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Speleogenesis in the hyperkarst of the Nakanai Mountains (New Britain, Papua New-Guinea). Evolution model of a juvenile system (Muruk Cave) inferred from U/Th and paleomagnetic dating

P. Audra[1], S. E. Lauritzen[2] and P. Rochette[3]

[1] *UMR 6012 ESPACE CNRS, University of Nice Sophia-Antipolis, 98 boulevard Edouard Herriot, 06000 NICE, FRANCE (audra@unice.fr).*

[2] *University of Bergen, Department of Geology, Allegaten 41, 5007 BERGEN, NORWAY (stein.lauritzen@geo.uib.no).*

[3] *UMR 6635 CEREGE CNRS, University of Marseille - Saint-Jérôme, Europôle méditerranéen de l'Arbois, 13545 Aix-en-Provence Cédex 04, FRANCE (rochette@cerege.fr).*

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***Abstract:** Muruk is the deepest cave in the Southern Hemisphere (1178 m of depth). It gives an access to go through the Nakanai Mountains and across large galleries, sometimes more than 50 m wide. Considering the important rainfall, the very active uplifting and the presence of a rainforest, Papua can be regarded as a hyperkarst, with large morphological forms evolving very quickly. U/Th and paleomagnetic dating on cave sediments confirm this point of view, assigning a very recent age to this cave system (100 to 200 kyr). Muruk is a model of juvenile systems with a regularly inclined profile and with a monophase evolution excluding any old perched level, unlike usual cave systems. These characteristics are essential for understanding not only the first speleogenetic phases, but also the more evolved systems found throughout the world.*

***Key words:** speleogenesis, hyperkarst, Nakanai Mountains, New Britain, Papua New-Guinea, juvenile cave system, Muruk Cave, U/Th and paleomagnetic dating.*

1. Introduction

Karst systems begin to develop when a hydraulic head appears, generally following uplift. For this reason, most of the large alpine karst systems are post-Miocene. However, study of these systems is difficult because of nearly 5 million years of complex evolution and the lack of reliable dating methods for these periods. The goal of this research was to study karst system development in a more recent environment and to determine the evolutionary characteristics of a simple case that could then be used as a model, taking advantage of current dating methods. The New Britain island karsts are of Quaternary age, and no older than Upper Pliocene. They have been intensely uplifted and harbor huge karst systems, such as Muruk Cave, which is the largest through-cave in the Southern Hemisphere.

2. A recent karst, a large cave system

2.1. The hyperkarst of Nakanai mountains

The Nakanai Mountains are located on the island of New Britain, east of Papua-New-Guinea (Fig. 1). The island results from the subduction of the Australian plate moving northward under the Pacific plate. This crustal movement has generated the New Britain trench, edging the southern coast and an active volcanic arc on the north coast. The Miocene limestone platform lies on an old paleogene volcanic arc located along the south coast. These limestones were themselves covered by a thick Pliocene volcano-sedimentary series (Thery and Thery, 1987; Maire, 1990).

The active margin has been subjected to vigorous uplifting since the Upper Pliocene. The violent seismicity and regular explosive eruptions highlight the present tectonic activity. The Nakanai mountains include a large plateau, with a high point of 2185 m above see level (asl.) in the north, which descends to the south coast and is cut by canyons more than 1000 m deep. The area studied, around the Muruk cave entrance,

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Corresponding author: Email: audra@unice.fr

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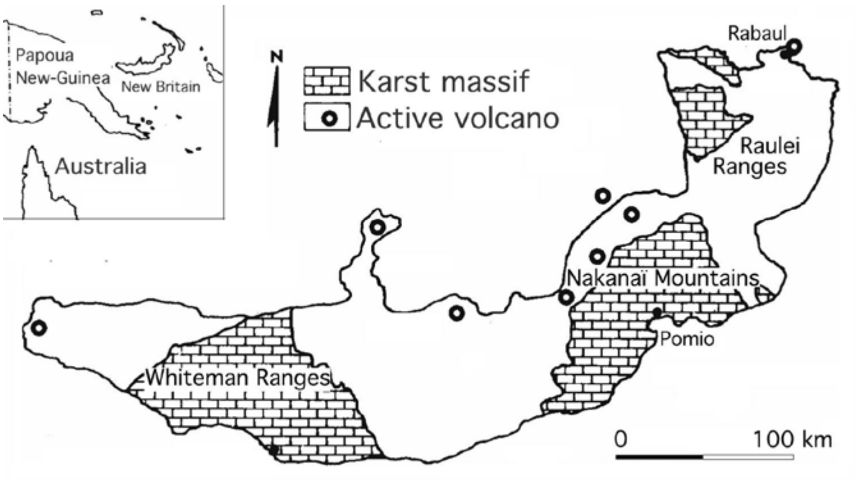

Fig. 1 - Location of Nakanai mountains, a New Britain karst in Papua-New-Guinea (after Maire et al., 1981).

is at an elevation of about 1400 m asl. on the edge of the Galowe canyon, the base of which is around 200 m asl., which represents an important topographic gradient.

Since the beginning of the Upper Pliocene uplift, the volcano-sedimentary deposits have been weathered and eroded, bringing the limestones to the surface and allowing the karst processes to occur. Clay sediments presently exist as detritic cover, only a few meters thick, covering the karst relief. This combination results in the formation of rounded hills and deep depressions joined by small valleys. During heavy rainfall, these valleys are filled by torrents with discharge reaching several m^3/s. The flow is absorbed after variable distances into sinkholes feeding the underground system.

The mountains are subjected to an oceanic monsoon climate, characterized by considerable rainfall (3 m on the coastline, 10 to 12 m in the mountains). This significant and continuous humidity, combined with warm temperatures all year round, allows a rainforest development, still untouched by industrial exploitation.

Karst processes in Muruk cave are directed by exceptional conditions:

- a host rock composed of very pure limestone subjected to solution; moreover, the lack of compaction and chalky facies make it very susceptible to mechanical erosion;
- significant rainfall supplies large amounts of water concentrated by the clay-rich valleys before being injected into the karst;
- a rainforest with a highly productive biomass, providing CO_2 and humic acids necessary for solution processes;
- a particularly great topographic gradient (1000 to 1500 m).

For these reasons, karstic denudation, which generally takes into account only solution processes, but to which it would be necessary to add mechanical processes, is estimated at 400 m^3/ km^2/ yr, a world record (Audra 2001b; Maire, 1990). Finally, Nakanai can be considered a “hyperkarst”, since so many factors favoring karst processes are pushed to an extreme. One can expect therefore to find cave systems characterized by a magnitude and evolutionary dynamic without equal.

2.2. Muruk, an exceptional cave system

Muruk Cave is presently the largest cave system in the southern hemisphere (Hache et al., 1995) with a hydrogeologic through-passage 10 km long, and a depth of 1178 m (Fig. 2). The entrance acts as a valley sinkhole during heavy rainfalls. Within the cave system, shafts are uncommon and rarely deep, the system being composed mainly of large gently sloping passages.

Morphological analysis shows that the system began as a tube sloping gently from sinkhole to spring. This tube evolved afterwards by entrenchment into a canyon and then in the downstream part into large passages that reach more that 50 m in diameter. It is a case of a monophased system, exceptional in a mountain environment, bearing no perched level except for some diffluences marking a local reorganization in the vicinity of the spring.

Water leaves the system at the Berenice resurgence, which has a porch entrance, perched 50 m above the Galowe river. This shows the lag time between karst processes compared to fluvial entrenchment, which is the result of the rapid uplift.

The morphology is typical to of monophased juvenile karst system. Taking into account the rapidity of karst processes, it suggests that the organization of Muruk system is relatively recent. The sediments ages support this hypothesis.

3. Chronological data

Sampling of fine detritic sediments and speleothems was made for paleomagnetic dating. The speleothems were also dated by U/Th method. Recent deposits such as flooding clays and active flowstones were avoided. The selection of the most ancient sediments was made according to stratigraphic location.

3.1. Two stratigraphic sequences of cave sediments

The older sequence consist of two types of sediments:

- more or less sandy clays, very compact, with a black coating (n° 9, 11 in Cassiquiare; n° 19 in -800 Bypass).
- laminated brownish speleothems, overlying the older black clays (n° 8, 10 in Cassiquiare; n° 17 -800 Shunt).

All of these first generation sediments have been intensively eroded by a subsequent resumption of the cave

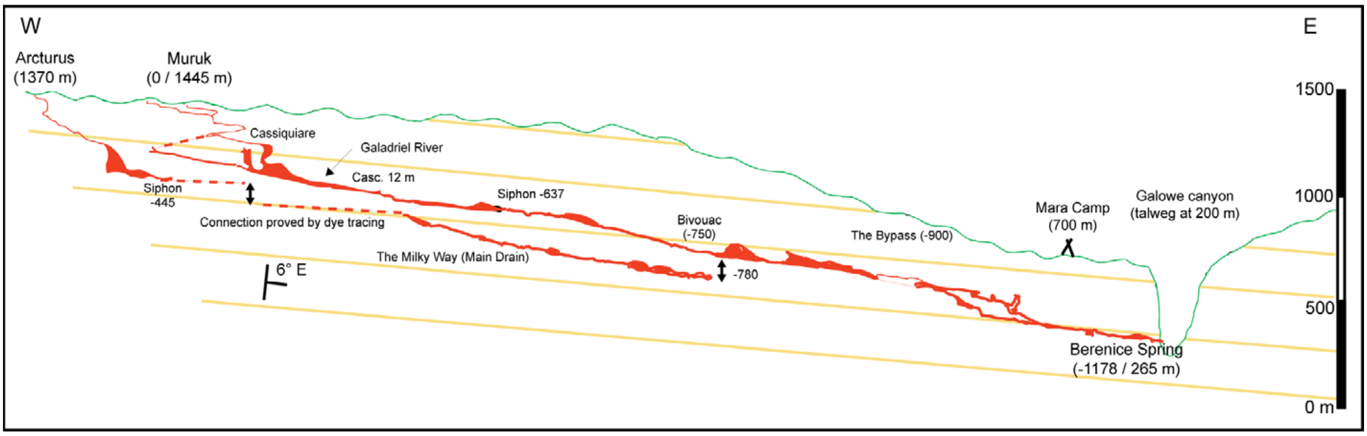

Fig. 2 - Profile of Muruk system (surveyed by Papou 1985, Hémisphère Sud 1995 and Nakanai 1998 expeditions).

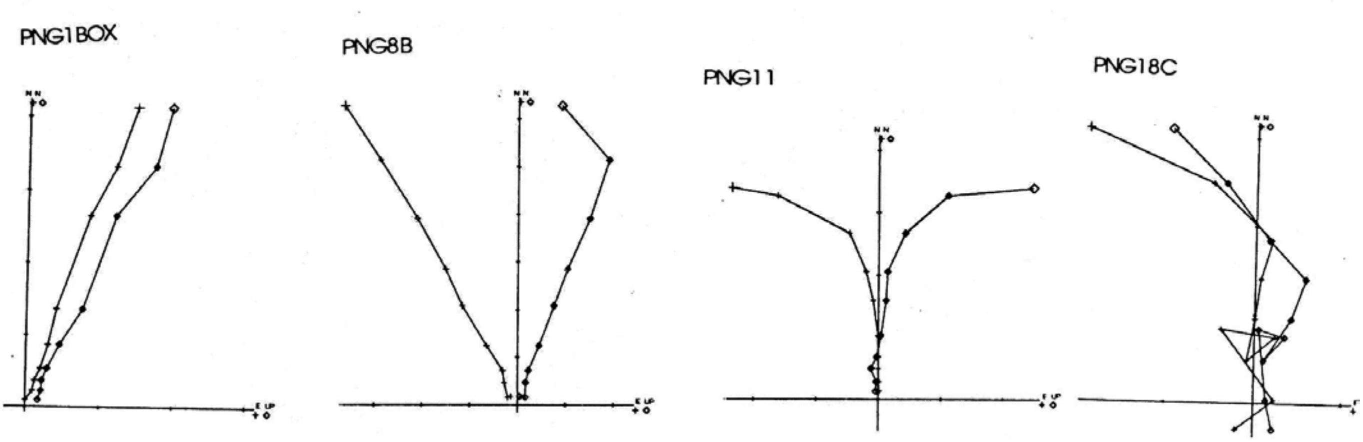

Fig. 3 - Orthogonal Zijderveld plots showing the NRM vector evolution during AF demagnetization up to 100 mT.

stream and subsist only as discontinuous clay veneer and eroded speleothems.

This older sequence is followed by a second sedimentation phase:

- a new detritic phase rich in clays (n° 1, 2, 3 in -800 Bypass; n° 4, 5 in the 12 m Waterfall tributary, around -500) and sandy clays (n° 13, 14, 15 in -800 Bypass), not eroded.
- a second calcite deposition phase with a sound surface uneroded by the stream (n° 18 in -800 Bypass).

It appears therefore that there were at least two consecutive sequences of stream activity, both followed by a diminished flow with speleothem deposition.

3.2. A recent paleomagnetic signature

The natural remnant magnetizations (NMR) from 25 samples were measured with a rotating remanometer (JR5A Spinner Magnetometer) during demagnetization in an increasing alternating field (AF), up to 100 mT (Table 1). Most samples show strong directional stability during demagnetization (specimen 1 and 8 b) while a few samples have either a large secondary component erased by an AF of 20-50 mT (e.g. 11) or poorly defined behavior due to low intensity (e.g. 18 c) (Fig. 3). All characteristic directions show normal polarities pointing toward deposition in the Brunhes period (< 780 kyr).

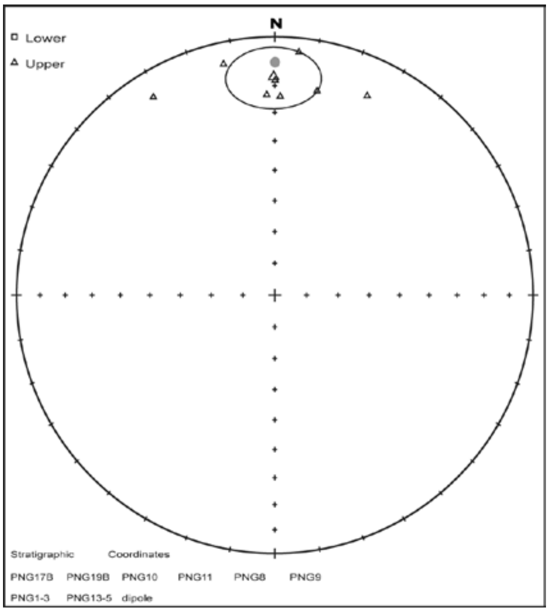

Fig. 4 - Stereoplot of site mean characteristic directions (site defined in table 1), excluding poorly defined specimen direction (α > 20). The mean direction with its circle of confidence appears as a large triangle while the predicted mean geomagnetic field is shown by a circle. All directions are in the upper hemisphere.

Table 1.

Paleomagnetic results. Specimen NRM intensity, characteristic directions with their confidence angles obtained from AF demagnetization diagram by principal component analysis (a few samples have only one demagnetization step and therefore no confidence angle), magnetostratigraphic interpretation (measurements performed in CEREGE).

Sample ref.	Location	Sediment type	Int. (mA/m)	Decl. (°)	Incl. (°)	α	Direction
PNG 1 box	-900 Bypass	Clay with mud-cracks	4,8 E-2	20	-24	2,7	Normal
PNG 2 box			4,9 E-2	16	-20	4,3	Normal
PNG 3 box			5 E-2	5	-20	2,4	Normal
PNG 4 box	12 m Waterfall tributary	Entrenched flood clay	3,7 E-2	330	34	24,9	Normal
PNG 5 box			4,3 E-2	60	9	6,4	Normal
PNG 8 a	Cassiquiare	Brown laminated flowstone, younger than PNG 9	5,3 E-2	332	-6	4,0	Normal
PNG 8 b			1,5 E-1	330	-7	2,2	Normal
PNG 8 c			3 E-2	323	36	13,5	Normal
PNG 9 a	Cassiquiare	Dense brown clay with black coating	1,7 E-1	342	-15	5,2	Normal
PNG 9 b			2 E-1	332	11	5,6	Normal
PNG 10 a	Cassiquiare	Brown laminated flowstone, younger than PNG 11	1,5 E-1	9	-22	4,0	Normal
PNG 10 b			1,5 E-1	10	-7	4,4	Normal
PNG 10 c			2,1 E-1	7	-12	2,4	Normal
PNG 11 a	Cassiquiare	Dense brown clay with black coating	2,4 E-1	326	-31	4,9	Normal
PNG 11 b			4,9 E-1	69	-13	4,2	Normal
PNG 11 c			3,9 E-1	17	-48	3,3	Normal
PNG 13 box	-900 Bypass	Muddy sand, older than PNG 18	3,9 E-2	347	-28	7,4	Normal
PNG 14 box			4,8 E-2	5	-23	8,2	Normal
PNG 15 box			3,2 E-2	5	-25	10,3	Normal
PNG 17a	-900 Bypass	Old calcite floor, broken by neotectonic	5,8 E-3	359	-13	-	Normal
PNG 17b			6,3 E-3	358	-23	5,3	Normal
PNG 17c			4,2 E-3	356	-17	-	Normal
PNG 18a	-900 Bypass	Stalagmite corroded by dripping solution	1,2 E-3	268	-23	11,2	Normal
PNG 18b			7,6 E-3	299	12	24,6	Normal
PNG 18c			3,8 E-3	329	15	24,3	Normal
PNG 19a	-900 Bypass	Grey sandstone with black coating	4 E-1	316	51	26,9	Normal
PNG 19b			5,6 E-1	72	6	17,6	Normal

Mean direction using all characteristic specimen directions is D = 1; I = -14; α95 = 10; N = 25; and a selection of well defined directions (α < 20) grouped by site yields D = 0; I = -17; α95 = 12; N = 9. Both directions show correct declination but higher inclination than the predicted mean geomagnetic field for Brunhes period at Muruk (-11), although this direction is within the 95% confidence (Fig. 4). This deviation, if statistically significant, may be due to a recent 6 degree southward tilting of the area. Alternatively, it may correspond to an insufficient averaging of secular variation. Indeed, the present day field shows an inclination of -25.

This first chronological approach confirms the recent age of the Muruk system. Speleothem U/Th dating confirms these measurements and produces more accurate chronological data as described below.

3.3. Speleothems less than 50 000 years old

Speleothems were also dated using the radiometric U/Th method by mass-spectrometry (Table 2). Uranium content has an average of around 0.5 ppm. The ^{230}Th / ^{234}U ratio allows us to calculate the sample age. The ^{234}U / ^{238}U ratio is slightly above 1 and the ^{230}Th / ^{232}Th is very high. This reveals the absence of detritic contamination linked to the opening of the system, so the ratios indicate a good reliability of calculated ages. Radioactive elements present correspond only to those trapped during calcite deposition. For all samples, ages are recent, dating between 8 and 50 kyr.

The data are useful for understanding the impact of climate change in the past in the warm and wet areas of the Earth, such as Papua. Compared to frequency statistics for cold and temperate flowstones from the northern hemisphere, the datings correspond to frequency minima linked to the last

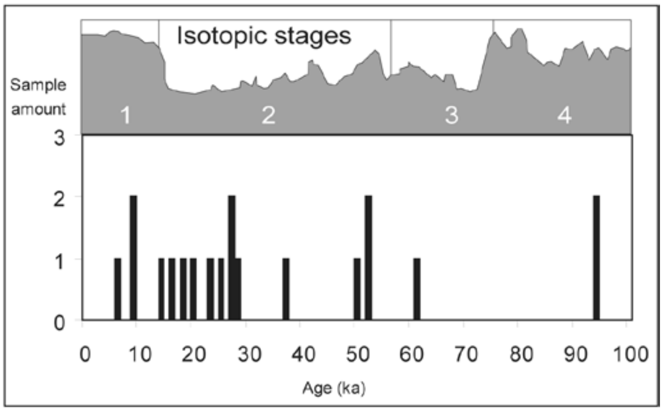

Fig. 5 - Distribution of low-latitude speleothem growth periods during the last 100,000 years, compared to the oceanic paleotemperature curve. Data from Borneo (Farrant, 1995) and Papua.

Table 2.

Geochemical data obtained by U/Th method and ages of Muruk speleothems (dating by S.-E. Lauritzen, Bergen).

Location	Sample ref.	U (ppm)	$^{234}U / ^{238}U$	$^{230}Th / ^{234}U$	$^{230}Th / ^{232}Th$	Age (ka)
Cassiquiare	PNG 8	0,79	1,594	0,0778	61	8,75 (± 0,48)
Cassiquiare	PNG 10	0,34	1,21	0,3718	75	49,7 (± 1,12)
Shunt -900	PNG 17	0,68	1,37	0,1937	492	23,13 (± 0,54)
Shunt -900	PNG 18	0,74	1,34	0,1225	301	14,1 (± 0,31)

cold periods, such as Boreal (for the sample at 8.78 ka), Older Dryas (for 14.1 ka), cold maximum of recent Wüm (for 23 ka) and to a less cold interstage (for 49.7 ka).

It appears therefore that these periods, characterized by a clear reduction or break in speleothem deposition in mid latitudes, do not show the same trend in low-latitude speleothem growth. Data from about twenty datings on Borneo's speleothems lead to similar conclusions (Fig. 5).

The dating provides a precise chronological frame. All the deposits are younger than 780 kyr, with the possibility that their age could be very recent within this window. None of the speleothems dated is older than 50 kyr. Though these are not the oldest sediments in the cave because they succeed an argillaceous sedimentation phase. These first known deposits could have been introduced into the cave some time after cave system initiation. However, it seems acceptable to suppose that the initiation of the karst system dates to a maximum of some hundreds of thousands of years. Very few in contrast to northern hemisphere alpine karst systems that initiate at the Mio-Pliocene limit, or even before (Audra, 1994).

4. Conclusion

The Muruk cave system probably initiated around 100 to 200 kyr, according to a base level located 50 m above the present Galowe River, as shown by the Berenice perched spring (Fig. 2). The efficiency of the karst processes, which led to such extraordinary dimensions in both vertical and horizontal extension, and in size can only be explained by the particular conditions discussed above. The most important are the high tectonic activity and the abundant rainfall. Can also be added the role of the rainforest and of clay covers concentrating the water. Finally, another originality comes from the poorly compacted host rock, creating galleries that enlarge quickly by a combination of chemical and mechanical processes from underground streams but also by vault collapse, as the cave is shaken regularly by seismic movements (Audra, 2001a; Maire, 1990).

Cave genesis can be described as follows: water flows over the clay cap and enters the limestone through the sinkholes. It then follows a nearly straight line to the springs into the limestone mass, not karstified in its deeper parts. Subsequently the cave system evolve by entrenchment and enlargement caused by torrential flows in the underground stream, this occurs mainly in the vadose zone, with only local flooding in the sections during high waters. The initial general disposition of the cave system was not greatly changed by subsequent evolution.

This stretched profile differs greatly from the conventional karst model, where shafts dip vertically into the vadose zone and horizontal galleries are located near the water table. Muruk can be regarded as a juvenile system model. Its case can help us understand other more ancient and generally more complex systems in the world. Taking into account the example of Muruk could renew the understanding of some old levels showing similar stretched profiles.

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