SOME SCIENTIFIC FEATURES OF THE PUERTO PRINCESA UNDERGROUND RIVER: ONE OF THE NEW 7 WONDERS OF NATURE (PALAWAN, PHILIPPINES)

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This paper describes some of the most significant scientific issues of interest of a cave system in the island of Palawan, Philippines. The Puerto Princesa Underground River and the surrounding protected area represent a unique karst environment under several points of view. Its geographical position in the tropical area and its closeness to the sea, making it a true underground estuary, create unique conditions in the fields of hydrology, meteorology, mineralogy and biology. These aspects are analyzed as elements contributing to the comprehension of the exceptionality of this karst phenomenon.

1. Introduction

Palawan covers an area of 12,000 km^2 and is located between 11°50' and 12°20' latitude N, and 117°00' and 120°20' longitude E, in the south-western part of the Philippines archipelago, not far from Borneo. The island is narrow, elongated and mostly mountainous. Two important N–S depressions, corresponding to valleys or lowlands, divide the island into three tectonic sectors. Along the depression which divides the northern from the central sector, we find the Saint Paul Dome karst ridge (Fig. 1).

Here, since 1991, the Puerto Princesa Subterranean River National Park was established in order to protect a unique underground system and the surrounding area. Originally covering only 3,900 ha, in 1999 the park was expanded to over 38,700 ha, and in the same year it was inscribed in the list of Unesco natural World Heritage Sites. Formerly managed by the Dept. for Environment and Natural Resources, since 1993 it falls under the rule of the City Government of Puerto Princesa.

The first recorded explorations in the underground River date back to 1930, witnessed by some writings on the walls of the outflow and the area called Rockpile. In 1973 a first sketch of the main gallery of the cave was carried out by the Hungarian geologist Balazs (Balazs 1976). In the early 80s two expeditions from Australia explored the whole main branch and some side tributaries, pushing the total development of the cave to over 8 km (Hayllar 1980, 1981). Between 1986 and 1992 several expeditions were organized by the Italian Speleological Society, leading to the discovery of giant fossil branches which brought the total development to over 20 km (Piccini and Rossi 1994). The first decade of the new millennium has seen a methodic research project carried out by the Association La Venta from Italy, also assisted by interesting explorations by the Gaia Exploring Club from the Philippines (De Vivo et al. 2009). The last La Venta expedition, in 2011, has brought the development of the cave to 32 km (Piccini and De Vivo 2012). In 2012 the PPUR has been elected on of the New 7 Wonders of Nature.

Figure 1. An aerial view of the Saint Paul Dome (1,028 m a.s.l.) from SE (photo L. Piccini, La Venta).

2. Geological and morphological overview

The St. Paul area is located east of Ulugan Bay, about 50 km NE of Puerto Princesa. The length of the ridge, placed between the Babuyan River valley to the E and the Cabayugan River Valley to the W, is about 10 km and its average width is 4 km (Fig. 2).

The carbonate rock covers an area of about 35 km^2 and is made of massive to roughly bedded, light to dark grey limestone showing levels rich in fossils. Such rock formation, more than 400 m thick, lays over sedimentary (mudstones, sandstones and marls) and volcanic rocks, dating back to Oligocene–Miocene and covering an older metamorphic basement (Hashimoto 1973).

The limestone outcrop is shaped as a NNE–SSW-elongated, asymmetric ridge sloping down to the west. From a structural point of view it consists of a multiple NW dipping homoclinal relief limited by NE–SW-oriented faults. Such lineaments have controlled both the general shape of the mountain and the karst landforms, determining the lining up of dolines and the development of the major caves.

The landscape of the area is a typical tropical karst consisting of towers, cones, pinnacles, and large depressions, occurring mainly in the northern and southern sectors of the ridge. Large closed depressions (cockpits and dolines) cover about 10% of the total limestone surface. Major depressions occur in the form of elongated blind valleys on the east side of the northern zone, and are mainly developed on clastic rocks.

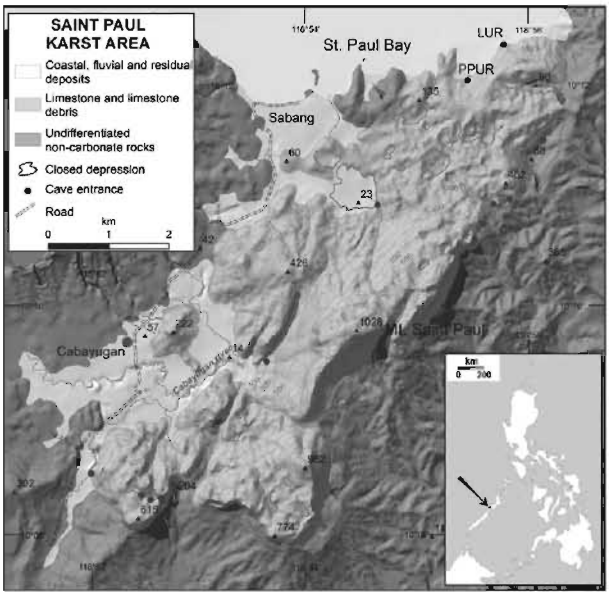

Figure 2. Geological sketch map of Saint Paul karst area.

Steep slopes and calcareous cliffs characterise the central part of the St. Paul Ridge, while to the north the landscape consists of an irregular plateau with several dolines. Large and deep depressions occur along the eastern limit of the limestone outcrop and can actually be considered as small blind valleys (Fig. 2). Some of the eastern sinking streams, located at 290 and 250 m a.s.l., feed two active Nagbituka caves), which consist of large tunnels, mainly vadose in origin, descending to the north along the contact between limestone and sandstone. At present, Nagbituka 1 is the deepest cave in the Philippines (Laumanns 2010).

The southern part of the St. Paul Ridge has a different morphology and is characterised by two mountains, which have plain summit surfaces gently descending toward the NW, intersected by large and deep elongated depressions and large sinkholes.

Along the coastline, a notch, located about 6–7 m above the present sea level, testifies the sea-level highstand which occurred about 120,000 years ago, when the mountain glaciers and polar ice-sheets had a much smaller extension than today. A similar notch can also be found inside the Underground River, up to 4 km from the entrance and at the same elevation (Piccini and Iandelli 2011).

3. Underground Hydrology

The Underground (or Subterranean) River is a cave stream about 8 km long which collects the water from a wide surface basin, diverting it to the sea through huge galleries flooded by water.

The main access to this cave is from the sea. On the side of a beach, a water stream carves a shallow canal through the coralline sand. Going upstream, after a few dozen metres you reach a small lagoon bounded by a calcareous cliff, at the foot of which a portal opens the way into the subterranean river. The main underground stream runs in a large tunnel, with lateral minor diverting passages and in some places upper old relict galleries joining with the active one through large chambers. This cave represents the main resurgence of the Cabayugan River, that disappears into the limestone 7 km upstream.

Another marine spring cave is located a few hundred metres further E and collects the water sinking in the closed basins occurring along the east side of the karst in its northern sector. This cave is named the Little Underground River. Based upon the known hydrologic setting of the area at least two drainage systems can be identified, one drained by the Underground River and one by the Little Underground River. However, the occurrence of submarine and presently unknown springs cannot be excluded.

As the entrance of the Underground River on the coast is at sea level, the tides affect a large part of the cave up to about 6 km inside the mountain (Forti et al. 1993). Along the whole navigable part, the salt water lies under a thin sheet of fresh water, just a few centimetres thick. This condition is only found during the dry season and in absence of rain. During the floods the cave is cleared of salt water, which later returns slowly once the flood has passed. Mixing phenomena between fresh and salt waters take place inside the cave causing particular processes of rock corrosion, which lead to the formation of water level notches (Mylroie and Carew 1988). In the past, sea level was often lower than now, so the PPUR has not always been a marine cave.

Figure 3. The Underground River just downstream the inflow, where the effect of tides does not occur. The lower limit of flowstone on the left wall indicates the water level during flood (photo by R. De Luca, La Venta).

Indeed, despite the occurrence of corrosion produced by the mixing of fresh water with saline water, the speleogenesis of the PPUR is mainly due to solution by continental water and to mechanical erosion by suspended load during floods (Fig. 3). Only in its downstream part, mixing corrosion has produced typical forms of coastal caves, such as waterline notches, spongework and lateral conduits. From this perspective, the system may be considered a classic example of an underground estuary.

This cave with its numerous branches houses, in fact, one of the world's largest and most important underground ecosystems. There are hundreds of thousands of swiftlets (*salangane*) nests, and almost as many bats. Seemingly, the *salangane* and bats have reached an agreement about the timing of their entry and exit from the cave, in general, when the bats begin to exit, almost all the swallows are back on their nests. Because of the great amount of organic matter that swallows and bats bring daily into the cave, there are many other animals present, made up of reptiles (snakes), fishes, crustaceans, and insects (Piccini and Rossi 1994).

A fact that has always been surprising is that the cave runs all along the north-western side of the Saint Paul ridge, this means that most of the karst surface lies on the right-hand (eastern) side of the cave; despite this the Underground River has no consistent tributary from the right side. Why? Where does the water infiltrated all over the karst area flow to? How does it reach the sea?

The first part of the cave, close to the seaward exit, presents a very complex pattern. Several branches divert from the main gallery. One of these lateral branches, just 150 m upstream of the outlet, was explored by the Filipino cavers of the Gaia Exploring Club in 2003. A large gallery, which they reached after a narrow flooded corridor, goes towards the E and closes at a huge stalagmite formation, 15 m high.

Beyond this obstacle, which stopped the exploration of the Gaia Club, a second dry and huge system of galleries exists: it is like entering another cave, a parallel system of new amazing galleries that are flooded only during very rainy seasons (Fig. 4).

Figure 4. The huge canyon of 150 Years Gallery formed by downcutting of a large epi-phreatic tube (photo by A. Romeo, La Venta).

The first part consists of a high gallery, about 10 m wide and 40–50 m high. The floor is formed by a sand deposit. On the right an upper sector hosts a hall with very nice helictites. On the left we reach a part of the passage where the floor is covered by extraordinary calcite crystals.

This branch probably represents the high inactive level of the main drainage pathway of the cave (Fig. 5).

In several points it is possible to descend in little branches that have typical epiphreatic morphologies until you reach a network of small horizontal often waterfilled tunnels, which lay at sea level. We can argue that the main tunnels collecting the infiltration water of the karst area lay now below the sea level, due to the present high-stand condition and that a new epiphreatic system is now developing. During the rainy season, the water level rises and inundates the upper galleries.

4. Geomorphology

The Underground River has a long and multiphase evolution history which is strictly linked with the sea level fluctuation and with the uplift phases (Piccini and Iandelli 2011). Features that indicate former water levels are present along the PPUR up to 5 or 6 km upstream from the coastal spring. In the last sector of the navigable path, where the ceiling of the main tunnel rises up to 20 m or more, there are two evident old corrosion notches carved by persistent levels of water. The upper notch is at 11–12 m above present mean sea level (pmsl). The second notch is at 7–8 m above the pmsl. Some of the lateral branches contain alluvial terraces consisting of sands and gravels, which are related to this second high-stand notch. This circumstance allows us to correlate the lower notch to the marine one, visible on the coastal cliff at about 7 m above sea level (Maeda et al. 2004; Omura et al. 2004), which dates back to the last interglacial phase (MIS 5e, about 125,000 years before the present time; Linsley 1996).

The morphology of the active level of the PPUR is clearly adjusted to the current sea level, but we have to consider that in the last 500,000 years, the sea was most of the time lower than now (mainly 50–60 m lower; Haq and Hardenbol 1987). This implies that the PPUR has functioned as a vadose through-cave affected by fresh water flow, with a substantial load of insoluble material, forming a subterranean canyon that is buried by the alluvial sediments that form the current riverbed.

The PPUR profile also shows several large passages at an elevation of mainly 50–80 m above the pmsl. This level consists of large inactive tunnels parallel to the current river containing thick alluvial deposits covered by flowstones, which in places almost completely fill the conduits.

In the upstream sector of the cave, erosion forms may be found, indicating a long phase of vadose entrenchment. This ancient "underground river" could reasonably be dated back to the Early Pleistocene, as suggested by the extrapolation of the recent low uplift rate of the coastal zone (Piccini and Iandelli 2011).

Several morphologic features, such as the presence of corrosion notches at 12.4 m above the pmsl, and the huge speleothems corroded and interbedded with alluvial deposits, suggest that this lower and presently active level experienced more than two sea level highstands and could have formed during most of the Middle-Late Pleistocene.

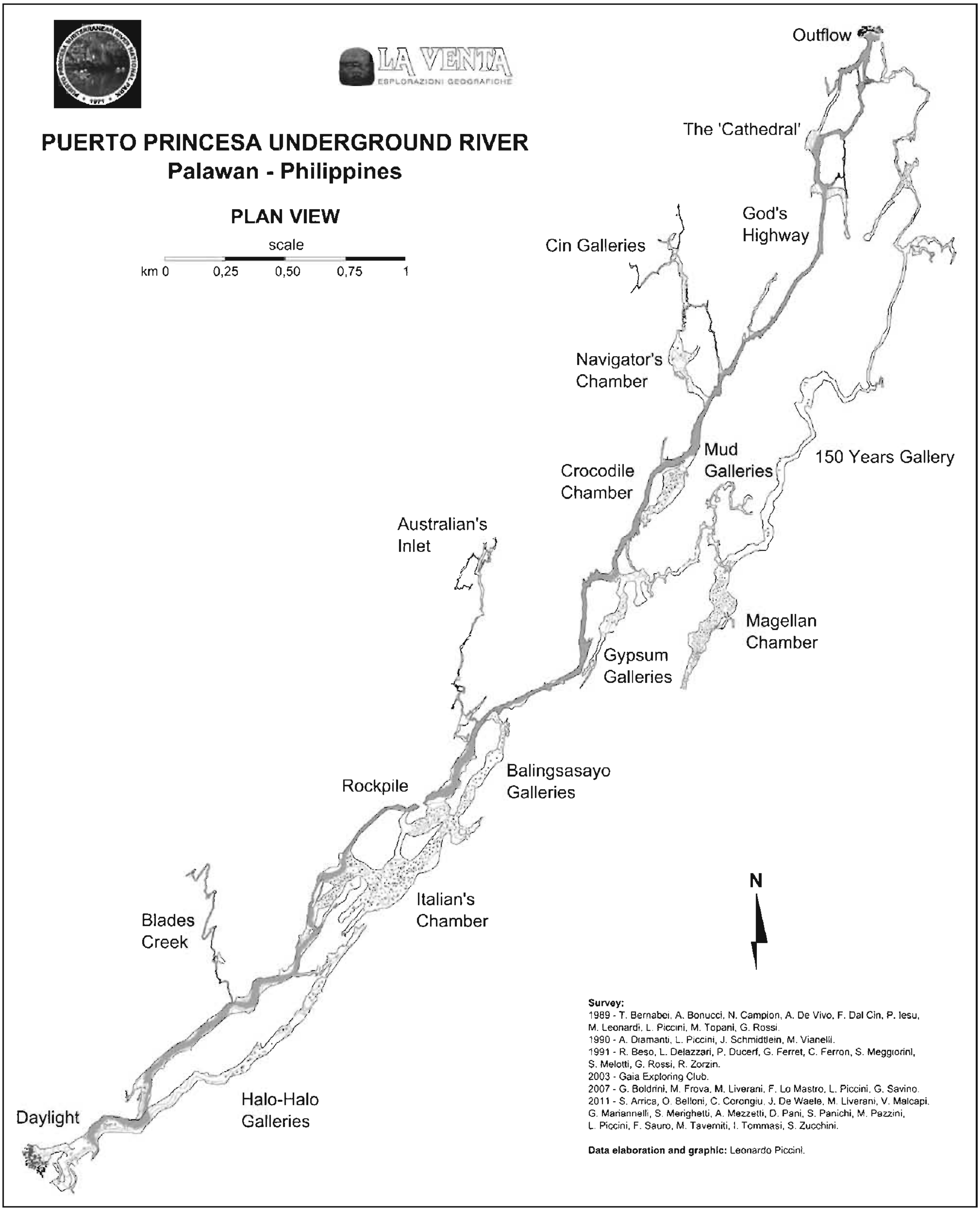

Figure 5. Survey of the PPUR in plan view.

5. Speleothems and cave minerals

Huge stalagmites and flowstones are abundant in several parts of the cave together with some rare speleothems. One of these speleothems is "calcite grass", an extremely rare kind of helictite, consisting of bended and twisted calcite monocrystals growing from the cave floor and covering several tens of square metres of the 150 Years Gallery (Fig. 6).

From the mineralogical point of view, recent and still ongoing investigations are evidencing that the number of cave minerals is much higher than supposed. Most of the minerals of the system are concentrated within the "black crusts", which are widespread along the main galleries of the PPUR. These crusts, often completely detached from the cave wall, are related to periods of strong biogenic reactions induced by the mineralization of guano in water filled conditions. The same process was active in all the other caves of the St. Paul karst: in two of these cavities the process also allowed peculiar black cave pearls to develop (Forti et al. 1991). In general, the crusts consist of several very thin layers of different colour: beside the far more dominant black ones, other layers are present from black to reddish and from yellow to white. Each colour corresponds to one or more compounds. In the black layers most of the minerals are manganese compounds, the reddish are characterised by iron-manganese minerals, while the white and yellow ones consist of gypsum and phosphates, many of which are amorphous.

Up to now eleven different minerals have been detected in the PPUR: calcite ($CaCO_3$), gypsum ($CaSO_4 \cdot 2H_2O$), apatite [$Ca_5(PO_4)_3$ (C,F,Cl,O,OH)], variscite [$AlPO_4 \cdot 2H_2O$)], strengite [(Fe, Al)$PO_4 \cdot 2H_2O$)], manganite [MnO(OH)], rhodochrosite ($MnCO_3$) pyrolusite (MnO_2), robertsite [$Ca_6Mn_9(PO_4)_9O_6(H_2O)_6 \cdot 3(H_2O)$)], janggunite [$Mn_{5-x}(Mn,Fe)_{1-x}O_8(OH)_6$] and serrabrancaite [$MnPO_4 \cdot 2H_2O$)]. The first 8 minerals were already known from the cavern environment while the last three (robertsite, janggunite and serrabrancaite) are new cave minerals, being restricted to the single St. Paul karst: in particular serrabrancaite is very rare even outside caves, being found before only once in Brazil.

6. The Sirenian fossil

During the scientific explorations carried out by La Venta Esplorazioni Geografiche inside the Puerto Princesa Underground River (February–March 2011), several partially articulated bones (ribs and dorsal vertebrae) exposed for approximately 10 cm of their length, were observed about 3 m above the river (Fig. 7). The bones emerge from the rock wall due to the differential dissolution of the limestone with respect to bones and were not extracted to preserve this rare paleontological site.

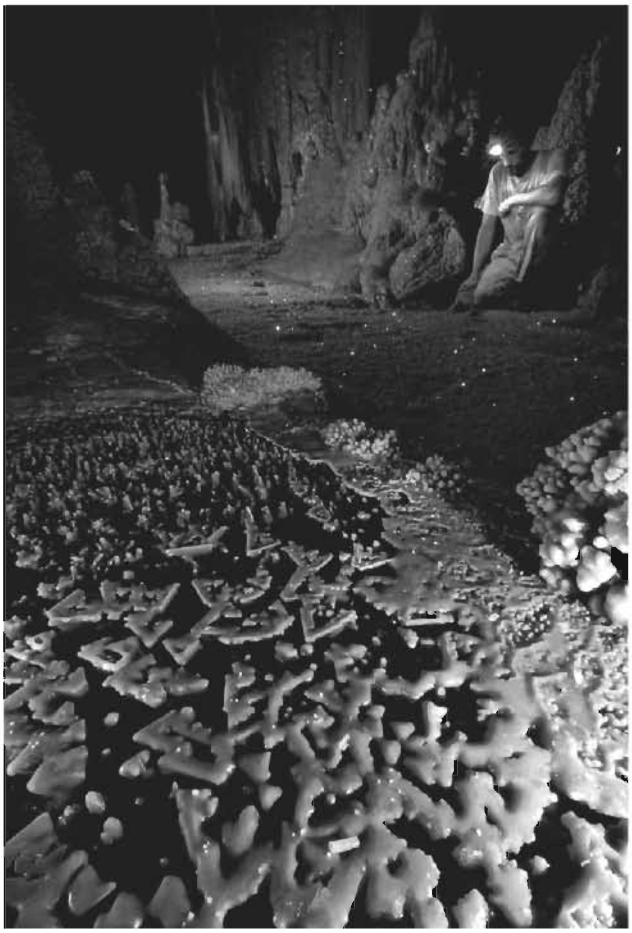

Figure 6. The crystallized pavement in the 150 Years Gallery (photo by A. Romeo – La Venta).

A detailed comparison of the bones with several available photos of closely related taxa, and with the fossil specimens present in many museums all over the world, has allowed us to state that they belong to a sirenid. The specimen discovered on the Island of Palawan represents the first from the Philippines and the easternmost occurrence in the region. The partially articulated thoracic elements include a well preserved vertebra with exposed neural spine and processes, partial centrum and complete articulation with the head of the ribs. Several bone fragments are well preserved in situ, showing broad and re-curved ribs typical of sirenians. The specimen is approximately 60 cm wide, whereas the vertebra is 10 cm wide and 15 cm high including the centrum. It is therefore possible to estimate a total length for the individual of 180 cm. This sirenid is obviously coeval with the hosting rock, the St. Paul Limestone, which is Oligo-Miocene in age.

Figure 7. The bones of a Sirenian fossil along the main active gallery of PPUR (photo N. Russo – La Venta).

7. Underground meteorology

The Underground River is a cave into which an external river flows and which transports all the meteorological events from the outside deep into the rocks: precipitation peaks, large biological load and temperature jumps. The peculiarity which makes this cave so unique is that it reaches the sea level already within the mountain, in the core of Mt. Saint Paul.

The flows of fresh water from upstream and salt water from downstream are not connected to each other and, on the contrary, for long distances they don't mix, the former flowing on top of the latter. This creates pockets of cooler air in contact with the water and, seasonally, generates flows of relatively warm and humid air which fills the galleries. Micro-meteorological niches and extremely complicated ecosystems are thus created, each having their own seasons, which at the moment we have only barely glimpsed. The island of Palawan lies directly on the thermal equator, therefore the UR cave is at the maximum temperature possible for a cave created by external water flows.

Then there is the wind, which is very noticeable when you pass through the portal to visit the cave on the *bancas*. The galleries are crossed by an important airflow, with peaks of up to 150 $m^2.s^{-1}$. The origin of air circulation within caves is usually the temperature difference between inside and outside. But, unique also in this, the PPUR is affected by a subtle factor which is insignificant elsewhere: the variations in the humidity of the outside air.

The cave has a very peculiar characteristic. On one hand it is very hot, as it opens in an area where the average temperature is especially high – in fact the highest possible – on the other, it opens in an area where the climate is "super-oceanic", that is characterised by a small – in fact, the smallest possible – thermal excursion between day and night and summer and winter. The result is therefore that the temperature difference between inside and outside is always small, just a few degrees difference, and it is very ineffective in creating an underground air circulation. In these conditions, a variation in the outside air density due to humidity variations can assume a decisive role. So, one of the powers of the "underground storm" is the humidity of the outside air, which in other places doesn't manage to move anything.

8. Final notes

The Puerto Princesa Underground River represents a unique karst environment under several points of view.

To start with, being an underground estuary, the PPUR hydrology is strongly affected by the sea tides, that reach up to 6 km inside the cave, with salt/fresh water mixture effects heavily influencing the cave genesis.

On the mineralogical front, the huge fossil levels above the main gallery, particularly the recently explored 150 Years Gallery, contain extremely interesting and rare cave minerals and speleothems, some of which new to science and still under study.

Absolutely unique is the presence of a sirenid fossil englobed in the wall of God's Highway, along the cave's main active branch. The paleontological specimen may supply interesting information on the geological history of the area and the cave genesis.

Among others, the biological aspect is also extremely significant. The presence of huge colonies of bats and swallows and their guano production, together with the biological mass carried inside the cave by the underground river, has allowed the development of a complex and rich trophic network. From the ecological point of view, the cave presents three distinct ecosystems, each characterised by the different nature and abundance of the trophic resources.

These features make the PPUR system an extraordinary natural laboratory to study the evolutionary processes and the ecology of hypogean environments. At present, the PPUR has become the most important show cave of the Philippines, with over 150,000 visitors per year. Its inscription in the New 7 Wonders of Nature will unavoidably increase the anthropic pressure on this cave. If the presence of the tides inside the cave is sufficient to guarantee the stability of its microclimate, the same cannot be guaranteed regarding its ecosystem, which might undergo serious alterations.

It is thus absolutely necessary that the cave managing authorities pay particular attention to the problems that might arise from its tourist overexploitation.

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