ELSEVIER

Tectonophysics 230 (1994) 241–248

TECTONOPHYSICS

The possibility of inferring paleoseismicity from paleomagnetic dating of speleothems, western Japan

Hayao Morinaga [a], Takafumi Yonezawa [b], Yasuhisa Adachi [c], Hiroo Inokuchi [b], Hiroya Goto [d], Katsumi Yaskawa [b]

[a] *Faculty of Science, Himeji Institute of Technology, 2167 Shosha, Himeji 671-22, Japan*
[b] *Faculty of Science, Kobe University, 1-1 Rokko-dai, Nada 657, Kobe, Japan*
[c] *Osaka College, Mihara, Minami-Kawachi, Osaka 587, Japan*
[d] *College of Liberal Arts and Sciences, Kobe University, 1-2-1 Tsurukabuto, Nada 657, Kobe, Japan*

(Received June 29, 1992; revised version accepted October 5, 1993)

Abstract

Paleomagnetic dating of continuously growing stalagmites by comparing their paleomagnetic records with a standard record, has been applied to study the paleoseismic history of a region of western Japan. Three stalagmites (speleothems), which are assumed to have started growing since collapse of the limestone blocks on which they are formed, were collected from two limestone caves located below the Akiyoshi plateau, western Japan. From the paleomagnetic results, it is estimated that they began to grow at 6000, 2500 and 2000 yr B.P., respectively. On the assumption that their growth began immediately after their host limestone blocks fell, these three ages are interpreted to indicate the dates of past earthquakes in this region which triggered the break-off and fall of the blocks. Earthquakes are suggested because many huge collapsed limestone blocks and speleothems are observed in many caves in this region.

1. Introduction

Collapsed host limestone blocks and speleothems can be observed in many limestone caves on the Akiyoshi plateau, western Japan. They are large in number and scale, raising the possibility that such collapse events are associated with earthquakes in the vicinity of limestone caves. It is possible that such collapse events bear no relationship to earthquakes, and may be caused, for example, by the artificial destruction and/or the natural collapse of limestone caves. However, in our view this does not adequately explain the large-scale extent of the collapse events in this region. In addition, in a region of seismic activity earthquakes contribute to a "ready-to-collapse" condition and may trigger block falls, even if they are sporadic. We consider it, therefore, reasonable to suppose that earthquakes triggered the natural break or fall of limestone blocks and speleothems.

Postpischl et al. (1991) demonstrated that the collapse and the growth anomaly of speleothems observed in limestone caves can be used for paleoseismic analyses. They dated the occurrence of the causative earthquakes from both ^{14}C and U/Th analyses of stalagmites (growing upward on the cave floor) that either showed interruption

SSDI 0040-1951(93)E0212-D

of growth during collapse or start of growth upon collapse of limestone blocks (fig. 3-F of Postpischl et al., 1991). Dating of stalagmites of which the growth is interrupted by collapsed blocks can give a lower age limit for strong earthquakes. In contrast, dating of stalagmites that started growing on collapsed blocks can give the upper age limit. They also reported that abrupt changes in the growth symmetry axis of speleothems may record earthquakes.

We have the same idea as Postpischl et al. (1991), that the collapse in limestone caves has been triggered by earthquakes. We report here results of a paleomagnetic dating of stalagmites and demonstrate the potential of the method as a promising dating tool.

2. Paleomagnetic dating of speleothems

It is known that speleothems have fairly weak but stable remanent magnetization (e.g., Latham et al., 1989; Morinaga et al., 1989). Thus, we may be able to determine paleosecular variation (PSV) of the geomagnetic field through paleomagnetic measurements of thin specimens of successively more interior parts of speleothems. Comparison of the PSV with the standard curve can give an estimate of the time of the beginning and end of their growth. This paleomagnetic method may be advantageous. It utilizes many data and may, therefore, result in ages that are determined with high precision.

Holocene stalagmites, which are observed on collapsed limestone blocks or on other speleothems in limestone caves, may have started to grow immediately after collapse of such limestone blocks and speleothems, assuming that climatic conditions for their growth have continued to be suitable during the Holocene. For paleomagnetic dating of stalagmites, we prefer stalagmites that started growing after collapse rather than stalagmites whose growth was interrupted by collapse.

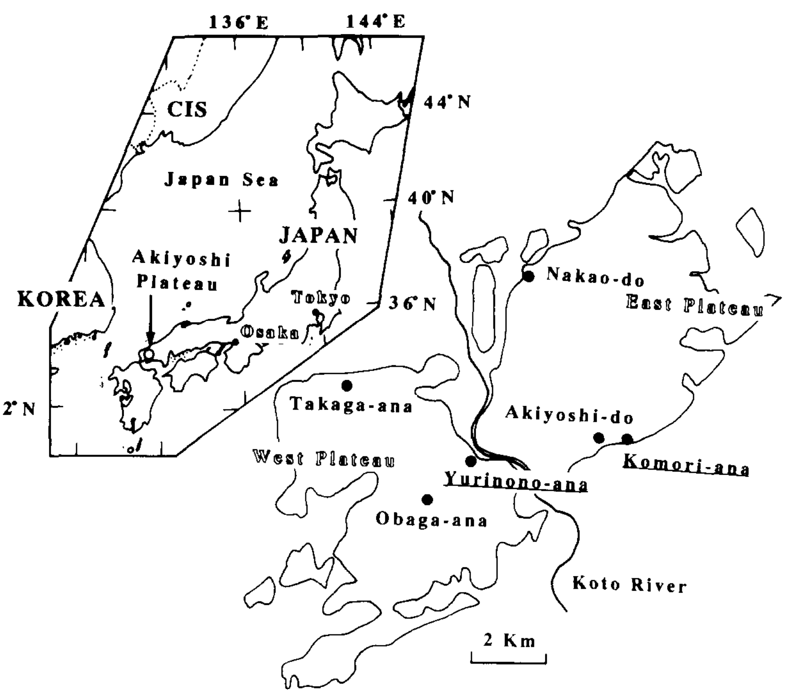

Fig. 1. Sampling location on the Akiyoshi plateau, western Japan. Many large collapsed limestone blocks and speleothems are observed in the Nakao-do, Takaga-ana, Akiyoshi-do, Komori-ana, Yurinono-ana and Obaga-ana caves. Paleomagnetic stalagmite samples were collected from the Komori-ana and Yurinono-ana caves.

The latter ones had been growing during an indeterminate period before the collapse, and the comparison of the PSV curve with the standard one becomes arbitrary. Therefore, we can not uniquely determine their ages. For the former ones, in contrast, we can judge whether they were growing at the time of their collection. If we were able to determine that they were growing upon collection, we can date the surface layer as of present origin and pin the PSV record accordingly. This method reduces the uncertainty when comparing their PSV curve with the standard one.

3. Sampling locality and stalagmite samples

Sporadic earthquake activity is known from the historic period (Usami, 1987) in the vicinity of Yamaguchi Prefecture (western Japan) that includes the Akiyoshi plateau (Fig. 1). Many collapsed huge limestone blocks, stalactites (growing downward from the cave ceiling), stalagmites and flowstones (growing on the cave floor and wall) are observed in some limestone caves throughout this plateau. Collapsed limestone blocks and speleothems are prevalent in the following caves: Akiyoshi-do, Takaga-ana, Nakao-do, Obaga-ana and Yurinono-ana caves (Fig. 1).

The stalagmites on collapsed blocks were investigated from two caves in this plateau; Yurinono-ana (YLI) and Komori-ana (KMR) caves. Both caves are almost horizontal with an extent of about 250 m. The Yurinono-ana cave is 10–35 m wide and 2–8 m high, whereas the Komori-ana cave is relatively narrow with several small passages; maximum width and height are 15 and 12.5 m, respectively. Many large collapsed blocks are observed in both caves, but the blocks in Yurinono-ana cave are generally larger than those in the Komori-ana cave. For example, many huge

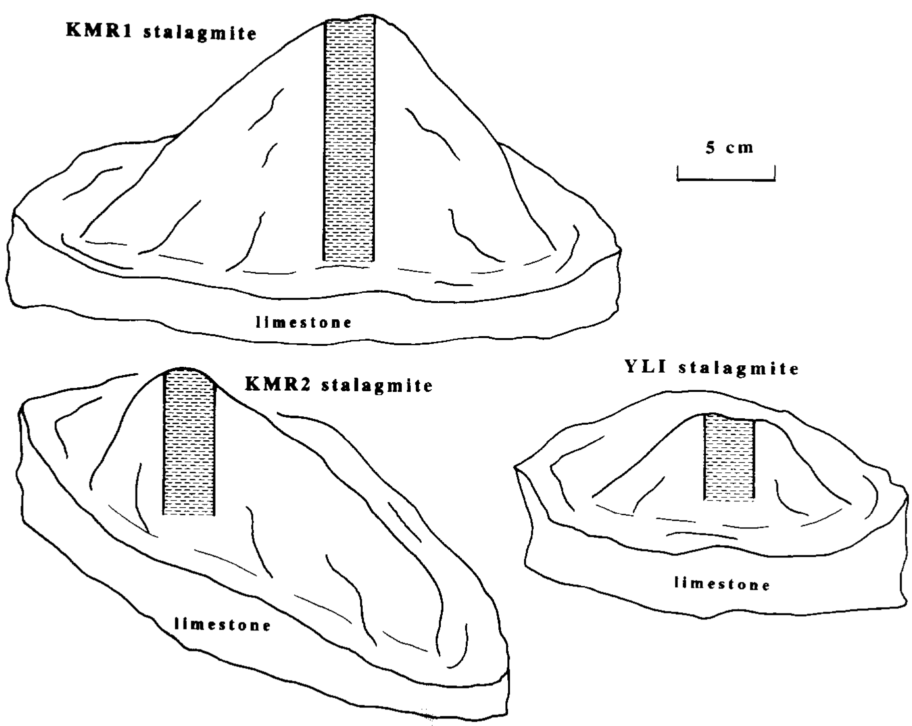

Fig. 2. Sketch of core samples within the three investigated stalagmite samples. All stalagmites are assumed to have continued growth until their collection. Only a small part of the collapsed limestone blocks is drawn.

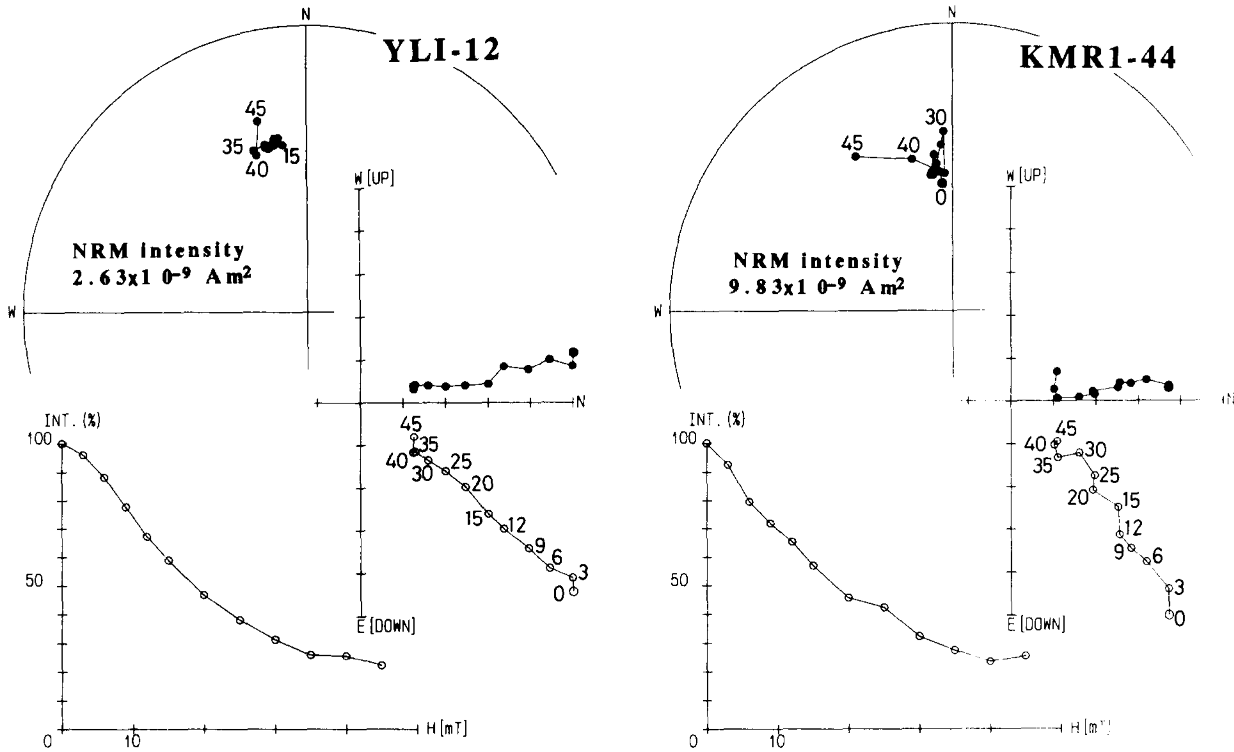

Fig. 3. Typical results of progressive alternating-field demagnetization for specimens showing the most stable NRM. Numbers adjacent to circles/dots denote peak intensity of alternating field in mT.

stalagmites about 1 m in diameter and many huge limestone blocks of a few tens of centimetres to over 1 m thickness have fallen down everywhere in the Yurinono-ana cave.

Three stalagmites on large collapsed limestone blocks were oriented in situ using a magnetic compass and then collected; one from the Yurinono-ana cave (YLI) and two from the Komori-ana cave (KMR1 and KMR2), respectively (Fig. 2). We judged that all these stalagmites had been growing until collection, because water had been dripping onto their tops from the cave ceiling.

4. Sample preparation and magnetic measurements

In the laboratory, core samples of 2.5 cm in diameter were drilled along the growth axis of the three collected stalagmites. These were then sliced into thin disc specimens of 2.0–3.5 mm thickness for magnetic measurements. The three core samples, YLI, KMR1 and KMR2, are about 4, 12 and 7 cm long, from which 15, 51 and 24 disc specimens were obtained, respectively. Their remanent magnetization was measured with a ScT cryogenic magnetometer whose sensitivity is 10^{-11} Am^2. Progressive alternating-field demagnetization (PAFD) was applied in order to test their magnetic stability and to eliminate a viscous component. PAFD steps were 3, 6, 9, 12, 15, 20, 25, 30, 35, 40 and 45 mT for all specimens.

Typical examples of the progressive AFD treatment are shown in Figs. 3 and 4. For the specimens with a total natural remanent magnetization (NRM) moment above 2×10^{-9} Am^2, a stable behaviour was observed during the PAFD treatment. But for the specimens with a NRM moment less than about 10^{-9} Am^2, a fairly unstable behaviour was observed. For the two weakest specimens from KMR1 and KMR2, even no sta-

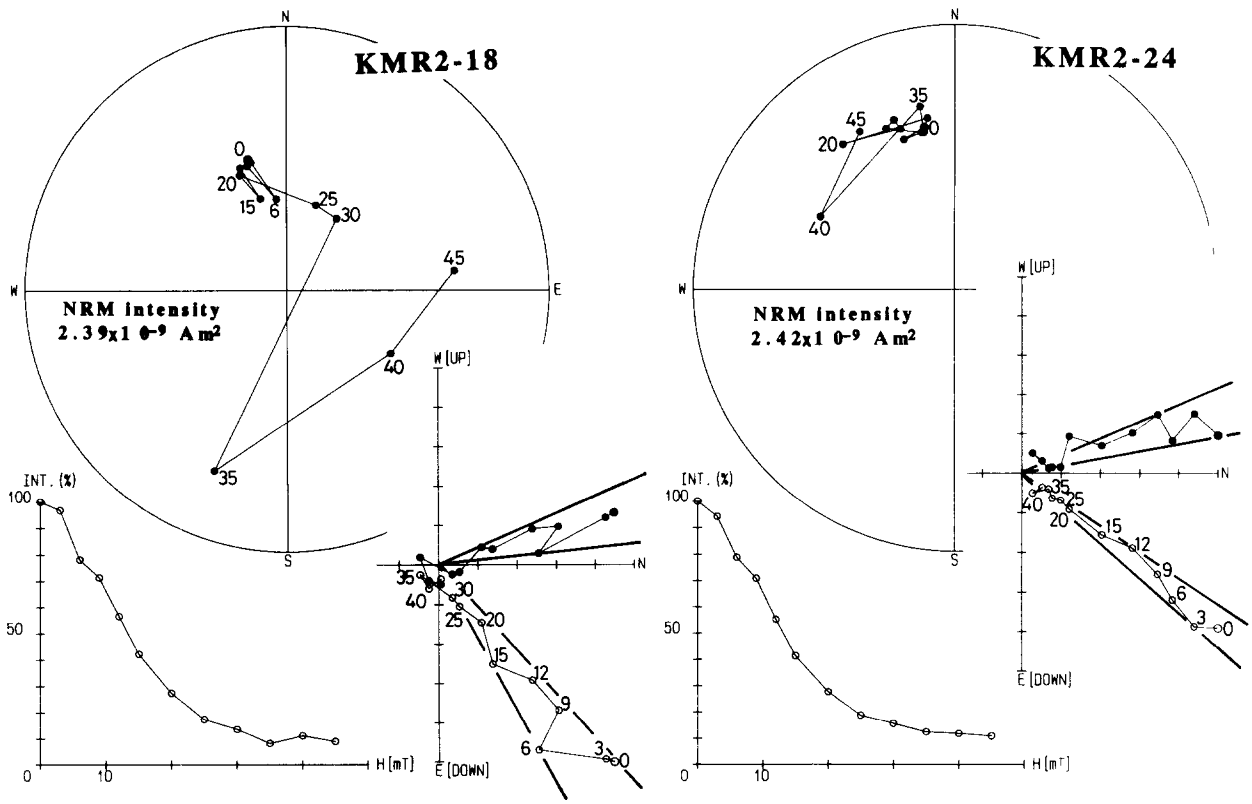

Fig. 4. Typical results of progressive alternating-field demagnetization for specimens showing NRM of an intermediate stability. Numbers adjacent to circles/dots denote intensity of alternating field in mT. Straight bold lines indicate the range of irregular behaviour.

ble component was obtained and they were not used for further paleomagnetic analysis.

Typical PAFD behaviours of the two specimens (YLI-12 and KMR1-44) of the most stable NRM are indicated in Fig. 3a and b. The median destructive fields (MDFs) are about 20 mT for these specimens. A stable component that converged toward the origin was recognized up to AF levels of 45 and 35 mT for YLI-12 and KMR1-44, respectively. A small number of specimens only show similar PAFD behaviour, particularly so for the two KMR stalagmites: namely 7(/15), 6(/51) and 2(/24) from the YLI, KMR1 and KMR2 stalagmites, respectively.

The typical PAFD behaviour for two specimens (KMR2-18 and -24) of an intermediate stable of NRM is indicated in Fig. 4a and b. The MDFs of these specimens range from 10 to 20 mT. The orthogonal plots are somewhat irregular. We suggest that this was caused by effects such as the inaccurate installation of disc specimens in the magnetometer holder, weak remanence compared to the noise level of the magnetometer (less than 10^{-10} Am^2), and/or unstable components. Most of the specimens show this kind of behaviour: namely 8(/15), 43(/51) and 20(/24) for the YLI, KMR1 and KMR2 stalagmites, respectively.

5. Paleomagnetic results and discussion

The characteristic direction for each specimen was calculated by principal component analysis (PCA) using visual inspection of the AFD data.

This procedure was effective in negating the demagnetization irregularities induced from causes such as those mentioned in the preceding section. The bulk NRM intensity before the AFD (A), declination (B) and inclination (C) of the characteristic direction after AFD treatment plotted against distance from the surface of each sample is shown in Fig. 5.

For the two stalagmite samples from the Komori-ana cave, the directions are rather scattered in the younger portion near the surface. Most of these younger specimens had weak intensities, less than 2×10^{-9} Am^2 (shown by broken lines in bulk NRM intensity figures). This suggests that the characteristic directions become successively more reliable with increasing NRM intensity. It is to be expected, therefore, that the younger portion of smoothed variation curves may not adequately represent the PSV of the geomagnetic field.

The three sets of curves, however, show considerably similar variation pattern (shown by letter sequence in Fig. 5). This similarity is interpreted as evidence that these curves reflect the geomagnetic secular variation. The difference in length of the variation records suggests that three stalagmites started growing at different times in the past. Under the assumption that the three stalagmites started growing on the collapsed limestone blocks immediately after their falling, this

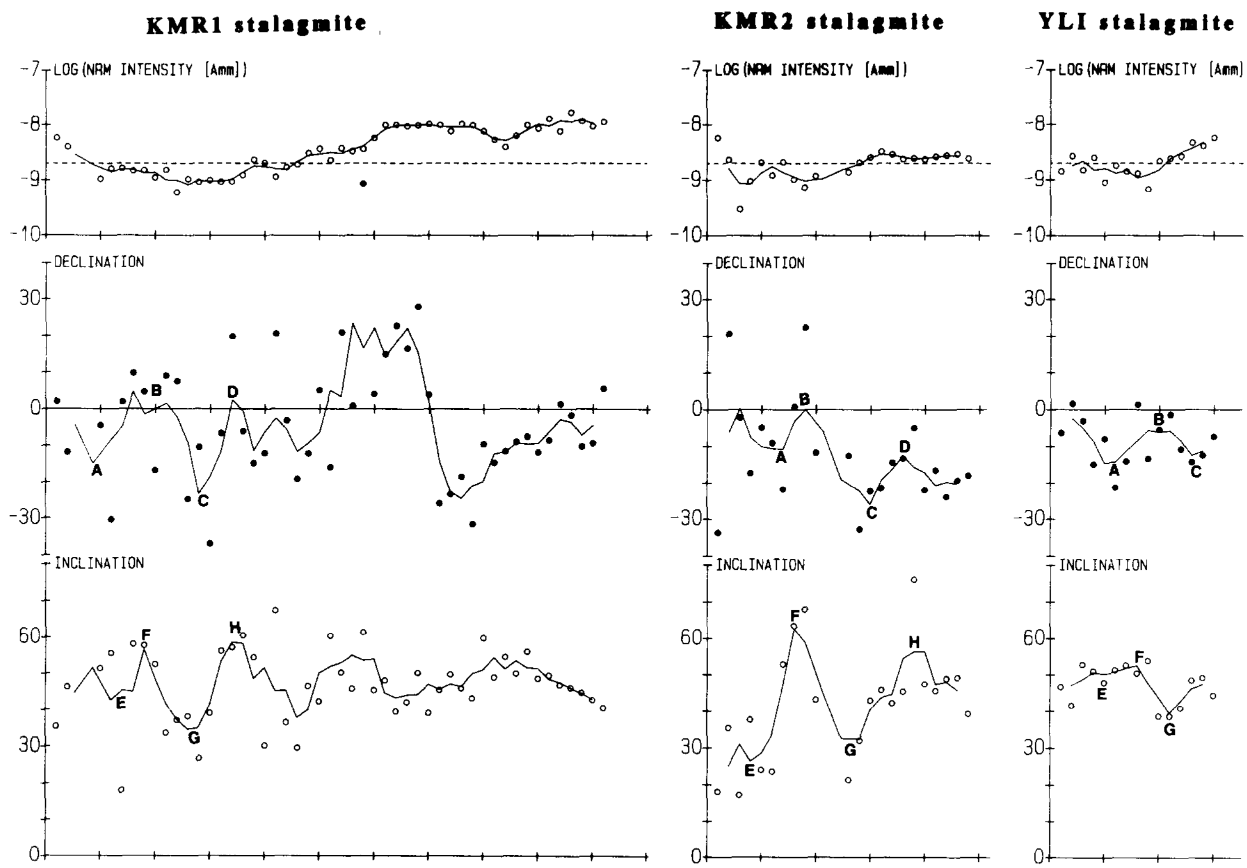

Fig. 5. Variations of bulk NRM intensity and characteristic direction throughout each stalagmite. The left end of the figures indicates the surface of each stalagmite, corresponding to the present time and the right side indicates the inner portion. The horizontal axis shows specimen numbers in increasing order from the sample surface and one division corresponds to five specimens. Solid lines show smoothed variation curves connecting three-point running-means. Letters adjacent to the curves indicate interpreted correspondence between the three results.

could suggest the occurrence of three different earthquakes.

In order to estimate the time of origin of the earthquakes, the longest smoothed record of KMR1 was compared with a PSV record from unconsolidated sediments in western Japan (Hyodo et al., 1993). Correlation of the KMR1 record and the sedimentary record (shaded range) is shown in Fig. 6. From this correlation, it is concluded that the KMR1 stalagmite started growing at about 6000 yr B.P., directly after collapse of the host limestone block. The KMR1 stalagmite is estimated having grown at an average rate of 2.0 cm per 1000 yr.

Comparison of the KMR2 and YLI results with the KMR1 record leads to the conclusion that these other two stalagmites started growing at about 2500 and 2000 yr B.P., respectively, under proviso of a constant growth rate of the KMR1 stalagmite. This suggests that two different earthquakes occurred at about 2500 and 2000 yr B.P. Average growth rates of these two stalagmites, KMR2 and YLI are accordingly estimated to be 2.8 and 2.0 cm per 1000 yr, which are nearly equal values to those of previously investigated stalagmites in western Japan (Morinaga et al., 1989).

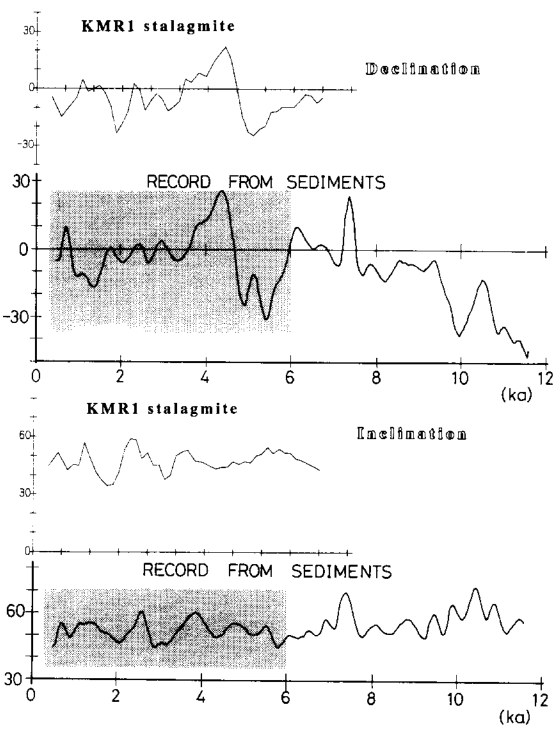

Fig. 6. Comparison of variation curves from the KMR1 stalagmite with a standard curve from unconsolidated sediments in western Japan (Hyodo et al., 1993). The KMR1 record can be correlated well with the shaded range in the sedimentary record.

The time resolution of this paleomagnetic method depends on the growth rates of the stalagmite samples and/or the thickness of disc specimens for magnetic measurements, if the magnetic records are reliable. Samples of higher growth rates and/or preparation of thinner disc specimens can bring about more reliable PSV records and facilitate comparison between records with a higher time resolution. However, in this study records of directions are rather scattered in the younger portions, implying that the time resolution of these records is not so high. Therefore, the difference of 500 yr between the ages of the KMR2 and YLI stalagmites is unsubstantial, although the KMR2 stalagmite apparently has an older paleomagnetic record than the YLI stalagmite.

6. Concluding remarks

Interpretation of the paleomagnetic records of three stalagmites from the Yurinono-ana and Komori-ana caves suggests initiation of growth at 6000, 2500 and 2000 yr B.P., respectively, on the collapsed limestone blocks. Previous paleomagnetic work (Morinaga et al., 1988) on another stalagmite collected from the Yurinono-ana cave, suggests that growth started at 4500 yr B.P. These four ages may represent upper age limits of past earthquakes that may have triggered the fall of host limestone blocks and speleothems. These earthquakes do not necessarily correspond to fairly strong ones, although the presence of many collapsed large-scale blocks suggests that this was the case.

Paleomagnetic dating of speleothems, as described in this paper, is proposed as a method for studying paleoseismicity in this region. These four ages, however, probably represent no more than a subset of paleoseismicity around the Akiyoshi plateau. For a full description of the periodicity and frequency of strong earthquakes, it will be necessary to obtain many more dates following this method. The method has the advantage that it may trace the paleoseismicity back to several hundreds of thousands of years B.P., when caves in this region started growing. However, practical application of the method is restricted to the last few tens of thousands of years, for which the standard PSV of the geomagnetic field direction in western Japan is known (Hyodo et al., 1993).

7. Acknowledgements

We express our special thanks to Dr. Tadashi Kuramoto of the Akiyoshi Museum of Natural History for his valuable advice during the sample collection in the caves. We would like to thank Mr. Yoshinori Kawamura of Faculty of Science, Kobe University for his help during magnetic measurement of stalagmite samples. This paper benefited from the reviews of the first manuscript by Drs. C. Klootwijk of Australian Geological survey Organisation, D.C. Ford of McMaster University, and Z. Zheng of Tokyo Institute of Technology. This work was supported by the Ministry of Education, Science and Culture Grant-in-Aid for Scientific Research on Priority Areas No. 02246208 and Grant-in-Aid for Encouragement of Young Scientists No. 03854035.

8. References

Hyodo, M., Itota, C. and Yaskawa, K., 1993. Geomagnetic secular variation reconstructed from magnetizations of wide-diameter cores of Holocene sediments in Japan. J. Geomagn. Geoelectr., 45: 669–696.

Latham, A.G., Ford, D.C., Schwarcz, H.P. and Birchall, T., 1989. Secular variation from Mexican stalagmites: their potential and problems. Phys. Earth Planet. Inter., 56: 34–48.

Morinaga, H., Horie, I., Murayama, H., Liu, Y.Y., Kuramoto, T. and Yaskawa, K., 1988. Age determination of collapse in limestone cave by paleomagnetism of speleothems—an example for Yuri-no-ana cave. Rock Magn. Paleogeophys., 15: 15–20.

Morinaga, H., Inokuchi, H. and Yaskawa, K., 1989. Palaeomagnetism of stalagmites (speleothems) in SW Japan. Geophys. J., 96: 519–528.

Postpischl, D., Agostini, S., Forti, P. and Quinif, Y., 1991. Palaeoseismicity from karst sediments: the "Grotta del Cervo" cave case study (Central Italy). Tectonophysics, 193: 33–44.

Usami, T., 1987. Materials for Comprehensive List of Destructive Earthquakes in Japan. Univ. Tokyo Press, Tokyo, 435 pp (in Japanese).