation record for the last 1,100 years in Northeast Japan

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Stable oxygen isotopic analysis was performed on the UT-A stalagmite with annual microbanding from the Uchimagi-do Cave in Iwate Prefecture on the Pacific side of Northeast Japan. High-resolution analysis of the uppermost portion of UT-A revealed a positive correlation between the stalagmite δ^{18}O value and R ((summer precipitation–winter precipitation)/annual precipitation) over the last several decades. This correlation is the result of the distinct seasonal shift in precipitation δ^{18}O. During the summer, rainfall with higher δ^{18}O values arrives from the humid atmosphere over the Pacific Ocean. In the winter, comparatively little snowfall/rainfall, with lower δ^{18}O values, arrives from the Japan Sea and is brought by Nangan cyclones (low-pressure systems that pass along the southern coast of Japan). In years with humid summers, large amounts of rainfall from the Pacific Ocean raise the δ^{18}O values of the cave dripwater and stalagmites. Changes in precipitation over the last 1,100 years, reconstructed from the δ^{18}O profile of the UT-A stalagmite, coincide with the historical records of famines and disasters triggered by rainfall excesses and shortages.

Keywords: Northeast Japan, stalagmite δ^{18}O, growth rate, precipitation, famine records

INTRODUCTION

Isotopic records of stalagmites are regarded as excellent archives for terrestrial paleoclimatic information. Stalagmites formed in caves near the anthroposphere may contain records of climatic changes that have directly influenced human activity (e.g., Fairchild *et al*., 2006; McDermott, 2004). Many factors are known to influence stalagmite isotopic composition, and the degree of influence of each factor differs by regional climate setting. Because of climatic variation, it is not a simple matter to associate stalagmite isotopic signals with climate factors in Japan. The East Asian Monsoon (EAM), ocean currents, and continental and oceanic air masses that conflict with one another influence the climate in the Japanese Archipelago, and the archipelago is deeply involved in the broader framework of the Asian climatic system.

Some climatic studies of stalagmites from the western part of Japan and the Japan Sea side have revealed the strong influences of the EAM and the East Asian Winter Monsoon (EAWM) on these areas (Fig. 1a). Shen *et al*. (2010) reconstructed the EAM evolution during the last deglaciation by analyzing a stalagmite from the Maboroshi Cave in Hiroshima Prefecture in western Japan, and they compared their data with data from Chinese stalagmites and Greenland ice cores. Sone *et al.* (2013) reconstructed the EAWM intensity and winter precipitation over the past 10,000 years. They analyzed a stalagmite from the Fukugaguchi Cave in Niigata Prefecture on the Japan Sea side of central Japan, a location that is subjected to heavy winter snowfall. However, the influences of EAM and EAWM in Northeast Japan have not been sufficiently clarified. Climate reconstructions using stalagmites have not been pursued, despite the presence of many limestone caverns along the Pacific side of Northeast Japan. This study was conducted to identify the major controlling factors that determine stalagmite oxygen isotopic compositions in Northeast Japan, through comparison of a high-resolution stalagmite δ^{18}O profile and meteorological observational data for the last several decades. The history of paleoclimatic change and its influence on human activity in this region over the last 1,100 years were reconstructed from a stalagmite δ^{18}O profile.

CLIMATE AT THE STUDY SITE

The Uchimagi-do Cave (40°02′ N, 141°38′ E, 481 m above sea level at the entrance) in Kuji, Iwate Prefecture, Northeast Japan is 16–17 km from the Pacific coast (Fig.

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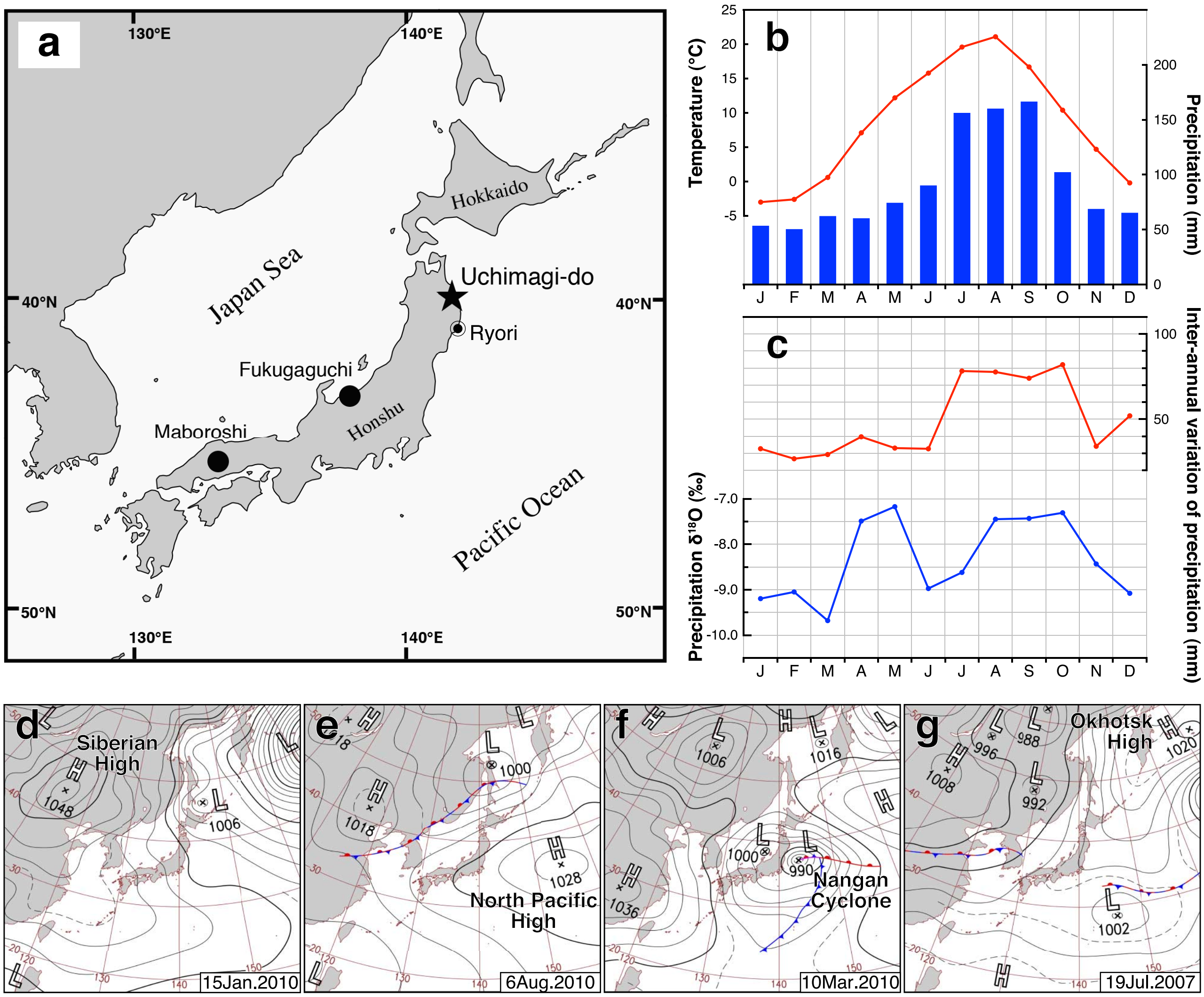

Fig. 1. Map and climatic conditions in the study area. a) Locations of the Uchimagi-do Cave, Ryori, and other caves considered in previous studies. b) Monthly mean temperature (°C) and precipitation (mm) at Yamagata, Kuji from 1981 to 2010. c) Interannual variation in the monthly precipitation (mm) in Yamagata and monthly mean precipitation $\delta^{18}O$ data (‰ VSMOW) at Ryori (Global Network of Isotopes in Precipitation, GIS Global Mapping System for Isotopes in the Water Cycle, International Atomic Energy Agency (http://www.iaea.org/water/)). d) Typical atmospheric pressure pattern in winter. e) Typical atmospheric pressure pattern in summer. f) The pressure pattern when a large amount of snowfall was brought to the Pacific side of Northeast Japan by the Nangan Cyclone. g) Typical atmospheric pressure pattern when the Yamase blows. Note that d), e), f), and g) were modified from daily weather charts provided by the Japan Meteorological Agency (http://www.data.jma.go.jp/fcd/yoho/hibiten/).

1a). The local mean annual rainfall during the period from 1981 to 2010, as recorded at the Yamagata Meteorological Station (AMeDAS Observation System, Japan Meteorological Agency), 13 km north-northeast of the Uchimagi-do Cave, was 1125 mm, and the mean annual temperature was 8.5°C (Fig. 1b). The total precipitation during the four rainy months (July through October) accounts for more than half of the annual precipitation at this location. As the general case in Japan, the precipitation source switches seasonally between the Pacific Ocean and the Japan Sea. From the early summer to the autumn, the temperate and humid North Pacific High (Fig. 1e) delivers the majority of the annual precipitation to the Pacific side of Northeast Japan. During the winter, cold and dry winds blowing out from the Siberian High (Fig. 1d) acquire moisture from the Tsushima Warm Current in the Japan Sea. Most of this moisture is then released as heavy snow/rainfall on the Japan Sea coast, although residual moisture also generates some snow/rainfall on the Pacific side. In addition, appreciable amounts of rainfall and snowfall are often brought to the Pacific side of Japan by Nangan cyclones (low-pressure systems that pass

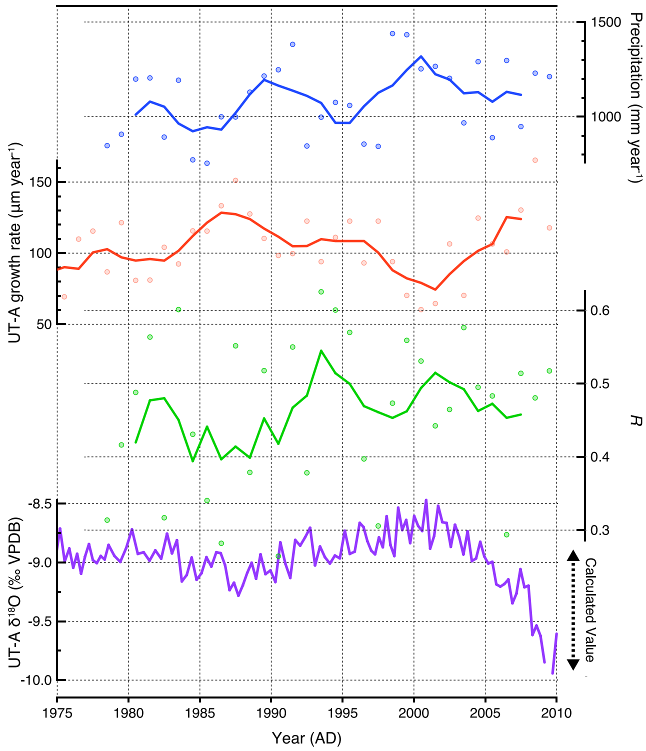

Fig. 2. Comparison of annual precipitation amounts (Yamagata), UT-A growth rate, R, and UT-A δ^{18}O values. Solid lines indicate five-year moving averages of the amount of precipitation, UT-A growth rate, and R. The dotted arrow indicates the calculated δ^{18}O value of calcite to deposit under isotopic equilibrium under modern conditions. The values were calculated using the δ^{18}O values of the dripwater on the UT-A that accumulated in a tank over 3–6 months and the cave temperatures from June 2010 to May 2012. The ranges of these calculated values are consistent with the contemporary UT-A δ^{18}O values.

along the southern coast of Japan) (Fig. 1f). This diversity of precipitation results in seasonal variation in the precipitation δ^{18}O value. This variation is caused by the fractionation process referred to as the "Rayleigh process" (Dansgaard, 1964). This process occurs when water is removed from an atmosphere without a moisture supply and the δ^{18}O of the remaining moisture gets lower as ^{18}O-enriched water molecules are preferentially removed. As a result, the δ^{18}O of subsequent precipitation events are lower than that of the initial precipitation. This fractionation is more conspicuous in cold winter atmospheres that can hold less moisture. In addition, the winter precipitation brought by Nangan cyclones (Fig. 1f) has a very low δ^{18}O value (Inoue *et al.*, 1986). Consequently, the precipitation δ^{18}O value on the Pacific side of Northeast Japan is higher during the spring-autumn period and lower during the winter (Fig. 1c), as rainfall δ^{18}O records collected at Ryori in southeastern Iwate Prefecture confirm (Fig. 1a). The exception is the low δ^{18}O rainfall in June–July, when a stationary "Baiu" front brings a substantial amount of rainfall (e.g., Matsubaya and Kawaraya, 2014; Yabusaki and Tase, 2005). However, the duration of the Baiu season varies each year, and the precipitation in June and July is not completely fed by the Baiu front. Furthermore, within the study region, Yamagata is less affected by Baiu rainfall than is Ryori. The mean monthly rainfall in Ryori in June is 172 mm, which is approximately twice that in Yamagata (90 mm).

From May to August, the Pacific Ocean side of Northeast Japan is often affected by cold and moist northeasterly winds associated with the Okhotsk high-pressure system referred to as Yamase (Fig. 1g). A persistent Yamase, which produces cold and humid summers in the coastal regions, often causes extreme damage to agricultural production and has resulted in severe famines throughout history (Kondo, 1988; Takai *et al.*, 2006).

Materials and Methods

Stable oxygen isotopic analysis was performed on the actively growing UT-A stalagmite from the Uchimagi-do Cave in 2010. The age model was obtained by counting the annual bands, which are clearly observable under a fluorescence microscope (Supplementary Fig. S1). In addition, a detailed analysis of the uppermost part of UT-A was conducted to identify the factors that influence the stable oxygen isotopic composition and stalagmite growth rate. Further information about the UT-A stalagmite, the Uchimagi-do Cave, and the analytical methods used in the study are provided in Supplementary Information.

Results and Discussion

Factors influencing the growth rate and δ^{18}O value of the UT-A stalagmite

Figure 2 shows the changes in growth rate and δ^{18}O value of the UT-A stalagmite, the annual precipitation in the Yamagata district, and the values of *R* ((summer (AMJJASO) precipitation–winter (NDJFM) precipitation)/annual precipitation) from the late 1970s to 2010. The UT-A δ^{18}O value was compared with five-year moving averages because each subsample may extend across several years.

The mean growth rate of the UT-A stalagmite over the last 35 years has been 0.105 mm/year. The time series plot of the growth rate exhibits positive peaks in the late 1980s and a negative trough in the early 2000s followed by an upward shift until the late 2000s (Fig. 2). The growth rate of UT-A correlates negatively with the annual precipitation in the Yamagata district ($r = -0.28$, $p = 0.12$, Fig. 2; Kato *et al.*, 2013), with UT-A growth occurring

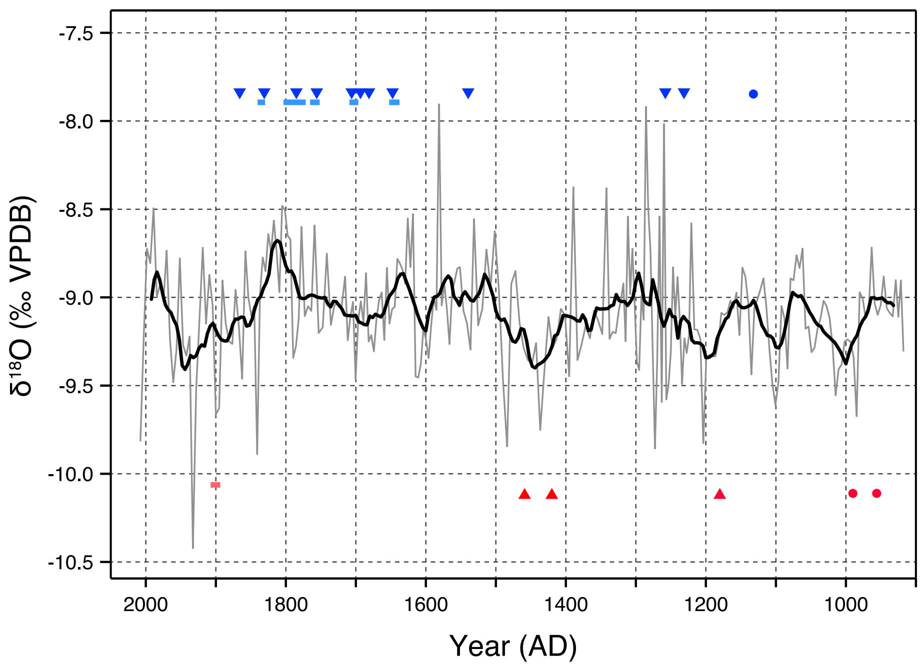

Fig. 3. Comparison of the UT-A $\delta^{18}O$ profile over the last 1,100 years with historical records. The gray solid line indicates raw data points, and the black solid line represents 36-year moving averages. The blue horizontal bars indicate periods with frequent rainy events (more than three years with long or heavy rain or floods recorded in a decade). The red horizontal bar indicates a period with frequent droughts. The blue triangles denote recorded famines with long-lasting rains (the Kanki famine of 1230–1231, the Shoka-Shogen famine of 1258–1260, the Tenbun famine of 1539–1540, the Kan'ei famine of 1640–1642, the Enpo-Tenna famine of 1680–1682, the Genroku famines of 1695–1696 and 1701–1703, the Horeki famine of 1755–1757, the Tenmei famine of 1782–1788, the Tenpo famine of 1833–1839, and the Keio famine of 1866). The red triangles indicate recorded famines due to droughts (the Yowa famine of 1180–1181, the Oei famine of 1420–1421, and the Choroku-Kansho famine of 1459–1461). The circles on the same levels as the triangles indicate older famous famines that could not be confirmed as having been influential in Northeast Japan.

more slowly during periods of heavy precipitation. This relationship is uncommon in comparison to those reported in previous studies from around the world (e.g., Fairchild and Baker, 2012; Kato and Yamada, 2013). Positive correlations between stalagmite growth rates and precipitation amounts have been reported for stalagmites from regions with distinct dry seasons (Baker *et al*., 2007; Cai *et al*., 2010; Holmgren *et al*., 1999; Yadava *et al*., 2004). Except for these examples, which suggest that a shortage of rainfall restricts stalagmite growth, many other studies suggest that stalagmite growth is influenced by the soil CO_2 concentration, which is controlled by the temperature and/or soil moisture (Frisia *et al*., 2003; Genty *et al*., 2001; Proctor *et al*., 2000, 2002; Tan *et al*., 2003). The study region is comparatively humid, and water drips on UT-A continuously throughout the year. Therefore, the amount of precipitation is not the primary factor restricting stalagmite growth. It can be inferred that cloudy weather impedes plant activities such as root respiration and thus that stalagmite growth is reduced by lower CO_2 concentrations in the soil and seepage water.

The time series plot of $\delta^{18}O$ values (–9.94 to –8.47‰ VPDB) exhibits a slightly negative trough in the late 1980s, a broad positive peak through 2000, and then a downward shift until 2010 (Fig. 2). The variation in UT-A $\delta^{18}O$ values cannot be adequately explained by the amount of annual precipitation. The correlation between UT-A $\delta^{18}O$ values and the five-year moving average of the annual precipitation is not very strong ($r = 0.41$, $p = 0.03$, Fig. 2). However, the fluctuation in the UT-A $\delta^{18}O$ value is more strongly correlated with the five-year moving average of R ($r = 0.47$, $p = 0.01$, Fig. 2). The moisture source of precipitation and the precipitation $\delta^{18}O$ value on the Pacific Ocean side of Northeast Japan changes seasonally, as mentioned previously. The positive correlation between R and UT-A $\delta^{18}O$ (Fig. 2) during the period 1980–2010 indicates that the stalagmite $\delta^{18}O$ was largely influenced by the difference between the high $\delta^{18}O$ summer precipitation and the low $\delta^{18}O$ winter precipitation (Fig. 1c). In addition, the interannual variation in the monthly precipitation at the Yamagata AMeDAS station is greater for the July–October period, during which more than half of the annual precipitation occurs (Fig. 1c). The UT-A stalagmite δ^{18}O value is strongly influenced by the amount of summer rainfall during this time. The summer rainfall has a significant positive effect on both the amount of annual precipitation and the UT-A δ^{18}O. Therefore, the amount of annual precipitation and the UT-A δ^{18}O value tend to have been positively correlated. This correlation appears to be the opposite of the "amount effect" used to estimate the historic monsoon activity in many stalagmite paleoclimate studies (e.g., Fleitmann *et al*., 2003; Shen *et al*., 2010; Sone *et al*., 2013; Wan *et al*., 2001).

Comparison of UT-A δ^{18}O and historical records

The plot of δ^{18}O values over the last 1,100 years (–10.42 to –7.91‰ VPDB) fluctuates on decadal-centennial time scales (Fig. 3). As discussed previously, this fluctuation can be attributed to changes in regional precipitation, particularly during the summer. The validity of this assumption was evaluated by comparison with historical records. Many historical records of regional famines and disasters are available. Major events caused by excesses or shortages of rainfall during the growing seasons of agricultural products, such as long or heavy rains or floods and droughts, have been identified. All of the famines identified in this study were confirmed to have influenced Northeast Japan, along with other well-known Japanese great famines, with numerous deaths occurring from starvation (Arakawa *et al*., 1964; Nakajima, 1976; Nihon'yanagi, 1968; Sendai District Meteorological Observatory, 1951). These historical events correspond well to the paleoprecipitation record reconstructed using the δ^{18}O profile of the UT-A stalagmite (Fig. 3). Famines and disasters caused by excess rainfall occurred when the δ^{18}O values were higher, and those caused by too little rainfall occurred when the δ^{18}O values were lower. In particular, during the period from the 16th through early 19th centuries, when the δ^{18}O value remained comparatively high, several major famines occurred intermittently. Note that most of these rainy events were accompanied by cold weather. Although the δ^{18}O values were not very high around 1700 and in the middle of the 19th century, serious famines were triggered by long periods of rain. Maejima and Tagami (1983) examined daily weather records in the official diaries of the Hirosaki Domain, Northeast Japan, that revealed that frequent snowfalls occurred in the periods 1690–1710 and 1820–1840. Lower δ^{18}O values of the UT-A stalagmite during these periods may be attributed to frequent snowfall, in addition to significant quantities of summer rainfall. It is worth stating that the most severe famines, such as the Great Tenmei famine (1782–1788) and the Great Tenpo famine (1833–1839), occurred at times when the δ^{18}O value was at a maximum. Consistency between the UT-A δ^{18}O record and the famine records exists because both the stalagmite δ^{18}O values and crop yields largely reflect summer weather. The agreement between the isotopic record and historical records also demonstrates that changes in the amount of precipitation in Northeast Japan were recorded on a millennial time scale during the formation of the UT-A stalagmite.

CONCLUSIONS

The δ^{18}O value of the UT-A stalagmite in the Uchimagi-do Cave in Northeast Japan has been positively correlated to the values of R ((summer precipitation–winter precipitation)/annual precipitation) over the last several decades. In the study region, the interannual variation in the monthly precipitation is higher in the summer (July–October) and strongly affects the annual precipitation amount. During humid summers, large amounts of rainfall with higher δ^{18}O values enter the soil layers and influence the stalagmite δ^{18}O value. Precipitation changes in the last 1,100 years, reconstructed from the δ^{18}O profile for the UT-A stalagmite, coincide closely with regional historical records. Famines and disasters caused by excess rainfall occurred when the δ^{18}O value shifted higher, and those caused by rainfall deficits occurred during periods of lower δ^{18}O values. The results of this study show that stalagmite δ^{18}O is a good proxy for past precipitation records in Northeast Japan, where stalagmite climatic studies have not advanced adequately, despite the widespread distribution of limestone caverns. Our results also show that the regional precipitation has fluctuated periodically. We are currently in an incremental phase that began in the 20th century. Thus, it may be possible to forecast precipitation changes in the near future based on this periodicity.

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Supplementary Materials

URL (http://www.terrapub.co.jp/journals/GJ/archives/data/50/MS417.pdf)
Figures S1 and S2