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The role of seismic activity in the formation of large underground cavities in the Muruk System, Nakanai Mountains, New Britain, Papua New Guinea

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Abstract: *Papua New Guinea is one of the world's most active seismic areas. On the surface, huge landslides are found on mountainsides and steep canyons slopes. Underground large passages and megadolines result mainly from the erosion of soft limestones by underground streams, but seismic movements may accelerate their evolution. Morphological characteristics were derived from statistical data and field observations.*
Key words: *seismic activity; caves; Nakanai, Papua New Guinea*

1. Seismic activity in Papua New Guinea

1.1 A subduction zone in the "Ring of Fire"

New Guinea, the Bismarck Archipelago and the Solomon Islands form an arc along the junction between the continental Australian plate in the south and the Pacific oceanic plate in the north (Fig. 1). The contact between these two plates is the origin of strong seismic and volcanic activity. This area of the famous "Pacific Ring of Fire" concentrates 5-10% of the world's seismic activity and is one most mobile and unstable regions of the earth's crust (Hobléa, 1997). The plate of the Solomon Sea is plunging towards the north beneath the island arc of New Britain at a speed of about 10 cm/year. This subduction is the cause of the New Britain trench (-7880 m) and of the active volcanic arc, which borders the northern coast of the island. Local seismic activity is recorded at Rabaul Volcanic Observatory (RVO), along with other parameters in order to gain better understanding of the seismic activity of the region. These data are then sent as input to the "Preliminary Determination of Epicentres" of the US Geological Survey. During our stay, 69 seismic events of a magnitude between 3 and 5.8 were recorded. The statistical treatment of these data has allowed the calculation of the frequency of major seismic events (Table 1). Large earthquakes of the type that ravaged Armenia in 1998 (m. 6.9) have a frequency of more than one a century while catastrophic earthquakes of the magnitude of the 1906 San Francisco earthquake (m. 8.25) have a frequency in the order of one every two centuries. If we apply this frequency to the Quaternary Period, the number of 'catastrophic' earthquakes (probably including magnitude 9+ events), is in the order of 10,000.

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1.2. Earthquakes felt during the expedition

Three earthquakes were felt in various degrees during our time in the Nakanai (Fig. 2).

1. At 7:14 am on the 21st of January (21:14 20/1/98, GMT), a magnitude 3.7 shock with its epicentre 75 km away and at depth of 33 km shook the bottles on shelves of medical equipment in Muruk camp (1445 m asl.). Only the expedition doctor noticed the earthquake (intensity III).
2. At 7:34 on the 27th of January (21:34 27/1/98 GMT), a magnitude 5.1 shock with its epicentre 50 km away at a depth of 83 km shook the camp from side to side for 10 to 15 seconds. The camp floor, built on fallen tree trunks, as well as the framework of the hut on stilts was noticeably shaken (intensity IV). At the same time, three members of the expedition were having breakfast in the –750 m bivouac. They felt no movement, but did hear a loud, dull boom. They thought that a violent flood was on its way, but nothing arrived.
3. At 8:30 on the 5th of February (the exact time is uncertain) a shock preceded by a rumbling noise was felt at Mara camp (intensity IV), at 700 m asl., above the Berenice resurgence. Nothing was felt at Muruk only 4 km away.

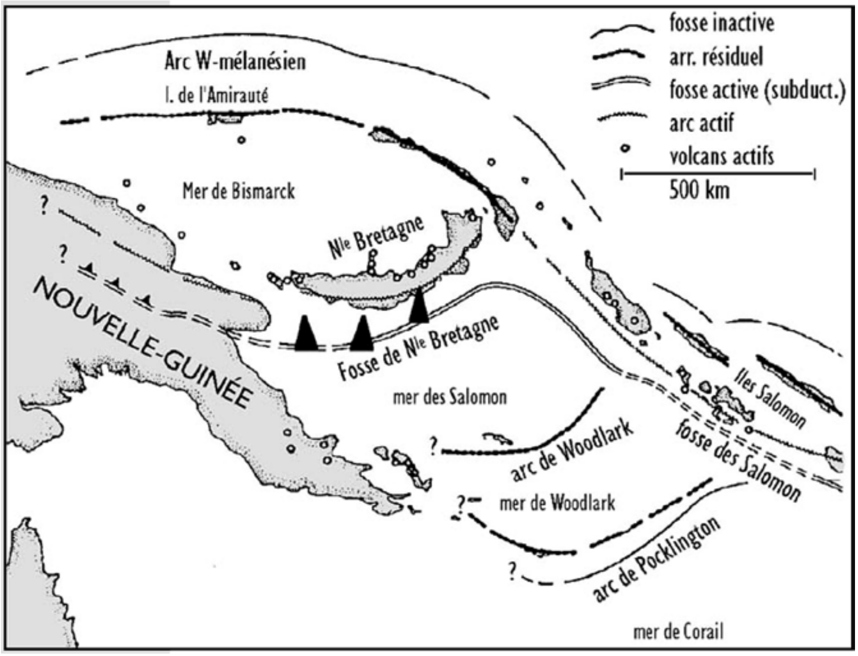

Fig. 1. Structural outline of the west Melanesian archipelago (after Karig, 1972, in Debelmas and Mascle 1993).

Table 1.

Recurring periodicity of large seismic movements in New Britain (after RVO).

Magnitude (Richter)	Local intensity (MMI)	Potential effects on landscape	Recurring periodicity (year)
6	7-8	Minor landslides and ground subsidence	1 / 30
7	8-9	Large landslides and ground subsidence	1 / 80
8	10-11	Catastrophic landslides and ground subsidence	1 / 200

To these we should add another earthquake at 00:54 (GMT) on February 5th, and another at 09:28 (GMT) on February 6th. The first had a magnitude of 4.6 with an epicentre 150 km away, and the second had a magnitude of 3.9 with an epicentre close to 250 km away. In general terms, the frequency of shocks felt at Muruk is in the order of one a week, which is quite a lot, especially when compared to the virtually non-seismic regions where we live. Differing effects at various locations is obvious. The rumbling and shock felt at Mara, which were no more than different manifestations of the same event, passed unnoticed at Muruk which is not far away but at a higher altitude. Finally, no shocks were felt underground. The same effect was noticed in 1995 (Hobléa, 1997). The dull explosion heard at –750 m could be interpreted as movement along a fault or joint moving suddenly, or more probably a block or part of the ceiling falling due to the vibration. This aspect of an only minor effect underground is because the rock mass is under lithostatic pressure, which limits its movement, and it's only at the surface that the waves transmitted by the lithosphere become obvious due to resonance and reflection. As well as these observations I should add that we observed rock shards, obviously ejected from a fault, and only washed a little by the rainy season. This therefore could have only occurred a few months before.

1.3. A considerable morphological impact

On the surface, the effect of seismic activity on the morphology is obvious. While it is insignificant on the gentle plateaux, it isn't in the 500 – 1000 m deep canyons such as the Galowe. Large white scars cutting the sub-vertical forested walls attest to the instability of these slopes (Fig. 3). The chalky Yalam limestones, which are porous, weathered and saturated with water, are particularly unstable. One such slide, fortunately a small one, occurred on the Berenice wall that was rigged with ropes. It's highly likely that it followed the shock that was felt so strongly at Mara on the 5th of February.

While seismic activity can't explain all of these gravitational movements, it is clear that it contributes to the breakdown of cliffs in the region. The 1985 earthquake (magnitude 7.1)

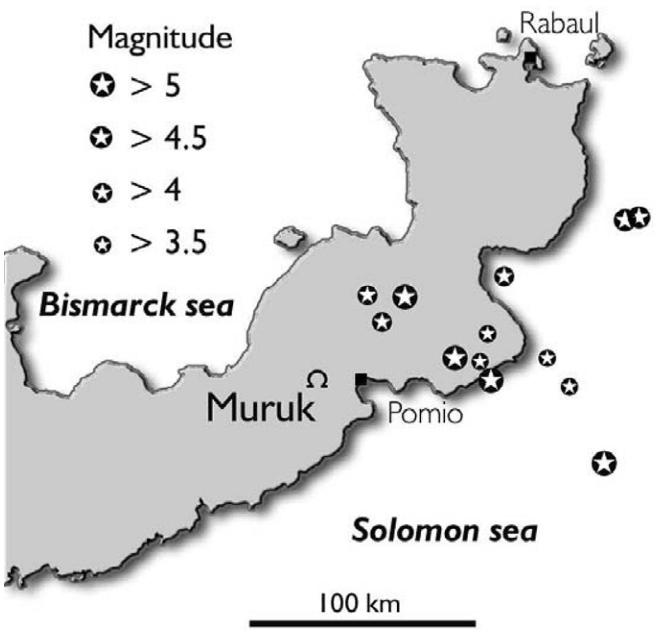

Fig. 2. Earthquakes that may have been felt in Nakanai in January and February 1998 (after RVO). Numbers between brackets correspond to earthquakes described in the text.

Fig. 3. Scar on the vegetated cliff of the Galowe canyon, on the left face to Berenice spring, probably linked to a debris flow provoked by a seismic movement or a cyclone; the height of the cliff is about 1000 m (photo by Ph. Audra).

caused a large number of landslides including one giant slide in the Bairaman canyon 25 km south of Muruk. This one kilometre long cliff collapse produced a dam 200 m high which had to be blasted to avoid a potential catastrophe for residents downstream should the reservoir fill, and then break (King et al., 1987, in Maire, 1990). An estimate of the rock mobilised by earthquakes combined with the frequency of events puts the estimated volume of rock moved by seismic activity in the same order as that moved by karst dissolution, though of course the former occurs sporadically in both time and place while dissolution is much more diffuse and generalised (Maire, 1990).

At depth, numerous effects can be seen. Tectonic readjustment can cause movement along structural discontinuities. We have seen fissures a few millimetres long in active calcite formations in nearby Tucana cave (top of crystals). At –900 in Muruk the route through the cave takes a small, perched, inactive passage "the Bypass", which is developed along a sloping bedding plane. Large cobbles have been jammed in the bedding plane when the passage was an active watercourse, then cemented by calcite. The joint has later moved a few centimetres and the chalky cobbles have been sheared apart as they were weaker than the calcite cementing them (Fig. 4). This evidence is all that we've so far found and is rather moderate when compared to that found in some alpine caves. This can partly be explained by the lack of dry levels which tends to conserve such features better, and also due to the low mechanical strength of the rock which is regularly reworked by floods and collapses so that any surface irregularities are quickly removed. It is highly likely that the older markings have long since been removed by erosion.

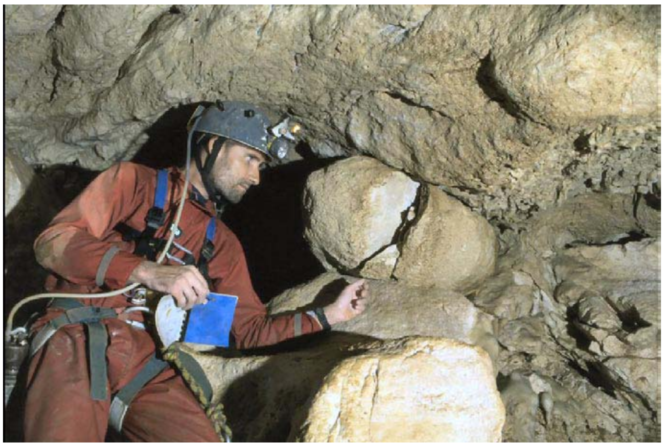

Fig. 4. Cobble cemented into the ceiling, sheared off by a recent movement of the bedding plane (photo by J.-P. Sounier).

Vibration effects are likely to cause collapses of the walls and ceilings in varying degrees. This seems to correspond with the phenomenon heard at –750 m, and it is probable that seismic activity is one of the factors, which explains the existence of such large passages and megadolines in the area.

2. Development of large underground cavities and the role of seismic activity

The formation of large cavities depends on the state and the size of different passages observed. It is possible to reconstitute the evolution of a passage from a 'normal' to a giant passage (Fig. 5).

2.1. Successive stages of evolution towards a large passage (based on field examples, mainly in Muruk Cave)

A (entrance passages of Tucana Cave)

Due to a lack of fractures, the majority of passages start at bedding planes. The majority of these are later modified due to tectonic constraints and slippage between layers, as indicated by obvious striations. This reworking is critical in the widening of the discontinuities. The initial passage develops as a sinuous passage along the joint. Owing to extremely contrasting water flow regimes, the passage is either 'dry', with limited erosion (modest, non-aggressive flow in normal conditions; Audra, 2001b), or flooded. In the latter case - high, aggressive flows - the passage functions as a tube with enlargement of the ceiling and floor on either side of the joint.

B (entrance passages of Tucana and Muruk Caves, Cassiquiare passage)

Enlargement of the tube allows some of the water to have an air surface in moderate flood. This produces a deepening of the canyon as it traces the passage's initial sinuous route without exaggerating it. The walls of the canyon are washed by torrential flows, while during larger floods the passage is totally flooded. As the flood subsides, suspended clays are deposited on the walls of the tube. These clays stay in place, as the torrential flows can't reach them to remove them.

C-D-E (extreme upstream of the Milky Way Main Drain)

As the passage is enlarged, there is a differentiation of the walls depending on their stability which is linked to the distribution of various mechanical constraints (Renault, 1967). A rounded ceiling is very stable. The walls at the base of the canyon develop due to widening and deepening. Meanwhile, the most unstable zone is at the top of the canyon. With the unloading on one side, the decompression severely affects the walls, which spall off plates, which are then removed by the water below (Gilli, 1984). This eventually produces an inverted "water drop" passage. Depending on the flow regime, large floods may still fill the passage to the roof and deposit more clay. If not, there will be a slope of dusty gravel covering a sloping wall of plates in the process of spalling.

F (Galadriel River downstream to its confluence with the Elmedir River)

Continued enlargement of the passage causes instability in the ceiling. Bed collapses at a time forms an "inverted ladder", and tends towards a new profile with its ceiling in equilibrium (Fig. 6). It is also possible the ceiling collapse could be stalled when it encounters thicker beds.

G (Milky Way passage upstream to the confluence)

Continued enlargement causes collapse of the ceiling due to decompression and unhinging of wall plates. The volume of blocks that accumulate in the river limits any increase in depth of the canyon. The water's energy dissipates passing through these rock obstacles as well as against the walls. As the passage is no longer deepening, it enlarges and may reach a diameter of 50 m. The size of the fallen blocks increases as the collapse increase in magnitude and passage development is very active. The presence of a major fault can allow an even greater enlargement and form a large room, although it is in fact no more than a localised section of structurally enlarged passage.

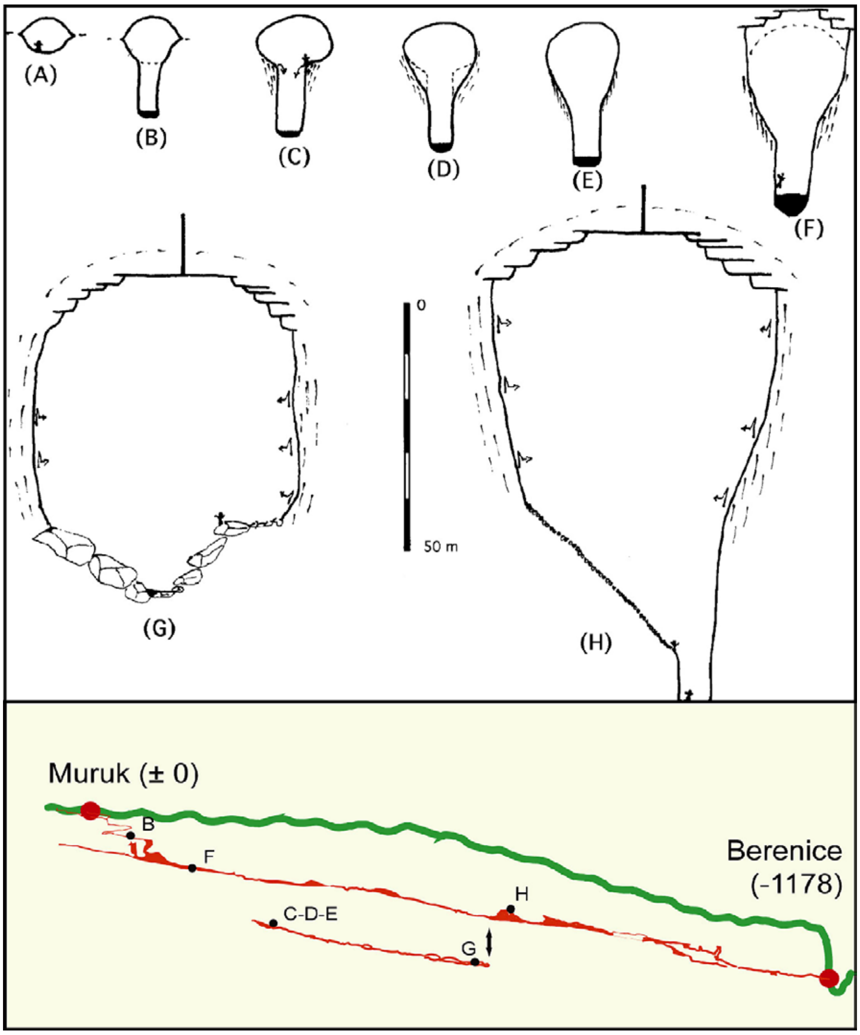

Fig. 5 - Evolutionary stages of Muruk passages (see comments in the text).

H (-780 Confluence Chamber, Mirror of Galadriel)

Once a section of passage has attained a certain equilibrium, collapse of large rock plates ceases. The talus on the floor becomes covered with small chalky rocks, which come from wall collapse in the final stages of equilibrium. As the rocks get smaller, is river once again able to deepen its course and begin then next phase of collapse and enlargement.

2.2 - Development of large passages

It is necessary to remember that the different stages of development do not as a whole have any chronological significance. All of the passages described are contemporaneous, each being at a particular stage of development. A given passage moves from one stage to the next due to erosion, each following an almost identical pattern,

Fig. 6. Cantilever roof in one of Muruk's large passages (photo by J.-P. Sounier).

with differences in detail due to local structure. This erosion is proportional to the force of water running through the passage. It is therefore logical to see the largest passages, those which have developed the most, at the greatest depths where the waters have concentrated into powerful underground rivers. The flow observed in low conditions is in the order of 1 to 2 m^3/s. In flood it has been estimated at 20 m^3/s while in extreme flood it could reach 100 m^3/s (Audra, 2001c).

The final phase of development is the formation of a megadoline, which forms an open window to the subterranean river below. This is due to the stooping upward of the ceiling of a large passage roof below the floor of a doline, as in seen in Nare and Minye (Maire, 1981). In the upper Galowe plateau where Muruk lies megadolines are practically absent, apart from Wunung and Haricot, both of which are blocked with fill and don't give access to the underground river. This difference is simply explained by the much greater depth below the surface of the major drains. Around Minye the drains are at a maximum depth of around 350 m. With ceilings up to 150 m high and dolines above, the thickness of rock in the roof can be quite thin. At Muruk, where the depth is in the order of 450 m, the thickness of limestone between the highest ceilings and the deepest dolines is never below 350 m, which explains the virtual non-existence of collapses.

The difference in structure must also be considered. From the lithological point of view, the chalky limestones of the Yalam provide sufficient mechanical strength for the development of large voids, helped along by stratification that favours equilibrium and cantilever ceilings (White and White 1997). Following their collapse the rocks break easily and are readily removed by the underground river. Moderate fracturing on a local scale allows the passage volume to grow as large as possible without its enlargement being interrupted by any major discontinuity.

The principle of undermining-unloading has already been recognised as the major processes in the formation of large underground voids (Gilli, 1984). After studying numerous examples in France and around the world this author has ranked it in front of faulting, the abundance of water flow in underground rivers, and the presence of a contact between massive fractured limestone and underlying soft marls or equivalent. In our case, the high flow rate is the main force of downcutting. In every case, the large passages develop in the very heart of the limestone with no particularly soft underlying rock that will erode laterally. Certainly, the chalky Yalam limestone favours this process more than does a massive limestone. It is also apparent that the abundance of high-energy water flow generates large voids without having to consider the structural context, even though it didn't appear in Gilli's work. We also must note that the passages in Muruk don't exceed 50 – 70 m in width, which is in the order of a quarter of the size of the world's largest known passages.

Even though the driving force for the formation of large voids is the torrential flows which provokes gravity collapse, it is also clear that seismic activity and tectonic reworking can do nothing but accelerate this process. Fractures are rare, but nevertheless, the bulk of large rooms are aligned along large faults (Fig. 6). Also, the horizontal bedding is broken into individual blocks by well defined joints, as can be seen by slide marks, which add to the number of discontinuities and aid in their removal from the ceiling. Tectonic activity plays a dual role: on one hand it helps create the discontinuities and 'prepare' the rock for collapse, on the other hand it actually provokes the collapse by moving the rock along the discontinuity, or simply unbalancing rocks with a sudden jolt. The Muruk system, with an age of a few hundred thousand years (Audra, 2001a; see also Audra, Lauritzen and Rochette in this issue), has, in its development, probably been subjected to more than a thousand very large earthquakes. The importance of seismic activity as a parameter cannot be ignored if we want to understand the size of these caves and the rapidity of their development.

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