Numerical simulation of formation and preservation of Ningwu ice cave, Shanxi, China: A discussion.

Stuart A. Harris,

Department of Geography, University of Calgary, Calgary. T2N 1N4, Canada.

Introduction.

This paper is one of a number of papers discussing the possible mechanism or mechanisms explaining the existence of the Ningwu ice cave in Shanxi Province on the slopes of the mountains on the south side of the Hexi Corridor (Meng et al., 2004; Gao *et al*., 2005; Meng *et al*., 2006; Shi and Yang, 2014; Yang and Shi, 2015). This cave is also sometimes referred to as the Luyashan ice cave (State Council, 2015), and has been known to the local population for a very long time. Villagers used to come there to take ice when there was a shortage of water (Sukha, 2014), as well as to cool their body temperature when they had a fever. Subsequently, the cave has been developed commercially like many of the numerous karst caves elsewhere in China, *e.g*., near Guilin.

Before the scientists visited the cave, the entrance below the cave had been modified (Yang and Shi, figure 1c), a corridor had been developed to access the base of the massive ice, stairs had been installed rising in a spiral upwards for most of the 80 m height of the cavern (Yang and Shi, figure 1d), one or more budhas had been carved in the rock, and coloured lights had been installed throughout the cave. Thus the original condition of the cave prior to these modifications is unknown and may be difficult to determine.

The Ningwu Cave is the largest of the known Chinese ice caves and is situated along the mountain slopes south of the Hexi Corridor. It also contains the greatest amount of ice among the small number of known ice caves in China. The small number is largely due to the low latitude where the caves are found and the effects of the East Asia Monsoon in summer. The currently held origin of the Ningwu ice cave is that it accumulated glacier ice in the "Early Pleistocene", and is regarded as being more than 3 million years ago (Meng *et al*., 2006). This follows the concept of Han (2004), who interpreted the vertical cave as being a moulin mill eroded into bedrock beneath a glacier. As such, it has been regarded as the potential repository for valuable palaeoclimatic and palaeoenvironmental information for the region during this span of time. As a result, the Ningwu ice cave (Wanniandong in Chinese) was made a National Geo-park in 2005, and subsequently a national AAAA tourism location in March, 2011. The models in the papers by Shi and Yang (2014) and Yang and Shi (2015) attempt to explain why the ice persists today using limited information regarding the true shape of the cave, and the mean annual air and ground temperatures at the site. Essentially, they model possible reasons for the persistence of the ice, assuming that the ice can be treated as a form of permafrost.

Weaknesses in the current interpretation

There are several potential or actual problems with the current interpretation, some of which can readily be solved, while others need much more work. They are best dealt with separately below, but include a re-examination of the age of the formation of the ice.

1. The geometry of the cave

In North America, we are fortunate because the Speleologists almost always map the cave geometry very accurately (Halliday, 1954; Thompson, 1976). This enables studies of the temperature regime in the ice caves to be carried out with excellent geometric control, e.g., Harris (1979) and Dickfoss *et al.* (1997). When continuous data on the air temperature outside and inside the cave is available, it is possible to study the actual temperature regime and associated processes occurring inside the cave. The temperature regime varies with the past temperature history of the cave, the amount of air diffusion into the cave, the number of entrances, the geometry of the cave, and the presence or absence of air or water entering the cave along open joints and cracks. Unfortunately, the available data provided by a magnetotelluric survey of the Ningwu ice cave (Shao *et al.*, 2007) consists of data on the vertical cross-section of the cave, but there is no data provided on the relationship of the passage beneath the cave to the 85 m vertical chamber. The cross-section provided in Figure 1b of Yang and Shi (2015) suggests that there is also a vertical entrance above the chamber to the outside, but no detailed information is provided about its dimensions, nor whether it is open throughout the year. Enlarging the diagram, the upper entrance appears to be about 4-5 m wide and cylindrical, i.e., it is large enough to allow large quantities of summer monsoon rain and winter snow to enter the top of the cave. This information is critical when considering the validity of their model and their proposed mechanisms.

2. Mean annual air temperature.

It is very dangerous to take the mean annual air temperature from a site at a lower elevation and apply a standard lapse rate to correct the value without considering the environmental conditions at the two sites. The Ningwu ice cave is situated in a dense larch forest on a steep, north-facing slope of a mountain. The weather station used is situated at a lower elevation where the natural vegetation is probably steppe grassland at an elevation close to the average height of the semiarid floor of the Hexi Corridor. No data is provided as to the slopes and vegetation around the sites.

As was pointed out by Kudryavtsev *et al.* (1974), there are thermal offsets at all boundaries affecting the amount of incoming solar radiation that is actually transferred to the ground. The total thermal offset consists of the sum of the offsets at the top of the forest canopy, the underlying shrub layer, the herb layer, any mosses and/or lichens, the litter layer, the soil organic layer, and the underlying mineral layer. In winter, the snow cover is an additional seasonal complication, while the amount and temperature of summer precipitation and/or overland flow further complicate the total thermal offset. Slope and aspect are also important. The weather station at lower elevations has a different vegetation cover, slope and microclimate to the forest, so that there is likely to be a significant error in the value used in the calculation. To further make the point, Figure 1 shows the results of plotting mean annual ground and air temperatures against one another for sites in Canada and Norway. There is at least a 10˚C difference found at some sites, and the ground temperature is usually noticeably lower than the air temperature.

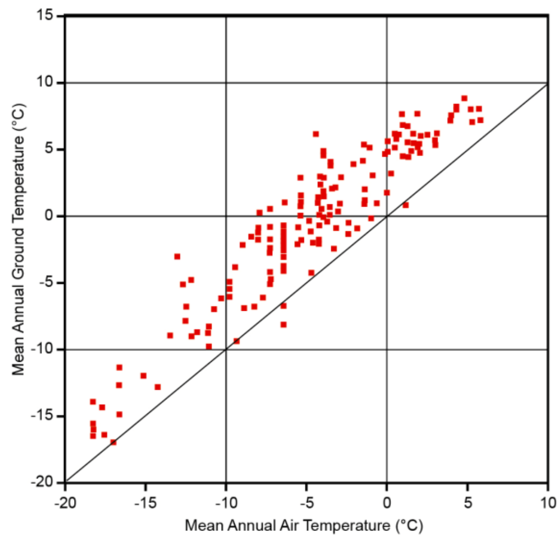

Figure 1. Mean annual ground surface and air temperatures for sites in areas overlying or close to permafrost in Canada and Norway (modified from Harris, 1981a).

Accordingly, the interpretation of the authors appears to be suspect. An obvious problem is that they conclude that the area has 7 months of above-freezing mean monthly temperatures and the apparent freezing and thawing indices appear to be similar (Figure 2 in Yang and Shi, 2015). To have icy permafrost persist, it is usually necessary to have a higher mean annual freezing index than the thawing index using mean daily air temperatures. In Canada, even ice caves with 7 months of freezing temperatures and 5 months of thawing temperatures are marginal for retaining permafrost (see the measurements for the Canyon Creek ice cave in Harris, 1979). The presumption that the ice at Ningwa is stable is belied by the spectacular icicles in the cave, and the fact that the cave lies in area visited periodically by the East Asia Monsoon in summer, which brings with it copious amounts of warm (c. 20˚C) precipitation, some of which must enter the cave if there is a broad upper entrance.

The obvious solution to obtain reliable climate data for the site is to install a weather station at the Ningwa cave site in the natural vegetation cover at an undisturbed site close to the cave, on a similar slope and aspect. The ice cave represents a pocket of sporadic permafrost by definition, but the extent of the pocket needs to be determined. A deep borehole to a depth of about 100 m that is instrumented with thermistors and a data logger could determine whether the adjacent ground contains permafrost. It would also provide basic data for comparison with temperatures measured in the cave itself.

3. Some basic types of ice caves

Yang and Shi (2015) refer to the process-based classification of alpine ice caves of Luetscher and Jeanin (2004). However, their classification only considers ice caves with massive ice occurrences, and assumes that a distinction can be made between congelation ice (endogenic ice) and snow and firn accumulation (exogenic ice). They assume that the caves have developed the ice under a stable climate, just as is sometimes assumed when interpreting the isotopic composition of speleothems (Hendy, 1971). As most scientists have finally realised, climate is always fluctuating, and this inevitably results in corresponding fluctuations in the ice in most ice caves.

In the case of ice caves closely dependent on the stability of the local climate, year-to-year fluctuations produce important effects. The temperature data from within the Canyon Creek ice cave in southwest Alberta was obtained during a 13 month period from 1977 to 1978 (Harris, 1979). The ice cave had a full range of stalactites and stalagmites, columns, and banded ice, while the floor was covered by a seasonally frozen ice at that time. Two years later, fluctuations in the local climate had resulted in the complete loss of the ice. By 1982, the range of ice forms was back, and its continued presence has also been reported by Yonge and MacDonald (2014).

Relict ice in caves is a different matter. It can persist for long periods if there is a swan-neck in the outer entrance preventing the exchange of air from outside with that inside, *e.g.,* the Plateau Mountain ice cave (Harris, 1979). As a result, the air temperature in the main body of the cave where the ice is found is essentially isothermal at 0˚C. The bulk of the ice there was probably formed during the last Neoglacial event (c.1650-1900) and also possibly during the Late Wisconsin glaciation. It has subsequently undergone substantial changes as it slowly dissipates. The walls of the cave are covered in hexagonal plates of ice crystals. Thawing of the ice is primarily due to geothermal heat flow and warm summer precipitation thawing ice in the cracks in the overlying permafrost and subsequently descending into the cave, as has been observed during and after heavy summer precipitation events. Even so, there is still some ice remaining at the back of the cave today.

Tubular ice caves descending into the underlying rock accumulate snow below the entrance in winter, *e.g.,* the Candelaria ice cave in New Mexico (Dickfoss *et al.,* 1997). These authors demonstrated that in winter, cold air descends into the entire cave, displacing warmer air. In summer, less dense warm air only produces a weak inflow into the cave, as is also the case in the ice cave on Mount Fuji (Ohata *et al.,* 1994a). The outer portion of the cave exhibits the maximum annual temperature fluctuation, and the mean cave temperature rises with distance within the cave, associated with decreasing annual temperature variation. Faimon and Lang (2013) have demonstrated that upward air flows of warm air are systematically higher than downward air flows, regardless of the number of entrances. Ohata *et al.* (1994b) found that wind speed of air entering the Mount Fuji ice cave was proportional to the square root of the temperature difference between the air inside and outside the cave, with a maximum speed of more than 0.8 m/s^{-1}.

In the case of the Candelaria ice cave, ice cores from the upper 3m of the icy mound of accumulated snow indicated that it was cold from 1,800-3,000 years B.P. and again from 1,650-1,850 years A.D., *i.e.*, the last two Neoglacial periods. Since then, the climate has been fluctuating with increasing ice deposition from 1924-1936 and again, from 1947-1991. In between, it was ablating.

Sloping caves with two entrances, e.g., the Eisriesenwelt ice cave in Austria, have a different temperature regime. The warm air in the cave can escape upwards, while cold air descends downwards to cool the lower portion of the cave. Dripping water from joints and cracks in the enclosing rock are regarded as the source of the banded ice encrusting the walls near the lower entrance (May *et al.*, 2011). However, there is an abrupt change in the ice 3 m into the 7 m ice core indicating an environmental change of undetermined origin. Similar deposition from percolating meteoric water was reported by Wimmer (2007) from the Schönberg system, Totnes Gebirge, Austria.

Yet another possible source of ice could be by condensation of water from warm air in a humid, subtropical climate (*c.f.*, de Freitas and Schmekal, 2003). This is likely to occur at Ningwu ice cave if there is significant inflow of air into the cold cave in summer.

Obviously, there is too little published data to classify the Ningwu ice cave, let alone determine what processes have led to the formation of the ice in it. However, it should be noted that there is a continuum between massive ice occupying a cavity in bedrock, and a cavity in bedrock partially filled with ice. These can change back and forth with climate changes.

4. Environmental history of the region

As the name implies, the Ningwu ice cave is potentially very old. Certainly, the earliest glaciation in northwest North America was 3.5 Ma (Harris, 1994; 2001), and this should also be the case for the west side of the Bering Strait. A cold event dated at 3.0 Ma has been inferred from sediments around Lake Baikal (Fortiev, 2009), so that there must have been earlier cold events in Asia than in the areas of Western Europe that were warmed by El Niño that was following the course of the current Gulf Stream prior to the collision of South and North America and the closing of the Panamanian Gateway at about 2.4 Ma. However, central China has been greatly affected by the collision between the Indian and Asian Plates (Harris *et al.*, 2015).

The Tibetan Plateau has undergone a series of phases of uplift, punctuated by periods of erosion. The southern part near Lhasa was uplifted about 50-52 Ma, and had a warm, seasonally dry climate until 40 Ma (Wang *et al*., 2013). However, the climate became cool and arid between 40 Ma and 26 Ma. The uplift was periodic, with rapid erosion occurring during the intervening periods. The sediment was deposited in the subsiding intermontane basins. The southern part of Tibet had reached 4,500 m by 25 Ma, and the northern part of Tibet was starting to rise (Li *et al.*, 2012). Both the Indian and Asian Monsoons stared to develop around this time.

The uplift resulted in the development of a fortress-like structure. The Tibetan Plateau is surrounded by mountain ranges on all four sides with mountain peaks exceeding 6,000 m in elevation. The passes through the mountains lie between 4,500 and 4,800 m elevation. Since the East Asia Monsoon only reaches to 4,500 m in northern Tibet, there is no moisture source for the ice cap that has been postulated by Kuhle (1988; 1998; 1999; 2001; 2002; 2004). Instead there were local ice caps on the higher mountain ranges, especially on the eastern side of the Tanggula Range (Shi *et al*., 1979; 1990; 2006; Shi and Mi, 1983; Zheng *et al.*, 2014).

The known glaciations only extend back to about 1.1 Ma B.P. due to the effects of erosion. The maximum glaciation was the Kunlun glaciation at 0.6-0.7 Ma B.P. The area covered in ice on the high mountains has been dwindling during the three subsequent glaciations, being replaced by the development of permafrost (Zheng *et al.*, 2014). Cui (1982) had mapped the distribution of periglacial features across northern China, and this has been steadily added to in subsequent studies (Zhao *et al.* 2014). Thus the idea of the ice in the Ningwu ice cave being of glacial origin is untenable. Its origin must be as a type of permafrost.

The earliest evidence for the presence of permafrost reported to date comes from ice-wedge pseudomorphs in the gravel layer of fluvio-alluvial sediments on the Da'Heba sandbar in Xinghai, Qinghai Province (135,700+/-10,500 years B.P. – Pan and Chen, 1997), and ice-wedge pseudomorphs in the loess at North Yangsigeguzui village, Junger Banner, Inner Mongolia (132+/-13 ka B.P. – Zhou *et al.*, 2008). These features record the time of thawing of the ice in the ice-wedges. It was followed by an interglacial period lasting until 80 ka, and it was warm and dry in the Qaidam Basin at 2700 m elevation (Han *et al*., 2013).

Liu and Lai (2012) reported a wedge with a sand infilling dated at 62.4+/-5.7 ka B. P. from west of the Qinghai Lake at Tianjun (c. 3300 m). They therefore concluded that it was formed during the marine isotopic stage (MIS) 4, dated at 80-53 ka B.P. It was followed by a short warmer period.

The last glacial maximum in the northeast part of the Plateau began about 40 ka when the surface of the basins on the Qinghai-Tibet Plateau had reached 4,500 m elevation (Zheng *et al.*, 2014). Cheng *et al*. (2005) reported a TL-date of 39.83 ka B.P. for cryoturbated and frost-shattered bedrock at 4301m elevation along the Ngörin access road to Niutoushan on the northeast slopes of the Qinghai-Tibet Plateau. It was cut by rock tessellons (Harris and Jin, 2012), one of which was truncated by a sand-filled ice-wedge cast TL-dated at 13.49 ka B.P. During the maximum, the China Sea became dry land interspersed with lakes because of the lowering of sea level due to the growth of glaciers elsewhere around the world (Fairbanks, 1989; Voris, 2000). Thus the source of water to supply moisture to the East Asia Monsoon had disappeared, while there was probably a southward movement of the Trade Winds until the climate started to ameliorate. The absence of the East Asian Monsoon resulted in the extremely cold, dry conditions that permitted the rock tessellons to develop at lower elevations, together with sand tessellons that have been described from along the north and northeast slopes of the Plateau and southern slopes of the Hexi Corridor (Harris *et al.*, 2015).

By about 17 ka, the floor of the South China Sea became inundated by the sea, and the movement of moist air onshore permitted the growth of ice-wedges throughout the region (Cui *et al.,* 2002; Wang *et al.,* 2003; Vandenburghe *et al.,* 2004). However, the climate became warmer, and the last ice-wedge casts resulting from thawing of the ice in these wedges are dated at 9.16+/- 0.17 ka B.P. (Jin *et al.*, 2006) with cryoturbation features dating as late as 8.86+/- 0.2 ka B.P. (Li *et al*., 2012). Subsequently, the climate fluctuated with periodic cold events (Liu *et al.,* 2013), but the Megathemal (Altithermal/Hypsithermal) only lasted from 8,500 to 6,000 years B. P. During this time, permafrost was absent from the area.

During the Hypsithermal, the flood plains in northeastern China developed peat deposits indicating warm, humid conditions (Yang and Jin, 2011; Yang et al., 2015). However at about 6 ka, there was an abrupt change in climate, with the development of ice-wedges that persist today. Three intense cold periods are recorded in the Gong'he Basin at 5.3- 4.7, 3.1-1.5, and 0.7-0.1 ka B.P. (Liu et al., 2013). Cheng *et al. (*2006) reported a group of sand-filled depressions about 2 m wide and 1 m deep, suggesting the growth of small blocks of ground ice in loess between 5,690 and 5,430 years B.P. In 1985, two deep boreholes in bedrock in the Huola River basin in Northeast China penetrated two layers of massive ice in Cretaceous shale and coal measures (Wang, 1990). The thickest was over 20 m thick. Thus the development of substantial bodies ground ice was common in northeast China after 6 ka B.P. This suggests that the ice in the Ningwu ice cave may only date back about 6 ka instead of 3 million years. The cave may also be a former mass of ice in the cavern that is currently suffering from thawing of the relict ice as a result of a warming climate.

Conclusions

Yang and Shi have to be thanked for bringing to the attention of the permafrost community the existence of this intriguing ice cave. Unfortunately, it has been significantly modified by the local population, so that it may be difficult to determine its exact environmental history. Based on the regional climatic history, it certainly does not contain glacier ice as previously suggested, and the ice is probably less than 6 ka in age. However, it is a most interesting example of an ice cave at low latitudes that is surviving in spite of hot, humid summers with Monsoon precipitation, interspersed with very cold winters. There are no studies of ice caves persisting under comparable conditions, so that it will be very desirable for more detailed observations, climatic and ground temperature measurements to be carried out, so as to learn as much as possible about the processes occurring in this unique environment.

References

Cheng, J., Jiang, M., Zan, L., Liu, X., Xu, X., Lu, P., Zhang, X. and Tian, M., 2005. Progress in research on the Quaternary Geology in the source area of the Yellow River. *Geoscience*

19(2): 239-246. [In Chinese].

Cheng, J., Zhang, X., Tian, M., Yu, W., Tang, D. and Yue, J., 2006. Ice-wedge casts discovered in the source area of the Yellow River, Northeast Tibetan Plateau and their palaeoclimatic implications. *Quaternary Sciences* 26(1): 92-98. [In Chinese].

Cui, Z. J., 1982. Basic characteristics of periglacial landforms in the Qinghai-Xizang Plateau. *Scientia Sinica* 25 (1): 79-95.

Cui, Z. J., Zhao, L, Vandenberghe, J. and Zhang, W., 2002. Discovery of ice wedge and sand wedge networks in Inner Mongolia and Shanxi Province and their environmental significance. *Journal of Glaciology and Geocryology*, **24**(6): 708-716 [In Chinese].

De Freitas,C. R. and Schmekal, A., 2003. Condensation as a microclimatic process: Measurement, numerical simulation and prediction in the glowworm cave, New Zealand. *International Journal of Climatology* 23: 557-575.

Dickfoss, P., Betancourt, J. L. and Thompson, L., 1997. History and paleoclimate potential of Candelaria Ice Cave, west-central New Mexico. In: Zidek, G., Ed.. *A natural history of El Malpas. New Mexico Bureau of Mines and Mineral Resources* Bulletin 1561: 91-112.

Faimon, J. and Lang, M., 2013. Variances in airflows during different ventilation modes in a dynamic U-shaped cave. *International Journal of Speleology* 42(2): 115-122.

Fairbanks, R. G., 1989. A 17,000-year glacio-eustatic sea level record, influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. *Nature* 342: 637-642.

Fortiev, S. M., 2009. Siberian geocryological chronologies. *Earth Cryosphere* 13(3): 3-16. [In Russian].

Gao, L., Wang, X., and Wan, X, 2005. Analysis of ice cave formation in Ningwu Shanxi. *Journal of Taiyuan University of Technology* 36(4): 455-458. [In Chinese].

Halliday, M. D., 1954. Ice caves of the United States. *National Speleological Society Bulletin* 16: 3-28.

Han, T., 2004. *Moulin discovered*. Beijing. Hua Xia Publishing House.

Han, W. X., Ma, Z. B., Lai, Z. P., Appel, E., Fang, X. and Yu, L., 2014. Wind erosion on the north-eastern Tibetan Plateau: Constraints from OSL and U-Th dating of playa salt crust in the Qaidam Basin. *Earth Surface Processes and Landforms* 39: 779-789.

Harris, S. A., 1979. Ice caves and permafrost zones in southwest Alberta. *Erdkunde,* 33: 61-70.

Harris, S. A., 1981. Climatic relationships of permafrost zones in areas of low winter snow-cover. *Arctic,* 34: 64-70.

Harris, S. A., 1994. Chronostratigraphy of glaciations and permafrost episodes in the Cordillera of western North America. *Progress in Physical Geography* 18: 366-395.

Harris, S. A., 2001. Sequence of glaciations and permafrost events. In: Paape, R. and Melnikov,V., Eds.. *Permafrost Response on Economic Development, Environmental Security and Natural Resources.* Kluwer Academic Publishers: 227-252.

Harris, S. A. and Jin, H. J., 2012. Tessellons and "sand wedges" on the Qinghai-Tibet Plateau and their palaeoenvironmental implications. Proceedings of the 10th International Conference on Permafrost, Salekhard, Russia, 26-29th June, 2012, 1: 149-154.

Harris, S. A., Jin, H. J., He, R and Yang, S., 2015. Tessellons, Topography, and Glaciations on the Qinghai-Tibet Plateau. *Geomorphology*, In Press.

Hendy, C. H., 1971. The isotopic geochemistry of speleothems – 1. The calculation of the effects of different modes of formation on the isotopic composition of speleothems and their applicability as palaeoclimatic indicators. *Geochimica, Cosmochimica Acta* 35: 801-824. Doi: 10.1016/0016-7037(71)90127-X.

Jin, H. J., Zhao, L., Wang, S. L., and Guo, D. X.2006. Evolution of permafrost and environmental changes of cold regions in eastern and interior Qinghai-Tibet-Plateau since the end of the Holocene. *Quaternary Sciences* 26(2): 198-210. [In Chinese].

Kudryavtsev, V. A., Garagula, L. S., Kondrat'yeva, K. A. and Melamed, V. G., 1974. *Osnovy merzlotnogo prognoza.* MGU. 431p. [In Russian].

Kuhle, M. 1988. The Pleistocene glaciation of Tibet and the onset of ice ages - An autocycle hypothesis. *Geojournal* 17(4): 581-596.

Kuhle, M. 1998. Reconstruction of the 2.4 million km^2 Late Pleistocene ice sheet on the Tibetan Plateau and its impact on the global climate. *Quaternary International* 45-46: 71-108.

Kuhle, M., 1999. Tibet and High Asia V. Results of investigations into high mountain geomorphology, paleo-glaciology, and climatology of the Pleistocene. *Geojournal* 47(1-2): 3-276.

Kuhle, M., 2001. The Tibetan Ice Sheet; its impact on the palaeomonsoon and relation to the Earth's orbital variations. *Polarforschung* 71(1-2): 1-13.

Kuhle, M., 2002. A relief-specific model of the ice age on the basis of uplift-controlled glacier areas in Tibet and the corresponding albedo increase as well as their positive climatological feedback by means of the global radiation geometry. *Climate Research* 20: 1-7.

Kuhle, M., 2004. The high glacial (Last Ice Age) ice cover in high and central Asia. In: Ehlers, J. and Gibbard, P. L., (Eds.). *Development of Quaternary Science 2c. (Quaternary glaciation extent and chronology, Part III: South America, Asia, Africa, Australia, Antarctica),* pp. 175-199.

Li, S. J., Chen, W., Jiang, Y. J., Jin, C. F., Li, C. C., Luo, R. Q. and Wang, X. D., 2012. Geological records for the Holocene climatic and environmental changes derived from glacial, periglacial and lake sediments on the Qinghai-Tibet Plateau. *Quaternary Sciences* 32(1): 151-157. [In Chinese].

Liu, B., Jin, H, Sun, L. J., Sun, Z., Su, H. Z. and Zhang, C., 2013. Holocene climatic change revealed by aeolian deposits from the Gonghe Basin, northeastern Qinghai-Tibetan Plateau. *Quaternary International* 296: 231-240.

Liu, X. J. and Lai, Z. P., 2012. Optical dating of sand wedges and ice-wedge casts from Qinghai Lake area on the northeastern Qinghai-Tibetan Plateau and its palaeoenvironmental implications. *Boreas* 42: 333-341.

Luetscher, M. and Jeannin, P., 2004. A process-based classification of alpine ice caves. *Theoretical and Applied Karstology* 17: 5-10.

May, B., Spötl, C., Wagenbach, D., Dublyansky, Y. and Liebl, J., 2011. First investigations of an ice core from Eisriesenwelt cave (Austria). *The Cryosphere* 5: 81-93.

Meng, X-G., Zhu, D-G., Shao, Z-G., Tu, J., Ha, J-R, Meng, Q-W., 2004. The discovery and sense of the Quaternary period glacial traces on the northern part of Lüliang Mountain of Ningwu, Shanxi Province. *Journal of Geomechanics* 10(4): 327-336. [In Chinese].

Meng, X-G., Zhu, D-G., Shao, Z-G., Tu, J., Ha, J-R, Meng, Q-W., 2006. A discussion of the formation mechanism of the "Ten-Thousand-Year-Old Ice Cave" in Shanxi Province. *Acta Geoscientica Sinica* 27(2): 163-168. [In Chinese].

Ohata, T., Furukawa, T. and Higuchi, K., 1994a. Glacioclimatological study of perennial ice in the Fuji Ice Cave, Japan. Part 1: Seasonal variation and mechanism of maintenance. *Arctic and Alpine Research* 26(3): 227-237.

Ohata, T., Furukawa, T. and Osada, K., 1994b. Glacioclimatological study of perennial ice in the Fuji Ice Cave, Japan. Part 2. Interannual variation and relation to climate. *Arctic and Alpine Research* 26(3): 238-244.

Pan, B. T. and Chen, F. H., 1997. Permafrost evolution in the Northeastern Qinghai – Tibetan Plateau during the last 150,000 years. *Journal of Glaciology and Geocryology* 19(2): 124-132. [In Chinese].

Shao, Z., Meng, X., Zhu, D., Yu, J., Han, J., Meng, Q, and Lv, R., 2007. Detection for the spatial distribution of "Ten Thousand Ice Cave" in Ningwu, Shanxi Province. *Journal of Jilin University (Earth Science Edition)* 37(5): 961-966.

Shi, Y. and Yang, S., 2014. Numerical modeling of formation of a static ice cave – Ningwu ice cave, Shanxi, China. In: *International Workshop on Ice Caves, NICKRI Symposium* 4: 7-11.

Shi, Y. F., Li, J. J. and Xie Z., 1979. The uplift of the Qinghai-Xizang Plateau and its effect on China during the Ice Age. *Journal of Glaciology and Cryopedology* 1: 6-11. [In Chinese].

Shi, Y. F. and Mi, D. H., 1983. A comprehensive map of snow, ice and frozen ground in China (1:4,000,000). *Proceedings of the 4th International Conference on Permafrost, Fairbanks,* *Alaska, USA, 18-22nd July, 1983.* Washington. National Academy Press Vol. II: 1148-1151.

Shi, Y. F., Zheng, B. X. and Li, S. J., 1990. Last glaciations and maximum glaciations in Qinghai-Xizang Plateau—A controversy to M. Kuhle Ice Sheet Hypothesis. *Journal of Glaciology and Geocryology* 12(1): 1-16. [In Chinese].

Shi, Y. F., Cui, Z. J. and Su, Z., 2006. *The Quaternary glaciations and environmental variations in China*. Shijiazhuang. Hebei Science and Technology Publishing House: 134-138. [In Chinese].

Shi, Y. F., Zheng, B. X. and Yao, T. D., 1997. Glaciers and environments during the Last Glacial Maximum (LGM) on the Tibetan Plateau. *Journal of Glaciology and Geocryology* 19(2): 97-113. [In Chinese].

Shi, Y. F., Zhao, J. D. and Wang, J., 2011. *New understanding of Quaternary Glaciations in China.* Shanghai. Shanghai Popular Science Press: 130-135. [In Chinese].

State Council, 2015. Fantastic Luyashan ice cave in China's Shanxi Province. http://english.gov.cn/news/photos/2015/04/18/content_2814750912799. Retrieved on 5th May, 2015.

Sukha, 2013. An underground Million years ice cavern – Ningwu. *Sukha,Sunday, March 10th., 2013.* http://sukhasights.blogspot.ca/2014/03/an-underground-million-years-ice-cavern-Ningwu. Retrieved on 8th May, 2015.

Thompson, P., 1976. *Cave Exploration in Canada.* Edmonton. The Canadian Caver. 183p.

Vandenberghe, J., Cui, Z. J., Zhao, L. and Zhang, W., 2004. Thermal-contraction-crack networks as evidence for Late-Pleistocene permafrost in Inner Mongolia. *Permafrost and Periglacial Processes* 15(1): 21-29.

Voris, H. K., 2000. Maps of Pleistocene sea levels in Southeast Asia: shorelines, river systems and time durations. *Journal of Biogeography* 27 (5): 1153-1167.

Wang, B. L., 1990. Massive ground ice within bedrock. *Journal of Glaciology and Geocryology* 12(3): 209-218. [In Chinese].

Wang, C., Hong, H., Li, Z. H., Liang, G. J., Xie, J., Song, B., Song, E.,and Zhang, K., 2013. Climatic and tectonic evolution in the North Qaidam since the Cenozoic: Evidence from sedimentology and mineralogy. *Journal of Earth Science* 24(3): 314-337.

Wang, N., Qiang, Z., Li, J.J., Hu, G and Hongyi, C., 2003. The sand wedges of the last ice age in the Hexi Corridor, China: paleoclimatic interpretation. *Geomorphology* 51: 313-320.

Wimmer, M., 2007. Eis- und temperaturmessungen im Schönberg System (Totes Gebirge, Öbersterreich/Steiermark). *Alpin Untertagr, Berchesgarden 9-11 Proceedings.* Munich. Deutsches Höhlen- und Karstforscher: 93. [In German].

Yang, S. and Shi, Y., 2015. Numerical simulation of formation and preservation of Ningwu ice cave, Shanxi, China. *The Cryosphere Discuss* 9: 2367-2395.

Yang, S. Z. and Jin, H. J., 2011. $\delta^{18}O$ and δD records of inactive ice wedge in Yituli'he, Northeast China and their paleoclimatic implications. *Science China, Earth Sciences* 54: (1): 119-126. Doi: 10.1007/s11430-010-4029-5

Yang, S. Z., Cao, X., and Jin, H. J., 2015. Validation of wedge ice isotopes at Yituli'he, Northeast China as climate proxy. *Boreas,* In Press.

Yonge, C. J. and Macdonald, W. D., 2014. Stable isotope composition of perennial ice in caves as an aid to characterizing ice cave types. In: Land, L., Kern, Z., Maggi, V. and Turri, S. (Eds.). *Proceedings of the 6th International Workshop on ice caves*: 41-49.

Zhao, L., Jin, H. J., Li, C. C., Cui, Z. H., Chang, X., Marchenko, S. S., Vandenberghe, J., Zhang, T. J., Luo, D. L., Guo, D. X., Liu, G. G. and Yi, C. L., 2014. The extent of permafrost in China during the local Last Glacial Maximum (LLGM). *Boreas* 43(3): 688-698.

Zheng, B. X., Shen, Y. P., Jiao, Y. P. and Yin, X. F., 2014. New progress and problems of Quaternary moraine dating in the Tibetan Plateau. *Sciences in Cold and Arid Regions* 6(3): 183-189.

Zhou, T., Pan, B. T. Liu, X.J., *et al.*, 2008. The discovery of ice wedge casts in Erdos: Rebuilding the permafrost boundary during the penultimate glaciation in China. *Journal of Glaciology and Geocryology* 30(1): 108-112. [In Chinese].