CLIMATE AND LAND USE RECORDS FOR CHINA FROM CAVE STALAGMITES AND SATELLITE IMAGES

by

HONGLIN XIAO

(Under the Direction of GEORGE A. BROOK)

ABSTRACT

Stalagmites and satellite images have been used to construct a record of climate and land use/cover changes for China. Grey color, luminescence, $\delta^{18}O$, $\delta^{13}C$, and petrographic studies reveal that there was a progressive weakening of the summer monsoon from 8.5 ka to present and that this was accompanied by an increase in El Niño activity. The climate was relatively constant and La Niña-like conditions were more common prior to 5 ka, but the amplitude of climate fluctuations increased and the frequency of El Niño increased after this. The temperature at northwest China decreased from 146-140 ka and the climate became drier. The research demonstrates the potential of stalagmites to provide detailed paleoenvironmental information for both short and long periods of time. Furthermore, it is clear that suitable stalagmites will allow comparison of Chinese historical records of climate change with proxy records of climate change obtained from stalagmites. This research also indicates that a hybrid unsupervised/supervised classification of satellite data can yield high land use/land cover accuracy in karst terrain.

INDEX WORDS: Karst, El Niño, La Niña, monsoon, environmental change

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DEDICATION

This dissertation is dedicated to my dear wife, Zhi Wang,

my son, Kelvin, and my parents in China.

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TABLE OF CONTENTS

| Page |
|--|
| ACKNOWLEDGEMENTSv |
| CHAPTER |
| 1 INTRODUCTION AND LITERATURE REVIEW1 |
| 2 GMITE RECORD OF HOLOCENE CLIMATE CHANGE IN GUIZHOU, |
| CHINA14 |
| 3 STALAGMITE RECORD FROM SOUTHEASTERN CHINA OF |
| MONSOON AND ENSO ACTIVITY IN THE PERIOD 8-4 KA57 |
| 4 HIGH-RESOLUTION CLIMATE RECORD FOR 146-140 KA FROM A |
| STALAGMITE IN WANXIANG CAVE, GANSU PROVINCE, CHINA90 |
| 5 HUMAN-RELATED ENVIRONMENTAL CHANGE IN GUIZHOU |
| PROVINCE, CHINA, 1991-1998, FROM SATELLITE IMAGES118 |
| 6 CONCLUSIONS |

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

A major concern of scientists today is to unravel global environmental changes due to natural variations in climate and human activities. Turner et al. (1994) argue that human actions rather than natural forces are the source of most contemporary change in the biosphere, while Singh (1996) notes that the major causes of global environmental changes are various anthropogenic activities not only of the present but also of the integrated past. Land-use/land-cover changes are one of the most visible results of humans modifying the terrestrial ecosystem. However, most studies of such changes have been limited to the last 10-30 years, a very short period compared to the history of human activity. So, there is a need for high resolution climate data for the last few thousand years and also for information on land-use/land-cover changes as a result of human activities for the same time period.

Although tree rings, ice cores, corals, and lake sediments can provide highresolution information on climate, none of these data sources can at the same time give a reliable indication of the impact of human activities on the environment. However, cave stalagmites may have the potential to do this. Cave speleothems have proven to be an extremely valuable source of paleoenvironmental data. They can be dated accurately by the ¹⁴C and U-series methods and in many regions ages alone can provide information about past wetter or drier conditions (Brook et al., 1990a, 1996a, 1997, 1999a). In addition, speleothems may contain pollen grains that provide information on past vegetation near the cave (Brook et al., 1990b; Brook and Nickman, 1996b). Speleothem carbonate and fluid inclusion δ^{18} O data (fluid inclusion δ^{18} O is estimated from the δ D value) can provide information on relative and in some cases absolute changes in mean annual temperature near the cave if the speleothem was deposited under conditions of isotopic equilibrium. If equilibrium is maintained between HCO₃⁻ and CO_{2(aq)} the calcite precipitated will be in isotopic equilibrium with the water and variations in ¹⁸O/¹⁶O will depend on climate alone. In this case δ^{18} O may provide information about the temperature when deposition occurred (Hendy, 1971). The stable carbon isotope characteristics of speleothem carbonate can provide information on rainfall characteristics and whether the vegetation near the cave was predominantly C₃ or C₄ (Brook et al. 1990b; Talma and Vogel, 1992).

Many speleothems have annual layers visible under the petrographic microscope (Broecker et al. 1960; Railsback et al. 1994; Brook et al. 1999b) or as luminescent bands when the formation is exposed to UV light (Shopov et al. 1994; Baker et al. 1993). Annual layers in speleothems can provide an annual chronology, and have the potential to provide a high-resolution paleoclimate or paleoenvironmental record (Brook et al., 1992; Baker et al., 1993; Shopov et al., 1994; Tan et al., 1998). In an actively growing stalagmite, the topmost layer is assumed to have formed during the last hydrological year (Railsback et al., 1994). Relationships between stalagmite layer thickness and climate have been noted (Brook et al.1992; Chen 1992; Railsback et al. 1994) while Brook et al. (1999b) have shown that in areas affected by El Niño, annual layer thickness may be a

proxy for ENSO activity. Luminescence originates from soil fulvic and humic acids in the carbonate (Lauritzen et al., 1986). Baker et al. (1996) have also shown clear relationships between luminescence and vegetation characteristics. The thickness of laminae is usually controlled by a number of climatic and hydrological factors (Baker et al., 1998), and in teleconnected areas it may respond to ENSO (Brook, et al, 1999b). In a stalagmite from Drotsky's Cave, Botswana, variations in gray color along the growth axis were found to be a proxy for the amount of aeolian detritus and therefore for the degree of aridity (Railsback et al., 1999).

Study Areas

This study examined caves in three provinces: Guizhou, Guangdong, and Gansu in SW, SE, and NW China respectively. Guizhou's climate is subtropical wet monsoon, that of Guangdong subtropical humid monsoon, and that of Gansu temperate monsoon. Historical records about the study areas can be traced back to several thousand years ago. The climate of all three provinces is influenced by the Asian summer monsoon, one of the most energetic components of the Earth's climate system (Wang et al., 2001). During winter, the continental land mass cools off rapidly, resulting in very low temperatures over central Asia. As cold air accumulates, pressure rises and a huge continental anticyclone develops over Siberia with the Tibetan Plateau forming an effective barrier blocking the southward spread of cold air from the anticyclone. Under the influence of upper air disturbances, cold air from this anticyclone moves southward through China and brings cold and dry air to the study sites. In summer, intense solar heating leads to high temperatures over the Asian land mass heating the air and causing it to rise. This leads to the formation of a semi-permanent low pressure area near the heart of the continent. Warm and moist air from the Indian Ocean and the South China Sea flows into this low pressure area and the study sites experience their summer monsoon season.

There is now substantial evidence to indicate that the Asian monsoon plays an important role in global climate changes such as El Niño. In El Niño years the monsoon is weaker and the subtropical high in the western Pacific Ocean moves southward because of increasing sea surface temperatures (SSTs) in the eastern equatorial Pacific and decreasing SSTs in the equatorial west Pacific. As a result, the belt of monsoon rains stays south of the Yellow River Basin reducing precipitation in Gansu Province but bringing more rainfall to Guizhou and Guangdong provinces (Li et al., 1987; Zhao, 1996). In China this is known as "floods (drought) in the north and drought (floods) in the south" (Ku et al, 1998; Li et al., 1997; Qian and Zhu, 2002). ENSO also affects the winter monsoon in East Asia. During El Niño (La Niña) years the winter monsoon is generally weaker (stronger) resulting in warmer (cooler) winters and cooler (warmer) summers (Li, 1988, 1989, 1990). Gansu Province is drier, and Guizhou and Guangdong are wetter in the fall and winter of El Niño years (Huang and Wu, 1989; Huang et al., 1996; Huang and Zhang, 1997). Guangdong Province is affected by more typhoons in La Niña years than in El Niño years.

Because rainfall in China appears to be linked to ENSO events, climate records may also be proxies for ENSO frequency and intensity. As the ENSO phenomenon, through teleconnections, affects climates in many regions of the world, data on ENSO is of considerable value to scientists studying climate change elsewhere. The data should also resolve whether the Holocene hypsithermal in China was wetter or drier than today and whether it was warmer or colder. Information on climate change will help to interpret the history of human activities in China as these were almost certainly affected by environmental conditions - particularly the magnitude of summer monsoonal rainfall which greatly affects agricultural production.

Study Objectives

Stalagmites have the potential to provide proxy climate data, and because they are impacted by changes in surface characteristics, such as vegetation or even crop type, they also have the potential to provide land use/land cover information. The initial research objectives of this dissertation were to verify that stalagmites could provide highresolution climate records for different regions of China (particularly using annual layers) using historical information in local gazetteers. A second objective was to determine if stalagmites preserved any information on changes in land use at the surface above the caves. During one short field season in China in July-August, 2000 active stalagmites were collected that it was hoped would provide the necessary information – particularly one from Yangzhipo Cave in Guizhou Province. However, laboratory analysis soon revealed that the stalagmites collected were not going to give the kind of information needed by the original objectives despite some indication in the Yangzhipo stalagmite of a record on human activities over the last few hundred years. As a result of this, the original objectives were modified to the following:

1) To determine if satellite images could provide detailed land use change data over the last 10 years or so that could be compared with stalagmite information in the areas mapped.

2) To develop proxy climate records for the Holocene from stalagmites in caves in Guizhou and Guangdong Province and establish conditions during the Holocene hypsithermal interval.

3) To determine if stalagmites can provide information on changes in rainfall and temperature over time, and information on monsoon and ENSO activity.

4) To determine if published summaries from historical records support the climate records derived from stalagmites.

5) To determine if stalagmites of considerable age (e.g. >100 ka) contain high resolution information on decadal or annual changes in climate. To achieve this a stalagmite from Gansu Province dating to the coldest period of marine isotope stage 6 was examined.

Structure of the Dissertation

This dissertation consists of an introduction, four publishable papers, and a conclusion. The introduction (Chapter 1) reviews the overall theme of the study and sets forth the main objectives. The last chapter (Ch. 5) summarizes the findings of the study that are presented in detail in Chapters 2-4. In addition it discusses problems encountered during the research and outlines the significance of the findings for future research along the lines used here.

Chapter 2 presents results from the study of an active stalagmite from Yangzhipo Cave in Guizhou Province, SW China. The stalagmite was first cut in half along the central growth axis. Five samples were drilled at 6 mm intervals in the top 3 cm of the stalagmite for ²¹⁰Pb dating. Ten samples were drilled at intervals from 4.2-17 cm from the

top of the stalagmite for AMS ¹⁴C dating with duplicate samples taken at 5.2 and 17 cm for TIMS U-series dating. As the stalagmite was active at the time of collection, annual layers in the stalagmite were studied. Seventy six samples were drilled at 2.5 mm intervals along the central growth axis for δ ¹³C and δ ¹⁸O analysis using a dental drill, while viewing the stalagmite under a binocular microscope. A series of samples was also taken at intervals of 2 cm along three distinct growth layers at 1.9, 12.8, 16.2 cm to test for isotopic equilibrium deposition following the criteria of Hendy (1971). Variations in petrography, gray color, and luminescence were examined to extract paleoclimatic data. The resulting proxy climate record was compared with other records of regional and global climate change and with published summaries of Chinese historical documents that include information on past climate.

Chapter 3 outlines a study of a 23 cm long and 14-5 cm wide stalagmite from Xianren Cave, Guangdong Province, China. The methodology and study procedures were similar to those described in Chapter 2. The stalagmite was first cut along the central growth axis and after polishing and wetting to enhance color differences one exposed surface was photographed. Six samples were drilled and dated by AMS radiocarbon. Ninety three samples for δ^{13} C and δ^{18} O analysis were drilled along the central growth axis. Samples were taken at 2 mm intervals. A series of samples was also taken at intervals of 2 cm along three distinct growth layers to test for isotopic equilibrium deposition following the criteria of Hendy (1971). Petrography, color intensity, and luminescence were examined. The resulting data provided a proxy record of climate change in the area. As in Chapter 2, results were compared with other published records of climate change.

Chapter 4 outlines information obtained from a stalagmite collected from Wanxiang Cave, Wudu County, Gansu Province. Two samples for TIMS U-series dating were drilled from 2 mm and 115 mm from the top of the stalagmite. Variations in gray color and UV-laser induced luminescence along the central growth axis were measured. Seventy-three samples were drilled for δ^{18} O and δ^{13} C analysis at 2 mm intervals along the central growth axis. The thickness of distinct layers visible in thin section was measured. Relationships between luminescence and δ^{18} O and δ^{13} C, and thickness and δ^{18} O and δ^{13} C, were studied quantitatively. Results were compared with other regional and global climate data for marine isotope stage 6.

In Chapter 5 land use and land cover changes in a part of Guizhou Province were examined over the period 1991-1998. Three Landsat TM scenes, acquired in November 1991, December 1994, and December 1998, were used in the study. Land use/cover was classified into five categories: water, natural vegetation, agricultural, urban or built-up, and barren land. A hybrid unsupervised/supervised method was used in the classification and to map LU/LC at each time slice. The 120 classes were assigned in the original unsupervised classification, and then they were combined into 5 classes. Based on the information obtained from the unsupervised classification, 400 sites, or about 3 from each of the 120 unsupervised classes, were chosen as training sites for the supervised classification. To achieve a higher accuracy, the study area was divided into its four counties and then classified use the same procedure. This yielded a significantly improved classification accuracy. The nature of LU/LC changes was examined and the driving forces for the changes were assessed.

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CHAPTER 2

A STALAGMITE RECORD OF HOLOCENE CLIMATE CHANGE IN GUIZHOU, CHINA¹

¹Xiao, Honglin, Brook, George, and B. Railsback. To be submitted to *Quaternary Research*.

Abstract

An active stalagmite from Yangzhipo Cave in Guizhou Province, SW China, dated by ²¹⁰Pb, AMS ¹⁴C, and TIMS U-series was deposited during the last 8.5 ka. The basal three-quarters of the formation consists of aragonite with a series of narrow calcite layers suggesting generally warm and dry conditions during deposition. The upper onequarter of the formation is calcite indicating a change to a cooler, wetter climate in the area. Overall, the record shows a gradual weakening of the Asian and Indian monsoons during the period of growth. Five calcite layers in the aragonite at ca. 8.1, 6.0, 4.0, 3.0, and 1.5 ka record cooler and wetter intervals of slow deposition when both the Asian and Indian monsoons were weak. δ^{18} O of stalagmite carbonate suggests that both monsoons were stronger 8.5-5.0 ka and that the associated warmer and drier climate correlates with the worldwide "Holocene hypsithermal", which in China occurred from 10-5 ka. La Niña-like conditions may have existed during this interval. From 5 ka to present El Niño activity increased, the Asian monsoon weakened, and Guizhou's climate became wetter and cooler.

Introduction

The Asian monsoon dominates the climate over the Asian continent and its surrounding areas including India, Southeast Asia, and Australia (Yasunari 1991). In El Niño years, the monsoon is weaker, and the subtropical high in the Western Pacific Ocean moves southward because of increasing sea surface temperatures (SSTs) in the eastern equatorial Pacific and decreasing SSTs in the equatorial west Pacific. As a result, the belt of monsoon rains stays south of the Yellow River Basin reducing precipitation in the north but bringing more rainfall to the Yangtze-Huaihe River basin (Li et al., 1987; Zhao, 1996). In China this is known as "floods (drought) in the north and drought (floods) in the south" (Ku et al, 1998; Li et al., 1997; Qian and Zhu, 2002). During El Niño (La Niña) years the Asian winter monsoon is generally weaker (stronger) resulting in warmer (cooler) winters and cooler (warmer) summers (Li, 1988, 1989, 1990). Northern China is drier, and most parts of south China are wetter in the fall and winter of El Niño years (Huang and Wu, 1989; Huang, Fu and Zang, 1996; Huang and Zhang, 1997).

This paper will present evidence from Yangzhipo Cave on changes in monsoon activity and climate in southwest China during the Holocene and will demonstrate relationships with El Niño and La Niña activity.

Study Area

Yangzhipo Cave is in the middle reach of the Yangtze River on the east side of the Yunnan-Guizhou Plateau in southwest China. It is near the village of Gujing 30 km southwest of Guiyang the capital of Guizhou Province (Fig. 1). The 3.6 m high and 4 m wide entrance to the cave is on the slope of a fengcong (peak cluster) karst hill; the cave is 200 m long. Gujing was first settled by Miao people around AD 1850. The land–cover

above the cave is mainly secondary evergreen and deciduous trees. Soils above the cave are mainly red podzolic and yellow calcareous.

The area has a subtropical wet monsoon climate. In the summer rainy season, the East Asian monsoon brings warm, moist air from the South China Sea, and the Indian monsoon may bring rain from the Bay of Bengal (An et al., 2000)(Fig. 2). In the winter dry season, northerly winds bring cold and dry air into the area. Precipitation is affected by the "mei-yu", a quasi-stationary belt of heavy rainfall in May and June (Domrös and Peng, 1988). Mean annual temperature is 15.4°C with the highest mean monthly temperature in July (24.2°C) and the lowest in January (4.9°C). Annual precipitation is 1140 mm with a distinct summer wet season and winter dry season. Almost 80% of annual precipitation falls in the four-month period from May to August. Mean monthly humidity ranges from 74-78%. El Niño (La Niña) leads to weaker (stronger) monsoons and to increased (decreased) rainfall in Guizhou. In La Niña years rainfall comes mainly from the Indian monsoon (Xu et al., 1996). Climatic data for Guiyang (60 years) and Huaqi City, 16 km from Yangzhipo Cave (40 years), indicate that annual precipitation in La Niña years is 10 cm below average and in El Niño years 120 cm above average. Thus, Guizhou is drier during La Niña years and wetter during El Niño years (Table 1).

Methodology

In 1999 an active stalagmite 18.6 cm long and 4-5 cm wide was recovered from 180 m into Yangzhipo Cave. The stalagmite was cut along the central growth axis and after polishing and wetting to enhance color differences and one exposed surface was photographed (Fig. 3A). This photo was scanned at 600 dpi and the gray-scale along the central growth axis was measured in 8-bit format (bright white = 255; black = zero) using image analysis software. Humic and fulvic acids luminesce in stalagmites when exposed to ultraviolet (UV) light, a UV laser was used to measure luminescence along the growth

axis. Humic acids are produced by organic decomposition in the soil while fulvic acids are produced by photosynthesis. One half of the stalagmite was mounted on a Parker Systems 60 cm motorized linear stage and translated under a focused UV laser beam. Humic and fulvic acids can be optically excited using UV radiation and exhibit broad band emission in the blue green region of the spectrum. UV laser excitation at 355 nm was achieved using the frequency tripled emission from a Q-switched Nd:YAG laser. The laser emission was focused on to the stalagmite using a 250 mm focal length lens resulting in beam spot size of 1.8 mm on the stalagmite as determined using a knife-edge technique. Emission from the stalagmite was collected using an optical fiber and spectrally filtered with a center wavelength of 514 nm and a band pass of 80 nm using a Jobin Yvon 0.125 m monochromator. Signal detection was achieved using an Oriel 33741 photo-multiplier tube and data acquisition was implemented using a Stanford Research gated photon counter. The 1 ms gate was delayed 20 ms with respect to laser pulse to minimize the effects of laser scatter. The linear stage translation and synchronized data acquisition was controlled using a microcomputer.

Five samples of ~1g were drilled at 6 mm intervals in the top 3 cm of the stalagmite for ²¹⁰Pb dating at the Skidaway Institute of Oceanography, University of Georgia (Baskaran and Iliffe, 1993). ²¹⁰Pb is derived from the decay of ²²²Rn - a product in the decay chain of ²³⁰Th. It has a half life of 22 years and is useful in dating over about 200 years (Appleby and Oldfield, 1978, 1983; Bradley, 1999). Ten samples of about 150 mg were drilled at intervals from 4.2-17.0 cm from the top of the stalagmite for Accelerator mass spectrometer (AMS) ¹⁴C dating at the University of Georgia with duplicate samples of 100 mg taken at 5.2 and 17.0 cm for thermal ionization mass spectrometry (TIMS) U-series dating (Fig. 3A; Table 2) at the Department of Geology and Geophysics, University of Minnesota. Seventy six samples of about 150 mg were drilled along the central growth axis for δ^{13} C and δ^{18} O analysis. Samples were taken at

2.5 mm intervals using a dental drill while viewing the stalagmite under a binocular microscope. A series of samples was also taken at intervals of 2 cm along three distinct growth layers at 1.9, 12.8, 16.2 cm depth to test for isotopic equilibrium deposition following the criteria of Hendy (1971). δ^{18} O and δ^{13} C of speleothem carbonate were measured in the University of Georgia, Department of Geology, Stable Isotope Laboratory on a Finnegan-MAT 252 mass spectrometer. Thin sections (13 x 5 cm) were prepared from one half of the stalagmite. δ^{13} C and δ^{18} O of aragonite samples were corrected to equivalent calcite values. This entailed subtracting 1.7 ‰ from the carbon values (Romanek et al., 1992) and subtracting 1.0 ‰ from the oxygen values (Grossman and Ku, 1986) of material that was 100% aragonite.

Chronology

TIMS U-series ages of 3273 ± 29 and 8348 ± 29 years were obtained for samples from 5.2 and 17.0 cm from the top of the stalagmite. These were assumed to be accurate calendar year ages given high 230 Th/ 232 Th ratios indicating little or no 230 Th contamination and no evidence of re-crystallization (Table 2). Libby AMS 14 C ages for duplicate samples were 3877 ± 28 and 7928 ± 40 BP (Table 3). By varying the percentage of old carbon in the AMS samples by increments of 1% from 1-20% and then calibrating each age using OXCAL v. 3.5 we determined that the sample from 5.2 cm had to be corrected for 10% old carbon (-800 years) for the calibrated AMS age (3265 years) to match the U-series age (3273 years). The sample from 17 cm had to be corrected for 6% old carbon (-500 years) for the ages to match (AMS = 8315 years; TIMS = 8348 years). A greater correction indicates that more of the carbon in the stalagmite was derived from the bedrock and less from soil CO₂. This might result from more intense rainfall and more rapid flow to the cave giving waters less time to dissolve soil CO₂. When rainfall is less intense waters have more time to dissolve limestone while still in contact with soil

19

 CO_2 and so they may contain less old carbon from the bedrock. $\delta^{18}O$ of stalagmite carbonate can also provide evidence about rainfall amount and intensity with low values generally indicating increased rainfall (Bar-Matthews et al., 1996). As we shall see later, $\delta^{18}O$ of the stalagmite was consistently lower prior to about 5 ka and much higher after this date suggesting increased rainfall and thus more rapid flow to the cave after 5 ka. Because of this the Libby AMS ages younger than 5000 were corrected for 10% old carbon and ages older than 5 ka for 6% old carbon (Table 3).

²¹⁰Pb dating of four samples in the upper 3 cm of the stalagmite indicates a deposition rate of 0.31 mm/yr. Thin section analysis revealed 125 distinct layers in the upper 4.1 cm of the stalagmite which if annual indicates a deposition rate of 0.32 mm/yr, almost identical to that estimated by ²¹⁰Pb dating (Figs. 3C, 4). As the Yangzhipo stalagmite was collected in December 1999 the topmost layer was laid down in this year.

The various ages indicate that the stalagmite was deposited from ca. 8.5 ka to the present and that there were several periods of slow or no growth and even erosion.

Results

<u>Petrography, color and luminescence</u>

The basal three quarters of the stalagmite is aragonite with a number of prominent, dark, calcite bands (Fig. 3B); the upper part of the formation is mainly calcite (Fig. 3D). In areas of calcite, crystals are 0.02-0.10 mm wide and elongated along the growth axis with euhedral or nearly flat terminations. Aragonite areas have botryoids of needles with curved upper surfaces, and the botryoids are usually clustered together. Most botryoids are 1-3mm across but occasionally range up to 7.5 mm across. Aragonite botryoids and individual aragonite needles are well defined as are boundaries between calcite and aragonite. The calcite is primary with no evidence of recrystallization from

aragonite. Detrital grains in the calcite suggest heavier rainfall during the time of calcite deposition.

Gray color varies from 42-218 averaging 171 (black = 0; white = 255). The upper calcite section averages 102 and the aragonite 195. Luminescence ranges from 80-780, and averages 381. Luminescence averages 173 in the upper calcite zone and 456 in the aragonite (Fig 5 A&B). Variations in luminescence may be a proxy for changes in climate that influence productivity in the overlying soil and plant cover (Shopov, et al., 1994; Lauritzen, et al., 1986). The light color of aragonite areas indicates an absence of humic acids, luminescence being due to colorless fulvic acids. As humic acids are more difficult to leach from the soil, and are quickly broken down by bacteria into fulvic acids in a warm environment, their presence in the calcite is a strong indication of much heavier rainfall and a cooler climate at times of calcite deposition. Color differences between the calcite and aragonite may also be due to the more porous nature of the aragonite and the presence of detrial grains in the calcite.

Aragonite is precipitated rather than calcite when Mg/Ca molar ratios are high (Gonzalez and Lohmann, 1988; Folk, 1994; Morse et al., 1997) possibly in excess of ~1.0 (Denniston et al., 2000). Also, Mg-calcite or high-Mg-calcite is more likely when carbonate precipitation rates are high (Denniston et al., 2000). Higher temperature and evaporation often lead to increased Mg/Ca ratios (Folk, 1994; Deleuze and Brantley, 1997; Gonzalez and Lohmann, 1988; Bar-Matthews et al., 1991; Railsback et al., 1994). At Yangzhipo the wettest month is June, but the highest monthly temperatures are in July and August. As a result, the cave is very dry in the late summer to fall. Sixty years of data for the Yangzhipo area show that July-December rainfall in El Niño years (weak monsoon) is 66 cm higher than normal and in La Niña years (strong monsoon) is 12 cm below normal. Therefore, the drier and warmer conditions associated with La Niña years and a strong monsoon, are more favorable to the deposition of aragonite.

Growth was fairly rapid in the aragonite sections of the stalagmite, at 0.21mm/year from 12.5-18.6 cm, 0.11mm/year from 10.8 to 12.5 cm, and 0.07mm/year from 5.3 to 8.2cm. It was also rapid (3.1 mm/yr) in the upper 4 cm calcite zone. Periods of slow or no growth characterize the intervals separating these periods of rapid growth. Growth rate is a function of drip water supersaturation (Chernov, 1984; Morse and Mackenzie, 1990) and the supply of CO₂ (Denniston et al, 2000). At Yangzhipo, stalagmite growth is likely to be more rapid during warmer, drier summers which may be La Niña years or years with a strong monsoon. In these years soil CO₂ is higher because of the higher temperatures, water flows through the soil relatively slowly having time to equilibrate with soil CO₂, so that upon reaching the cave the water is close to saturation with respect to both calcite and dolomite. Because of high CO₂ in the water relative to the cave, degassing is rapid and leads to drip water supersaturation and rapid deposition of carbonate. By contrast, during El Niño years, or in other years with a weak monsoon, lower summer temperatures lead to lower soil CO₂, and increased rainfall results in the more rapid flow of water to the cave. As a result drainage waters do not pick up as much biogenic CO₂ from the soil and so degassing does not always supersaturate drip waters leading to less deposition of carbonate in the cave.

Stable Isotopes

 δ^{13} C of stalagmite carbonate may record variations in the C₃/C₄ composition of vegetation above the cave and also the amount of carbon derived from the atmosphere, soil, and bedrock. δ^{18} O of stalagmite carbonate can provide information on drip water temperature if deposition was in isotopic equilibrium with precipitating waters, and if the δ^{18} O of these waters is known. If deposition is not in isotopic equilibrium then kinetic effects including rapid degassing of CO₂ and evaporation lead to higher δ^{18} O and δ^{13} C. We tested for isotopic equilibrium by examining variations in δ^{18} O and δ^{13} C along three

growth layers using the criteria of Hendy (1971). δ^{18} O remains essentially constant along layers 1.9 and 16.8 cm from the top of the stalagmite but increases gradually in the layer 12.6 cm from the top. There is no significant correlation between δ^{13} C and δ^{18} O in any of the three layers suggesting that the stalagmite was deposited in isotopic equilibrium with precipitating waters and that variations in δ^{18} O may provide climate data for the Yangzhipo Cave area (Fig. 6).

Dissolved carbon in the seepage waters that deposit speleothems is derived from three main sources: the atmosphere, organic matter and respired CO₂ in the soil, and the carbonate bedrock. δ^{13} C is mainly controlled by δ^{13} C of soil air. Normally, C₃ plants and respired CO₂ have an average δ^{13} C of - 27‰, whereas the average for C₄ plants is -13‰ (Cerling, 1984). Because of different atomic weights, ¹²CO₂ and ¹³CO₂ diffuse from the soil to the atmosphere at different rates, so that soil CO₂ is isotopically heavier than soil organic matter and respired CO₂ (Brook, 1999). Under a C₃ biomass, the first speleothem calcite deposited in isotopic equilibrium with seepage waters is likely to have a δ^{13} C in the range –12 to –9 ‰, depending on whether open or closed system conditions prevailed. Beneath a C₄ biomass, δ^{13} C of calcite will be in the range –2.3 to +1.5‰ again with higher values for closed system solution. Under non-equilibrium conditions and at temperatures <20°C, δ^{13} C will be higher (Brook, 1999).

Along the growth axis of the stalagmite.¹³C varied within the narrow range -4‰ to -9‰ averaging -6.5‰ (Fig. 5C). This implies a vegetation with about 50% C₃ and 50% C₄ plants. Higher δ^{13} C up to about -4‰ was observed in calcite layers that mark slow growth possibly due to much wetter conditions and undersaturated dripwaters. Faster flow and/or an increase in C₄ plants would explain such changes. The increase in δ^{13} C might result from a change to wetter conditions with more intense rains leading to an increase in the proportion of carbon from bedrock rather than from soil CO₂. Human activities above the cave may also have affected δ^{13} C. Forest declined during the mid- to

late Holocene in China has been ascribed to human activities rather than climate change (Ren, 2000). If the forest cover on the hill slopes above Yangzhipo Cave was removed this would lead to higher δ^{13} C which could explain some high values in the stalagmite record. In fact, the lowest δ^{13} C values (~ -8.8‰) occur from AD 1400-1875, which corresponds fairly well with the period of the Little Ice Age from about 1470 to 1890 AD (Lamb, 1972; Zhu, 1973). Values between -9 and -8‰ suggest a higher percentage of C₃ plants either because of cooler temperatures and more effective rainfall, or because the natural forest was allowed to grow back.

 δ^{18} O of drip water is influenced by temperature (higher at lower temperatures) and by amount and intensity of rainfall, as well as by distance from moisture source (increasing rainout) with increases in all three being accompanied by isotopically lighter drip water (Dansgaard 1964). δ^{18} O ranged from -7.5% to -11.2%, and averaged -9.7% (Fig. 5D). δ^{18} O of precipitation in China is affected by moisture source and distance from it (Zheng et al., 1983). In southern China δ^{18} O is lower in areas receiving substantial rainfall from the Indian monsoon. This moisture comes from the Bay of Bengal and so travels a greater distance than moisture from the South China Sea, and so is isotopically lighter due to greater rainout (Cai et al., 2001). As more of Guizhou's rainfall comes from the Indian monsoon when the monsoons are strong, as in La Niña years, the δ^{18} O of rainfall in these years is lower than during an average year or during an El Niño year when the monsoons are much weaker. From 1983-1998 the mean δ^{18} O of precipitation at Guiyang, Zunyi (100 km from Yangzhipo cave), Chengdu City, Wuhan City and Guilin City, mainly brought by the Asian monsoon, was -6.32‰ (Global Network of Isotopes in Precipitation (GNIP); <http://isohis.iaea.org/>). By contrast, the mean δ^{18} O of rainfall at Kunming City, receiving mainly Indian monsoon rainfall, was -10.4‰ from 1986-1991 (Hodell et al.,1999). These data indicate that in southern and southwest China lower $\delta^{18}O$ indicates precipitation from both the Indian and East Asian monsoons during a year with

strong monsoon conditions. In weak monsoon years, sometimes El Niño years, the Indian summer monsoon is too weak to bring precipitation to Guizhou, and so rainfall derives largely from the East Asian monsoon leading to higher δ^{18} O. The average δ^{18} O in the El Niño years 1986 and 1987 was -6.01‰; it was 0.7‰ lower (-6.71‰) in the La Niña year 1988 (GNIP).

A negative relationship between δ^{18} O of precipitation and monthly temperature is also apparent in the GNIP data for the Guizhou region (Fig. 7). At Guilin 250 km from Yangzhipo cave δ^{18} O is lower when global temperatures increase and the summer monsoon is stronger (La Niña years)(Qing et al., 2000). At Shihua Cave 50 km south of Beijing a weak monsoon brings ¹⁸O-depleted rainfall because of rainout in the Yangtze-Huaihe River region before it moves north, whereas a strong monsoon moves rapidly northwards, suffers less rainout, and so brings precipitation with higher δ^{18} O to Beijing (Tan et al., 1998). In Beijing the difference in δ^{18} O between a strong summer monsoon (1979) and a weak summer monsoon (1980) was 2.8‰.

As deposition of the Yangzhipo stalagmite appears to have been in isotopic equilibrium, we have used the equation of O'Neil et al.(1975) in our analysis:

$$T = 16.9 - 4.38 (\delta^{18}O_c - \delta^{18}O_w) + 0.10 (\delta^{18}O_c - \delta^{18}O_w)$$

where T = temperature in 0 C, δ^{18} O_c = δ^{18} O (PDB) of the stalagmite carbonate, and δ^{18} O_w = δ^{18} O (SMOW) of precipitating dripwater. If we assume no change in δ^{18} O_w during deposition of the stalagmite, this implies that the temperature ca. 8 ka (δ^{18} O_c = -11‰ PDB) was about 12⁰C warmer than today (δ^{18} O_c = -8‰ PDB). This figure is clearly far too large and indicates that δ^{18} O_w was much lower in the early Holocene. Unfortunately, we do not know the δ^{18} O_w of the dripwater that precipitated the most recent layers of the stalagmite but we can estimate this using the temperature of the cave as the dripwater temperature (15.4^oC) and the δ^{18} O_w of -7.7‰ SMOW. Assuming that the temperature

was 2^oC warmer than today 8-6 ka (e.g. Zhu, 1973; Shi et al., 1992; Wang et al., 2001), a $\delta^{18}O_c$ of -11‰ translates to a dripwater $\delta^{18}O_w$ of -10.9‰ SMOW. The implication of these calculations is that during the mid-to late Holocene dripwater $\delta^{18}O_w$ was much lower than today presumably because of strong monsoonal conditions and the dominance of La Niña-like conditions. After ca. 5 ka dripwater $\delta^{18}O_w$ clearly increased as the monsoon weakened and temperatures rose.

Discussion of Results

The Yangzhipo Cave stalagmite was not deposited at a constant rate over the last 8.5 ka. In fact, sample ages clearly indicate several periods of slow growth, no growth, or even erosion. Despite this, petrographic, color, luminescence and isotopic data reveal significant, broad-scale changes in climate during the mid- to late Holocene. Deposition of aragonite in the basal three quarters of the stalagmite suggests warmer and drier conditions with high Mg/Ca molar ratios. Colder, wetter conditions and lower Mg/Ca ratios are implied after about 3 ka because of the change to calcite deposition on the stalagmite. A change in climate to cooler, wetter conditions is also indicated by the isotopic evidence. Prior to ca. 5 ka δ^{13} C was never less than about -6.5% but subsequently reached almost -9‰ around 0.6 ka indicating a higher percentage of C₃ plants due to increased rainfall and/or reduced temperatures. At the same time there was a gradual increase in δ^{18} O that we believe records the gradual weakening of the East Asian and Indian monsoons. When the monsoons are strong a large amount of late summer rainfall at Yangzhipo is brought by the Indian monsoon and because this moisture travels a long distance from the Bay of Bengal it is much more depleted in ¹⁸O than rainfall brought a much shorter distance by the Asian monsoon. This translates into lower δ^{18} O of stalagmite carbonate and suggests stronger monsoons prior to about 5 ka with steady, long-term weakening to the present. Weaker monsoons bring lower temperatures and

increased precipitation to southern China and lower temperatures and decreased precipitation to the north of China. Lower temperatures and higher rainfall from the Asian monsoon in the south result in isotopically heavier rainfall and stalagmite carbonate, an increase in C_3 vegetation, and the precipitation of calcite rather than aragonite.

The five calcite layers in the aragonite of the lower three quarters of the stalagmite at ca. 8.1, 6.0, 4.0, 3.0, and 1.9 ka may record cooler and wetter intervals of slow deposition when the Asian and Indian monsoons were weak - a condition that brings increased precipitation to southern China because the front of moist, tropical air stalls in this region. Importantly, these periods with weak monsoonal conditions correspond well with evidence from the Arabian Sea of weak monsoon conditions at ca. 8.2, 5.8, 4.4, 3.3, and 1.7 ka (Gupta et al., 2003)(Fig. 8).

The data also show that color and luminescence are inversely related to δ^{13} C and δ^{18} O. As color darkens and luminescence decreases δ^{13} C and δ^{18} O increase. Together these changes suggest increased rainfall (higher δ^{18} O), the dilution of organic acids in the cave drip waters (reduced luminescence), the incorporation of detrital grains and some humic acid because of intense rains and cooler temperatures (darker colors), and the reduced importance of soil CO₂ in the solution process because of the rapid percolation of water to the cave (higher δ^{13} C). As stronger monsoons and warmer, drier conditions in south China are typical of La Niña conditions, and weaker monsoons with cooler, wetter El Niño conditions, changes in climate recorded by the Yangzhipo stalagmite suggest a change from predominately La Niña-like conditions prior to about 5 ka to a higher frequency of El Niño events after this date.

The Yangzhipo Cave Data in Regional Context

During the early to mid-Holocene radiation over the northern hemisphere was 5-18% higher in July and 8% lower in January than it is today (Joussaume et al., 1999; COHMAP, 2000). As a result, summer temperatures were 2-4^oC higher than at present in Eurasia. After 9 ka these seasonal radiation extremes decreased towards modern values but summer temperatures remained $2-4^{\circ}$ C higher until ~ 6 ka. The resulting increased land-sea temperature contrast enhanced low-level convergence into monsoon flow over subtropical Africa, China and northern India. Precipitation increases over northern India correlate with warmer temperatures over Central Asia (Joussaume et al, 1999). The increased summer insolation enhanced the Asian summer monsoon between 9-6 ka and it became weaker afterwards (Winkler and Wang, 1993; Liu et al., 2000). A stalagmite from Qixing Cave in Guizhou Province, about 100 km from Yangzhipo, reveals that the summer monsoon reached its maximum strength from 7.7-5.8 ka (Cai et al., 2001). The summer monsoon weakened from 5.8-3.8 ka and continued to lose strength from 3.0-0.15 ka the change being accompanied by high amplitude climate fluctuations. The Yangzhipo data suggesting strong summer monsoons prior to about 5 ka with steady weakening afterwards agree well with the Qixing evidence. An et al. (2000) compared the East Asian monsoon index (difference in sea-level pressure between 160° and 110° E longitude at 25-50⁰N latitude) and the Indian monsoon index (difference in sea-level pressure between ocean and land within the region 45° to 120° E longitude and 45° N to 15° S latitude) over the past 15 ka with climate model simulations for July using CCMO, and with solar radiation anomalies (Prell and Kutzbach, 1987)(Fig. 9A). The δ^{18} O record for Yangzhipo shows an inverse correlation with these indices with sharp changes in the curve at 6 and 3 ka corresponding with sharp changes in the Indian monsoon index at these times (Fig. 9B).

Studies in different parts of China indicate that the Holocene hypsithermal lasted from ca. 8.5-3.0 ka and that temperatures dropped afterwards (Zhuo, 2000; Chun et al., 2000; Liu et al., 1992). During the Holocene hypsithermal temperatures were 3-4^oC higher than today in Beijing (Zhang et al., 1981), 2-4^oC higher in the East China Sea and the lower reaches of the Yangtze River (Meng et al., 1989), 2⁰C higher in Zhenjiang (Xu, 1989), 4-6°C higher in some areas of Tibet (Wang et al., 1981), and 1-2°C higher on the Yunnan Plateau (Walker, 1986). Pollen records from Tibet reveal that from 8-5 ka both January and July temperatures were 2-3^oC higher than now (Tang et al., 2000). After 5 ka temperatures decreased linearly and steppe vegetation began to degenerate. Based on Chinese historical writings and archaeological artifacts, Chu (1973) has shown that temperature in China decreased from 5 ka to present (Fig. 10B). Warmer and drier conditions prior to 5 ka are confirmed by the deposition of 18 O-depleted aragonite on the Yangzhipo stalagmite, while cooler and wetter conditions are indicated after 5 ka by ¹⁸Oenriched calcite. If δ^{18} O of stalagmite carbonate is a proxy for changes in temperature, which is reasonable given that deposition appears to have been under isotopic equilibrium, the timing and magnitude of temperature variations in the Yangzhipo record closely match changes suggested by Chu's (1973) findings (Fig. 10A). Pollen records from Guizhou, the Pearl River Delta, Gushantun, East Hebei and Jianhu Lake have been used to reconstruct temperatures during the last 10 ka (Wang et al., 2001). The results indicate that conditions were warmer than present (Holocene hypsithermal?) from 8.5-3 ka with temperatures throughout China 2°C higher than now 5.6-6 ka and ca. 7 ka. The δ^{18} O record of the Yangzhipo stalagmite appears to support these findings (Fig. 10C).

China was warmer and drier in the south during the hypsithermal (3-8 ka) and warmer and wetter in the north (Shi, 1992; Shi and Zhang, 1996). After 3 ka the north became cooler and drier and the south cooler and wetter. Based on saline lake, loess and glacial evidence, Ji (1996) found that in NW China the hypsithermal from 9/8.5-3.5/3 ka
was warmer and wetter leading to the spread of forests and steppe vegetation. From 3.5/3 ka to present, glaciers advanced, deserts expanded, the rate of loess deposition increased, and temperatures dropped. Conditions were more arid ca. 6.0, 5.1 and 3.8 ka with maximum aridity during the Holocene being recorded at Lake Sumxi at 3.8 ka (Lamb 1981, p135, quoting Zhang and Gong, 1987). Chun et al.(2000) found a marked decline in the Neolithic culture in the Guanzhong basin due to aridity from 6-5 ka based on lake level, pollen, and loess/paleosol evidence. Wei et al.(1999) report maximum drying of lakes in NW China during the Holocene at 3.5 ka. Pollen records from the southern part of Liaoning Province in northern China indicate that the climate became progressively warmer from 8-5 ka with the mean annual temperature 3-5°C higher than now (Guiyang Institute of Geochemistry, 1978). From 5-2.5 ka the climate became more arid and colder and afterwards even colder but more humid. In the loess area of China a strong summer monsoon brings warm and moist air to the region and soils are formed with a high magnetic susceptibility. When the summer monsoon is weak accumulated loess has a low magnetic susceptibility (Zhou and An, 1994; An et al., 1991,1993; Kukla et al., 1988). Paleosol complexes dating to 10-5 ka indicate that the Holocene climatic optimum was warm and moist while more recent deposits indicate cooler and drier conditions (Zhou and An, 1994). The loess magnetic susceptibility and Yangzhipo stalagmite records are in broad agreement on climatic changes over the last 10 ka (Ji, 1996) (Fig. 10E).

Each dark band in the stalagmite corresponds to a peak in δ^{13} C and δ^{18} O, which suggests that the dark bands record much wetter and cooler conditions in the Guizhou area. An et al. (2000) suggest that the precipitation peak shifted to southern China ~ 3 ka. This may correspond to the dark band at 3 ka in the stalagmite. The calcite layer dating to 3.3-1.8 ka corresponds to the colder interval, which was 2^oC lower than at 5.0 ka (Zhang, and Gong, 1987). At this time the temperature in Europe was 1^oC lower than the postglacial maximum and 0.5^oC lower in SW North America, corresponding to the interval separating the sub-Boreal and sub-Atlantic periods from 3-2 ka (Lamb 1981, p135, quoting Zhang and Gong, 1987). There were several periods of rapid deforestation in the Guilin area of southwest China at 6.1, 4.2, 2.2, and 1.3 ka, and at AD 1790, the first possibly due to climate change but the others possibly related to human activities (Qing, et al. 2000). Calcite layers in the Yangzhipo stalagmite may record both natural and human-induced changes at the surface.

The sharp increase in δ^{18} O and decreases in δ^{13} C, luminescence, and gray scale color around 5 ka indicate a dramatic climatic change at that time. Records from elsewhere also record a major change at this time. Otolith records from Peru indicate that summer SSTs were 3-4^oC warmer than present around 5 ka and that upwelling of the Peru-Chile current intensified (Andrus et al., 2002). The modern El Niño periodicity was established about 5 ka (Rodbell et al., 1999). Coral records from the tropical western Pacific reveal a generally warmer climate 7-4 ka (Gagan et al., 1998). Geoarchaeological evidence from Peru also indicates a permanent warm period from 8.4-5.25 ka, so La Niña-likeconditions may have dominated this period (Sandweiss et al, 1996, 1999). An increase in the frequency of El Niño after ~5 ka is also indicated by data from Lauana Pallcacocha, southern Ecuador (Moy et al, 2002). Ice core records from Huascaran, Peru (Thompson et al., 1995) suggest that the climate was warmest from 8.4 -5.2 ka and cooled gradually afterwards. There was a period of glacier activity beginning after ca. 5.7 ka in New Zealand (Gellatly et al., 1998).

Conclusions

The stalagmite data indicate a progressive weakening of the summer monsoon from 8.5 ka to present, and hence increased ENSO activity. δ^{18} O combined with δ^{13} C, luminescence, and petrographic studies reveal that the Asian summer monsoon was strong from ~ 8.5 to ~5 ka and Guizhou experienced warmer and drier conditions. La Niña-like years were more common during this period. From about 5 ka to present the Asian summer monsoon become weaker and Guizhou experienced wetter and cooler conditions, and the frequency of El Niño increased. The climate was relatively constant before 5 ka, but the amplitude of fluctuations increased from then on. Periods with a stronger Asian monsoon bringing warmer and drier conditions to SW China occurred around 8.5-8.1, 5.8-5.2, 3.4-3.2, 2.4, and 0.7 ka. Periods of cooler, wetter climate when the Asian monsoon was weaker occurred around 8.0-6.0, 5.0-3.4, 3.2-2.4, and 2.4 to 0.7 ka. Throughout most of the record vegetation was a mixture of C₃ and C₄ plants although a slight, long-term decrease in δ^{13} C of stalagmite carbonate may indicate a slight increase in C₃ plants since 5 ka.

Weak Asian and Indian monsoon intervals with cooler and wetter climatic conditions at ca. 8.1, 6.0, 4.0, 3.0, and 1.9 ka from Yangzhipo Cave correspond well with evidence from the Arabian Sea of weak monsoon conditions at ca. 8.2, 5.8, 4.4, 3.3, and 1.7 ka (Gupta et al., 2003).

This study of a stalagmite from Guizhou Province in China suggests that stalagmites from this region may provide a high-resolution record of climate change for the last several thousand years. Because rainfall in Guizhou appears to be linked to ENSO events, with La Niña bringing decreased monsoonal rainfall, and El Niño bringing increased rainfall, climate records developed from stalagmite data may also be a proxy for ENSO frequency and intensity.

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Fig. 2.1. Monsoons affecting china's climate and the location of Yangzhipo Cave.



Fig. 2.2. Precipitation and temperature of Yangzhipo Cave, Guizhou Province, China.

The top of stalagmit



Fig. 2.3. Characteristics of a 18.6 cm long stalagmite from Yangzhipo Cave, Guizhou Province, China. A. Half of the stalagmite. The letter A-I indicate the sample sites for age dating; letter X,Y, and Z indicate the locations for pictures in B; number 1, 2, and 3 indicate the locations for pictures in C. B. Calcite layer at site Z in A; Dark calcite layer for site X in A; Dark layer for site Y in A. C. Annual layers visible at site 1, 2, and 3 in A. Annual layers average 0.327 mm in thickness. Darker colors likely reflect wetter climatic conditions. D. Areas of calcite and aragonite growth represents cooler and wetter climatic conditions.



Fig. 2.4. Pb210 Activity versus distance from top curve.



Fig. 2.5. Records from a stalagmite at Yangzhipo Cave, Guizhou province, China. The dotted lines in C and D are original isotope values for calcite and aragonite, solid lines show equivalent calcite values for aragonite deposits.



Distance along layer from the central growth axis (mm)

Fig. 2.6. Test of isotopic equilibrium along single layers at Yangzhipo Cave. A. The relationship between δ^{18} O and δ^{13} C (‰ PDB) along single layers 12.6 (A1), 16.8 (A2), and 1.9(A3) cm from the top. B. δ^{18} O along layers 12.6, 16.8 and 1.9 cm from the top.



 $\delta^{18}\text{O}$ o/___, SMOW

Fig. 2.7. Relationship between annual temperature and $\delta^{18}O$ for stations in the Yangzhipo Cave area.

Ages (calendar years)



Fig. 2.8. Color and δ^{18} O variations in the Yangzhipo stalagmite compared with variations in G. bulloids percentage in Arabian Sea core 723A (After Gupta, et al., 2003).

Time $(10^3 \text{ astronomical yr ago})$



Fig. 2.9. Comparison between variations in solar radiation (Δ S) and the E. Asian and Indian monsoon indices (A) and δ^{18} O in the Yangzhipo stalagmite (B). The E. Asian index is the difference of sea level pressure between 160^o and 110^oE Longitude along 25-50^oN Latitude and the tropical Indian monsoon index is the difference of sea level pressure between ocean and land within region 45^o to 12^oE Longitude and 45^o to 15^oS Latitude (Δ M(hPa).(Prell and Kutzbach, 1987; recited from Fig. 15 in An et al's paper, 2000)



Fig. 2.10. Comparison between the Yangzhipo stalagmite record and records from other sources. A. δ¹⁸O in Yangzhiipo Stalagmite.
B. Temperature over the past 5000 years from Chinese History (Chu, 1972). C. Temperature for the Holocene based on pollen from 10 regions, including Guizhou, Pearl River Delta, etc. in China (Wang, et al., 2001). D. Magnetic susceptibility from Chinese loess (after An, et al., 1991b; recited from Ji, 1996).

El Niño years June-July difference from La Niña years June-July difference from mean (mm) mean (mm) 1923 82.3 1924 -117.5 1925 100.1 1928 171.8 1930 251 1931 33.8 1932 140.1 1938 149 1940 -238.4 1942 -54 1946 234.7 1944 -54 1951 190.8 1945 -82.3 1953 724 1949 248.1 1957 -25 1954 -251.9 1963 261.6 1964 78 1965 -164.4 1970 112.3 1969 120.6 1973 -35.1 1972 235.6 1975 63.4 1976 312.7 1988 -385.6 1998 1977 -136.4 -1.8 1982 23 Average -14.1 1986 211.6 1991 -64.1 1992 120.8 1993 141.8 1997 41.3 Average +121.3

Table 2.1 Departure of annual rainfall in El Niño and La Niña years from the long-term average at Guiyang City (1921-1998) (after Kiladis and Diaz(1989) and http://www.coaps.fsu.edu/lib/elninolinks)

| Sample Number | ²³⁸ U (ppb) | ²³² Th (ppt) | δ^{234} U* (measured) | ²³⁰ Th/ ²³⁸ U (activity) | ²³⁰ Th Age (Ka)** (uncorrected) | ²³⁰ Th Age (Ka) (corrected) | $\delta^{234} U_{initial}^{**}$ (corrected) |
|------------------|---------------------------|----------------------------|------------------------------|---|--|--|---|
| YAN99-1 | 11183±21 | 31630±310 | 507.0±1.2 | 0.04530±0.00014 | 3327±11 | 3273±29 | 511.7±1.2 |
| YAN99-2 | 10621±21 | 10469±75 | 584.4±1.6 | 0.11736±0.00035 | 8366±27 | 8348±29 | 598.3±1.7 |

Table 2.2 TIMS uranium-series data and ages.

 $\lambda_{230} = 9.1577 \ x \ 10^{\text{-6}} \ y^{\text{-1}}, \ \lambda_{234} = 2.8263 \ x \ 10^{\text{-6}} \ y^{\text{-1}}, \ \lambda_{238} = 1.55125 \ x \ 10^{\text{-10}} \ y^{\text{-1}}.$

 $\delta^{234}U = ([^{234}U/^{238}U]_{activity} - 1)x1000.$

** The error on the age in 2σ

*** δ^{234} U_{initial} was calculated based on ²³⁰Th age (T), i.e., δ^{234} U_{initial} = δ^{234} U_{measured} xe^{8234xT}.

Corrected ²³⁰Th ages assume the initial ²³⁰Th/²³²Th atomic ratio of $4.4\pm2.2\times10^{-6}$. Those are the values for a material at secular equilibrium, with the crustal ²³²Th/²³⁸U value of 3.8. The errors are arbitrarily assumed to be 50%.

| Sample ID | Distance From Top (cm) | Applied Dilution Factor (%) | δ ¹³ C (‰) | Libby Age | СРМ | Calibrated Age BC or AD +/- 2 sigma | Calibrated Age wrt Today## |
|---------------|------------------------------|-----------------------------------|--------------------------|-----------|------|---|----------------------------------|
| Yangzhipo14 | 4.2 | 90 | -6.12 | 1344±39 | 497 | 1480-1390 AD | 565 |
| UGAMS99 | 4.7 | 90 | -8.82 | 2469±28 | 1623 | 540-340 | 2440 |
| UGAMS100** | 5.2 | 90 | -6.66 | 3877±28 | 3037 | 1410-1120 | 3265 |
| UGAMS101 | 7.4 | 90 | -6.5 | 4004±39 | 3158 | 1520-1370 | 3445 |
| UGAMS127 | 8.3 | 94 | -4.7 | 5024±42 | 4527 | 3370-3090 | 5230 |
| Yangzhipo36 | 10 | 94 | -6 | 5619±39 | 5122 | 3990-3790 | 5890 |
| Yangzhipo45 | 10.8 | 94 | -6 | 7851±48 | 7345 | 6270-6070 | 8170 |
| Yangzhipo52 | 12.6 | 94 | -6.26 | 7835±55 | 7338 | 6260-6060 | 8160 |
| Yangzhipo54 | 13 | 94 | -6.17 | 7908±41 | 7422 | 6400-6200 | 8300 |
| Yangzhipo69** | 17 | 94 | -6.26 | 7928±40 | 7431 | 6410-6220 | 8315 |
| Yan99-1* | 5.2 | | | | | 3273±29 | 3273±29 |
| Yan99-2* | 13 | | | | | 8348±29 | 8348±29 |

Table 2.3 AMS radiocarbon and TIMS U-series ages for the Yangzhipo stalagmite.

*Yan99-1 and 99-1 are ²³⁰Th ages.

* Yangzhipo 21 and 69 both have TIMS and AMS ages and are used to obtain the old carbon correction factor.

AMS ages calibrated using OXCAL program.

Ages calibrated by applied 90% dilution to samples prior 5000, and 94% dilution after that date.

CHAPTER 3

STALAGMITE RECORD FROM SOUTHEASTERN CHINA OF MONSOON AND ENSO ACTIVITY IN THE PERIOD 8-4 ${\rm KA}^1$

¹Xiao, Honglin and G.A. Brook. To be submitted to *Geochimica et Cosmochimica Acta*.

Abstract

A 4000-year record of monsoon and ENSO activity has been constructed from a 23 cm long stalagmite from Xianren Cave in Guangdong Province, China. δ^{18} O and δ^{13} C of stalagmite carbonate increase gradually towards the top of the formation, while the gray color and luminescence decrease. Data indicate that the Asian monsoon became weaker and the climate of China slightly cooler and wetter from 8-4 ka. From 8 to ~5 ka the East Asian summer monsoon was strong and temperatures higher. La Niña-like conditions and typhoons were more active during this time and southern China received less but more intense precipitation. This period was also the warmest in the entire record. Starting at ~5 ka the strength of the East Asian summer monsoon decreased gradually and temperatures dropped. ENSO activity increased and southern China received more precipitation. This long-term trend in climate was punctuated by several relatively short intervals at ~6, 5, 4.5 and 4 ka when the climate was cooler and wetter, the monsoon weaker.

Introduction

The Asian summer monsoon is one of the most energetic components of the Earth's climate system. Its seasonal variability dominates the climate over the Asian continent and surrounding areas including India, Southeast Asia, and Australia (Yasunari, 1991). In addition, there is increasing evidence to indicate that the strength of the Asian monsoon is intimately linked to El Niño activity. In El Niño years, the monsoon is weaker, and the subtropical high in the Western Pacific Ocean moves southward because of increasing SSTs in the eastern equatorial Pacific and decreasing sea surface temperatures (SSTs) in the western equatorial Pacific. As a result, the belt of monsoon rains stays south of the Yellow (Huang He) River basin reducing precipitation in the north but bringing more rainfall to the Yangtze-Huaihe River basin (Li et al., 1987; Zhao, 1996). In China this is known as "floods (drought) in the north and drought (floods) in the south" (Ku and Li, 1998; Li et al., 1997; Qian and Zhu, 2002). ENSO also affects the winter monsoon in East Asia. During El Niño (La Niña) years the winter monsoon is generally weaker (stronger) resulting in warmer (cooler) winters and cooler(warmer) summers (Li, 1988, 1989, 1990). Northern China is drier, and most parts of south China are wetter in the fall and winter of El Niño years (Huang and Wu, 1989; Huang, Fu and Zang, 1996; Huang and Zhang, 1997). In addition, the mei-yu or 'plum rains' which normally occur in May are delayed in the middle and lower reaches of the Yangtze River basin. In El Niño years the number of typhoons, which form in the northwestern Pacific Ocean and the South China Sea, is reduced as well as the number of typhoon landings in China. The number of typhoons forming in the western Pacific and landing in Guangdong and Guangxi Province is above average in La Niña years (Li, 1997).

Natural disasters caused by extreme variations in the Asian monsoon have led to economic losses totaling 3-6% of GDP and have caused several thousand deaths annually over the past ten years. Sustained damage and loss of life is increasing due to population and economic growth. There is an urgent need for more information on the East Asian monsoon. The past history of the monsoon is important in understanding what brings about changes in monsoon activity and the severity and regional extent of these changes (An et al., 2000). To better understand the frequency, magnitude and causes of changes in the monsoon, we need a long and detailed record for the past. This paper presents climate data obtained from a stalagmite in Xianren Cave (Fairy Cave) in Guangdong Province, SE China. The stalagmite has provided information on monsoon and ENSO activity for the period 8-4 ka.

Study Area

Xianren Cave is located in Yangshan county in northern Guangdong Province (Fig. 1). It is about 200 meters long and has numerous active and fossil speleothems. The climate is subtropical humid monsoon (Fig. 2) and it is affected strongly by the East Asian monsoon. In summer, this monsoon brings warm and moist air from the South China Sea and the Indian Ocean (http://www.xinhuanet.com) to this area during the rainy season, which lasts from April to September. In the winter dry season northerly winds bring in cold and dry air. Precipitation at Xianren Cave is also affected by the "mei-yu" (plum rains) system, which is a quasi-stationary belt of heavy rainfall in March and June (Domrös and Peng, 1988). Annual precipitation is 1983 mm with more than 81% falling in the six months April-September, and more than 50% in the four months June-September. The period from July to September is the typhoon season ordinarily accompanied by heavy rains and widespread destruction. Mean annual temperature at Xianren Cave is 21.7^oC. The highest average monthly temperature (38.7^oC) is in July and the lowest (0⁰C) is in January. Average monthly humidity ranges from 67-85%. Xianren Cave is about 150 km from the Pacific Ocean and is one of the first areas to receive summer monsoon rainfall moving in from the South China Sea. Since the East Asian monsoon is closely associated with the global circulation system, especially with ENSO activity, Xianren Cave is ideally located for studying the frequency and magnitude of the East Asian monsoon.

Today El Niño (La Niña) leads to a weaker (stronger) monsoon and to increased (decreased) rainfall in Guangdong Province. Thus, the Xianren Cave area is drier during La Niña years, and wetter in El Niño years. Climatic data (40 years) from Hong Kong to the south indicate that in La Niña years annual precipitation is 406 mm lower than in El Niño years and 130 mm below average. By contrast, annual precipitation in El Niño years is 276 mm above normal (Global Network of Isotopes in Precipitation (GNIP); <http://isohis.iaea.org/>). Climatic data for Hong Kong indicate that 7 of the 10 wettest years in the last 5 decades were El Niño years, namely 1957, 1972, 1973, 1982, 1983, 1994 and 1997 (http://www.info.gov.hk/hko/wxinfo/news/pre1012e.htm).

Methodology

In 2000 a stalagmite 23 cm long and 14-15 cm wide was recovered from Xianren Cave. The stalagmite that was active when collected was cut along the central growth axis and after polishing and wetting to enhance color differences one exposed surface was photographed (Fig. 3A). The photograph was scanned at 600 dpi and gray-scale along the central growth axis was measured in 8-bit format (bright white = 255; black = zero) using image analysis software. As humic and fulvic acids in stalagmites luminesce when exposed to ultraviolet (UV) light we used a UV laser to measure variations in luminescence along the growth axis. Humic acids are produced by organic decomposition in the soil while fulvic acids are produced by photosynthesis. One half of the stalagmite was mounted on a Parker Systems 60 cm motorized linear stage and translated under a focused UV laser beam. Humic and fulvic acids can be optically excited using UV

radiation and exhibit broad band emission in the blue green region of the spectrum. UV laser excitation at 355 nm was achieved using the frequency tripled emission from a Q-switched Nd:YAG laser. The laser emission was focused on to the stalagmite using a 250 mm focal length lens resulting in beam spot size of 1.8 mm on the stalagmite as determined using a knife-edge technique. Emission from the stalagmite was collected using an optical fiber and_spectrally filtered with a center wavelength of 514 nm and a band pass of 80 nm using a Jobin Yvon 0.125 m monochromator. Signal detection was achieved using an Oriel 33741 photo-multiplier tube and data acquisition was implemented using a Stanford Research gated photon counter. The 1 ms gate was delayed 20 ms with respect to laser pulse to minimize the effects of laser scatter. The linear stage translation and synchronized data acquisition was controlled using a microcomputer.

To establish a chronology for the stalagmite six samples were drilled for AMS radiocarbon dating at 8, 93, 114, 130, 158, and 212 mm from the top of the formation (Table 1). Ninety three samples of about 150 mg were drilled along the central growth axis for δ^{13} C and δ^{18} O analysis. Samples were taken at 2 mm intervals using a dental drill, while viewing the stalagmite under a binocular microscope. A series of samples was also taken at intervals of 2 cm along two distinct growth layers at 7.9 and 13.5 cm from the top to test for isotopic equilibrium deposition using criteria outlined by Hendy (1971). δ^{18} O and δ^{13} C of speleothem carbonate were measured in the University of Georgia, Department of Geology, Stable Isotope Laboratory on a Finnegan-MAT 252 mass spectrometer. Thin sections (13 x 5 cm) were prepared from one half of the stalagmite.

Chronology

AMS ages for stalagmite carbonate were corrected for the presence of old, dead carbon derived from the bedrock above the cave before the ages were calibrated. Several studies have shown that stalagmites contain about 15% dead carbon so that ages were

corrected by subtracting 1200 years before calibration (e.g. Franke and Geyh, 1971; Cooke and Verhagen, 1977; Hennig et al., 1980). Calibrated AMS ages indicate continuous deposition from about 8-4ka (Fig. 4; Table 1). As the formation was active when collected it is clear that deposition began only recently after a lengthy hiatus since 4 ka. The stalagmite did not deposit at a constant rate increasing toward the top of the stalagmite. Based on the calibrated ages, the deposition rate is nonlinear and is approximated by the equation:

Age (years) =
$$4251 + 4.67X - 0.066X^2 + 0.0005X^3$$

where X = the distance from the top (mm) measured along the central growth axis. This equation was used to estimate ages for samples taken from the stalagmite.

An important concern about the calibrated AMS ages is that if the content of old carbon in the stalagmite is more or less than 15% this would significantly change the calibrated ages used. For example, old carbon in a stalagmite from Yangzhipo Cave in Guizhou Province contained 6-10% old carbon requiring corrections of -490 to -840 years respectively. If old carbon percentages in the Xianren stalagmite are similar to those in the Yangzhipo formation, the corrected Libby ages quoted could be from 360-710 years too young.

Results

Petrography, color and luminescence

The stalagmite is mainly calcite with no evidence of recrystallization from aragonite or evidence of growth hiatuses. Calcite crystals are elongated along the growth axis, 0.08-2.12 mm wide with euhedral or nearly flat terminations. Calcite crystals usually have a block shape with diameter greater at the top of the stalagmite than at the bottom. Detrital grains are present particularly in darker calcite deposits.

The color of the stalagmite becomes darker from the base (gray color 228) towards the top (gray color 195) averaging 208. There are two prominent dark bands at 150-130mm (gray color 152) and 70-60mm (gray color 187) (Fig 3A).Darker color is believed to reflect the increased presence of humic acid. Luminescence varies from 59-767 averaging 370 (Fig. 3B). Changes in luminescence may be a proxy for climate changes that influence productivity in the overlying soil and plant cover (Shopov, et al., 1994; Lauritzen, et al., 1986). A darker color is an indication of humic acids or organic detrital grains. Light colored areas indicate an absence of humic acids, luminescence being due to colorless fulvic acids.

The growth rate of the stalagmite varies over time being ~0.02 mm/yr prior to 5 ka and 0.11mm/yr thereafter. Growth rate is a function of drip water supersaturation (Chernov, 1984; Morse and Mackenzie, 1990) and the supply of CO₂ (Denniston et al, 2000). At Xianren Cave stalagmite growth may be slower when summer rainfall is more intense such as during La Niña years when typhoons bring above-average rainfall to the area. During heavy downpours the water flows rapidly through the soil and underlying limestone and into the cave. The shear volume of water means that it picks up little soil CO₂ and is undersaturated when it reaches the cave. With low levels of CO₂, degassing is not sufficient to bring about supersaturation of drip waters leading to less deposition of secondary carbonate in the cave. By contrast, during El Niño years, or in other years with a weak monsoon, the less intense rainfall picks up more soil CO₂ and because of slower flow to the cave is more saturated when it reaches the cave. The higher CO₂ produces more degassing in the cave and leads to supersaturation and increased deposition of carbonate. Thus the more rapid growth rate after 5ka suggests a weakening of the monsoons.

Stable Isotopes

 δ^{13} C of stalagmite carbonate may record variations in the C₃/C₄ composition of the vegetation above the cave and also the amount of carbon derived from the atmosphere, soil and bedrock. δ^{18} O of stalagmite carbonate can provide information on drip water temperature if deposition is in isotopic equilibrium with precipitating waters, and if the δ^{18} O of these waters is known. If deposition is not in isotopic equilibrium then kinetic effects including rapid degassing of CO₂ and evaporation lead to higher δ^{18} O and δ^{13} C. We tested for isotopic equilibrium by examining variations in δ^{18} O and δ^{13} C along two growth layers using the criteria of Hendy (1971). δ^{18} O remained essentially constant along layers 7.9 and 13.5 cm from the top of the stalagmite, nor was there a significant correlation between δ^{13} C and δ^{18} O in either layer. These findings suggest that the stalagmite was deposited in isotope equilibrium with precipitating waters and that variations in δ^{18} O may provide climate data for the Xianren Cave area (Fig. 5).

Dissolved carbon in the seepage waters that deposit speleothems is derived from three main sources: the atmosphere, organic matter and respired CO₂ in the soil, and the carbonate bedrock. δ^{13} C is mainly controlled by δ^{13} C of soil air. Normally C₃ plants and respired CO₂ have an average δ^{13} C of - 27‰, whereas the average for C₄ plants is -13‰ (Cerling, 1984). Because of different atomic weights ¹²CO₂ and ¹³CO₂ diffuse from the soil to the atmosphere at different rates, so that soil CO₂ is isotopically heavier than soil organic matter and respired CO₂ (Brook, 1999). Under a C₃ biomass, the first speleothem calcite deposited in isotopic equilibrium with seepage waters is likely to have a δ^{13} C in the range –12 to –9 ‰, depending on whether open or closed system conditions prevailed. Beneath a C₄ biomass δ^{13} C in calcite will be in the range –2.3 to +1.5‰ again with higher values for closed system solution. Under non-equilibrium conditions and at temperatures <20EC, δ^{13} C will be higher (Brook, 1999).
Along the growth axis of the stalagmite δ^{13} C varies from -12.6 to -3.7‰ PDB averaging -9.8‰ (Fig. 3C). In fact during most of the record δ^{13} C is between -12 and -10‰ indicating the dominance of C₃ plants above the cave. However, there are four marked intervals of significantly higher δ^{13} C at about 6, 5, 4.5, and 4 ka.

 δ^{18} O of drip water is influenced by temperature (higher at lower temperatures) and by amount and intensity of rainfall, as well as by distance from moisture source (increasing rainout) with increases in all three being accompanied by isotopically lighter drip water (Dansgaard, 1964). δ^{18} O increases steadily from around -7.2‰ at the base of the stalagmite to -5.6‰ PDB near the top with the average being -6.03 ‰ (Fig. 3D).

 δ^{18} O of precipitation at Xianren Cave is strongly influenced by storm intensity. Forty years of data for Hong Kong, about 100 km to the south of Xianren Cave, reveals a negative relationship between monthly precipitation in the typhoon season (July-October) and δ^{18} O (Fig. 6A). A similar relationship is reported for precipitation in Israel where heavier rainfall is isotopically lighter (Bar-Matthews et al., 1997). In southeast China 47% of precipitation in La Niña years when the monsoon is strong falls during the typhoon season; the figure is 42% in El Niño years. The more intense storms in La Niña years result in lower δ^{18} O in rainfall and thus in cave dripwaters.

 δ^{18} O of precipitation in China is also affected by moisture source and distance from it (Zheng et al., 1983). In southern China δ^{18} O is lower in areas receiving substantial rainfall from the Indian monsoon as this moisture comes from the Bay of Bengal and travels a greater distance and so is affected by rainout (Cai et al., 2001). When the monsoons are strong, as is the case in La Niña years, more of Guangdong's rainfall comes from the Indian ocean, the δ^{18} O of rainfall in these years is lower than during an average year or during an El Niño year when the monsoons are much weaker. δ^{18} O of rainfall in the study area also has a negative relationship with temperature (Fig.6B). δ^{18} O in southeast China is lower when global temperatures increase and the summer monsoon is stronger (La Niña years) (Qing et al., 2000). Temperature, precipitation intensity, and moisture source interact to produce higher (lower) δ^{18} O in rainfall in El Niño years (La Niña years) in the Xianren Cave area. The average δ^{18} O of rainfall is -5.1‰ SMOW. In El Niño years it is -4.4‰, and in La Niña years -5.3‰. Average δ^{18} O during the typhoon season in El Niño years is -6.4‰ and in La Niña years it is -7.6‰ (GNIP). In the rainy season from April-October δ^{18} O in strong El Niño years (1982 and 1997) was 1‰ heavier than in strong La Niña years (1973, 1975, and 1988). At Shihua cave 50 km south of Beijing a weak monsoon brings ¹⁸O-depleted rainfall because of rainout in the Yangtze-Huaihe River region before it moves north, whereas a strong monsoon moves rapidly northwards, suffers less rainout, and so brings precipitation with higher δ^{18} O (Tan et al., 1998). In Beijing the difference in δ^{18} O between a strong summer monsoon (1979) and a weak summer monsoon (1980) was 2.8‰ SMOW.

Discussion of Results

Color, luminescence and isotopic data record significant, broad-scale changes in climate in SE China during the mid-Holocene. The gradual increase in δ^{18} O suggests a change towards cooler and wetter conditions from 8-4 ka with peaks and troughs in both δ^{18} O and δ^{13} C recording drier and wetter intervals respectively. When the monsoons are strong some of the summer rainfall at Xianren Cave is brought from the Indian Ocean and because this moisture travels a long distance from the Bay of Bengal it is much more depleted in ¹⁸O than rainfall brought from the South China Sea. This produces stalagmite carbonate with lower δ^{18} O. The trend to higher δ^{18} O is therefore an indication of a gradual weakening of the summer monsoons. This trend in the stalagmite data is punctuated by short intervals of much drier conditions at 6, 5, 4.5, and 4 ka, the second of these intervals being the longest and the most prominent. Weaker monsoons bring lower temperatures and increased precipitation to southern China and lower temperatures and

decreased precipitation to the north of China. Lower temperatures and higher but less intense rainfall from the Asian monsoon in the south result in isotopically heavier rainfall and stalagmite carbonate.

The data show that color and luminescence are inversely related to δ^{13} C and δ^{18} O. As color darkens and luminescence decreases δ^{13} C and δ^{18} O increase. Together these changes suggest increased rainfall (higher δ^{18} O), the dilution of organic acids in the cave drip waters (reduced luminescence), and the incorporation of detrital grains and some humic acid because of cooler temperatures (darker colors). As stronger monsoons and warmer, drier conditions in south China are typical of La Niña conditions, and weaker monsoons and cooler, wetter conditions are typical of El Niño conditions, changes in climate recorded by the Xianren stalagmite suggest a change from La Niña-like conditions prior to about 5 ka to a higher frequency of El Niño events after this date. Short periods when the monsoon appears to have been especially weak occurred at 6, 5, 4.5 and 4 ka. These periods correspond with peaks in El Niño activity at ~ 6 , 4.9, 4.5, and 4 ka evident in deposits from Lake Lauguna Pallcacocha in the southern Ecuadorian Andes (Moy et al., 2002)(Fig. 7D), and weak monsoon activity at ~ 5.8 and 4.4 ka evident in Arabian Sea sediments (Gupta et al., 2003).

The Xianren Cave Record in Regional Context

During the early to mid Holocene radiation over the Northern Hemisphere was 5 to 18% higher in July and 8% lower in January than it is today (Joussaume, et al., 1999; COHMAP, 2000). The increased insolation caused summer temperatures to be 2^o to 4^oC higher than at present in Eurasia. After 9 ka these seasonal radiation extremes decreased towards modern values but summer temperature remained 2-4^oC higher than present to 6 ka. The resulting increased land-sea temperature contrast enhanced low-level convergence into the monsoon flow over subtropical Africa, China and northern India. The increased summer insolation enhanced the Asian summer monsoon between 9-6 ka

and it became weaker afterwards (Winkler and Wang, 1993; Liu et al., 2000). Data from a stalagmite in Yangzhipo Cave in Guizhou Province shows that the summer monsoon was strong from 8-5 ka and decreased in intensity thereafter (Xiao et al., 2003). A stalagmite from Qixing Cave, also in Guizhou Province, shows that the summer monsoon reached its maximum from 7.7 to 5.8 ka and that the summer monsoon weakened from 5.8 to 3.8 ka (Cai et al., 2001). The record from Xianren Cave agrees well with data from Yangzhipo and Qixing Cave suggesting that stalagmites at all three sites are recording major changes in regional climate (Fig. 7A-C).

The Holocene hypsithermal in China appears to have lasted from ~8.5-3 ka with the climate becoming colder subsequently (Zhuo, 2000; Chun et al., 2000; Liu et al., 1992). During the Holocene hypsithermal temperatures were 3-4⁰C higher than today in Beijing (Zhang et al., 1981), 2-4^oC higher in the East China Sea and the lower reaches of the Yangtze River (Meng et al., 1989), 2°C higher in Zhenjiang (Xu, 1989), 4-6°C higher in Tibet (Wang et al., 1981) and 1-2⁰C higher on the Yunnan Plateau (Walker, 1986). Pollen records from Tibet reveal that from 8-5 ka January and July temperatures were 2-3°C higher than now (Tang et al., 2000). After 5 ka temperature decreased linearly and steppe vegetation began to degenerate. Based on Chinese historical writings and archaeological artifacts, Chu (1973) has shown that temperature in China decreased from 5 ka to present. Wang & Gong (2000) used pollen data from several sites, including the Pearl River Delta in Guangdong Province, to reconstruct temperature over the last 10 ka. The results indicate that mean annual temperature in China was 2^oC higher than present during the hypsithermal at 5.6-6 ka and at 7 ka. Temperatures then decreased causing contraction of deciduous forest and expansion of coniferous forest and grassland in northern China, and a decrease in evergreen forest in south China. The lower temperatures also led to a decrease and in some areas the disappearance of forests in Tibet and Inner Mongolia (Sun and Chen, 1991). If δ^{18} O of stalagmite carbonate is a proxy for temperature change at Xianren Cave, and stalagmite deposition was apparently

69

in isotopic equilibrium, the timing and magnitude of variations agree well with the findings of Wang & Gong (2000).

North China was warmer and wetter (warmer and drier in the south) during the hypsithermal (3-8 ka) (Shi, 1992; Shi and Zhang, 1996) becoming cooler and drier thereafter. At the same time south China was warmer and drier later becoming cooler and wetter. Based on saline lake, loess and glacial evidence, Ji (1996) found that in NW China the hypsithermal from 9/8.5-3.5/3 ka was warmer and wetter leading to the spread of forests and steppe vegetation. After 3.5/3 ka temperatures dropped, glaciers advanced, deserts expanded, and the rate of loess deposition increased. Maximum aridity occurred about 6, 5.1 and 3.8 ka at Lake Sumxi (Lamb 1981, p135; quoting Zhang and Gong, 1987). Chun et al. (2000) found a marked decline in the Neolithic culture in the Guanzhong basin due to aridity from 6-5 ka based on lake level, pollen, and loess/paleosol evidence. Pollen records from Liaoning Province in northern China indicate that the climate became progressively warmer from 8-5 ka with the mean annual temperature 3-5°C higher than now, and after 5 ka conditions became more drier and colder until about 2.5 ka (Guiyang Institute of Geochemistry, 1978). In the Loess Plateau of China a strong summer monsoon brings warm and moist air to the area, and soils form with a high magnetic susceptibility. During periods when the monsoon is weak, loess is deposited with a low magnetic susceptibility (Zhou and An, 1994; An et al., 1991, 1993; Kukla et al., 1988). Loess-paleosol sequences within the Loess Plateau of China indicate that paleosol complexes associated with the Holocene hypsithermal date to 10-5 ka. After 5 ka neoglacial activity is characterized by recent loess deposition (Zhou and An, 1994). There is a good correlation between magnetic susceptibility of Chinese loess and δ^{18} O (proxy to monsoon strength) of the Xianren Cave stalagmite for the interval 8-4 ka (Ji, 1996).

The peak in δ^{18} O and δ^{13} C, and the trough in luminescence intensity and gray scale intensity values at about 5 ka, indicate a significant climate change. Records from

elsewhere also record a major change in climate at about this time. Otolith data from Peru indicate that summer SSTs were $3-4^{0}$ C warmer than present and the upwelling of the Peru-Chile current intensified after 5 ka (Andrus et al., 2002). The modern El Niño periodicity was established about 5 ka (Rodbell et al., 1999). Coral records from the tropical western Pacific reveal that the climate was generally warmer from 7-4 ka (Gagan et al., 1998). Geoarchaeological evidence from Peru also records a permanent warm climate from 8.4-5.25 ka, so there was no ENSO in that period (Sandweiss et al, 1996, 1999). Ice core records from Huascaran, Peru suggest that the climate was warmest from 8.4 -5.2 ka and it cooled gradually after that (Thompson et al., 1995).

Conclusions

 δ^{18} O and δ^{13} C of stalagmite carbonate increase gradually during the period 8-4 ka while color becomes darker and luminescence decreases. The record indicates that the climate became gradually cooler and wetter, and that the East Asian summer monsoon weakened as El Niño activity increased. From 7.5-5.5 ka the Asian monsoon was strong leading to generally drier and warmer conditions in southern China. La Niña and typhoons were probably more frequent in this period as Xianren Cave received less rainfall but more intense rainfall. After 5.5 ka there was a steady increase in the strength of the East Asian monsoon and an increase in the frequency of El Niño. The area around Xianren Cave became cooler and wetter. The general trend in climate was punctuated by short intervals of cooler and wetter conditions at 6, 5, 4.5, and 4 ka when a weaker summer monsoon brought more rainfall to SE China possibly due to increased El Niño activity. These intervals correspond well with periods of peak El Niño activity at ~6, 4.9, 4.5, and 4 ka indicated by sediments in Lake Lauguna Pallcacocha in the southern Ecuadorian Andes (Moy, et al), and weak monsoon activity at ~5.8 and 4.4 ka recorded in Arabian Sea sediments (Gupta et al., 2003).

71

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Fig. 3.1. The study area.



Fig. 3.2. Precipitation and temperature of Guangzhou City, Guangdong Province, China.



Distance From Top (mm)

Fig. 3.3. Variations in color, luminescence, and stable isotopes in Xianren Cave stalagmite.



Fig. 3.4. Age-distance relationship, Xianren stalagmite, Guangdong Province.





Fig. 3.5. Relationship between δ^{18} O and δ^{13} C along two growth layers in the Xianren stalagmite.



Temperature (⁰C)

Fig. 3.6. Relationship between amount, temperature and $\delta^{18}O$ (‰SMOW) of rainfall during the typhoon season at Hong Kong.



Fig 3.7. Comparision of stalagmite δ^{18} O records from Xianren, Yangzhipo, and Qixing (Cai, 2001) Caves in southern China (A-C) with proxy evidence of El Niño frequency from southern Ecuador(D) (Moy, et al., 2002).

| Sample ID | Distance From Top (mm) | Δ ¹³ C | Libby Age | Old Carbon Correction (years) | Calibrated Age +/- 2 sigma |
|-----------|------------------------------|--------------------------|-----------|-------------------------------------|-------------------------------|
| UGAMS102 | 8 | -11.2 | 4878±39 | -1200 | 4443-4151 BP |
| UGAMS103 | 212 | 11.56 | 7636±40 | -1200 | 7593-7429 BP |
| UGAMS104 | 114 | -10.5 | 5316±37 | -1200 | 5051-4829 BP |
| UGAMS105 | 158 | -8.12 | 5619±39 | -1200 | 5488-5313 BP |
| UGAMS106 | 93 | -11.5 | 4956±37 | -1200 | 4549-4248 BP |
| UGAMS106 | 130 | -10.7 | 5373±41 | -1200 | 5073-4849 BP |

Table 3.1 AMS Ages for Xianren Cave

Ages were calibrated using the University of Washington Calib program (http://www.depts.washington.edu/qil/calib).

CHAPTER 4

HIGH-RESOLUTION CLIMATE RECORD FOR 146-140 KA FROM A STALAGMITE IN WANXIANG CAVE, GANSU PROVINCE, CHINA¹

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Abstract

Samples taken 2mm and 115mm from the top of a Chinese stalagmite produced TIMS Useries ages of 139.6 ± 1.1 and 144.8 ± 1.8 ka, respectively, indicating that the stalagmite was deposited from about 146-140 ka during isotope stage 6 and at the beginning of Termination II. Variations in gray scale color, and in UV-laser induced luminescence, were measured along the central growth axis. Seventy-three samples were drilled for δ^{18} O and δ^{13} C analysis at 2mm intervals along the central growth axis under a binocular microscope. Thin sections were cut from the formation. Variations in δ^{13} C show that the region had a C₃ vegetation dominated at the beginning of deposition with values reaching a minimum (< -10%PDB) at about 144 ka. The percentage of C₄ plants increased steadily toward the top pf deposition indicating drier conditions with marked dry intervals at ca. 144 and 140 ka when δ^{13} C values reached >- 4 ‰. Steadily increasing δ^{18} O throughout the period suggests weaker monsoon and cooling conditions with marked cooler intervals. Decreased layer thickness and increased grey scale intensity agree well with the conclusions drawn from the stable isotope data. Luminescence data match well with the δ^{18} O and δ^{13} C records, with r = -0.77 and -0.57 respectively. Layer thickness also matches well with the δ^{18} O and δ^{13} C records, with r = -0.73 and -0.67, respectively. At the periods of those two much drier and cooler intervals, both gray scale intensity and the layer thickness reached their smallest values. Three thin sections from the stalagmite revealed about 548 annual layers. The stalagmite record matches climatic change evidences from deep ocean (SPECMAP), ice cores (MD84641), loess records from China, and other speleothems at the deposition period. The records in the stalagmite

revealed that the East Asian summer had a decreased trend from 140 to 146 ka, and the global temperature decreased.

Introduction

The East Asian monsoon is an important component of the global climatic system affecting an extensive area east of the Bay of Bengal and Tibetan Plateau (An, 2000a). The monsoon develops as a result of thermal differences between the Asian landmass and the Pacific Ocean, and is further enhanced by the thermal and dynamic effect of the Tibetan Plateau (Chen and Li, 1981). East Asian circulation is closely associated with climatic features of northern high latitudes, and is also linked with the equatorial ocean and the Southern Hemisphere (An, 2000b). In addition, increasing evidences have shown that Asian monsoon plays an important role in global climate changes such as El Niño. Study the history of East Asian monsoon is very important for us to understand the variation of the global climatic change. High-resolution records extending from the present back through the last glacial cycle or longer is crucial for us to better understand and predict the frequency, magnitude and causes of environmental changes (Crowley and Kim, 1994).

Wanxiang Cave is located on a north-facing hillslope in the Qilian Mountains of SE Gansu Province, China near the SW margin of the Loess Plateau. It is close to the northern limit of the modern East Asian summer monsoon and has a temperate monsoon climate (Johnson and Ingram, 2001) (Fig. 1). The climate is cold and dry with a mean annual temperature of 10^oC and precipitation 474 mm/yr. About 70% of rainfall occurs in summer with July being the wettest month (Fig. 2). There is only 29 mm of rain during the 5-month dry season from November-March. Most precipitation is brought by several thunderstorms in the summer.

Wanxiang Cave is located at the intersection area of dry and wet climate in China, and the precipitation decreases sharply north of its latitude. Wanxiang Cave has a temperate monsoon climate with the marked transitional characteristics of a continental climate. During the summer, the wind brings warm and humid air masses from South China Sea, and the study area experiences the wet season. In the winter, cold and dry wind from the Gobi Desert dominates, and the study area has the dry season. The seasonal march of the wet and dry periods is highly influenced by the strength of the monsoon wind (Domros and Peng, 1988). When the temperature is higher, hence a strong summer monsoon wind, the rain belt penetrates further north and brings more rainfall to the study area (Kukla et al., 1988; An et al., 1990; Ding et al., 1992). During the times of colder periods, the cold and dry westerly wind dominates, and the study area receives less rainfall. At time scales longer than 100 years, the summer monsoons generally are stronger during (globally) warmer periods, leading to wetter conditions in the study area. On the other hand, drier conditions prevail during global colder periods. Study suggests this region receives about 397 cm precipitation in weak summer years, which is about 80 and 200 cm lower than in normal years and strong summer monsoon years respectively (Global Network of Isotopes in Precipitation (GNIP); http://isohis.iaea.org/). Temperature shifts greatly from day to night as well as from season to season. The average temperature is -14°C to 3°C in January, and 11°C to 27°C in July (http://www.chinakontor.de/m-gansu.htm). Because of the unique geographic location, Wanxiang Cave is ideal for examining the fluctuation, intensity, and frequency of the Asian monsoon system in the past.

This study examined the East Asian monsoon record from a stalagmite at Wanxiang Cave, Gansu Province, China. Deposition layers, layer thickness, luminescence, gray scale, stable isotope, and color variation have been examined from the stalagmite. Results indicate that this stalagmite has recorded the East Asian monsoon in the period of 140 - 146 ka.

Sampling and Analytical Methods

In 2000, a broken stalagmite 13.4 cm long and up to 12.8 cm in diameter, was removed from Wanxiang Cave (Fig. 3). The stalagmite was cut in half along its central growth axis and one exposed surface was photographed after polishing and wetting to enhance color variations. The photograph was scanned at 600 dpi and gray color along the central growth axis was measured in 8-bit format (bright white = 255, black = zero) using image analysis software. As humic and fulvic acids in stalagmites luminesce when exposed to ultraviolet (UV) light we measured luminescence along the growth axis in order to record variations in organic acid abundance over time. Humic acids are produced by organic decomposition in the soil while fulvic acids are produced by photosynthesis. Measurements were made on one half of the stalagmite mounted on a Parker Systems 60 cm motorized linear stage and translated under a focused UV laser beam. Humic and fulvic acids can be optically excited using UV radiation and exhibit broad band emission in the blue green region of the spectrum. UV laser excitation at 355 nm was achieved using the frequency tripled emission from a Q-switched Nd:YAG laser. The laser emission was focused on to the stalagmite using a 250 mm focal length lens resulting in beam spot size of 1.8 mm on the stalagmite as determined using a knife-edge technique.

Emission from the stalagmite was collected using an optical fiber and spectrally filtered with a center wavelength of 514 nm and a band pass of 80 nm using a Jobin Yvon 0.125 m monochromator. Signal detection was achieved using an Oriel 33741 photo-multiplier tube and data acquisition was implemented using a Stanford Research gated photon counter. The 1 _s gate was delayed 20 ms with respect to laser pulse to minimize the effects of laser scatter. The linear stage translation and synchronized data acquisition was controlled using a microcomputer.

Samples 2mm and 115mm from the top of the stalagmite were TIMS U-series dated in the Department of Geology and Geophysics, University of Minnesota. Seventythree samples of ~150 mg were drilled along the central growth axis for δ^{13} C and δ^{18} O analysis. Samples were taken at 2 mm intervals using a dental drill while viewing the stalagmite under a binocular microscope. Samples for stable isotope analysis were also taken at 2 cm intervals along two distinct growth layers 2.1 and 10.2 cm from the top of the stalagmite to test for isotopic equilibrium deposition using the criteria of Hendy (1971). δ^{18} O and δ^{13} C of speleothem carbonate were measured in the University of Georgia, Department of Geology, Stable Isotope Laboratory on a Finnegan-MAT 252 mass spectrometer. Thin sections (13 x 5 cm) were prepared from one half of the stalagmite.

Results

The upper and lower quarter of the stalagmite are light brown and clearly stained by humic acids; the central section is much lighter. Gray color varies from 56-232 averaging 172 and there is a slight trend to darker colors towards the top of the stalagmite (Fig. 4A). Distinctly darker layers at 43 mm and 116 mm may record hiatuses in deposition. Luminescence decreases steadily towards the top of the stalagmite with values in the range 444-1342 averaging 981 (Fig. 4B). Thus lighter colors are associated with increased luminescence most likely resulting from the presence of fulvic acids which are colorless. As humic acids are more difficult to leach from the soil, and are quickly broken down by bacteria into fulvic acids in a warm environment, this suggests that lighter areas of the stalagmite reflect warmer, wetter conditions at the surface above the cave and increased plant growth (Shopov et al., 1994; Lauritzen et al., 1986).

The stalagmite has distinct layers visible to the naked eye and in thin section using a Leitz Lab 12 Pol S microscope. The layers could be identified by the color variation at the base of each layer (Fig. 3A & B). The stalagmite is mainly calcite with calcite crystals 0.05-0.4 mm wide and elongated along the growth axis with euhedral or nearly flat terminations. The calcite is primary with no evidence of recrystallization from aragonite. Calcite crystals usually grow within individual layers extending from the base of the layer and terminate at the top. There are also some crystals in the light color sections that continue to grow across layers and they can be seen by similarity in color. Crystal size is usually 0.05-0.1 mm in darker sections and 0.2-0.6 in the light parts of the deposit. Detrital grains occur especially in darker-colored areas.

Carbonate samples from 2 and 115 mm produced TIMS U-series ages of 139.6 ± 1.13 and 144.8 ± 1.77 ka, respectively, indicating that the stalagmite was deposited from about 146-140 ka during the coldest part of marine isotope stage 6. Thin section studies show that there are 548 layers in the stalagmite. In the very dark horizons of the stalagmite at 43 and 116 mm layers became so thin that they could no longer be identified

individually. Numerous studies have demonstrated annual layers from stalagmites (Brook et al., 1992; Baker et al., 1993; Shopov et al., 1994; Tan et al., 1997), and the reason that the layers do not indicate an annual deposit may result from the two possible long hiatuses in growth at 43 and 116 mm from the top.

From the base of the stalagmite there are 52 layers followed by a period of slow or no growth at 116 mm. From 116-43 mm there are 288 layers followed by a second period of slow or no growth. In the section from 43 mm to the top of the stalagmite 208 layers were identified. Layer thickness ranges from 0.05-0.62 mm/yr averaging 0.26 mm/yr. Layers in the top 4.0 cm and the basal 2.8 cm sections with darker color are denser and thinner than those in lighter colored areas from 4.3 cm-11.6 cm. The growth rate is ~ 0.31 mm/yr in lighter sections of the deposti and 0.056 mm/yr in darker parts, and much lower in the dark deposits at 43 and 116 mm. The growth rate of a stalagmite is a function of drip water amount (Railsback et al., 1994), degree of supersaturation (Chernov, 1984; Morse and Mackenzie, 1990), and the supply of CO₂ (Denniston et al, 2000). As the climate of Wanxiang Cave is semiarid with only 474 mm/yr rainfall, stalagmite growth is more rapid, and layers thicker, during years with a strong summer monsoon that brings increased rainfall, higher temperatures, and increased plant growth and soil CO_2 production. When the summer monsoon is weak temperatures are lower, there is less rainfall, rates of plant growth and soil CO₂ production drop, less water infiltrates the cave, and layers on stalagmites are thin or non-existent. If the strength of the summer monsoon was also crucial to stalagmite growth during isotope stage 6, as seems likely, then thicker layers point to an a stronger summer monsoon and thinner layers to a weaker monsoon.

 δ^{13} C of stalagmite carbonate may record variations in the C₃/C₄ composition of vegetation above the cave and also the amount of carbon derived from the atmosphere soil and bedrock, which can be influenced by hydrological conditions. Beneath a C₃ vegetation cover speleothem calcite deposited in isotopic equilibrium with seepage waters is likely to have a δ^{13} C in the range -12 to -9‰, depending on whether open or closed system conditions prevailed with higher values for closed system conditions. Beneath a C₄ biomass δ^{13} C should be in the range -2.3 to +1.5‰ again with higher values for closed system solution. Under non-equilibrium conditions and at temperatures <20EC δ^{13} C will be higher (Brook, 1999). Along the growth axis of the Wanxiang stalagmite δ^{13} C increased steadily from about -10% PDB near the base to -6.5% at the top, with prominent peaks to about -4‰ at 43 and 118 mm (Fig. 4C). In the lighter-colored parts of the stalagmite δ^{13} C lies between -9 and -81 suggesting a complete C₃ plant cover while in darker sections, with values of -7‰ or higher, C₄ plants may be present in the vegetation cover. At 43 and 116 mm (~145 and 140 ka) δ^{13} C increases to about -4‰ and subsequently drops to about -9.5%, indicating the change from C₄ dominated vegetation to C₃ dominated vegetation.

 δ^{18} O can provide information on drip water temperature if deposition is in isotopic equilibrium with precipitating waters, and if the δ^{18} O of these waters is known. If deposition is not in isotopic equilibrium then kinetic effects including rapid degassing of CO₂ and evaporation lead to higher δ^{18} O and δ^{13} C. δ^{18} O remained constant along the flat portions of growth layers 2.1 and 10.2 cm from the top of the stalagmite and there was no significant correlation between δ^{13} C and δ^{18} O in these parts of the layer. However, when the layers pass down the steep flanks of the stalagmite δ^{13} C and δ^{18} O are correlated suggesting that as flow rate increases kinetic effects become important. We believe that along the flat, axial section of the stalagmite deposition was in isotopic equilibrium but that down the steep flanks kinetic effects dominated. Thus we believe that isotopic data for the growth axis of the stalagmite is a proxy for climate but that values from the stalagmite flanks are not (Fig. 5).

Studies by Bar-Matthews et al. (1996) and Tan et al. (1998) suggest that heavier rainfall is more depleted in ¹⁸O. In general, δ^{18} O of precipitation in China is negatively correlated with precipitation amount, and positively correlated with temperature in areas influenced by monsoon precipitation (Johnson, and Ingram, 2001). Johnson and Ingram (2001) report more negative δ^{18} O in a stalagmite during interglacial than glacial periods from 19.8-313 ka, and temperature and δ^{18} O are inversely correlated. The mean δ^{18} O of the local precipitation (Johnson and Ingram, 2001). Isotope data for the region for Xian, Laozhou, and Yingchuang (Global Network of Isotopes in Precipitation (GNIP); <http://isohis.iaea.org/>) indicate that δ^{18} O averages -6‰ SMOW when the summer monsoon is weak and –7.85‰ when it is strong. If there was a similar relationship during isotope stage 6 then δ^{18} O of stalagmite carbonate is an indicator of summer monsoon strength.

 δ^{18} O increases steadily towards the top of the stalagmite with values ranging from -9.9‰ to -4.0‰ and averaging -7.9‰ (Fig. 4D). Peaks in δ^{18} O at 43 and 118 mm are indicative of lower rainfall at the site at these times. The long-term trend suggests a gradual decline in rainfall towards 140 ka when the stalagmite stopped growing.

The isotopic evidence suggests a change from warmer, wetter conditions supporting a C₃ vegetation at 146 ka. The color, luminescence, annual layer thickness, and isotope data all indicate that conditions became colder and drier from 146-140 with two marked cold, dry intervals at ~145 and ~142 ka when deposition on the stalagmite may have ceased. Weaker (stronger) monsoons are accompanied by lower (higher) temperatures and decreased (increased) precipitation in northern China, and bring isotopically heavier (lighter) rainfall and an increase in C₄ (C₃) vegetation.

Data from the Wanxiang stalagmite show that gray color and luminescence are inversely related to δ^{13} C and δ^{18} O. As color darkens and luminescence decreases δ^{13} C and δ^{18} O increase. Together these changes suggest decreased rainfall (higher δ^{18} O), a reduction in organic acids in the cave drip waters (reduced luminescence), and the incorporation of some humic acid because of cooler temperatures (darker colors). At stable isotope sampling points, luminescence is inversely related to δ^{18} O (r = -0.77) and δ^{13} C (r = -0.57) (Fig. 6 a & b) suggesting that the summer monsoon was stronger at the beginning of the stalagmite deposition, and the study area was wetter and warmer. The vegetation was predominantly C₃ type. The summer monsoon then gradually weakened, and the climate became cooler and drier with the percentage of C₄ plants increasing slightly towards the top of the deposit.

Layer thickness is also inversely related to δ^{18} O (r = -0.66) and δ^{13} C (r = -0.73)(Fig. 7 a&b). Considering the low precipitation (474 mm) and temperature (10EC) in the area, stalagmite growth is likely to be more rapid in warmer, wetter summers with a strong summer monsoon. In these years soil CO₂ will be higher because of the higher temperatures, and rainfall sufficient to flow through the soil and have time to equilibrate
with soil CO_2 levels, so that upon reaching the cave the water is close to saturation with respect to both calcite and dolomite. Because of high CO_2 in the water relative to the cave, degassing is rapid and leads to drip water supersaturation and rapid deposition of carbonate. By contrast, during weak monsoon years lower summer temperatures lead to lower soil CO_2 , and decreased rainfall results in very little or no flow of water to the cave. As a result, drainage waters do not pick up as much biogenic CO_2 from the soil and so degassing does not always supersaturate drip waters leading to less deposition of carbonate in the cave.

Discussion

The stalagmite from Wanxiang Cave has revealed broad changes in climate. δ^{18} O in ocean cores recorded the global temperature and changes in ice volume. It is higher (lower) when the global temperatures were relative higher (lower) and the ice-caps smaller (larger) (Goudie, 1992). Because the Wanxiang stalagmite was deposited under isotopic equilibrium, it can be used as an indicator of climatic change. As we mentioned earlier, it is higher (lower) when the global temperature is lower (higher), and the summer monsoon is stronger (weaker). The records from Wanxiang Cave and Atlantic Ocean (SPECMAP, Imbrie, et al., 1991) match very well at the specific periods (Fig. 8 D). The amount of influx of dust to the Atlantic Ocean from Africa (MD84641, Bareille et al, 1994) increased(decreased) when the global temperature was low(high). The influx curve and the δ^{18} O in Wanxiang Cave have recorded the same temperature changes (Fig. 8 B). At nearby Chinese Loess Plateau, magnetic susceptibility from Chinese loess reflects the changes in the intensity of the Asian summer monsoon (An, 2000). It is higher when the

global temperature was higher and the Asian summer monsoon was stronger, whereas it was lower during a colder and weaker Asian summer monsoon (Kukla, and An, 1989). The temperature and the monsoon strength from the two different sources have recorded the same events (Fig. 8C). The records also match very well with the speleothems records from Jerusalem (Frumkin, et al., 1999) and Shuinan Cave from Guilin, China (http://www.karst.edu.cn/paleo/images/paleo1.htm) (Fig. 9). All records show that the climate became colder at the end of substage 6, although substage 5e was the most recent period warmer than the Holocene climate (Crowley and Kim, 1994).

The relative short period of record back to 140 ka years ago makes the direct comparison with other records difficult, but the change trend can be revealed in the particular time, and they all have recorded similar climatic events. The records from the stalagmite in Wanxiang Cave seemed to be a global event, and match very well with the climatic changes evidences recorded in deep marine cores, ice cores, and loess profiles at that period around the world.

Conclusion

Variations in gray color, luminescence, layer thickness, δ^{18} O, and δ^{13} C of a stalagmite from Wanxiang Cave, Gansu Province, China, deposited 146-140 ka during the coldest period of marine isotope stage 6, record a gradual cooling and drying of the climate. δ^{13} C data show that the region had a C₃ vegetation at ~144 ka (δ^{13} C < -10 ‰ PDB) and that the percentage of C₄ plants increased to about 50% ~140 ka (δ^{13} C > -5 ‰ PDB). The steady increase in δ^{18} O from –9.9‰ at 146 ka to –4.0‰ at 140 ka marks a trend towards cooler and drier conditions. Darker colors and thinner layers toward the top

of stalagmite indicate increased cooler and drier condition and confirm conclusions drawn from the stable isotope data. Decreasing luminescence further supports the above arguments. Results from different methods reveal that the East Asian summer monsoon weakened from 146 to 140 ka. The temperature decreased during that time, and it became drier toward the top of the stalagmite. There were two intervals with much drier and cooler periods in the 6 ka span.

The records from this stalagmite show that speleothems are one of the best terrestrial resources for reconstructing paleoenvironmental change. They not only have the potential to provide long-term climate information to several hundred thousand years ago, but also the ability to provide high-resolution climate information at an annual resolution.

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Fig. 4.1. Location of Wanxiang Cave.



Fig. 4.2. Temperature and precipitation at Tianshui City, Gansu Province.



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Fig. 4.3. Wanxiang Cave stalagmite (A) and photomicrographs (B and C) of annual layers at sites 2 and 3. Label 1 and 4 in A show the locations of samples dated by TIMS.



Fig. 4.4. Records in color, luminescence, and stable isotopes through a Wanxiang Cave stalagmite.



Fig. 4.5. The relationship between δ^{18} O and δ^{13} C at layers 2.1 and 10.2 cm from the top.



Luminescnece Intensity

Fig. 4.6. The relationship between luminescence and $\delta^{18}O(A)$, and $\delta^{13}C(B)$.





Fig. 4.7. The relationship between layer thickness and $\delta^{13}C(A)$ and $\delta^{18}O(B)$.



Fig. 4.8. Comparison of the Wangxiang Cave record with other studies locally and globally. A. δ¹⁸O, Wangxiang Cave. B. Influx of dust to the ocean. C. Chinese loess magnetic susceptibility. D. δ¹⁸O, marine core.



Fig. 4.9. Comparison of records from stalagmites at Wanxiang and Guilin China

CHAPTER 5

HUMAN-RELATED ENVIRONMENTAL CHANGE IN GUIZHOU PROVINCE,

CHINA, 1991-1998, FROM SATELLITE IMAGES¹

¹Xiao, Honglin, Brook, George, and C.P. Lo. Submitted to *International Journal of Remote Sensing*, 06/18/02.

Abstract

Karst covers about 15% of the world's land area, and supports more than 1 billion people. Human activities have created many environmental problems in these areas which, by their nature, are highly susceptible to degradation. Although there has been a great deal of research on land use and land cover (LU/LC) change detection using satellite images and geographic information systems (GIS), there has been little on karst areas. In this paper human-related LU/LC changes are examined in a part of Guizhou Province in southern China from 1991 to 1998. Data were obtained from Landsat Thematic Mapper (TM) images for November 7, 1991, December 5, 1994, and December 19, 1998. Five categories of LU/LC, namely water, natural vegetation (mainly forest), agriculture, urban/built-up, and barren, were examined. A hybrid unsupervised/supervised method was used to map these categories at each time slice. Initially, 120 classes were assigned in the unsupervised classification, and then these were combined into the five classes of interest. Using information from the unsupervised classification, 400 sites, or about 3 from each of the 120 unsupervised classes, were selected as training sites for the supervised classification. Results showed that by dividing the study area into its four counties and then classifying land yielded significantly improved accuracy. If our results are representative of Guizhou Province as a whole, they indicate significant changes in human-related LU/LC from 1991 to 1998. Agricultural land decreased, urban areas expanded dramatically, the area under forest increased slightly, and barren land increased from 1991 to 1994, and then decreased from 1994 to 1998. The driving forces for the changes observed appear to be strong economic growth,

inconsistent government policies, poor land-use planning, low educational levels, and the fragile nature of the karst ecosystem.

1. Introduction

Turner et al. (1994) argue that human actions rather than natural forces are the source of most contemporary change in the biosphere. Land use/land cover (LU/LC) changes are one of the most visible results of humans modifying the terrestrial ecosystem. Land use (e.g. settlement, cultivation, rangeland, and recreation) is the use humans put to the land. Land cover (e.g. forest, grassland) is the biophysical state of the earth's surface and immediate subsurface, defined by biota, soil, topography, surface and ground water, and human structures (Weng, 1999). Land use involves both the manner in which the biophysical attributes of the land are manipulated, and the purpose for which the land is used (Turner et al., 1993). Changes in LU/LC impact the local, regional, and even the global environment. Natural or human-induced environmental changes also have feedback effects on LU/LC and the human driving forces for change (Weng, 1999).

Karst is a terrain with distinctive hydrology and landforms arising from a combination of high solubility and well-developed secondary porosity (Ford and Williams, 1989). Karst landscapes are characterized by closed depressions of various size and arrangement, disrupted surface drainage, caves and underground drainage systems (White, 1988). Satellite images have been used extensively to study temporal changes in LU/LC (e.g. Lo, 1981, 1986; Seto, et al., 2002; Kaufmann and Seto, 2001; Ji et al., 2001). However, there have been few studies of LU/LC change in karst areas, which account for about 15% of the world's land area or about 2.2 million km², and support around 1 billion people or more than 17% of the world's population (Yuan, et al, 1988). In fact, Ford and Williams (1989) suggest that 25% of the world's population is supplied largely or entirely by karst waters, including deep carbonate aquifers.

Not only are studies of environmental change in karst important because of the large area and large population involved, they are also important because karst environments are often extremely fragile, comparable with desert margins, because once they are damaged recovery can be slow and difficult. Fragility is due to the rapid movement of surface water underground, which promotes dry conditions at the surface (a lithologic desert), the typical thin soils, which often derive entirely from small amounts of insoluble residue released by the weathering of the limestones and dolomites, low levels of organic matter, and limited biodiversity (influenced by the often dry and highly alkaline, calcareous surface). Common environmental problems in karst areas include severe soil erosion, deforestation, and severe droughts and floods. Lithologic droughts are common in many karst areas because precipitation quickly drains underground via fissures and sinkholes. This causes water shortages for crops and even animals. At the other extreme, karst areas are frequently susceptible to flooding during the rainy season when the input of water may exceed the capacity of the subsurface drainage system (caves) to accommodate them. At such times karst depressions, including cockpits, dolines, uvalas and polies, may be flooded for periods of a few days to a few months, and in extreme cases even years. Thus, many karst areas with a highly seasonal climate are subjected to an annual cycle of drought in the dry season, and flooding in the wet season. As the only flat land suitable for agriculture is often in the floors of closed depressions, areas most likely to be flooded, the land is constantly under stress when used by humans for their livelihood.

In some karst areas, environmental problems threaten the livelihood of the people living there and so it is important that the causes of problems be studied in order to find

ways to protect, manage, and where necessary rehabilitate the land. Perhaps the most critical problem is "rock desertification", which is the transformation of a karst area formerly covered by soil and vegetation into a rocky landscape or lithologic desert almost devoid of soil and vegetation (Yuan, 1997). In most cases rock desertification results from human activities, especially the clearing of natural vegetation. Once the vegetation is removed, soil erosion and rock desertification can follow, particularly on steep slopes. This makes the rehabilitation of vegetation very difficult because in some areas there may be little or no soil remaining. According to Chen (1991), it takes 30-35 years for a karst environment to recover after deforestation, and recovery is longer and in some cases not possible if the land is too badly damaged. For example, it took about 60 years for a limestone pavement area in England to recover from being essentially a rock desert to the natural brush-grass vegetation (Yang, 1993). It takes 2000 – 8000 years for the weathering of carbonate rock to produce a 1 cm thick soil layer in Guizhou because of the very low levels of insoluble material left after dissolution (Li, et al., 2002).

Guizhou Province in southern China is a part of one of the largest, continuous karst areas in the world and has experienced many serious environmental problems in recent years. It is also within the fragile karst ecosystem belt that extends from the Mediterranean, through the Middle East and parts of southern Asia, to the central Americas (Yuan, 1997). According to Yang (1988), the rate of rock desertification in Guizhou was 933 km²/yr in the 1980s, and 41.2% of the land has experienced soil erosion and loss of water due to deforestation and agriculture. Soil erosion has converted 150,000 km² into karst desert. In addition, urban expansion consumed 15,600 ha of agricultural land by 1992, which could have supported 120,000 people (Yang, 1994).

This study will add to the work of Yang (1994) by examining LU/LC changes in a part of Guizhou Province from 1991 to 1998 using satellite imagery. The impacts of humans on the landscape will be examined, along with the driving processes. Finally, the study seeks effective ways for recovering, managing, and protecting the karst ecosystem, and makes recommendations about land use planning in these unique areas.

2. Study Area

Guizhou Province in southwest China, is located in the east side of the Yunnan-Guizhou Plateau (Figure 1). It covers 17,600 km² and has a population of 32.4 million. The main ethnic group is the Han, but in addition there are 47 minority groups, such as the Miao, Buyi and Dong. Guizhou has a subtropical wet monsoon climate (Table 1, Figure 2). The mean annual temperature is 20^oC. The highest average monthly temperature is in July and the lowest is in January. Annual precipitation is 1,140 mm and there is a distinct summer wet season and a winter dry season. Average monthly humidity ranges from 74-78%.

Guizhou is typified by rugged terrain, with numerous hills, steep valleys and underground caves. About 87% of the area is mountainous, 10% is hilly, and only 3% is classified as flat land. Mountainous areas with slopes of more than 15 degrees account for 60.0% of its area (Li, et al., 2002). The western part of the province is 1,500-2,000 m a.s.l. while the central part is about 1,000 m a.s.l. Elevations drop to about 500 m in the northern and southern regions. The highest point in Guizhou is 2,900 m and the lowest 137 m. About 73% of Guizhou is karst (Zeng, 1994), being underlain by up to 10,000 m of soluble carbonate rocks. In fact the karst areas of Guizhou, and neighboring Guangxi

and Yunnan provinces, form one of the largest, continuous karst areas in the world. The region contains a full suite of karst landforms including poljes, cockpits, towers and dolines. Soils are mainly red podzolic, yellow calcareous. The LU/LC varies from agricultural fields with crops such as rice, corn, soybeans, wheat, rape oil seed, oats, barley and sweet potatoes, to natural forests in remote areas and in local Feng-shui preserves. In addition, there are barren, water, and urban/built-up areas. The vegetation is subtropical with mainly evergreen trees although deciduous trees are found in some areas.

Since the beginning of China's "economic reforms and open door policy" implemented in 1978, China has experienced dramatic changes in its economy. Gross Domestic Product has increased significantly, to about 10% per year from 1990 to present, and has been accompanied by significant environmental changes as a result of urbanization, industrialization, deforestation and population pressure. As it is dominated by karst, Guizhou Province has experienced more significant environmental problems than most other parts of China. In many areas, agriculture on steep slopes has led to extensive soil erosion, which in combination with deforestation and overgrazing has left many areas barren or bare (Figure 3A). Once thin soils are eroded, exposing the underlying karst bedrock, the terrain is unsuitable for agriculture. As the limestones of the area are fairly pure, with very little insoluble residue, it takes a long time for a new soil cover to develop, and in areas where the insoluble material is removed by erosion as fast as solution produces it, soils may never develop. Some rock deserts in Guizhou were covered by natural forests or other vegetation in the 1950s and 1960s, indicating how rapidly areas can be degraded (Figure. 3A). Human activities, especially during the so-

called "Great Leap Forward" period from 1957 to 1960, destroyed large areas of the natural vegetation, which were then used for agriculture. For example, the percentage of forest in the upstream part of the Wujiang River dropped from 30% in the 1950s to 6.5% by the mid 1980s (Tu, 1994). Plowing or grazing in deforested areas loosened the soil, which was then eroded rapidly by heavy rains. From 1975 to 1980, the area of rock desert or semi rock desert in Guizhou increased from 4,666 km² to 13,466 km² (Tu, 1994). In some areas an attempt has been made to reclaim damaged lands by, for example, planting trees or grasses, but for the most part little has been accomplished.

Guizhou is a mountainous agricultural province, but agricultural land is very limited. Only 3% of its total area is flat explaining the saying " there is not three li (about 1.5 km) of flat area". The best lands are flat areas located in the karst valleys or karst basins, and closed karst depressions, that are in proximity to major settlements. In recent years, especially since about 1990, much high quality agricultural land is no longer used to produce crops. Strong economic growth has led to the expansion of urban areas into nearby agricultural lands and the building of better roads. New industrial districts have taken up much of the available flat land near the major cities, while in the countryside farmers have used precious flat land to build new houses. To evaluate the changes that have taken place, Guiyang city, the capital of Guizhou Province, tourist centers Anshun city and Qingzheng city, and Pingba County, were chosen for study (Figure 4). These are the most developed and flattest areas in Guizhou, and have been impacted the most in recent years by human activities.

The areas of the four counties are 2350, 1678, 1468, and 1000 km², respectively. They are located at the divide between the Yangtze and Pearl River systems. The main

rivers in the area are the Shancha in western Qingzheng and Pingba, the Miaotiao between Qingzheng and Guiyang, and the Nanming in Guiyang, all tributaries of the Yangtze River. In addition to these major rivers, there are numerous smaller streams in karst valleys and basins, which either flow north to the Shancha, Miaotiao, or Nanming rivers or flow south to join tributaries of the Pearl River. Some of the rivers are not continuous and they go to underground (Figure 4 C). Landforms include rugged fengchong (peak cluster) and fengling (peak forest) karst, as well as cockpits, dolines, and karst valleys. The Shancha River and the downstream part of Maotiao River have cut deeply into fengchong karst to form narrow, deep karst canyons usually more than 200-300 m deep. The study area has the province's largest lake, Hongfeng Lake, and many smaller reservoirs and lakes. Rice fields are commonly located in the floors of karst valleys and closed depression, while dry fields are located on the slopes of the karst hills and mountains. Forest is common in areas of fengchong and fenglin karst, and on the flanks of closed depression. Information about LU/LC changes in these areas will provide the spatial and temporal data needed to assess environmental problems facing Guizhou, and will provide background for informed land use planning in the future.

3. Data, Methodology, and Changes in Land Use/Cover

3.1 Data collection and pre-processing

For satellite LU/LC studies of Guizhou, LU/LC is best seen in the early summer (May-July) when the vegetation is green and vigorous. Unfortunately, this period is also the rainy season with cloudy skies, hence the saying "there are never three consecutive days of clear sky". Despite this, three cloud-free Landsat TM scenes were obtained for

November 7, 1991, December 5, 1994, and December 19, 1998, and were used in this study. The images provided complete coverage of Anshun and Pingba, but only 75% and 78.7% (801 and 1155 km²) of Guiyang and Qingzheng, respectively. The areas of Guiyang and Qingzheng not covered by our imagery are largely remote mountainous areas in the northern parts of these two counties. Environmental changes in these areas probably parallel those in other mountainous regions in our study area. The three images we used were taken at a similar time of year so that LU/LC should be comparable from image to image. In November and December deciduous tree have dropped their leaves and typical crops are rape oil seed and wheat, which at this time of year are in the early (green) stage of growth. Rice has just been harvested so that the rice fields are normally bare. A county boundary file obtained from CIESIN

(http://sedac.ciesin.org/china/econ/ybook/ybk90sources.html), 1:50,000 scale topographic maps, a 1:50,000-scale vegetation map of Guizhou, as well as old photographs and LU/LC documents were also used in assessing LU/LC changes.

The satellite images were corrected to remove the haze effect using the radiometric enhancement function in ERDAS Imagine. Nine ground control points, distributed evenly across the study area, were identified on the images and in the field. Their locations were measured using a GPS receiver on the ground. The three images were then rectified to their ground-true coordinates based on the nine ground control points using ERDAS Imagine. The county boundary file was re-projected using Arc/info. All data were examined in the UTM coordinate system. The three images were re-sampled to give a 28.5 m pixel size using the cubic convolution method.

3.2 Unsupervised classification

Five LU/LC types were considered referencing the classification at level I in the United States Geological Survey scheme (Anderson et al., 1976): natural vegetation (largely forest), water, agriculture, urban/built-up, and barren land. To achieve high accuracy, a hybrid unsupervised/supervised classification was used. Hybrid classifiers are particularly valuable in analyses where there is complex variability in the spectral patterns or individual cover types (Lillesand and Keefer, 2000). Unsupervised classification can provide information about the numerous spectral classes in the image and help in the selection of representative sites to adequately classify the images. Hybrid unsupervised/supervised classification has been conducted in many LU/LC studies and in most cases the results are better than those from supervised or unsupervised classifications alone (Garcia and Alvarey, 1994; Rutchey and Vilcheck, 1994). The unsupervised classification was carried out using the Iterative Self-Organizing Data Analysis (ISODATA) algorithm to identify spectral clusters in the image. This algorithm uses the minimum spectral distance to assign a cluster for each candidate pixel. The ISODATA algorithm first treats the entire data set as one cluster and then identifies a series of natural spectral clusters by iteration in a self-organizing way (ERDAS Imagine 8.5 manual). The radiometric contrast of the image data affects the degree of homogeneity of the natural clusters generated. The number of classes is very important because it affects the capability of an ISODATA classifier to capture most of the land surface variability from the image data being analyzed. If the number of classes is too small, relatively broad clusters are likely to be generated, which will not produce useful information. If the number of classes is too large, some of the areas defined will be very

small and may even be difficult to identify on the satellite images (Yang and Lo, 2002). In this study, 30 and 60 classes were used in the initial analysis. However, comparison with LU/LC on the ground showed that many areas had been incorrectly classified, and so the number of classes was increased to 120 and to 160 with the former giving the best results. Using maps, field data, interviewing with local people, and our knowledge of the area, the 120 classes were combined and recoded into natural vegetation, water, agriculture, urban/built-up, and barren land using ERDAS Imagine software.

3.3 Supervised classification

Based on the results of the unsupervised classification, 400 training sites were chosen from the images. To obtain a high accuracy for every class, they were fairly evenly distributed among the 120 classes of the unsupervised classification. ERDAS Imagine was then used to conduct the classification. For each image, spectral signatures for the training sites were carefully chosen from the images using AOI tool and those signatures were saved into a reference file for the classification. A maximum likelihood classifier was used for the image classification. It is the most frequently used classifier, because it takes the most variables into consideration. The maximum likelihood decision rule is based on the probability that a pixel belongs to a particular class. The basic equation assumes that the probabilities are equal for all classes, and that the input bands have normal distributions (ERDAS Imagine8.5 Field Guide). It quantitatively evaluates both the variance and covariance of the category spectral response patterns when classifying an unknown pixel (Lillesand and Kiefer, 2000). The resultant classified images were then recoded into LU/LC thematic maps.

To identify spatial-temporal patterns of change in the five LU/LC classes, and to examine conversions from one class to another, a thematic change detection analysis was conducted using ArcView software. LU/LC maps for 1991 and 1994, and for 1994 and 1998, were superimposed to create two maps showing changes between the two pairs of years. To emphasize changes in urban/built-up, agriculture, natural vegetation and barren land, changes in "water" were deleted from the change maps as were areas that showed no change during the period under investigation.

Confusion matrices were created to check accuracy of the LU/LC maps and it was determined that the accuracy was not acceptable. For example, examination of producer's accuracy in the change map for 1994 to 1998, shows that water was the most accurately classified LU/LC class with 83% of pixels correctly classified. Errors in this category resulted from confusion between topographic shadows and water bodies. Natural vegetation (mainly forest) was also accurately classified with 81% of pixels interpreted correctly. Some 76%, 69%, and 63% of pixels were correctly classified as barren land, agriculture, and urban/built-up, respectively. Percentages were even smaller for user's accuracy, which were 81%, 75%, 71%, 64% and 60% for water, natural vegetation, barren, agricultural and urban/built-up respectively. Misclassification errors may include boundary and spectral confusion. For example, water was confused with shadows in steep-sided karst valleys and dolines. Water was also confused with the shadows of high buildings in the centers of large cities. Agriculture and urban/built-up were difficult to differentiate because they have a similar appearance in some areas. Built-up areas were easily confused with dry agricultural lands as they sometimes have similar spectral characteristics. In some villages, thin limestone tiles are used to cover the

roofs of houses, leading to misclassification as barren land. In other villages, roofs are thatched with rice straw, which can be confused with agriculture land.

To minimize such misclassification, each original image was divided into four smaller individual images based on the county boundaries, and then each individual image was reclassified using the methods already described and then they were then reassembled to create an entire image. Using smaller areas for classification has several advantages. For example, building shadows in cities are no longer confused with topographic shadows because the land in Guiyang City is relatively flat and has few valleys or dolines that produce shadows. The LU/LC pattern and tone in the smaller areas is more homogeneous than when all four areas are considered together. This makes spectral identification easier. Once classified, the images were merged to create LU/LC change maps for the entire study area. As a result of this approach, classification accuracy improved significantly for every LU/LC category. For example, in the LU/LC map for 1997, classification accuracy for water, agriculture, natural vegetation, urban/built-up, and barren land is 88.9%, 86.4%, 83.0%, 77.6%, and 78.6% respectively (Table 2). The overall accuracy for the map is 83.5%. Similar accuracies were obtained for the 1991 and 1994 maps (Tables 3 and 4).

Despite improvements in accuracy, some land was still misclassified by the approach we used, largely because several LU/LC categories may occur in a very small area, making absolute accuracy impossible at the resolution of the satellite images (Figure 3B). Higher-resolution, commercial satellite images would probably improve upon the classification accuracy that we achieved. However, the accuracy of the LU/LC maps we present here is sufficient to meet the objectives of this study.

3.4 Land use/cover in the study area

Natural vegetation, consisting largely of forest, was the largest land use/cover category in the study area. It accounted for 40.0%, 47.8%, 41.8% and 45.3% of the total land in Anshun, Guiyang, Pingba and Qingzheng. Agricultural land was the second largest category, covering 44.6%, 32.8%, 39.3% and 37.4% of Anshun, Guiyang, Pingba and Guiyang. Barren land was widely distributed, accounting for 10.8%, 4%, 10.2% and 11.9% of the land in the four counties while urban/built-up land covered 3.3%, 8.1%, 3.1% and 2.9% of these areas. Natural vegetation was almost exclusively located in regions of fengchong and fenglin karst. Forest was well preserved near county boundaries, in mountainous karst regions far from population centers. A high proportion of the agricultural land is in the central part of the study area in the flat floors of karst basins, uvalas, and poljes. There are also many long, narrow strips of rice cultivation along karst valleys, with smaller rice paddies in the floors of karst depressions. Rice cultivation is mainly adjacent to rivers and streams, where the land is flat and water is available for irrigation. Dry agricultural fields are in transitional areas between fengchong and fenglin karst, and karst depressions (dolines, cockpits, uvalas, polies) or lowlands along valleys. Most of these lands are on the lower slopes of karst hills in areas of fenglin and fengchong karst, where slopes generally exceed 15° . However, some agricultural lands are found on slopes $40-60^{\circ}$. Barren land is found mainly along the boundary between forest and dry agricultural fields, especially in steeply sloping areas. Qingzheng and Pingba had more barren land than Anshun and Guiyang, and this was common in

mountainous areas where rivers have cut deep canyons. Urban and built-up land is commonly found in the floors of karst depressions and valleys.

3.5. Land Use/Cover Change

As Figures 5 and 6, and Tables 5 and 6, show, there were dramatic changes in LU/LC in the period 1991-1998. Urban/built-up land use increased significantly in every area (Figures 7 and 8). In Qingzheng City, it increased almost three times from 18 km² in 1991 to 53 km² in 1998, in Anshun City from 32 to 81 km², in Guiyang City from 71 to 148 km², and in Pingba County from 30 to 58 km². During the same period, agricultural land decreased in all four areas, at about 4% per year, in Anshun from 823 to 693 km², in Guiyang from 765 to 598 km², in Pingba from 544 to 358 km², and in Qingzheng from 517 to 366 km². This rate is about twice the average rate of around 2% for the whole province during this period (Oakes, 1999). From 1991-1994, about 11% of the agricultural land that was converted to other uses became natural vegetation (largely forest), 9.2% was left barren, and 2.3% was involved in urban development. For 1994-1998 the Figures were 10.4%, 6%, and 3.9%, respectively. Almost all of the urban expansion resulted from the conversion from agricultural land. About 75%, 85.3%, 88.4% and 80% of the increase in urban/built-up land in Anshun, Guiyang, Pingba and Qingzheng was from agricultural land. Most of the changes involved land under rice cultivation. Most of the agricultural land that became barren or forest was in the mountains, especially along boundaries between these three LU/LC types. From 1991-1998 forested areas increased slightly, in Anshun from 664-698 km², in Guiyang from 765-768 km², in Pingba from 314-369 km², and in Qingzheng from 424-433 km². The

area of forest that was cleared for urban development, or which became barren land, almost equaled the area of agricultural and barren land converted to forest. From 1991 to 1994, about 11%, 1%, and 7% of the forested area was converted to agriculture, urban, and barren land, respectively. The conversion continued at a similar rate from 1994 to 1998. All of those changes were near boundaries between forested land and the other land categories. By contrast, barren land in Anshun City increased from 1991-1994 and again from 1994-1998, from an initial 151 km² to a final 228 km², while in Guiyang, Pingba, and Qingzheng it increased in the period 1991-1994, and then decreased from 1994-1998, from initial values of 189, 95, 168, and 95 km² in 1991 to 200, 102 and 178 km² in 1998, respectively. Again, most of the changes in barren land were near boundaries with forested and agricultural lands on the slopes of karst mountains. Along the incised Shancha River Valley, and along the downstream stretch of Miaotiao River, the land is very rugged, being dominated by fengchong karst with deep closed depressions. In these areas agricultural land is on mountain slopes normally greater than 30° . Agricultural activities have led to severe soil erosion and to the formation of areas of karst desert. Because the land is not very fertile, farmers do not cultivate every year. A typical practice is to allow the fields to lay fallow for a few years, which allows growth of natural vegetation. Then the vegetation is burned to fertilize the soils and planting is resumed. Hence some lands in these areas go through a transition from agriculture to natural vegetation to barren in just a few years.

4. Forces responsible for changes in LU/LC

LU/LC changes in our four-county study area in Guizhou Province can be explained under two principal headings: 1) rapid economic growth and population pressure, and 2) ineffective government planning. Economic growth and population pressure are typical catalysts for LU/LC changes in many areas of the world and are difficult to control. However, when government planning contributes to LU/LC problems, remedies are possible. We will discuss each of these broad topics in turn.

4.1 Rapid Economic Growth and Population Pressure:

China has enforced a one-child birth-control policy since the early1980s and despite its success in reducing the rate of population increase, the total population is still increasing. In the 7-year period from 1991 to 1998, the population of every county in Guizhou increased by more than 10%, including increases of 100,000; 249,400; 54,000; and 55,400 people in Anshun, Guiyang, and Qingzheng, respectively (Guizhou Statistical Yearbook, 1991, 1995, 1998). The additional 458,800 people have placed considerable pressure on the land for new housing and for increased food production. In many cases new residential and commercial areas have been constructed on prime agricultural land with the attendant loss in food production from the best lands. To replace food production lost from converted prime agricultural land, and to provide additional output for the increased population, marginal lands have been cultivated, many of them on steep hillslopes. For example, at Jiuqi village, Anshun, 100 ha of marginal land in the hills, most with slopes of more than 10⁰ was converted from forest to agriculture (Yang, H., 1994). This conversion led to droughts, lower groundwater levels, and more floods. Five

of the 10 wells in the village become dry and the remainder lost 1/3-2/3 of their original capacity. In 1993 a rainstorm-induced landslide took place and the rocky materials covered a large area of agricultural land. The use of these marginal lands has produced a vicious cycle in which "more people are born-more land is exploited destroying the environment-the people become poorer-more people are born"(Yang, 1994).

In addition to increased population pressure on the land, Guizhou's gross domestic product increased from 100 billion yuan in 1990 to 636 billion in 1995 and 793 billion in 1997, almost an eightfold increase in only 7 years (Statistical Yearbook of Guizhou 1991, 1995, 1998). The strong economy has accelerated industrialization and urbanization so that large areas of forest, agricultural and barren land have been converted to residential apartments, shopping centers, and industrial parks.

Since 1991 many urban areas have expanded (Figure 7). Anshun city, a famous tourist center, more than doubled in area from 1991-1998, while Qingzheng, which changed from a county-level to a state-level city, and also a popular tourist destination because of Hongfeng Lake, also expanded dramatically by almost doubling its original size. In addition to urban expansion, there have been significant changes to the old sections of cities. Ten to 20 years ago, such changes were limited to digging up streets to put in a new gas pipeline, or to repair or install water sewage lines. In the last 10 years, a great deal of land in the old sections of cities has been cleared by the government or by private companies for the construction of new residential, shopping, and industrial facilities. In fact, urban areas are growing so fast that in Guizhou there is a saying that "if you have not gone back to your hometown for 2 or 3 years, you will not find your way home".
A major reason for the rapid increase in urban/built-up land is that since the reform and open policy to the outside began in 1978 people have been able to earn and save enough to buy a house. In 1990, the average annual income was 1217 Chinese yuan for urban residents and 435 yuan for farmers. Equivalent incomes in 1995 were 3427 yuan and 1087 yuan, and in 1997 they were 4442 yuan and 1298 yuan (Guizhou Statistical Yearbook, 1991, 1997, and 1998). In China, especially in rural areas, having a house is extremely important and people will invest their life savings to build a new house or to improve an old one. Ten to twenty years ago, sisters and brothers shared the same house with their parents even after they were married and had children. This situation is rare today. From 1995 to 1997, the average living area for urban residents increased from 7.5 m² to 8.2 m² and from15.9 to 16.4 m² for farmers (Guizhou Statistical Yearbook, 1997, 1998). Obviously, such a large increase in living area means that urban/built-up land use has expanded considerably.

Industrialization has been rapid during the past ten years. The government has relocated many factories to industrial zones on the outskirts of cities to make them more competitive. In addition, some new factories have been built by private companies. The new factories, along with needed access roads, are frequently located on good agricultural land while the old factories they replaced are abandoned and the land they occupy unused (Figures 9). Because of limited flat land near Guiyang City, the city government has used agricultural land in the Baiyun Qi district for new urban and industrial development. This has resulted in a large loss of agricultural land. Population pressure has forced farmers to seek additional areas for cultivation to replace the lost agricultural land. All that is available are steep or forested hillslopes, which when cultivated, results in rapid

soil erosion and resulting loss of productivity. If the present trend continues, it may be difficult for farmers to grow enough food to feed the growing population.

4.2 Ineffective Government Planning:

After the reforms of 1978, land, and in some areas forested land, was assigned to individual farmers to manage. According to government policy, all land belongs to the state. Individuals could manage land but did not have the right to cut or sell trees. The policy did not work well in rural areas where trees were often cut to build houses or to sell for profit. When trees were cut down and no one was punished, others followed and in some cases managed areas were totally deforested. For example, in Menzhai village in Pingba County, there used to be a large area of bamboo forest, which was divided into small units and assigned to individuals. Despite the government policy on cutting down trees, all of the bamboo in the area has been cut. As one of the residents replied when asked why they did this, he said "we just worry about a change in the policy. Right now other people have cut the bamboo and earned a lot of money. If I did not cut it and the government changed its policy and started to cut and collect the bamboo, I will deeply regret not cutting it and earning some money". Such concerns about changes in government policy, and exploitation of natural resources by the government, have resulted in long-term damage to the land around this village.

In the study area land was assigned to individuals in 1978. The policy for distributing the land was based on population information at that time. Twenty or 30 years later, families have changed in size and structure. In families with many sons at the time of land assignment, the amount of land given when divided among the sons would

not be enough to provide a living for them after marriage. According to Chinese tradition, especially in rural areas, female children were assigned land originally by the government. However, when they marry the land is not transferred to their family which must survive using only land assigned to the husband. When these families have children, the shortage of agricultural land will be even worse. In such cases, cultivation of steep mountain slopes is probably the only way the children will be able to feed their families, especially in remote areas.

Inconsistent government policies have thus contributed to LU/LC changes but so has government corruption. Before the 1980s individuals could not save very much money. Economic growth has changed this, and has also affected how some officials "do business", making government corruption a way of life in some areas. In some cases bribes have allowed developers to build on land that is best suited for agriculture or other uses, leading to poorly planned development and the often unnecessary loss of valuable agricultural and natural land. For example, every Sunday in Machang town, Pingba County, people from surrounding villages, cities, and factories came to the open-air market to sell products from their land and to buy their weekly supply of groceries. The market covered an area of about $60,000 \text{ m}^2$ and had been used for that purpose for about half a century. The officers in the local government wanted to obtain income from the trading that took place at the market, so they established a new market area of about $20,000 \text{ m}^2$ in a flat area of high quality agricultural land. Shops were constructed around the new market space, and these were rented to shopkeepers thus bringing in funds to the local government. Government officials then forced trading to be done at the new market, but because it was too small to meet the demand many sellers were forced to trade in

nearby streets. As a result, many streets are blocked to traffic on Sundays, causing great inconvenience to the people of the area. The new market has brought funds to the local government that rents shops and houses in the area, but these funds have been obtained by taking good quality agriculture land and by causing inconvenience to the local people. In addition, the much bigger, old market place lies empty and unused. With better planning, the loss of agricultural land, and traffic closures, could perhaps have been avoided.

Even positive government policy has been affected by low levels of education. For example, in the late 1980s the government realized that environmental degradation, especially soil erosion, was a serious problem and so they attempted to improve the situation by banning agricultural activities on steep slopes and in mountainous areas allowing reforestation to occur. As a result, forest re-established itself on former agricultural and barren lands. In some areas, there are even reports of the return of animals not seen for a very long time (Mr. Liu, Guizhou Normal University driver, personal communication 2000).

Unfortunately, the benefits of the new agricultural policy did not last long because of the low level of education in Guizhou, especially in the countryside. Most farmers have no other skills and so can only earn an income from the land. To support their families, they must cultivate new lands as old lands become barren. So, when the policy was first introduced, it was effective because it was strictly enforced by the government. As time passed, the government ceased to enforce the policy and farmers began to exploit new land for agriculture in areas that were not suitable for such activities. A few years

after their exploitation, many of these marginal areas became barren because of severe soil erosion.

5. Conclusions

In this study, five LU/LC types were considered: natural vegetation (largely forest), water, agriculture, urban/built-up, and barren land. To achieve high accuracy, a hybrid unsupervised/supervised classification was used. Because of the characteristics of karst terrain, classifying the images in large area produced a lower accuracy. Results indicated that dealing with the images in a single county at a smaller image size produced much higher accuracy. In our study, the producer's and user's accuracies for the three images were above or close to 80% for every LU/LC category. The overall accuracies for the three images information in studying LU/LC changes.

This study examined LU/LC changes in a four-county karst study area in Guizhou Province, China from 1991-1998. Findings indicate that urban/built-up areas expanded dramatically, areas under agriculture declined, and barren land increased. Naturally vegetated areas decreased from 1991 to 1994 but then increased from 1994 to 1998. The observed changes in LU/LC are due to population pressure on the land, a rapidly growing economy, poor land use planning, the low education level of many rural inhabitants, and to inconsistent or changing government policies.

Because some karst ecosystems in Guizhou are very fragile, environmental degradation in some areas was probably unavoidable. There is a dilemma between the land and the people. On the one hand, people need land to obtain food, on the other hand,

they damage the land when they cultivate fragile areas within the karst. Every year, natural and agricultural areas become barren due to the loss of soil and water. In spite of government efforts to control environmental degradation in the 1990s, little progress has been made. More effective ways or policies are needed to deal with the long-term problems of rock desertification. The present government policy is to "close the mountains for vegetation growth" in areas of steep slopes. Despite this policy, the amount of barren land that became forest from 1991-1998 was less than the amount of new barren land resulting from abandoned agricultural land or deriving from forested land (Figure 8). Agricultural activities were the major reason barren land. Guizhou has a subtropical wet monsoon climate, with more than 80% of its 1140 mm annual precipitation coming in summer, especially in May, June, and July (Figure 2 and Table 1). The raining season corresponds with the plowing season for the major agriculture activities. When the soil is loosened by these activities, it is easily eroded by heavy rains and surface runoff. If no action is taken to change traditional agriculture methods, all efforts to control the process of rock desertification will be unsuccessful.

Possible ways to limit land degradation due to cultivation include planting more tree crops, such as tea, Chinese medicinal herbs, fruit or seeds on steep slopes or in mountain areas. Some areas that have adopted such a scheme have benefited economically and ecologically (Yuan, 1997). To preserve the land and at the same time strengthen the economy, the government should re-educate or train farmers, provide financial support for new ventures, and distribute or recommend suitable trees for cultivation. To minimize the loss of agricultural land to urban development, enforced urban planning is necessary that would avoid development on rich agricultural land

wherever possible. Restrictions may be necessary on the building of luxury homes for individuals or companies as these take up too much valuable land. In addition, the government should encourage more high-rise apartment buildings as these are efficient in their use of land to house people. Only by taking such strict measures will it be possible to support more people on less land. To protect the environment, more emphasis should be placed on tourism. With its spectacular karst valleys, caves, mountains, canyons and waterfalls, Guizhou has the potential to become major tourist destination in China. Tourism would provide jobs for rural workers and might preserve marginal areas from agricultural exploitation as these could be left under forest.

Guizhou might benefit from China's West Development Plan by making present policies more flexible in order to attract investment from other areas of China or from overseas, to establish light industries that could be located away from areas of prime agricultural land or valuable natural forest. If cultivation on steep slopes is necessary to feed the population, the government should encourage and help fund the building of terraces on the slopes to minimize soil erosion.

Whatever approaches the government takes to combat environmental degradation should involve consistent, enforced policies. In the past, frequent changes in policy have led to them being ignored – because the policy may be changed soon anyway. Efforts are also needed to raise education levels as an educated population is more aware of environmental problems and is therefore more likely to abide by laws that protect the environment. Unfortunately, it is more difficult to enforce laws in remote, rural areas. For example, the one child policy is more stringently enforced in urban than in rural areas.

Only when people become aware of the importance of protecting the environment, can China's development goals be achieved.

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| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Ann |
|---------------|-----|------|------|------|------|------|------|------|------|------|------|------|------|
| Max Temp EC | 8.9 | 10.6 | 16.7 | 21.7 | 24.4 | 26.7 | 28.9 | 28.3 | 25.6 | 20.6 | 15.6 | 11.1 | 19.9 |
| Min Temp EC | 2.2 | 3.3 | 7.8 | 12.2 | 16.1 | 18.9 | 20.6 | 20 | 17.2 | 13.3 | 8.9 | 4.4 | 12.1 |
| Rainfall (mm) | 18 | 20 | 30 | 107 | 185 | 216 | 163 | 137 | 94 | 94 | 53 | 23 | 1140 |

Table 5.1. Climatic Summary for Guizhou Province (from http://www.fwcc.org/Guizhou.htm).

Table 5.2 Error Matrix of the land use and land cover map,1998

| | | R | eference Da | | Accur | racy | | | | |
|---|-------|--------|-------------|-------|--------|-----------|----------|--------|--|--|
| Classification data | Water | Forest | Agriculture | Urban | Barren | Row Total | Producer | User | | |
| Water | 40 | 6 | 2 | 2 | 0 | 50 | | 80.00% | | |
| Forest | 3 | 200 | 15 | 7 | 5 | 230 | 83.00% | 87.00% | | |
| Agriculture | 0 | 21 | 235 | 13 | 9 | 278 | 86.40% | 84.50% | | |
| Urban | 2 | 7 | 11 | 76 | 1 | 97 | 77.60% | 78.40% | | |
| Barren | 0 | 7 | 9 | 0 | 55 | 71 | 78.60% | 77.50% | | |
| Column Total | 45 | 241 | 272 | 98 | 70 | 726 | | | | |
| Overall Accuracy=(40+200+235+76+55) / 726 = 83.5% | | | | | | | | | | |

Table 5.3 Error Matrix of the land use and land cover map,1994

| | | R | eference Da | ata | | | асу | | | |
|---|-------|--------|-------------|-------|--------|-----------|----------|--------|--|--|
| Classification data | Water | Forest | Agriculture | Urban | Barren | Row Total | Producer | User | | |
| Water | 35 | 2 | 3 | 1 | 0 | 41 | 83.30% | 85.30% | | |
| Forest | 2 | 147 | 10 | 4 | 10 | 173 | 83.50% | 84.90% | | |
| Agriculture | 2 | 11 | 185 | 25 | 10 | 233 | 82.20% | 79.40% | | |
| Urban | 3 | 5 | 20 | 83 | 2 | 113 | 73.40% | 72.80% | | |
| Barren | 0 | 12 | 7 | 1 | 57 | 77 | 72.10% | 74.00% | | |
| Column Total | 42 | 177 | 225 | 114 | 79 | 637 | | | | |
| Overall Accuracy=(35+147+185+83+57) / 637 = 79.6% | | | | | | | | | | |

| | | R | eference Da | | Accur | uracy | | | | |
|---|----------------|-----|-------------|-------|--------|-----------|----------|--------|--|--|
| Classification data | Water Forest A | | Agriculture | Urban | Barren | Row Total | Producer | User | | |
| Water | 40 | 3 | 3 | 2 | 0 | 48 | 87.00% | 83.30% | | |
| Forest | 2 | 163 | 6 | 13 | 10 | 194 | 85.30% | 84.00% | | |
| Agriculture | 1 | 8 | 150 | 18 | 8 | 185 | 83.30% | 81.00% | | |
| Urban | 2 | 11 | 16 | 88 | 2 | 119 | 74.00% | 71.00% | | |
| Barren | 1 | 6 | 5 | 3 | 47 | 62 | 70.10% | 75.80% | | |
| Column Total | 46 | 191 | 180 | 124 | 67 | 608 | | | | |
| Overall Accuracy=(40+163+150+88+47) / 608 = 81.4% | | | | | | | | | | |

Table 5.4 Error Matrix of the land use and land cover map, 1991

Table 5.5 Percentage of land use/cover conversion from 1991 to 1994

| | | Forest | to: | | | Agricultu | Barren to: | | | |
|-----------|--------|-------------|-------|--------|--------|-------------|------------|--------|--------|--------|
| | Forest | Agriculture | Urban | Barren | Forest | Agriculture | Urban | Barren | Forest | Barren |
| Anshun | 80 | 13.3 | 0.69 | 6 | 9.4 | 82.4 | 2.1 | 7.3 | 38.7 | 60 |
| Guiyang | 81.6 | 12.10 | 1.42 | 5 | 12.3 | 78.1 | 3.8 | 7 | 30.2 | 67 |
| Pingba | 86.3 | 8.60 | 1.1 | 7.4 | 14 | 78.8 | 1.5 | 11 | 40.2 | 58.5 |
| Qingzheng | 83.2 | 9.7 | 0.3 | 7.8 | 9.7 | 81.1 | 1.9 | 11.7 | 35 | 63 |

Table 5.6 Percentage of land use/cover conversion from 1994 to 1998

| | | Forest | to: | | | Agricultu | Barren to: | | | |
|-----------|--------|-------------|-------|--------|--------|-------------|------------|--------|--------|--------|
| | Forest | Agriculture | Urban | Barren | Forest | Agriculture | Urban | Barren | Forest | Barren |
| Anshun | 89.9 | 8.2 | 0.7 | 7.4 | 10.1 | 80.2 | 3.1 | 5.1 | 38 | 60.5 |
| Guiyang | 83 | 10 | 0.7 | 6.1 | 10.1 | 78.2 | 4.9 | 6.4 | 35.8 | 63 |
| Pingba | 83.8 | 6.6 | 0.8 | 9 | 8.7 | 78.8 | 3.3 | 4.8 | 32.6 | 67.2 |
| Qingzheng | 80 | 6.7 | 1.5 | 11.8 | 12.7 | 81.5 | 4.3 | 7.7 | 37.8 | 60.2 |



Fig. 5.1. Location of the study region. A) Guizhou Province in southern China, B) Major cities, rivers, and mountains in Guizhou Province, and the four counties studied.



Fig. 5.2. Climograph for Guiyang, Guizhou, China (1920-1999).



Fig. 5.3 Typical Landscapes in the study area. A) Rock desertification in Pingba County. The land was forested 40-50 years ago, but trees have been cleared for agriculture. As a result, soil has been eroded from slopes in the fengchong karst (peak cluster) and the area is now a rock desert. B) Fenglin karst (peak forest) in Anshun with forest on the karst hills, and rice fields, settlements and the transportation routes in the lowlands.

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Fig. 5.4. Geographical features in Anshun, Guiyang, Pingba, and Qingzheng counties of the study area. A) Major cities, roads, and railways, B) Mountainous areas, C) major rivers and lakes.



Fig. 5.5. Land use/cover change in the study area from 1991 to 1994. In the legend, "Forest" is used for natural vegetation and "Urban" is used for urban/built-up.



Fig. 5.6. Land use/cover change from 1994 to 1998. In the legend, "forest is used for natural vegetation, and "urban" is used for urban/built-up.



Fig. 5.7. Expansion of urban/built-up land from 1991 to 1998.



Fig. 5.8. Area of natural vegetation (forest), urban/built-up, agriculture, and barren land at Anshun, Guiyang, Pingba, and Qingzheng, 1991, 1994, and 1998.



Fig. 5.9. Loss of Agricultural land from 1991 to 1998.

CHAPTER 6

CONCLUSIONS

This study has constructed a record of climate and land use/cover changes for some parts in China from cave stalagmite and satellite images. Results from Chapter 2, in which a stalagmite from Yangzhipo Cave in Guizhou Province was studied, indicate that there was a progressive weakening of the summer monsoon from 8.5 ka to present and that this was accompanied by an increase in El Niño activity. $\delta^{18}O$, $\delta^{13}C$, luminescence, and petrographic studies reveal that the Asian summer monsoon was strong from 8.5-5 ka and that Guizhou experienced warmer and drier conditions. La Niña years were more common during this time interval. From ~ 5 ka to present, the Asian summer monsoon weakened and Guizhou experienced wetter and cooler conditions as the frequency of El Niño increased. The climate was relatively constant prior to 5 ka, but the amplitude of climate fluctuations increased after this. Periods with a stronger Asian monsoon and increased La Niña activity, bringing warmer and drier conditions, occurred ~8.5-8.1, 5.8-5.2, 3.4-3.2, 2.4, and 0.7 ka at SW China. Periods of cooler, wetter climate when the Asian monsoon was weaker and El Niño more frequent occurred ~8-6, 5-3.4, 3.2-2.4, and 2.4 to 0.7 ka. During periods of stalagmite deposition vegetation was a mixture of C_3 and C₄ plants although a slight, long-term decrease in δ^{13} C of stalagmite carbonate may record a slight increase in the percentage of C3 plants after 5 ka. The Yangzhipo Cave stalagmite record corresponds well with evidence of climate change contained in Chinese historical records (Chu, 1973), and with the record of monsoon activity obtained from sediments in the Arabian Sea (Gupta et al., 2003).

Studies on the stalagmite from Xianren Cave in Guangdong Province deposited 8-4 ka, and described in Chapter 3, support conclusions presented in Chapter 2. From 7.5-5.5 ka the Xianren record suggests a strong Asian monsoon and generally drier and warmer conditions in Guangdong. As monsoon strength and ENSO activity are related, La Niña and typhoons were probably more frequent with reduced rainfall overall but more intense rainfall in the wet season. After 5.5 ka the strength of the East Asian monsoon increased steadily suggesting that ENSO activity also increased. The area around Xianren Cave became cooler and wetter. This general trend in climate was punctuated by short intervals of cooler and wetter conditions at 6, 5, 4.5, and 4 ka when a weaker summer monsoon brought more rainfall to SE China possibly due to increased El Niño activity. These periods correspond well with the record of El Niño activity obtained from sediments in Lauguna Pallcacocha in the southern Ecuadorian Andes (Moy et al., 2002), and evidence of monsoonal strength obtained from sediments in the Arabian Sea (Gupta et al., 2003).

Chapter 4 outlines data obtained from a stalagmite deposited 145-140 ka during the height of marine isotope stage 6. The study illustrates the enormous potential of stalagmites to provided high-resolution, even annual data over very long periods of time. Isotope and other data from the stalagmite indicate that the temperature at Wanxiang Cave decreased from 146-140 ka and the climate became drier. The stalagmite data and other proxy records (e.g. loess) indicate that the East Asian summer monsoon weakened from 146 to 140 ka.

The study presented in Chapter 5 indicates that a hybrid unsupervised/supervised classification of satellite data can yield high land use/land cover accuracy in Guizhou Province. Results show that dealing with the images in a single county at a smaller image size produced much higher accuracy, because of the characteristics of karst terrain. In doing so, higher producer's and user's accuracies can be achieved, which can provide us with accurate and useful information in studying LU/LC changes. Findings from Chapter

5 indicate that urban/built-up areas expanded dramatically from 1991-1998, while areas under agriculture declined and barren land increased. In the Guizhou area naturally vegetated areas decreased from 1991-1994 but then increased from 1994-1998. The observed changes in LU/LC were due to population pressure on the land, a rapidly growing economy, poor land use planning, the low education level of many rural inhabitants, and to inconsistent or changing government policies. More effective policies are needed to deal with the long-term problems of rock desertification.

Results presented in Chapters 2, 3 and 4 show that stalagmites are one of the best terrestrial resources for reconstructing paleoenvironmental change. They not only have the potential to provide information on long-term climate change to several hundred thousand years ago, but also the ability to provide high-resolution climate information at the decadal or even annual level. In the studies presented, stalagmite records were compared with proxy data from lake, pollen, and loess studies and with qualitative historical data on temperature and rainfall. These comparisons showed the reliability of the stalagmite records. The findings presented here indicate that stalagmites in Chinese caves have the potential to provide high-resolution records of climate change for the last several thousand years and beyond. Because summer monsoonal rainfall in China appears to be linked to ENSO activity these climate records would also be a proxy of changes in ENSO frequency and intensity over time.

The initial objectives of this study had to be modified because stalagmites collected in 2000 proved less than ideal for the study originally proposed. In particular, stalagmites that were active when collected were found later to have significant hiatuses in deposition. The Xianren stalagmite is an example. It was active when collected but an age for carbonate just below the top surface was ~4 ka. Such problems prevented the development of high-resolution climate records for the last 2 ka. As a result of these problems the study focused on developing lower-resolution records of climate change during the Holocene and on annual layers in a stalagmite deposited during the coldest

time of marine isotope stage 6. The original goal of comparing high-resolution climate records from stalagmites with information in Chinese historical gazetteers was not possible because few high-resolution data were obtained from the cave deposits. However, in Chapters 2 and 3 the records from Yangzhipo and Xianren Cave were compared with summary data taken from historical sources by other researchers (e.g. Chu, 1973) and this corresponded well with the stalagmite records. Satellite studies begun early in the project were completed and do show the potential of this method to obtain land use/land cover information that could be used in assessing evidence of such changes in recent stalagmite deposits.

Overall, the research presented here demonstrates the potential of stalagmites to provide detailed paleoenvironmental information for both short and long periods of time. Furthermore, it is clear that suitable stalagmites will allow comparison of Chinese historical records of climate change with proxy records of climate change obtained from stalagmites. The presence of what appear to be annual layers in a stalagmite deposited at the coldest time of marine isotope stage 6 indicates that high-resolution data are locked in stalagmites of considerable age. As to whether stalagmites do record changes in land use/land cover on the surface above the cave remains to be proven.

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