Exploration Projects

Tectonic uplift, sea level changes and Plio-Pleistocene evolution of a coastal karst system: the Mount Saint Paul (Palawan, Philippines)

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TECTONIC UPLIFT, SEA LEVEL CHANGES AND PLIO-PLEISTOCENE EVOLUTION OF A COASTAL KARST SYSTEM: THE MOUNT SAINT PAUL (PALAWAN, PHILIPPINES)

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Abstract

The St. Paul karst (Palawan, Philippines) is a tropical coastal karst, consisting of towers, cones, huge depressions and large caves. This area hosts the Puerto Princesa Subterranean River (PPSR, 24 km long), whose main entrance is a large spring along the coast and which is one of the largest cave complex in Eastern Asia.

A geomorphological study, performed by several field surveys, the morphometric analysis of the digital terrain model (DTM) and of 3D cave models, allowed to formulate a first evolutionary framework of the karst system. The DTM was extracted from maps and aerial photos in order to find different generations of "relict" landforms, through the morphometric analysis of topographic surface and karst landforms.

Several features suggest a long and multi-stage evolution of the karst, whose age ranges from Pliocene to present. The southern and northern sectors of the area differ in their altimetric distribution of caves. In the southern sector, some large caves lie between 300 and 400 m asl and were part of an ancient system, which developed at the base level of a past river network. In the northern sector, some mainly vadose caves occur, with a phreatic level at 120-130 m asl. An important phase of base-level cave development is well documented in the inactive passages of PPSR at 50-80 m asl. Morphological features, such as horizontal solution passages and terraced deposits, suggest a phase of stillstand of the base level, which is recorded in the topography as low-relief surfaces at 40-50 m asl. The age of this phase is probably Early Pleistocene, on the basis of assumed uplift rates. The more recent caves are still active, being located at the current sea level, but they show more than one cycle of flooding and dewatering (with calcite deposition). In the PPSR, several morphologic features, such as two main water level notches at +12.4 and +7.7 m asl and terraced alluvial deposits, suggest that the lower and active level passed through more than two high-stands of sea level and so it could have formed throughout most of the Middle-Late Pleistocene.

Key words: speleogenesis, coastal karst, morphometry, DTM, Philippines, Palawan.

1. Introduction

The St. Paul karst, in Palawan (Philippines), hosts one of the most significant coastal caves in the world (Figure 1): the Puerto Princesa Subterranean River (PPSR) which is included in the UNESCO World Heritage List (Restificar et al., 2006).

The PPSR is an extraordinary cave in many aspects and in particular from a biological point of view; the Subterranean River and its numerous branches house, in fact, an important underground ecosystem. There are hundreds of thousands of swiftlets (properly *salangane,* gen. *Aerodramus*) nesting inside this cave and just as many bats, which twice a day perform a "conflicting migration", with bats coming out and swiftlets going in at dawn, and the opposite at sunset.

Figure 1. The entrance of the Puerto Princesa Subterranean River along the NW coastline of Palawan (photo: L. Piccini, La Venta Esplorazioni Geografiche).

Because of the great amount of organic matter that birds and bats bring daily into the cave, around this flying neighbourhood there are many other animals, made up of reptiles (snakes), fish, crustaceans, arachnids and insects whose dimensions are sometime a bit "scary".
The PPSR has always been known to local people, who probably entered the cave to search for "swallows's" nests. Some writings left by visitors in the first part of the cave bear the date of April 13th, 1937. As far as we know, Balazs and some Philippine companions carried out the first documented exploration of the underground river (Balasz, 1976). In 1980 an Australian expedition (Hayllar, 1980) surveyed the entire length of the active trunk of the cave to a second entrance, the "Day-light hole". One year later, the Australian cavers discovered a third entrance at the terminus of a long inlet-branch situated about 4 km from the outflow (Hayllar, 1981). At the end of these expeditions the surveyed length of the cave reached 8.2 km.
In 1989 some Italian cavers partially explored the inactive level of huge tunnels above the underground river and some lateral active branches. In the course of the expedition, about 5.7 km of new passages were explored (Piccini & Rossi, 1994). In 1990 and 1991 the same team carried out geological and biological studies and explored some new branches.
In 2007 and 2008, the Mt. St. Paul was the object of a new research project carried out by "La Venta" Association, which achieved significant results regarding topography, research and documentation (Piccini et al., 2007; De Vivo et al., 2009). These last expeditions brought the total surveyed length of the PPSR to more than 24 km. Furthermore, surveys were extended to mountain areas, where new caves were discovered. Fragments of an ancient system of base-level

caves are in fact present in the southern inland zone. Their exploration has just begun but has already shown remarkable results.

Although the St. Paul karst area is far from being completely explored, the most recent investigation indicates the existence of a complex cave system whose evolution can be preliminarily deduced through a "holistic" analysis of the caves and the surface geomorphic setting. This paper presents a preliminary evolutionary model of the karst as a whole, as well as a first reconstruction of the complex relationships between speleogenesis, tectonics and sea level fluctuations.
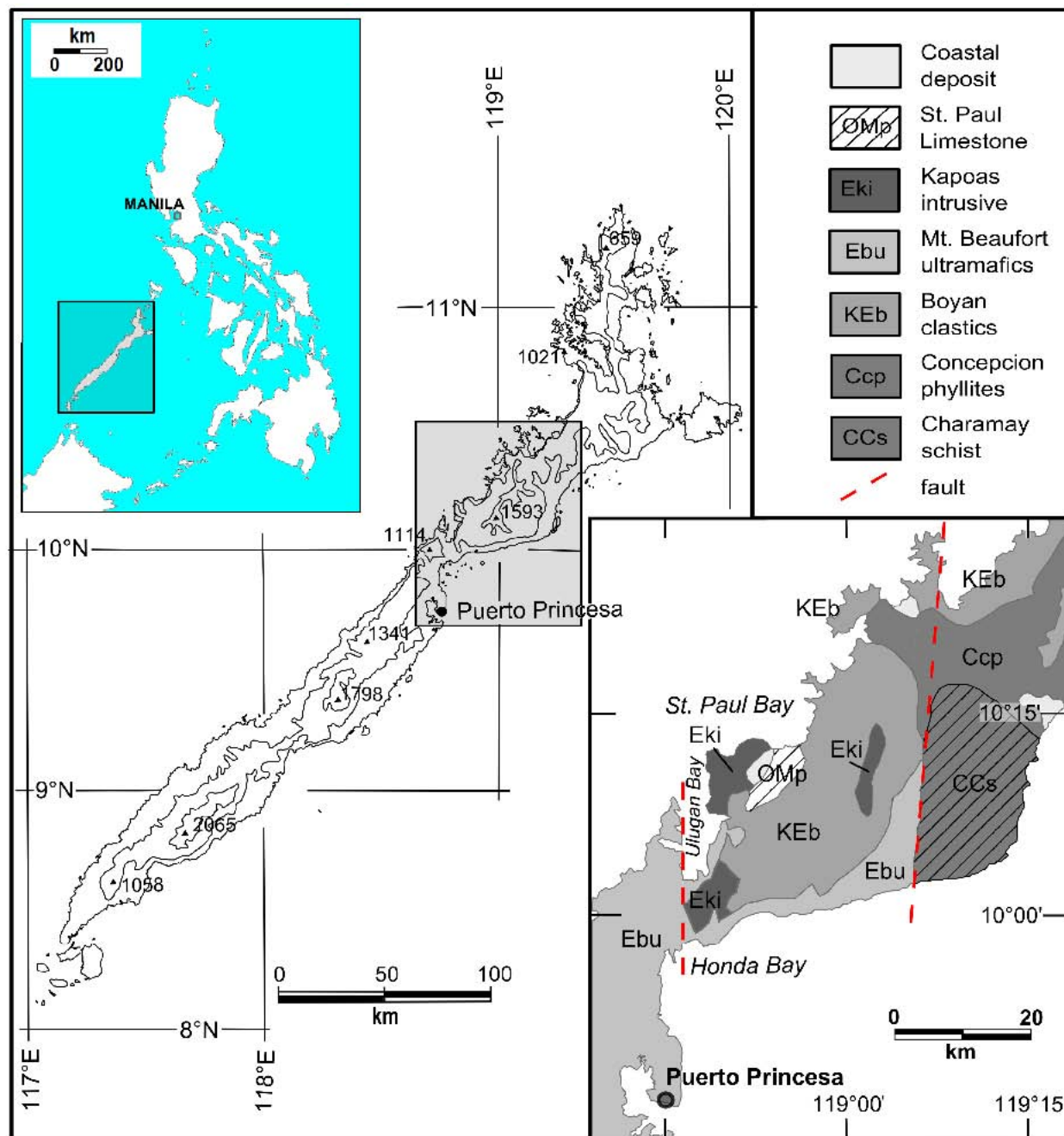
Figure 2. Topographic map and sketch geological map of northern Palawan, East of Puerto Princesa.

2. Geographical, geological and morphological setting

Palawan has an area of 11729 km^2 , and is the fifth largest island of the 7107 making up the Philippines archipelago. It is located in the south-western portion of the archipelago, near Borneo Island, and, together with Balabac and the Calamians, forms a line of islands spreading NE-SW for about 600 km, between 7°50' and 12°20' of latitude N, and 117°00' and 120°20' of longitude E (Figure 2).

The climate is influenced by the monsoon, and is characterized by a dry season, from November to May, and a wet season from June until October. The eastern coast has a shorter (2-3 months) dry season and no pronounced rainy period during the rest of the year. Temperatures are relatively homogeneous throughout the year, ranging from an average of 26.8 °C in January to 28.6 °C in April (Puerto Princesa, data from www.worldclimate.com).

Precipitation data are not available. Some generalized maps of the Philippines show a mean rainfall of about 2000 mm for the entire island, but at the highest elevations the precipitation is probably more than 3000 mm/year.

Palawan is a narrow and long island and is mostly mountainous throughout its entire length. A wide morphologic depression connects the bays of Ulugan and Honda, along an important N-S tectonic lineament, and separates central from northern Palawan (Figure 2).

Northern Palawan consists mainly of Late Palaeozoic to Jurassic metamorphites (schists, metasandstones, slates and marble) with small outcrops of granite and metatuffs (Hashimoto, 1973). Just east of the Ulugan-Honda lineament, a thick, Late Cretaceous clastic series of turbidites, with few conglomerates and red volcanics, is widely exposed and lies unconformably on the metamorphic basement (Müller, 1991).

The St. Paul karst area is located about 50 km NE of Puerto Princesa, just to east of Ulugan Bay (Figure 2). The karst covers an area of about 35 km^2 and is composed of a massive to roughly stratified, light to dark grey micritic limestone. The St. Paul Limestone formed in shallow water and contains layers rich in fossils of Late Oligocene to Early Miocene age (Fernandez, 1981; Almasco et al., 2000). This formation, more than 400 m thick, overlies Late-Cretaceous shales and siltstones (Boayan Clastics Fm.), with bedded or massive slumps of quartz sandstone.

The St. Paul Limestone is the only Neogene formation in the northern Palawan (emerged area). This indicates the strong uplift of the region since at least Middle Miocene, due to the collision between the Cagayan volcanic arc and the drifted Chinese continental margin, which formed an emerged imbricate thrust belt (Müller, 1991).

A second, Upper Miocene tectonic event is well dated in northern (only offshore) and southern Palawan; sediments deformed by this and the earlier activity are disconformably to unconformably overlain by gently tilted limestone and marl of latest Miocene-Early Pliocene age, whereas central Palawan was a relatively highland at that time (Williams, 1997).

The St. Paul ridge forms a roughly NE-SW range sloping down to the St. Paul Bay, located between the Babuyan River to the East and the Cabayugan River valley to the West (Figure 3). The length of the ridge is about 9 km, and its average width is 4 km; the highest peak is Mount Saint Paul, 1028 m in altitude. The structure is roughly that of a NNW dipping homoclinale ridge, laterally limited by major NNE-SSW faults and crossed by minor transverse faults and fractures (WNW-ESE and N-S). According to our study, the NNE tectonic lines have influenced both the general shape of the mountain and the major subterranean drainage, whereas dolines are often aligned along WNW lineaments (Figure 3).

On the east side, limestone forms an almost continuous cliff as high as 300 m, with the exception of the northern part, where the limestone merges gradually with the surrounding non-carbonate

terrains. On the west side, the edge of the limestone follows the border of the alluvial plain from the Cabayugan village to the sea.

The limestone outcrop can be divided into three sectors, on the base of differing morphological features. The northern, seaward sector has a rather gentle relief, with several remnants of planed surfaces from 40 to up to 250 m above sea level (asl) and a maximum elevation of about 460 m. Karst landforms are well developed, forming a typical cockpit-karst landscape. The central sector has a more rugged topography, reaching its highest elevation at the top of Mount St. Paul. This area contains steep slopes and high cliffs, while dolines and cockpits are infrequent. No significant caves are currently known in this central area. The southern sector consists of two peaks bordered by steep fault-scarps and, in places, by vertical cliffs up to 300 m of high (Figure 4); the highest elevation is 962 m. Large and deep karst depressions occur in both the peaks.
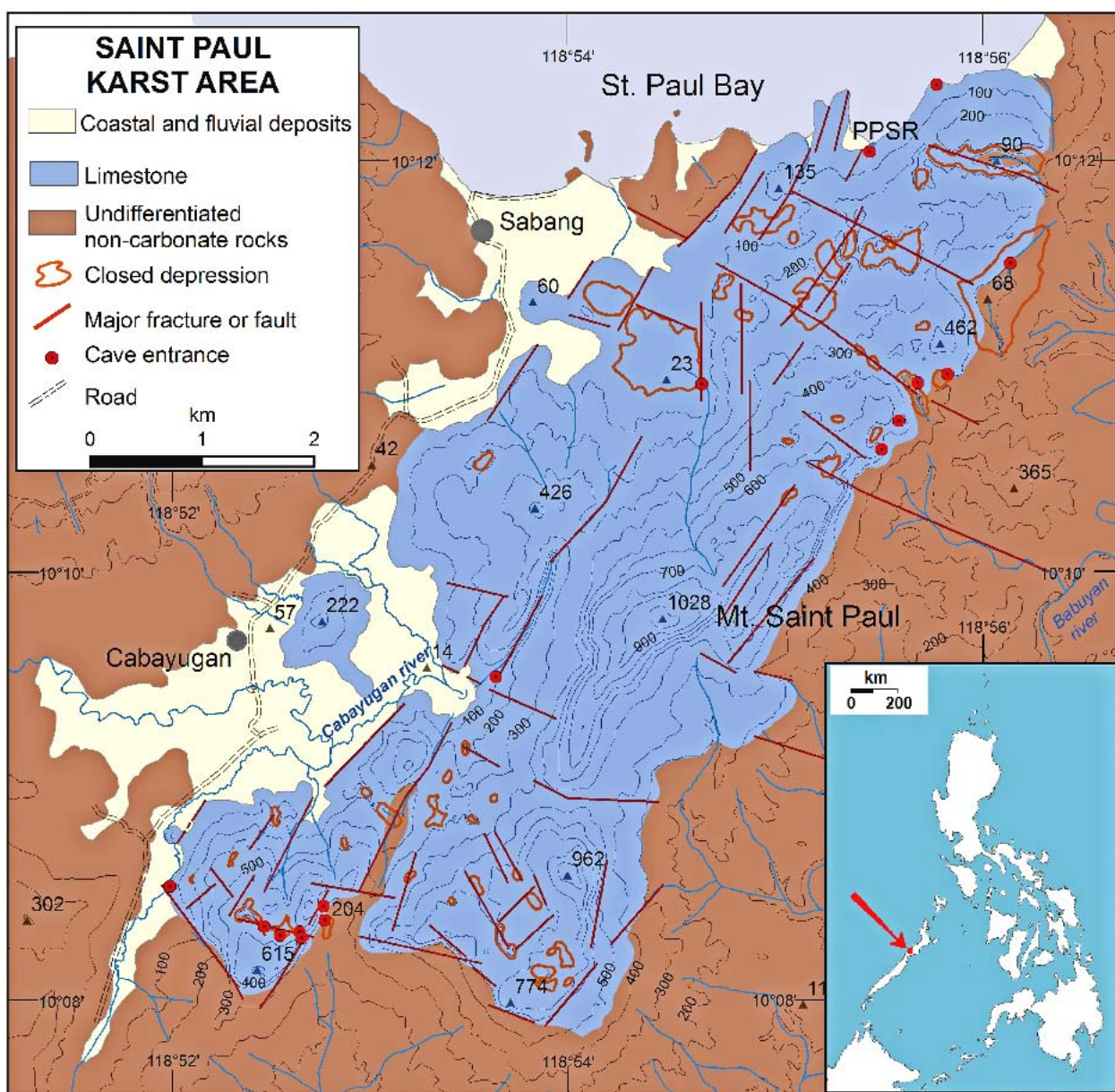

Figure 3. Geo-morphological map of St. Paul karst.

3. Karst and caves features
3.1. The karst landscape

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 12 % 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 4. Aerial view of St. Paul ridge from SW to NE. The south sector foreground shows a different morphology due to a stronger litho-structural control and a major development of karst landforms (photo: P. Petrignani, La Venta - Esplorazioni Geografiche).

The Cabayugan basin has a rectangular shape and consists of a structural polje, which collects the water from a catchment area of about 30 km^2. At the eastern border of the polje, and close to Cabayugan village (see Figure 3), the watercourse loses its entire flow (usually 200-300 L/sec in the dry season) at an elevation of about 15 m. Not far from there, at an altitude of 80 m asl, the huge upper entrance of the PPSR system is found, probably an ancient underground course of the cave stream, intersected by the slope retreat. To the north, beyond the sink point of water, the karst system receives additional allogenic water from minor closed valleys all along the western limestone boundary (Figure 5). The northern border of the karst area follows the coast of St. Paul Bay for about three kilometres. Along the limestone cliff, protected by a sand bank, the main entrance of the Subterranean River is found, whereas the entrance of another cave, called the Little Underground River, is located a few hundred meters toward east.
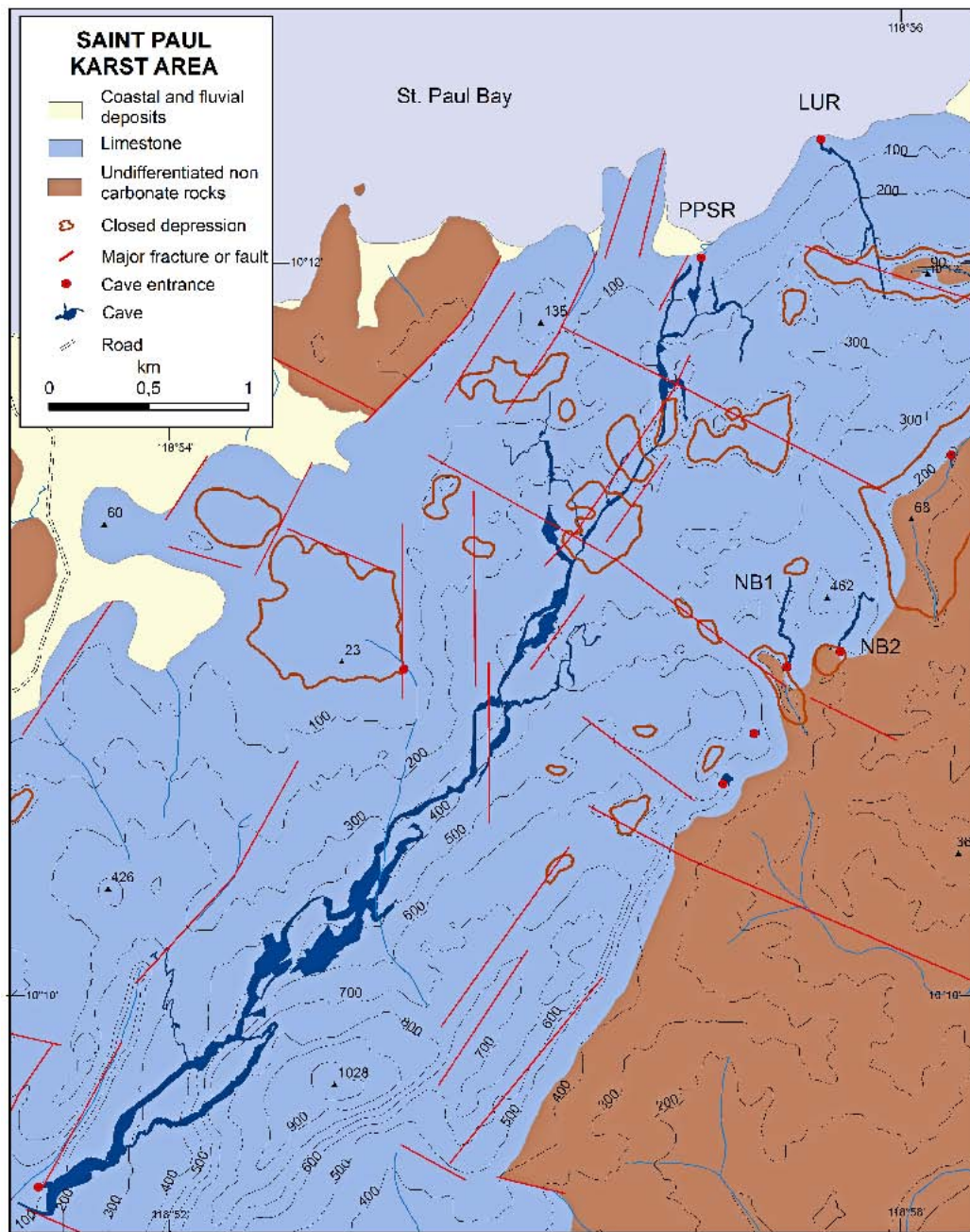
Figure 5. Plan view of Subterranean River and major caves of central and north sectors. The caves follow a set of NNE to NE oriented faults and fractures, whereas only short segments of cave passages are co-linear with bedding strikes. Major caves: PPSR = Puerto Princesa Subterranean River resurgence, LUR = Little Underground River, NB1 = Nagbituka 1, NB2 = Nagbituka 2.

Steep slopes and calcareous cliffs characterize the central part of the St. Paul Ridge, while to the north the landscape is distinguished by a subdued relief with several dolines. Large and deep depressions occur along the eastern limit of the limestone outcrop and can be actually considered as blind valleys. These depressions, the largest of which is more than 2 km in length, have several swallow holes at their bottom that are frequently active even during the dry season and feed minor karstic systems parallel to the PPSR, which flow directly to the sea. One of these secondary systems, the Little Underground River, is about 1 km long with a rectilinear pattern developed at sea level and acts as a resurgence during the rainy periods.

Some of the eastern sinking streams, feed two active caves, located at 290 and 250 m asl (± 10 m) and named "Nagbituka 1" and "Nagbituka 2" respectively (De Vivo et al., 2009). These caves consist of large active tunnels, mainly vadose in origin, descending to the north along the contact between limestone and shaly sandstone, with some phreatic passages in their lower parts (Figure 6).
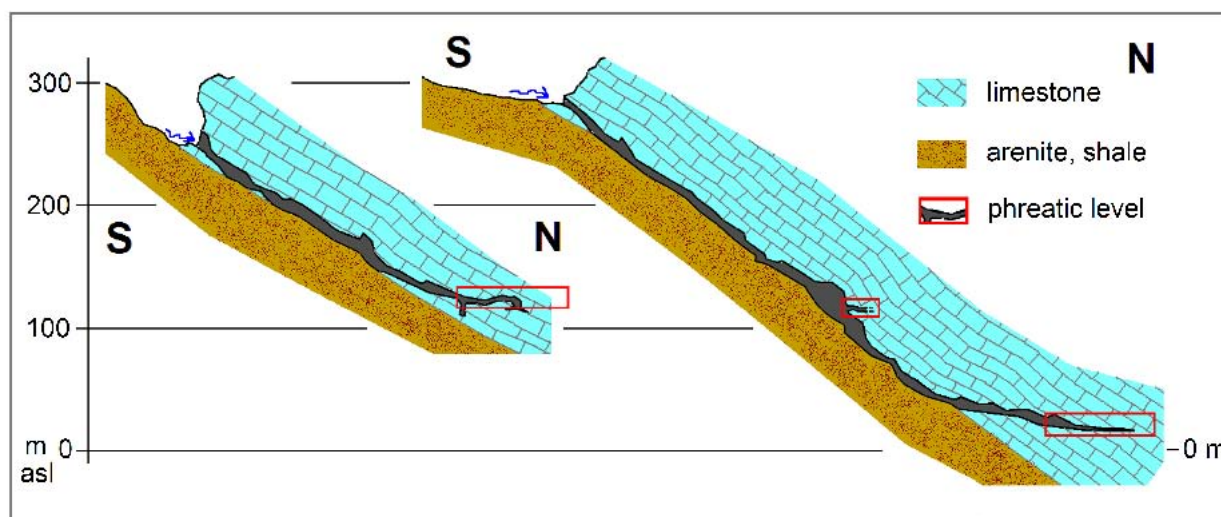

Figure 6. Sketch S-N geological profile of Nagbituka 2 (left) and Nagbituka 1 (right) caves. The two caves follow the contact with clastic rocks only in their first part, but not along the dip of bedding planes.

Figure 7. A section of a huge relict tunnel in the southern sector of St. Paul karst (Memory Cave). We can see the corrosion forms, which affect the bedrock wall and the oldest concretion buildings (persons for scale) (photo: A. Romeo, La Venta - Esplorazioni Geografiche).

The southern part of the St. Paul Ridge is characterized by two mountains, which have some planed summit surfaces gently descending toward the NW, intersected by large and deep elongated depressions and large sinkholes. Their average altitude is around 450 m for the western one, and 700 m for the eastern one. The eastern area has many sinkholes and cave entrances observed during helicopter flights, but the extreme rugged surface, by its sharp blades of limestone up to 10-15 m high, did not allow a field investigation.

Six caves were surveyed in the western mountain (Piccini et al., 2007; De Vivo et al., 2009). One of these contains a stream fed by a small catchment basin. The other five caves have similar morphological features and consist of large tunnels (Figure 7), developing between 300 and 400 m asl, that connect some of the deep depressions in the centre of the mountain with the steep external slopes (Figure 8).
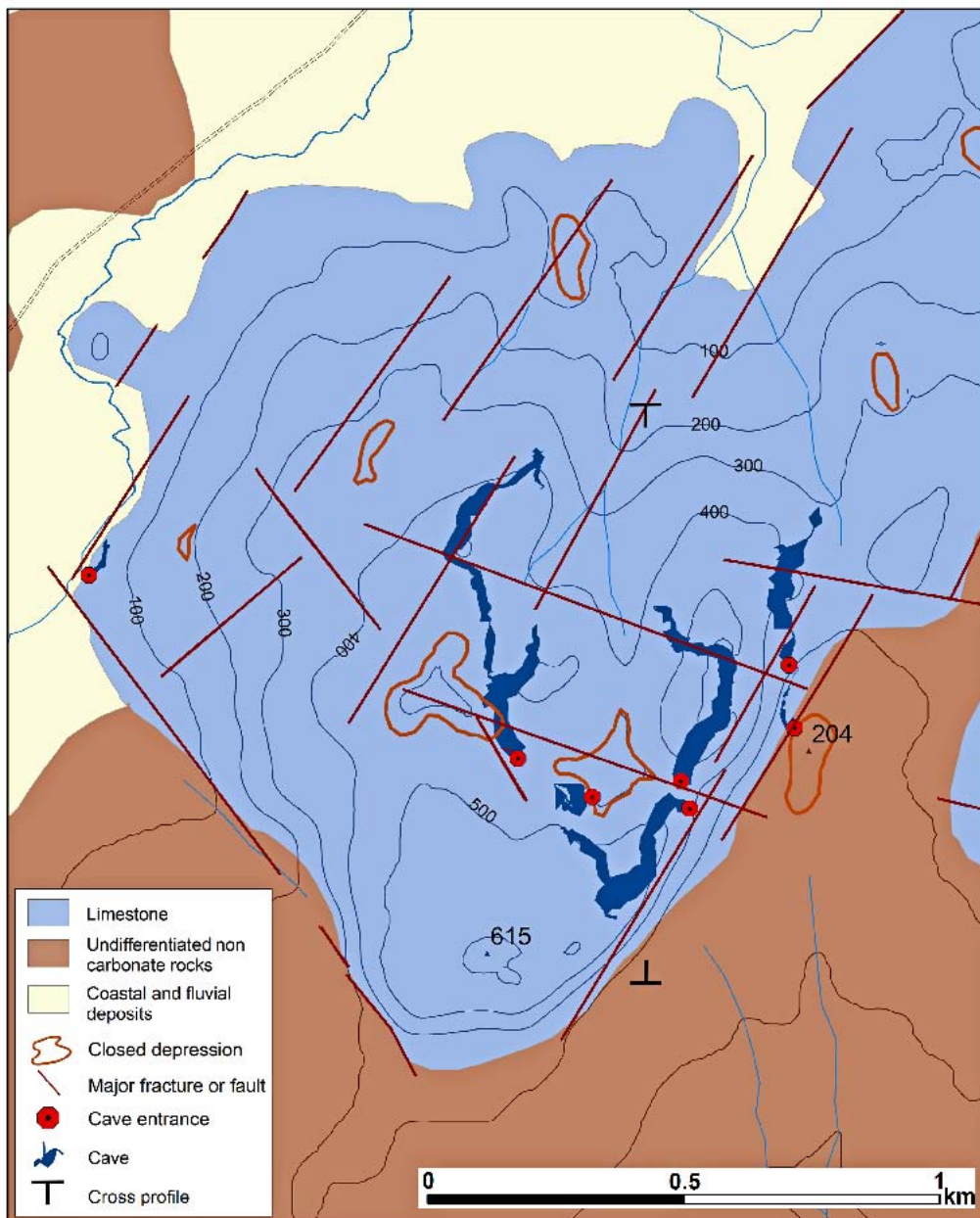

Figure 8. Plan view of the west peak of southern sector. The cross profile refers to Figure 12.

3.2. The Puerto Princesa Subterranean River

The Subterranean River is the longest known cave in the Philippines. The entrance, only a few tens of metres from the beach, continues as a low gallery with several lateral-diverting branches. The first part of the cave is a unique and astonishing flooded gallery that can be navigated on wooden canoes (Figure 9); this is one of the longest known underground boat rides in the World. Several large chambers represent a dry upper level of the underground river. Farther upstream, the gallery enlarges significantly. Some ramifications lead to parallel conduits, which are active only during the flood season. After a navigable route of 4.5 km, the boat ride terminates at the shore of a muddy riverbank. A lateral tunnel, of about 200 metres in length, leads to the river again, whereas a short climb opens into upper passages of exceptional dimensions. In this zone, at more than 100 metres above the present river level, there is a huge hall, 350 m long, 120 m wide and more than 80 metres high, which represents one of the largest known underground chambers in the World.

The underground river continues for three further kilometres, alternating vault-like galleries with large collapse chambers, to a hall where daylight filters in. This point is close to the sinking stream but it is not possible to pass through the active section. The light comes from a huge entrance" that opens about 100 metres above the level of the plain, near Cabayugan village.

In short, the structure of this karst system is characterised by a main active tunnel, connecting the Cabayugan River swallow hole (inflow) to the downstream entrance (outflow), and by two long left tributaries fed by sinking streams located on the western side of the karst (Figure 5). The cave is therefore a typical "through-cave," draining the waters collected in a surface basin of approximately 32 km^2.
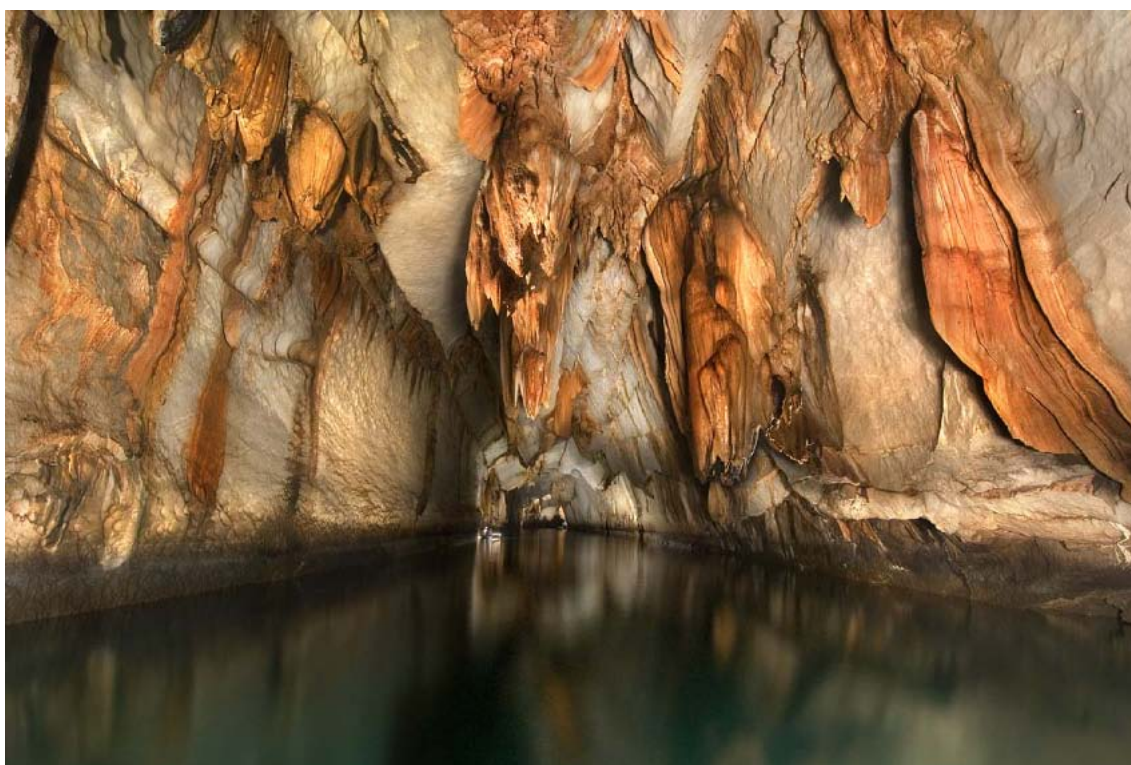

Figure 9. A long straight segment of the main flooded passages in the PPSR. On the ceiling, the fracture set along which the tunnel was formed is clearly visible (photo: P. Petrignani, La Venta Esplorazioni Geografiche).

The orientation of the whole cave network is aligned according to the major tectonic lineaments in the area; as a consequence the cave follows a roughly NE-SW fracture set, sub-parallel to the morphological structure of the mountain. Owing to the massive nature of the St. Paul limestone, tectonic discontinuities are more important than bedding planes for the development of cave passages.

One of the most significant hydrodynamic features of the cave is the fact that tides make their influence felt up to 4.7 km from the coast (straight line distance). Along the whole navigable part marine water lies under a thin layer of fresh water, just a few centimetres thick, with a transition zone of variable thickness (Forti et al., 1993; De Waele & Forti, 2003). During floods the cave is cleared of salt water, which later returns slowly because of tidal action, after floods have subsided. Despite the occurrence of corrosion produced by the mixing of fresh water with saline water, the morphological features of the system are mainly due to solution by continental water and to mechanical erosion by suspended load during floods. Only in its downstream part, mixing corrosion has produced typical forms of coastal caves, such as waterline notches (see Figure 9), spongework and anastomotic lateral conduits (Mylroie & Carew, 1988, 2000). From this perspective, the system may be considered a classic example of an underground estuary.

4. Methods

4.1. Survey and morphometric analysis of caves

In the St. Paul area, 15 caves are presently known, with a total length of about 30 km of underground passages. The PPSR alone has a total extent of 24 km, whereas seven further caves are more than 500 m long. All these caves have been surveyed using standard caver tools and mapping techniques (Ellis, 1976), except for the Little Underground River, which was quickly surveyed only using a field compass and a rope of fixed length. During the earlier explorations (1989-1991), distances were measured with a 20 m survey tape or with a thread distance-meter. Since 2007, a laser distance-meter, which allows a better measurement of cross sections, was used. Directions of cave segments have been measured with a 1° precision compass, slopes with a 1° precision rolling-disk inclinometer. No tripods were used.

In the first flooded part of the PPSR there was difficulty obtaining stable survey stations, as the mapping was done from boats. Despite this, because the easy working conditions and the gentle gradient of the galleries, the closure of survey lines has shown a sufficient grade of precision.

In general, the cave map accuracy conforms to grade UIS 4-2 (Union International de Speleologie), with an estimated error of ± 2% in the plan view and ± 3% in the vertical profile. Anyway, the vertical survey of the PPSR has a better precision, thanks to the fact that the underground river is at sea level for about 6 km far from the outflow entrance.

Cave maps were corrected to the current local magnetic declination (0°35' E), which is half than instrumental precision, and it is varying very slowly (in 1955 it was 0°40' E).

At first the cave maps were hand drawn, but later survey data have been re-processed with a GIS software package (ArcGIS, ESRI ®), by which the 3-D cave patterns were analysed, and comparisons with the local digital terrain model were obtained. Statistical analysis has been made both for orientation with respect to the north direction and for the altimetric distribution of caves. Elevations of cave passages refer to survey points, located 1-1.5 m above the floor.

This analysis allows us to recognize the main orientation of caves and to deduce the influence of tectonic discontinuities on the development of the underground network (Deike, 1969; Palmer, 2007). Elevation analysis is a quick method to determine the presence of cave levels (Palmer, 1987; 2000) whose origin can be due to a stillstand of the base level, where a litho-structural control does not occur (Bruno et al., 1995; Piccini et al., 2003).
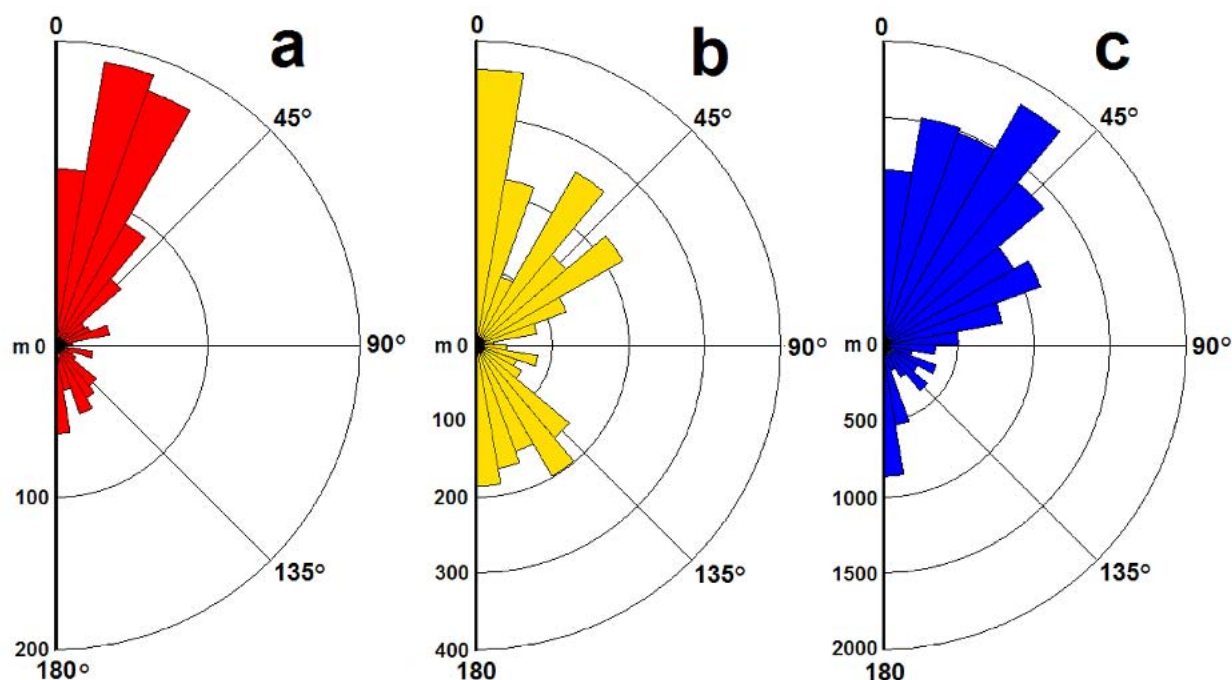
Figure 10. Cave passage orientation as determined by survey strikes: a) northern sector caves (PPSR is not included), b) southern sector caves, c) PPSR.

4.2. Topographical surface morphometry

The topographic analysis of the St. Paul area was based on the 1:50,000 topographic maps of the Board of Technical Surveys and Maps (BTSM – Philippines, edition 1955), using the 20 m contour lines in most of the study area, and the 10 or 5 m contour lines in the coastal and internal plain areas.

The first step was to obtain a vector map. The hardcopy was scanned at 300 dpi obtaining a TIFF-format image with a resolution of 4 m per pixel, then georeferenced and, finally, digitised to create two vector layers: one for the contour lines and one for the elevation points.

The digitising and vectorising of the elevation elements were automatically performed by ArcScan (a ArcGIS tool). Several data errors, mainly due to the automatic processing, were manually corrected with adjustments of contour lines, where these overlapped or were not well represented on the raster map. The water drainage networks was manually digitised from the map and corrected with aerial photos.

The topographic map fails to show the hydrographic features of the Cabayugan area adequately. A saddle, which separates the Cabayugan basin from the coastal plain of Sabang, is not shown on the map but is well visible on aerial images and on the Digital Globe image on Google Earth ®. For this reason, the stream paths were corrected using aerial photo interpretation, and compared to the new GDEM (Global Digital Elevation Model: with cell of 30 x 30 m) released on the 29th of June 2009 and obtained from the two near-infrared (NIR 3N and NIR 3B bands) ASTER stereo images (specifications available at http://www.ersdac.or.jp/GDEM/E/index.html).

The comparison with aerial photos and paper maps highlighted the good quality of the GDEM dataset in portraying the flood-plain areas and where limestone does not outcrop, whereas conspicuous errors and many artifacts appear in areas of limestone outcrops. In the highest part of the Saint Paul Ridge, for example, the GDEM shows several depressions, up to 500 m deep, which are incorrect. These errors are generated by the automatic filtering processes applied to the GDEM dataset, which probably fail to portray accurately the very rugged surface of limestone.

Another comparison was made with the SRTM (Shuttle Radar Topographic Mission) 90 x 90 m DEM, which did not provide data consistent enough to portray karst forms such as dolines. Both GDEM and SRTM DEM are, therefore, not useful for extracting morphometric parameters in the limestone area. The DEM created by digitising the photogrammetric maps has consequently been considered the most consistent dataset for the analysis.

Contours of dolines was obtained from aerial photo interpretation, and then compared to the topographic map. By overlaying the aerial images and the contour lines it was possible to obtain the mean elevation of the doline rim with a precision of ± 10 m. The digital terrain model (DTM), the relative morphometric analysis and the extraction of the main morphometric indexes were performed using the software application ArcGIS 9.1.

The DTM of St. Paul was first computed with the Triangulated Interpolation Network (TIN) method and then transformed into a 10 x 10 m raster file. The algorithm in ArcGIS was unable to portray the morphologic model because it introduces artifacts to the computed topography. For this reason, the DTM was re-processed using the "Topo to Raster" algorithm for obtaining better accuracy. "Topo to Raster" is an interpolation method specifically designed for the creation of hydrologically correct digital elevation models. It is based on the ANUDEM algorithm, version 4.6.3, developed by M. Hutchinson & Dowling (1991). This method takes into account contour lines, hydrographic network, closed depressions, and slope breaks. The algorithm was processed 45 times and the result was much more detailed and realistic, especially in low-relief areas and where large sinkholes are present.

The aim of performing the morphometric analysis on the DTM was mainly to find topographic elements that could be related to the origin and the development of the karst systems. To achieve this, it has been assumed that the different cave evolution stages have also been "recorded" on the topographic surface, as it appears that they were all influenced by the same morpho-tectonic evolution.

5. Results
5.1. Geomorphic analysis of caves

The geomorphic analysis was performed separately for the two major active caves occurring in the northern sector (Nagbituka 1 and Nagbituka 2), for all the caves surveyed in the southern sector and for the PPSR.

The active caves of the northern sector are mainly developed in the NNE direction, with the maximum concentration between 10 and 20° relative to true north (Figure 10a). This indicates that they follow the same fracture set as the PPSR, and that they are probably part of a parallel drainage system with an independent pathway towards the sea (maybe toward the Little Underground River coastal spring). Although mainly vadose in origin, Nagbituka 1 and Nagbituka 2 follow the contact between limestone and clastics not in the direction of the bedding dip, which is about NNW, but along a set of NNE oriented fractures (see Figure 5). This circumstance shows that bedding permeability is relatively low and only joints and faults allow effective groundwater flow. The Little Underground River has a N-S orientation but it has not been analysed due to the lack of a precise survey.

Conversely, in the southern sector, the cave orientations show a greater scatter (Figure 10b). Most strikes represented in the Figure are N, NE and NNW, but the plan views of these caves do not show well-defined prevalent directions (see Figure 8). As the NNE-SSW-oriented faults also continue in the southern zone, the different pattern of these caves indicates that when they were formed the morphologic and, possibly, the tectonic setting of the area was different from that which later controlled the pattern of the PPSR and of the northern caves.

The third graph (Figure 10c) is limited to the PPSR and shows a clear prevalence of strike orientation in the same direction as the main set of faults and joints (NNE to NE), with the

maximum between 30° and 40° with respect to north. It is important to note that such directions do not correspond to the mean strike of the beds, which is WSW-ENE in most of the area. Nevertheless some of the PPSR passages, either active or inactive, follow the lithological layers. As far as the altimetry of karst conduits is concerned, the graphs (Figure11, right) emphasise the distribution of all the passages of the northern and southern caves and of the PPSR alone.

The two northern caves show a wide range of passages elevations, with only a slight maximum at 120-130 m asl, which mainly depends on some inactive phreatic tubes in Nagbituka 2.
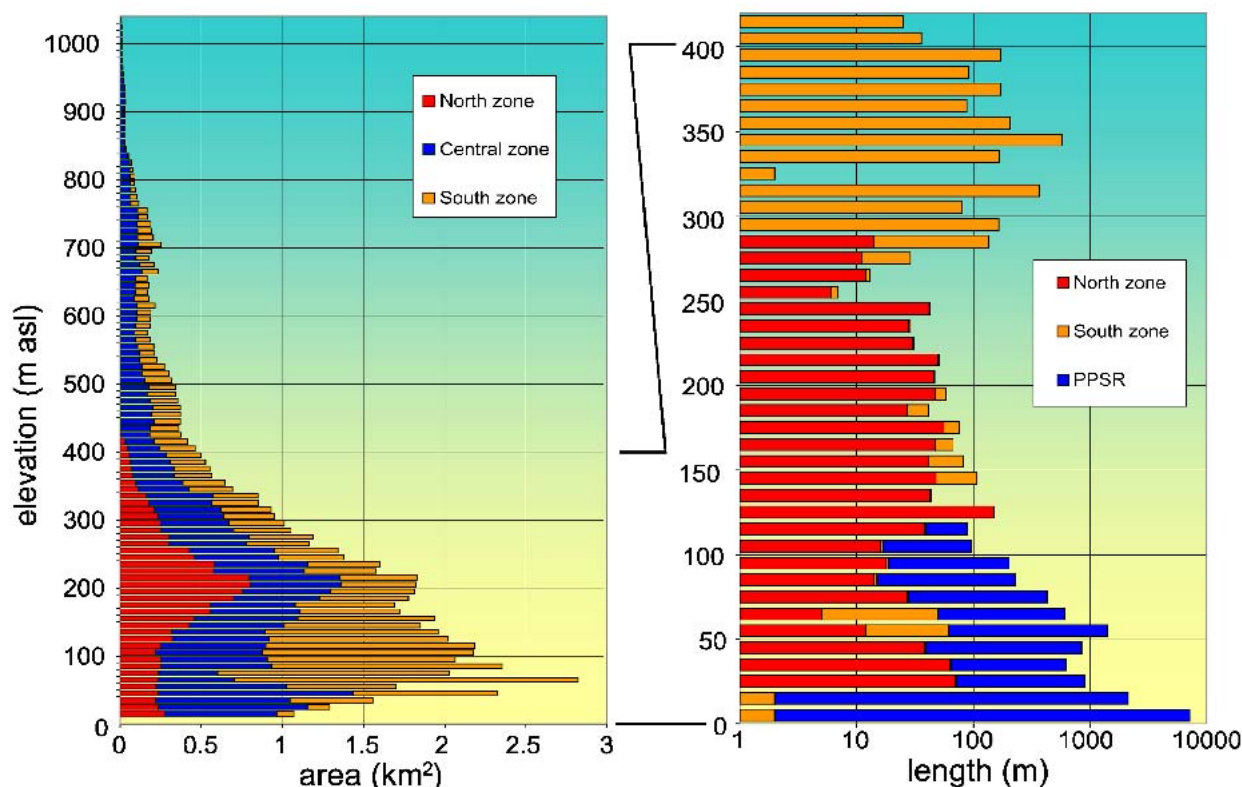

Figure 11. Hypsographic plot of the three sectors vs. altimetric distribution of passages of northern caves, southern caves, and PPSR.

The morphology of these caves indicates a vadose-phreatic transition ("piezometric limit" of Palmer, 2000) at 140 m asl, where the canyon acquires a lower gradient and ceases to follow the stratigraphic contact. Here, the cave becomes smaller in size and its cross-section changes from mainly vertical to mainly horizontal and contains some cupolas in the ceiling. This paleo-phreatic level cannot be structurally controlled (it is not a perched tube) and so it testifies to an old base level. At 130 m asl a clear phreatic conduit occurs (see Figure 6), which formed only a few meters below the piezometric surface.

A short segment of a paleo-phreatic conduit is found almost at the same elevation in the Nagbituka 1 cave. This cave ends close to the current sea level (15 m asl) with an epiphreatic tunnel almost completely filled with alluvial deposits. The vadose-phreatic transition is not clearly visible in this cave. Nevertheless, epiphreatic morphologies are found at 30-35 m asl, where the cave no longer follows the limestone/clastics contact anymore. At 25-30 m asl, typical forms due to corrosion in almost completely filled passages (paragenetic sculptures; Ford & Williams, 2007), such as anastomoses and pendants, are visible on the ceiling of the tunnel.
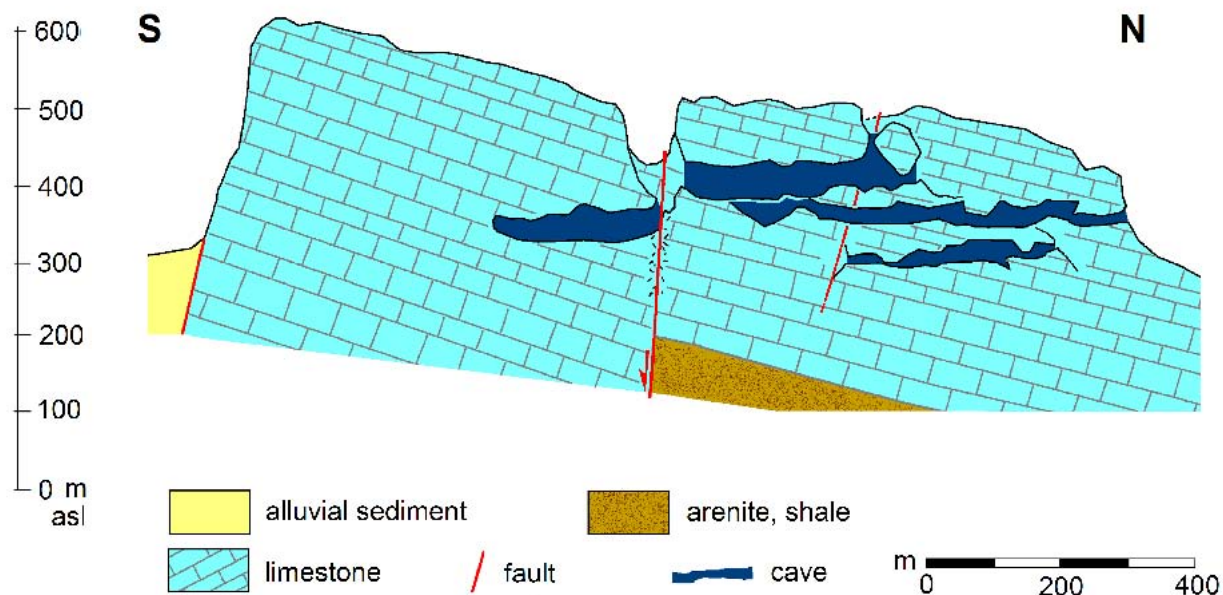
Figure 12. Compound, projected profile of the west peak of southern sector showing the major caves. Caves profiles are projected on N-S oriented vertical plane. Topographic profile is made by showing the most elevated points in a westward view.

In the southern sector of the karst area, the cave passages are distributed between 30 and 420 m asl. The conduits at 50-60 m asl represent a single cave, located just a few meters above the alluvial plain. This and other unsurveyed caves along the western border of the karst are the result of lateral dissolution at the present alluvial plain level. The conduits located between 140 and 200 m represent a vadose sinking-stream cave developed at the contact between the limestone and impermeable basement. In this sector, most of the conduits are located above 300 m asl and particularly around 350 m. Geomorphic surveys and analyses of longitudinal cave profiles show the presence of large relict phreatic tunnels, whose horizontal pattern is not controlled by the limestone bedding, readjusted by the erosion of free-surface streams. These mainly epiphreatic caves have been formed at an old base level, and the current altimetric scatter is probably due to differential tectonic displacements along the visible faults nearby (Figure 12).

The PPSR is largely developed at sea level, or only a few meters above, with long segments of tunnels between 5 and 25 m asl. The profile also shows several large passages at an elevation of mainly 50-65 m. The general morphometric analysis of the survey data is not very precise in recognizing old epiphreatic levels, because in several places the current floors of the upper galleries have been modified by large rockfalls, which have caused an upward shift of the passage from the original elevation. If we take into account only the well-preserved conduits, and particularly those where we can recognize the old streambeds, we see that the altitude of the paleo-river floor is more precisely at 68 m asl (elevation of upper surfaces of fluvial deposits) in the northern (downstream) part of the cave, and at 45-55 m in the southern (upstream) parts. This apparent incongruence (the downstream part higher than the upstream one) can be explained in three different ways. It is possible that the downstream part became inactive, owing to the diversion of its stream into lower passages, before the upstream part, which remained affected by erosion after the northern passages became inactive. Another possibility is that this difference in elevation could be due to differential tectonic uplift, which affected the northern sector of the

cave more than the southern part, after dewatering of this paleo-level. Another alternate explanation involves exploration bias, because we cannot exclude the occurrence of inactive streamways at less than 68 m in the downstream part of the cave.

In short, the southern and northern sectors of St. Paul karst show a different distribution of cave elevations, which suggests the development of karst under a changing morphotectonic setting. The PPSR is closely related to the current tectonic setting and is not significantly disturbed by tectonic dislocations, whereas it was affected by a general uplift of the whole ridge.

5.2. Flooding and water level cave morphologies

The four major caves of the southern sector are located at 350-400 m asl and have an almost perfectly horizontal pattern not controlled by any litho-structural factors. We consider them as typical examples of base-level caves, formed by low-gradient, free-surface water flow; despite their huge dimensions and great age, rock collapses are rare.

Cave walls show water corrosion forms, which involve an ancient generation of flowstones too. The corrosion forms appear as rounded niches, up to 1-2 meters wide, and as horizontal water level notches, up to several meters long. We can exclude an origin due to condensation processes or to biogenic alteration (from guano), because: (i) such forms are uniformly distributed on rock and on flowstone, (ii) dissolution surfaces are clean and not significantly weathered and, finally, (iii) they are present also some tens of meters above the cave floor, where the effect of guano deposits cannot extend. In short, many elements lead us to argue for a general episode of re-flooding of these caves.

Features that indicate former water levels are also present along the PPSR. About 4 km upstream from the coastal spring, where the ceiling of the main tunnel rises up to 20 m or more, there are two evident old corrosion notches due to persistent levels of water (Figure 13). The upper notch is at + 12.4 m above present mean sea level (pmsl) The second notch is at + 7.7 m above pmsl and can be observed throughout the cave, wherever the ceiling is high enough (see Figure 6 on the left). Some of the lateral branches of the PPSR contain alluvial terraces consisting of sands and gravels ranging from about +7 to + 8 m, which are related to this second high-stand notch. This circumstance allows us to correlate this notch to the marine one, visible on the seacoast cliff at 6.8 m above pmsl, which dates back to the last interglacial MIS 5e (Maeda et al., 2004).

Close to the current notch are two minor notches at ca +2.3 and +3.2 above pmsl that can be related to the middle Holocene high-stands visible on the current seacoast (Omura et al., 2004; Maeda et al., 2004).

The morphometric analysis of marine notches and the dating of corals, collected along the seacoast close to the entrance of the PPSR, indicate differential movement between various areas, as much as some tens of decimetres, during the Holocene (Omura et al., 2004; Maeda et al., 2004). Nevertheless the elevation of the MIS 5e eustatic notch on the current coastline indicates a very low uplift rate, ranging from 0.01 to 0.02 mm/a, during the last 120 ka.

In general it is accepted that none of the last eustatic high-stands were higher than the MIS 5e (Linsley, 1996; Chappell et al., 1996; Esat et al., 1999). If the cave notch at about + 12 m relates to a eustatic maximum before the MIS 5e, this implies an uplift rate significantly higher than during the Late Pleistocene, depending on the age of this notch. If the hypothesis that this upper notch refers to the MIS 7a high-stand (about 200 ka BP), and that the uplift was mainly prior to 120 ka, the mean uplift rate would have been 0.12 mm/a, while if the notch should be related to MIS 9e (about 340 ka BP) the mean rate would have been 0.04 mm/a. Unfortunately there are not sea-level curves for this area prior to the last 150 ka to distinguish between these hypotheses.

In short, the elevation of sea-level notches along the coast and inside the cave suggests a substantial stillstand during the Late Pleistocene, while the uplift rate could have been more rapid during the Middle Pleistocene.
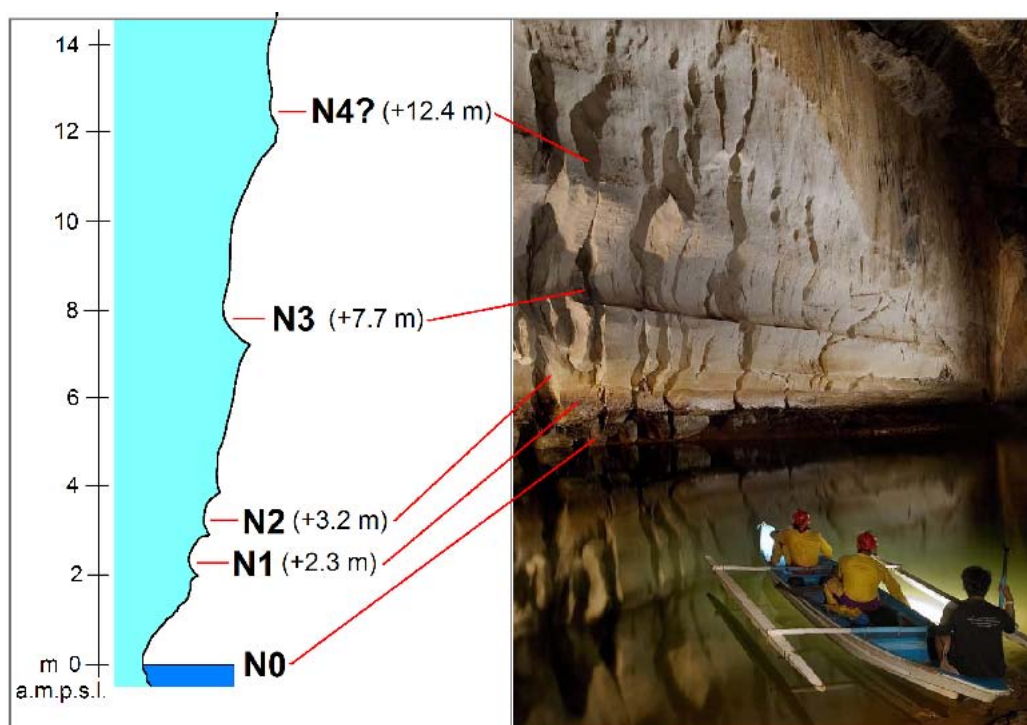
Figure 13. The sea level notches along the underground river, about 4 km upstream of the out-flow (photo: P. Petrignani, La Venta - Esplorazioni Geografiche)

The morphology of the active level of PPSR is clearly adjusted to the current sea level, but we have to consider that in the last 500 ka the sea was mainly lower than now (mainly at 50-60 m below pmsl; see e.g. Chappell and Shackleton, 1986; Chappell et al., 1996). This implies that the PPSR has functioned mainly as a vadose through-cave affected by fresh water flow with a substantial load of insoluble material. For this reason it is realistic to think that the alluvial sediment that forms the current riverbed throughout the cave hides a canyon several meters deep, whose rock bottom is probably some tens of meters below the current sea level.

5.3. Morphometric analysis of topography
The study area embraces the entire St. Paul ridge, delimited by the Babuyan River on the eastern and southern slopes, by the Cabayugan River along the western border, and by the seacoast on the north. The area can, therefore, be considered a single morphological unit (Figure 14). The ridge has been divided into three different sectors: northern, central and southern sector, delimited by two main transverse WNW-ESE tectonic lineaments. The morphometric analysis has been performed both on the whole area and on the limestone outcrop, to enhance the effect of lithology on the morphometric parameters.
The DTM allowed us to extract the following parameters: steepness of the slopes, hypsographic histograms, and the distribution of low relief surfaces (LRS).
Steepness is one of the most-utilised parameters for morphometric analysis of DTM (Weibel & Heller, 1991; Giles & Franklin, 1998; Jordan, 2003; Jordan et al., 2005). In karst areas, gentler slopes usually occur where the karst landforms generated by infiltration are better developed; whereas the steeper slopes usually occur where karst landforms are sparse (Williams, 1985; Ahnert & Williams, 1997). In the case of wet tropical karst, this is not always true, and diffuse infiltration forms can interrupt high steep areas, while runoff can be practically absent.
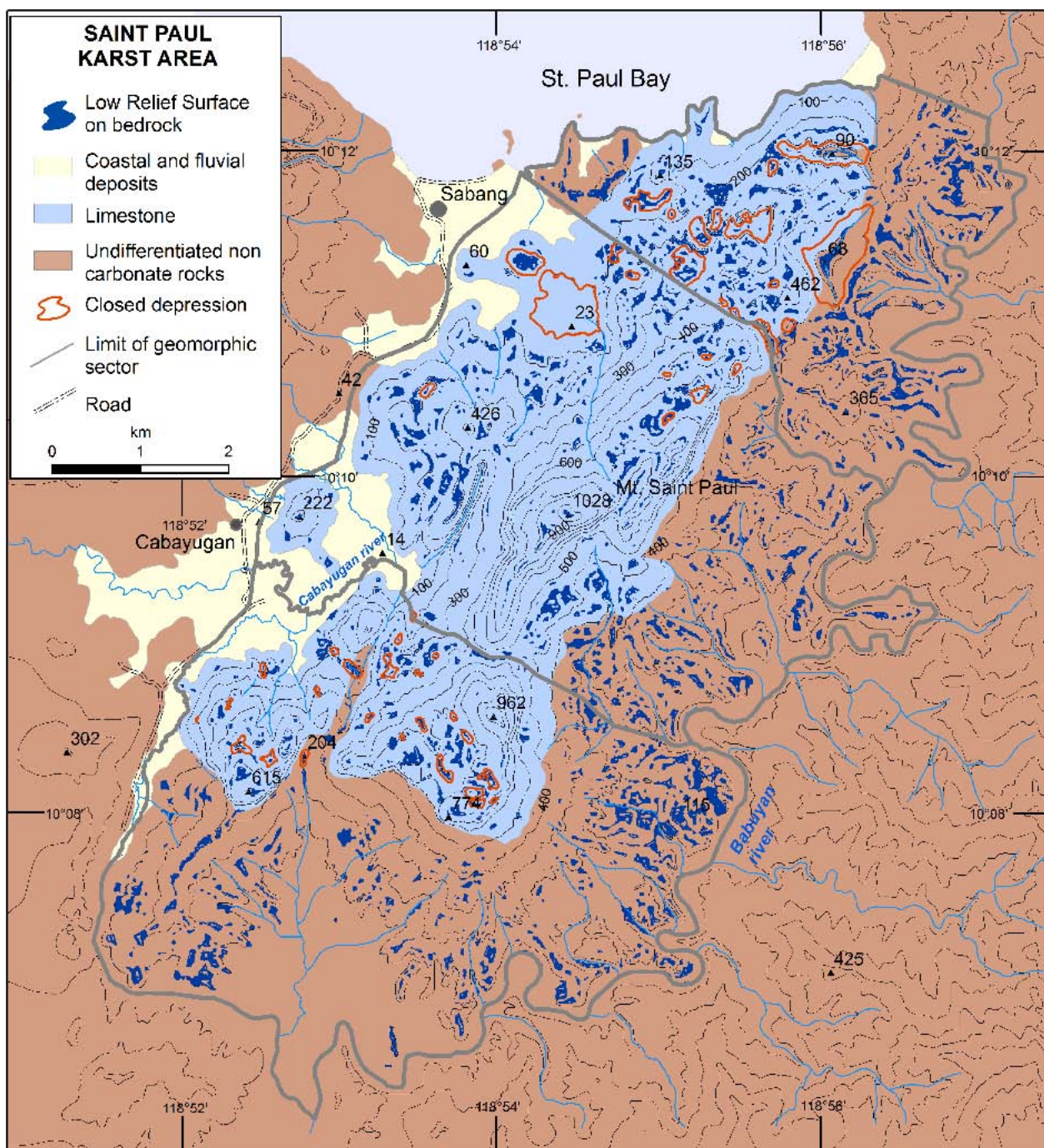
Figure 14. Boundary of the entire field area and of the three sectors, studied through morphometric analysis of DTM. Low-relief surfaces (LRS) are traced onto limestone and non-carbonate rock. Note that several LRS are located in the northern sector around major dolines.

In the St. Paul area, this kind of analysis allows a good characterisation of the overall morphology. The frequency distribution graph of slope inclination (Figure 15a) shows a bimodal pattern, one, with modal class at 2-4 °, related to valley plains and flat erosional surfaces, and one related to slopes, with modal class at 22-24°. Limiting the analysis to the limestone area (Figure 15b), the pattern becomes roughly unimodal with the maximum at 34-36° (68 %), which is a recurrent steepness of slopes on tropical karst (Tang & Day, 2000).
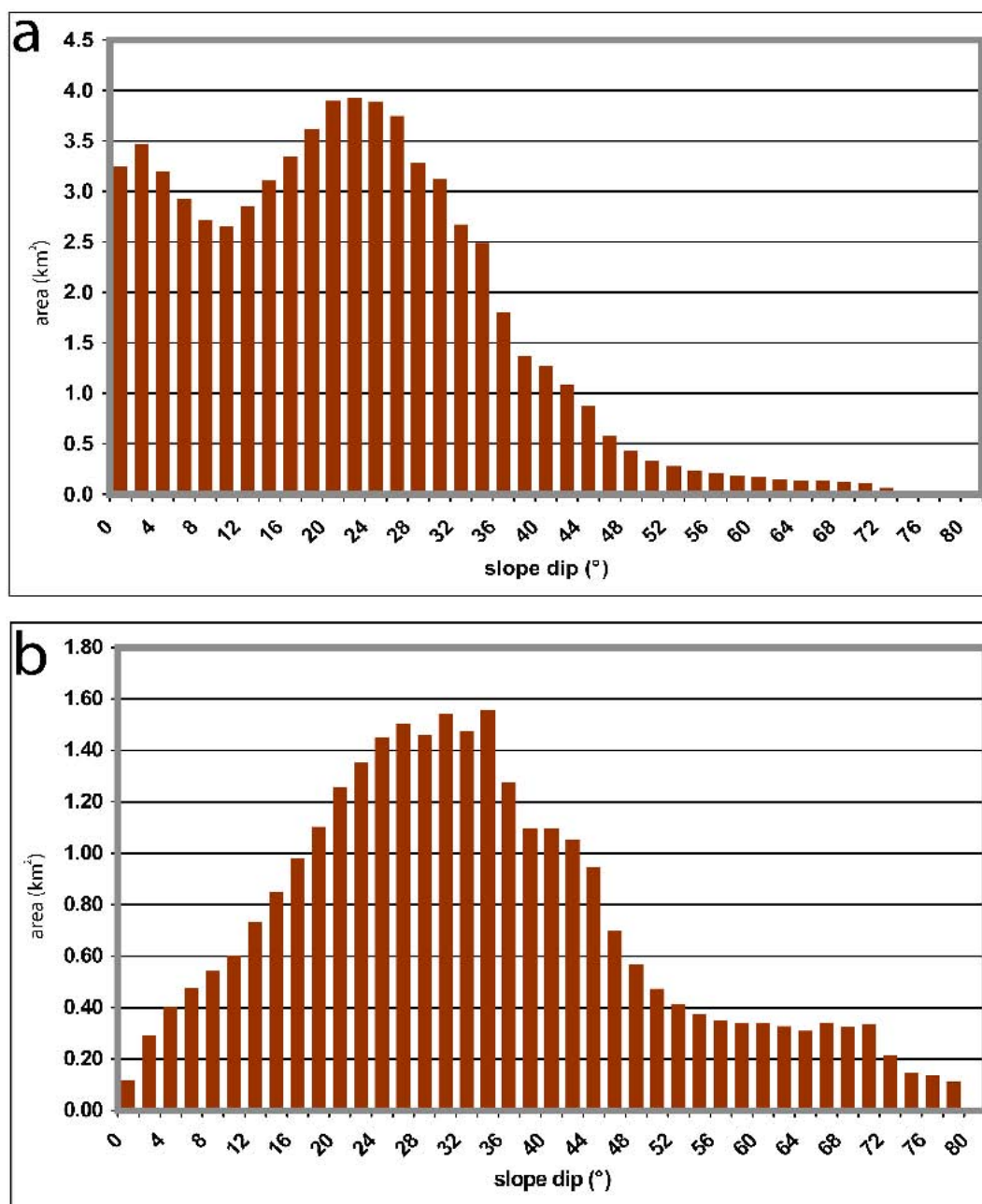
Figure 15. Frequency distribution of topography slope angle in the total area (a) and in the limestone outcrop (b).

The hypsographic histogram of the whole area (Figure 16a) shows that the most represented areas are the plains at 40-70 m asl, while the only significant anomaly is the peak in elevations around 200 m, which is mainly due to the morphology of the seaward northern sector, whose hypsographic data show significant development from 170 to 210 m asl (Figure 16b).
The altimetric distribution of LRS is more significant and can be better compared to the elevation of cave passages. This kind of analysis allows us to recognise the areas of gentle slope at the top or along the sides of mountains (Piccini, 1998). These roughly flat areas can be due to a local litho-structural control, or they can be the remnants of summit or pedemontane surfaces. The structural setting of St. Paul is characterised by a regular and medium-steep inclination of uniform and massive limestone and allows us to interpret the LRS as morphotectonic features linked to old base levels.
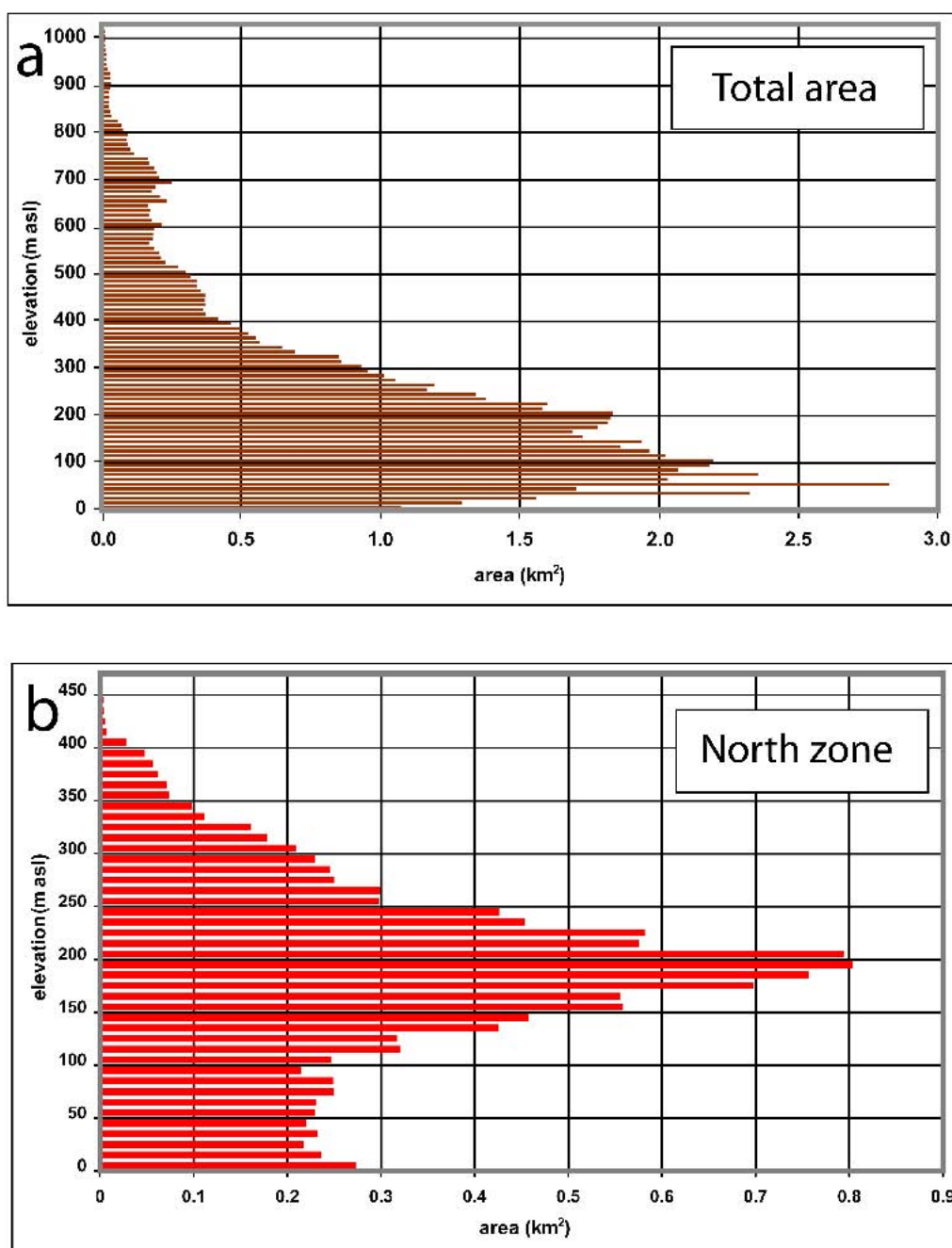
Figure 16. Hypsographic plot of the total karst area (a) and of the northern (seaward) sector (b). Note that the topographic surfaces around 200 m asl occur mainly in the northern sector.

A LRS has to be first defined with an upper value of steepness, which, in mountainous areas, usually ranges from 10° to 20°; this limit can be derived from the frequency graphs of slope. Figure 14a shows the frequency curve of slope at intervals of 2 degrees having a bimodal shape with a minimum in the class 10-12, consequently slopes between 0° and 12° can be defined as LRS because they belongs to a different family of topographic surfaces distinct from those of the mountain slope.
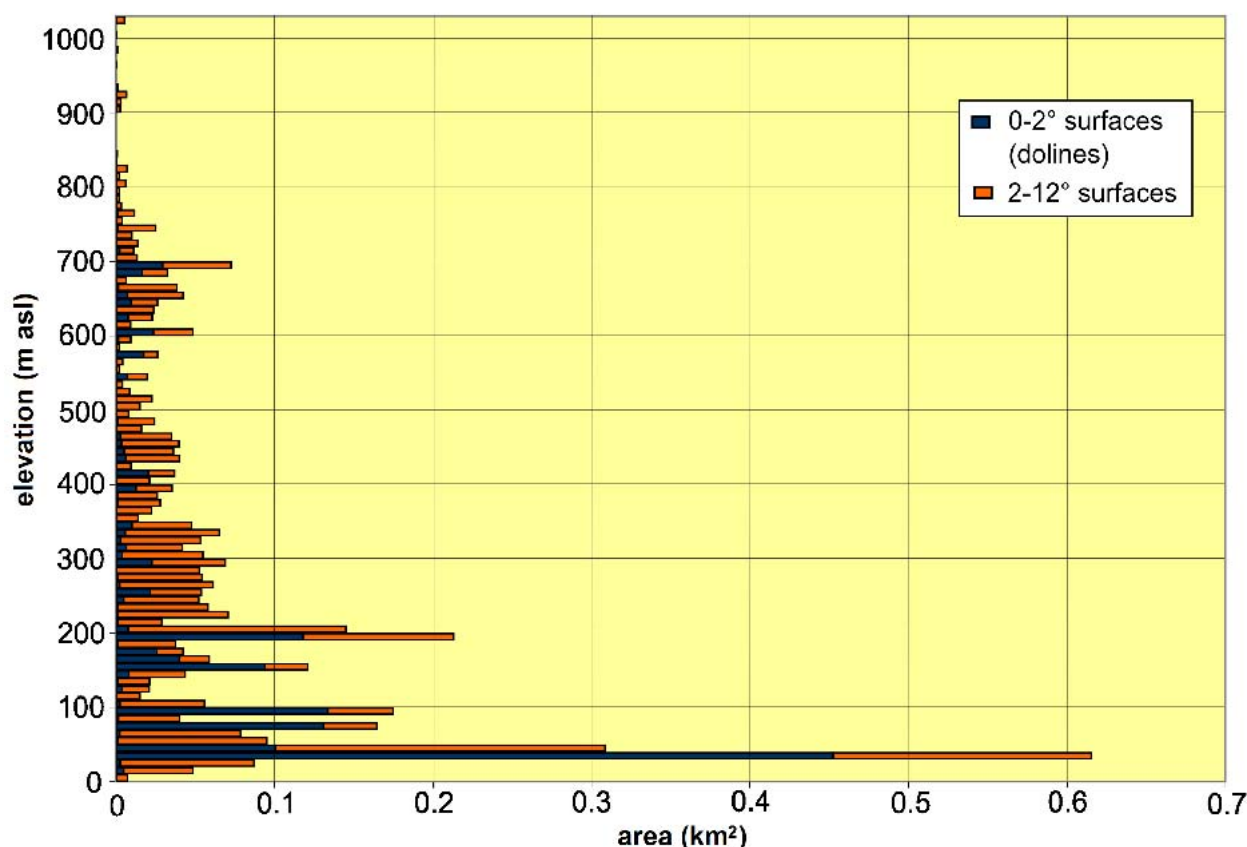
Figure 17. Altimetric distribution of low-relief surfaces (LRS) on limestone. "Horizontal" surfaces (0-2°) are only apparent, because they were obtained by "filling" of dolines and large closed depressions and so they represent the distribution and the extension of closed depressions on the karst area.

In the karst area the occurrence of several large and deep depressions (large dolines, cockpits) introduces to a further problem because the DTM shows them as high-gradient forms even where they occur on wide low-gradient areas. Dolines usually form on a low-gradient topography where infiltration exceeds runoff (White, 1990; Williams, 1985; Ford & Williams, 2007). For this reason we have modified the DTM by "filling" each closed depression to its upper border. This procedure is reasonable because our aim is to find remnants of old planed surfaces from which the dolines were progressively deepened due to centripetal runoff and dissolution, even if some of them may have formed by the collapse of underground cavities. This artificially adjusted topography allows us to emphasise the altitude distribution of the dolines, because they appear as 0° surfaces on the DTM (limited to limestone outcrop), and to recognize how much of the original surface, from which doline originated, survives.

Figure 17 shows the altimetric distribution of LRS (inclination < 12°) in the limestone area. Excluding the low elevation zones, the graph shows the presence of flat areas (large dolines) at 140-170 and 190-200 m asl. The latter maximum is particularly significant because between 190 and 210 m there is also a maximum development of real LRS (dip higher than 2°), which probably represent the remnants of an old low-gradient landscape from which the dolines began to form. This old topographic setting survives mainly in the northern sector and so could be interpreted as an old marine abrasion terrace.

LRS are well developed from 230 to 300 m asl, mainly in the seaward sector, while in the central and northern areas there are only a few scattered examples. Another significant maximum is at

390-410 m asl in the southern zone, which could be due to a local structural control or could represent the relics of a previous subdued topography related to the old generation of caves at 400 m (see Figure 12).

6. Discussion

Although far from exhaustive, the current knowledge of the morphological features of the St. Paul karst allows us to deduce the main stages of speleogenesis.

The oldest caves are located in the northern area, at 300-320 m asl, and in the southern sector, ranging from 300 to 400 m asl. The latter are portions of large passages that were greatly widened by free-surface water erosion and then abandoned. Afterwards, a long phase of flowstone deposition, which formed concretion masses up to several tens of thousands of cubic meters in volume, occurred. These ancient parietal flowstones are deeply corroded, with large wall-niches (megascallops) that affect the rock walls too. These corrosion forms seem to indicate a long phase of general re-flooding that affected all these relict caves.

Later, when the caves were again dewatered, a new phase of calcite deposition led to the formation of thick dripstones and huge stalagmites up to 12-14 m high and with a diameter of several meters. During this second stage of calcite deposition, rock falls occurred mainly close to the present entrances, due to the gravity collapse of sinkholes. These passages constituted an old unique system formed close to the local base level, which was probably the sea level. In this case, we can consider secondary dislocations of some tens of meters along minor faults have affected these caves.

A lower cave level is located between 50 and 80 m asl. This level is well represented inside the PPSR, where it consists of large inactive tunnels parallel to the current river. These tunnels are large epiphreatic passages containing thick alluvial deposits covered by flowstone and stalagmitic masses, which in places almost completely fill the conduits.

In the upstream sector of the cave, downcutting forms are found indicating a long phase of vadose entrenchment, the floor of which now is at 25 m asl. This cave level was firstly formed in conditions similar to that of the active underground river, while the vadose entrenchment could be due to a drop of base level.

The most recent speleogenetic stages are responsible for the formation of the currently active passages of PPSR. This level of mainly flooded tunnels was formed by fresh-water corrosion and by mechanical erosion during allogenic floods. Only in its downstream part does mixing with marine water occur, where it has been forced to move upstream and downstream by tidal fluctuations.

For what the chronology of caves formation is concerned, presently there are few constraints, which are related to the last speleogenetic phases only.

The St. Paul limestone age ranges from late Oligocene to early Miocene (Almasco et al., 2000); some authors (e.g. Williams, 1997) propose that Miocene terrigenous sediments have buried this formation. The exhumation of limestone probably occurred during the Middle-Late Miocene, due to the activity of the Ulungan Bay transverse fault, indicating that the speleogenesis probably embraces the whole Pliocene-Pleistocene period.

With regard to the morphological features and dimensions, the oldest and highest caves in the south of St. Paul ridge indicate a long evolutionary phase close to the local base level (i.e. sea level), followed by an important phase of flowstone deposition and later by a phase of general re-flooding. None of these caves contain fluvial deposits inside, although in some part of the main passages we can observe corrosion notches tens of metres above the floor, which mark the upper limit of corrosional forms on walls and flowstone masses. The elevation of these notches ranges from 300 to 345 m asl, indicating post-speleogenetic tectonic movements.

The age of these caves is not known, as no datable samples have yet been found. An interesting, but currently indemonstrable, thesis is that these large tunnels developed at sea level and were successively submerged by a global marine transgression, such as, for instance, the about 60 m Early Pliocene general rise of sea level (Haq et al., 1987; Wardlaw & Quinn, 1991). This old generation of caves may have been again dewatered during the Late Pliocene sea level lowstand. The lower and younger cave level mainly occurs between 50 and 80 m asl. This second level could reasonably be dated back to Early Pleistocene, as suggested by the extrapolation of the recent uplift rate of the coastal zone. As far as the current active cave system is concerned, we can surely state that it already had its current structure during the MIS 5e glacial phase and probably already during the previous glacial phases.

7. Conclusion

Several geologic and morphologic elements lead us to propose a long and multi-phase evolution of the St. Paul karst area, which possibly encompasses the period from Early Pliocene to the present.

The earliest stage of cave formation involved the origin of large tunnels in the southern sector, presently at 350-400 m asl, and some minor phreatic caves in the northern sector at 320 m. During this first stage, the shape of limestone ridge was only slightly influenced by the NE-SW fault set and probably had less relief. The hydrographic pattern was very different from the current one and the southern caves were portions of through-caves fed by wide surface basins. Cave morphologies indicate that this phase of cave development is related to a long stillstand of base level during a tectonically quiescent period. The later re-flooding could be explained as the result of a global transgression (Early Pliocene?). Tectonic uplift and/or lowering of sea level dissected these cave systems. The formation of a wide surface of planation, now preserved as a relict and heavily karstified surface at about 200-250 m asl, is probably related to the Late Pliocene sea level stillstand.

A second phase of base-level cave development is well documented in the northern sector, in some water-table caves of the southern area and mainly in the inactive level of PPSR (Figure 18). All these caves are largely influenced by NE-SW tectonic lineaments and were formed when the landscape and the river network have already assumed a structure similar to the current one. The morphological features of this second generation of caves suggest a further phase of base level stillstand, that is also recorded in the topography as LRS located at 50-80 m asl, and which could be the remnants of a sea abrasion platform (Figure 18). The age of this phase is probably Early Pleistocene, on the basis of the assumed uplift rates.

The third and most recent phase of speleogenesis is still active, as it is located at the current sea level, but it shows more than one cycle of flooding and dewatering (with calcite deposition), which indicates that it has been active at least from the penultimate interglacial stage.

huge concretion masses corroded and inter-bedded with alluvial deposits, suggest that this lower and presently active level passed through more than two high-stands of sea level and could have formed during most of the Middle-Late Pleistocene.

Several morphologic features, such as the presence of corrosion notches at + 12.4 m asl, and the Absolute dating of speleothems does not support the evolution scheme illustrated in this article, but would surely provide more consistent chronological constraints. Therefore, the interpretation given here should be considered as a working hypothesis. Further investigations, which are planned for the next future, will be assumed at determining more substantial dating of the speleogenetic history of this amazing cave complex.

Undoubtedly, these features make the St. Paul's karst a unique place in many respects, even in the worldwide karstic panorama, and the creation of the National Park and its insertion in the UNESCO Heritage List is a great opportunity for study and research for many years to come.
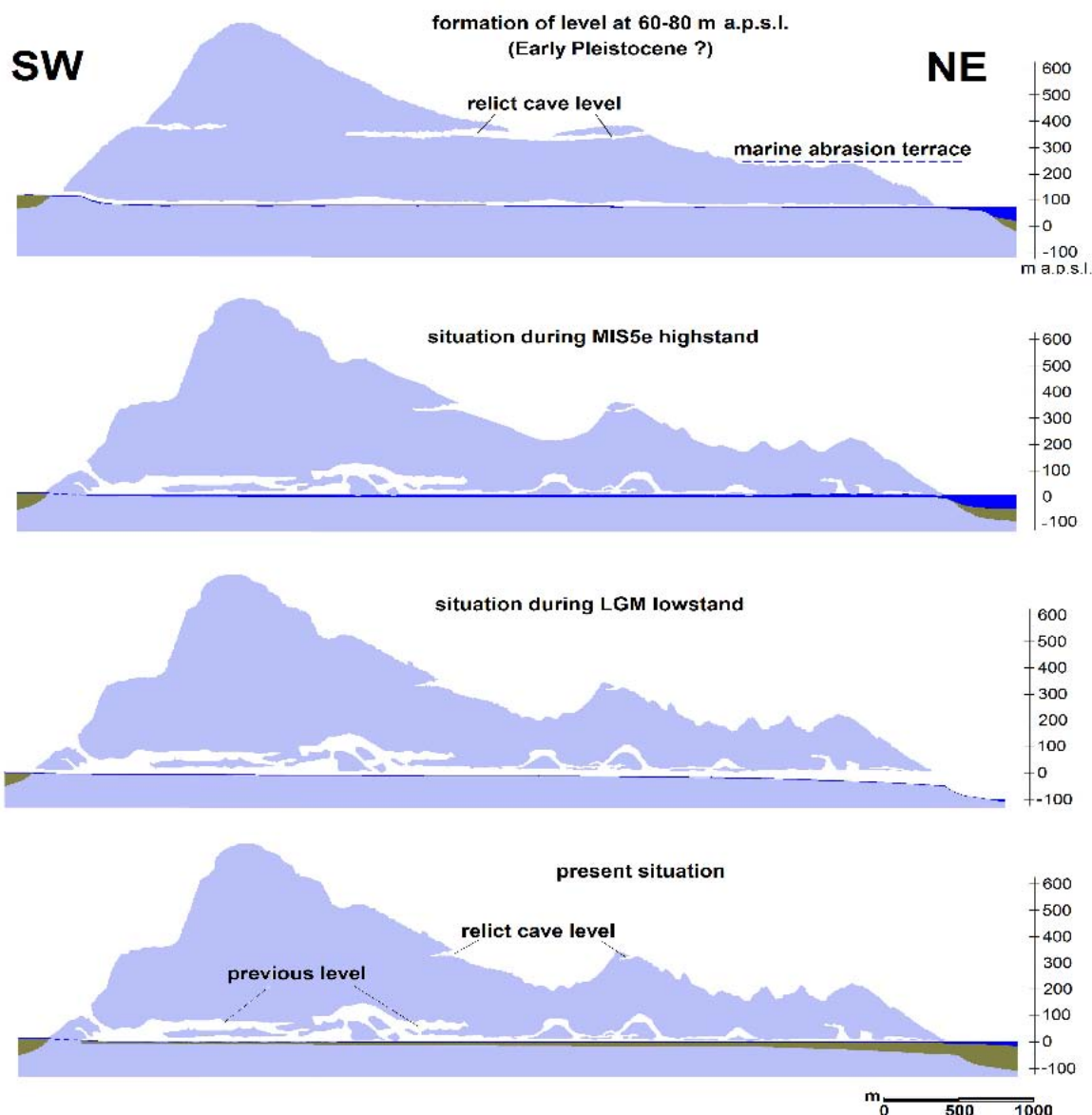
Figure 18. Evolutionary stages in the origin of caves and landscape of the St. Paul karst during the Quaternary (see text for explanation).

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