Appendix 1

Descriptions of studied caves in the Tucush Valley, Antamina Area, the Peruvuan High Andes

CTU162

The cave is the most northwestern one in the investigated sector of the Tucush ridge. It is located at elevation 4,561 masl, outside of the Tucush Valley topographic catchment, within the topographic catchment of the Cheguia Lake (Fig. 5). The cave occurs in the K-Ju2 limestone unit and consists of a steeply inclined entrance passage (Fig. 8 e), two successive main shafts (22 and 13 m deep), another shaft that opens in the ceiling near the base of the cave, and a slot-like pit that continues as a narrow passage with a pool at the bottom. The total explored depth is 46 m. Overall, the plan pattern of the cave is controlled by NE-trending fractures, with a strike-parallel connection between two major lineaments.

The steeply inclined entrance passage displays hypogene speleogens attesting to rising convection flow, particularly at the neck of a shaft to which it leads (Fig. 10 b). Photos c through f in Fig. 10 show the top parts of shafts as viewed from below, with remarkable assemblages of linked hypogene speleogens clearly indicating their formation by the rising flow. These assemblages include nested cupolas, ceiling channels, and side feeders (the latter are shown in Fig. 11 a and b). Overall, the entire upper part of the cave clearly demonstrates the overwhelming dominance of hypogene dissolution surfaces, as shown in the shaft profile (Fig. 8 e). Signs of vadose dissolution appear only in the lower part of the main pit and dominate in the second and third pits. The third (lowermost) pit represents a vadose meander with a perched water pool (Fig. 12 f). There is another pit with vadose morphology, which opens in the ceiling of a passage in the lower part of the cave.

Importantly, the second pit cuts vertically across a 2 m thick, steeply inclined, thinly-bedded marly unit separating massive limestone beds. This illustrates that such marly layers, typical for the Ju2 unit, do not prevent nor deviate the vadose flow and conduit development. Also importantly, the hydraulic connection from CTU162 cave to Ishpac Spring in the Ayash Valley has been established by dye tracing test (our unpublished study), indicating a minimum groundwater velocity of 1,392 m/day (based on a straight line distance of 4.15 km) or, the velocity estimated at 1,810 m/day assuming a tortuosity factor of 1.3. This connection is the most distant from Ishpac Spring and indicates the extent of its drainage area to the NW, along the Jumasha strike.

CTU09

This cave is located in the upper sector of the Tucush Valley (Fig. 5), at the contact of K-Ju3/K-Ju4 units. The entrance opens on a steep slope at elevation of 4,454 masl as a massive 95 m deep shaft which cuts into a larger cavity in the bottom area. The cave continues further down to the depth of 115 m through a series of rift-like passages (Fig. 8 b).

The main shaft is developed along a large N35E trending fracture and overall has distinctly vadose morphology with strictly vertical surfaces and vertical grooves (Fig. 12 a, b). Numerous remnants of hypogene cavities cut by vertical vadose surfaces are recognizable along the entire depth of the shaft (Fig. 12 a, b). Some of the cavities, cut over by the vadose shaft, represent side feeders of a former rising-flow shaft now largely reworked by the vadose dissolution.

Along the south-east wall of the bottom chamber, a series of typical hypogene rifts trending N35E extend for about 20 m in depth relative to the bottom of the main shaft. The rifts are largely inactive with respect to the modern vadose flow and are characterized by irregular jagged wall surfaces with numerous cusps and pockets (Fig. 10 g-i).

CTU122

This 42 m deep cave occurs in the middle section of the Tucush Valley at elevation 4,431 masl, at the contact between the K-Ju3 unit and Sucesión Marcadora (Fig. 5). The cave is about 42 m deep. From a morphogenesis perspective, it can be divided into an upper part with predominantly hypogene morphology, and the main shaft and the lower part having predominantly epigene morphology (Fig. 8 c).

Abundant morphological evidence of rising flow, e.g. rising wall channels (Fig. 11 d and e), rising chains of cupolas, nested cupolas and chimneys (Fig. 11 i), and numerous solution pockets, are found in the entrance passage, the open upper shaft, the following inclined passage, and the upper part of the main shaft. The upper shaft, despite of being opened to the surface, has well-preserved hypogene morphology on the walls (Fig. 10 a) only slightly modified by vadose film flow. A massive vadose flowstone formation exists at the bottom of this shaft - its outer layer is dated to be older than 700 ka (the limit of $^{234}U/^{230}Th$ dating at the Xi'an Jiaotong University Isotope Lab). The subsequent inclined passage with numerous cupolas (Fig. 11 h and i) follows a bedding plane and connects the first shaft with the second one. The top part of the latter has distinct hypogene morphology but the middle and bottom parts of this shaft are entirely reworked by vadose flow. The shaft walls in these parts are covered by a thick (up to 0.4 m) cover of residual clay and soft moonmilk formation (Fig. 12 d). This shaft is followed by a meandering passage of distinct vadose morphology (Fig. 12 g) leading to a narrow neck of the next shaft, which remains unexplored but has an estimated depth of ca. 30 m.

CTU89

This cave is located in the lower section of the Tucush Valley at elevation 4,329 masl. It occurs in the K-Ju3 unit, close to the contact with K-Ju4, and starts with a shallow entrance pit followed by an inclined passage, two successive larger pits, and a bedding-controlled chamber in the bottom section of the cave (Fig. 8 d). The total depth of the explored part of the cave is 74 m. All the elements except the bottom chamber are controlled by NE-trending fractures.

The first short pit and the inclined passage show signs of both hypogene and epigene dissolution, although the latter predominate. The subsequent two larger and deeper pits (ca. 15 and 25 m) are clearly vadose shafts. The last shaft intercepts a large bedding-controlled cavity, which is firmly identified as being of hypogene origin.

The core of the hypogene cavity is a chamber, 4-5 m wide and 3-5 m high, developed along a prominent bedding plane and extending updip as a single, steeply inclined (70°) flattened space (Fig. 10 j), ca. 50 m wide and 2-3 m high. A space in the lower part of the chamber lies mainly below the controlling bedding plane whereas in the updip part it extends above it (Fig. 10 j). Further updip, the chamber separates into three large conduits controlled by intersections of the bedding plane and vertical, NE-trending fractures (Fig. 19 k). Guided by these fractures, high ceiling channels run through the entire chamber, exhibiting abundant cupolas, bell-holes, and larger vertical chimneys (Fig. 10 l and Fig. 11 f and g). These assemblages of ceiling speleogens firmly indicate dissolution by convection currents rising along the NE fractures. Some feeders of rising flow are recognizable at the bottom (although are not human-passable) along the downdip limit of the chamber and some are possibly blocked by collapse material, which is suggested by depressions below the ceiling channels.

In the chamber ceiling, remnants of ferruginous material up to 5 cm thick filling an exposed, solutionally enlarged bedding-plane have been found. The emplacement of this mineralization pre-dates the main phase of hypogene speleogenesis as evidenced by hypogene solution morphs digging through the ferruginous “crust”. Spectrometry analysis by the Terraspec instrument has shown that the mineral assemblage of this material is dominated by beidellite, siderite, and silica-opaline, with Fe-oxides present such as goethite and hematite.

In the lower part of the main chamber, it continues to both sides along strike as passages. The SE-stretching passage pinches out shortly but the NW passage continues for ca. 30 m where it crosses with the transverse passage that runs updip along the intersection of this prominent bedding plane with another vertical NE-trending fracture.

CTU164

This cave is located at elevation 4,552 masl in the upper slope of the middle section of the Tucush Valley and develops in the K-Ju2 limestones (Fig. 5). The entrance is within a poorly-defined surface corridor trending at NE15°, one of several in this area. The entrance opens at the top of a large shaft-like chamber elongated in the same direction (Fig. A1), with a cave base at 17 m filled with breakdown clasts and loose material. The irregular morphology of hanging walls of the chamber is consistent with hypogene origin whereas no morphological signs of vadose flow are observed.

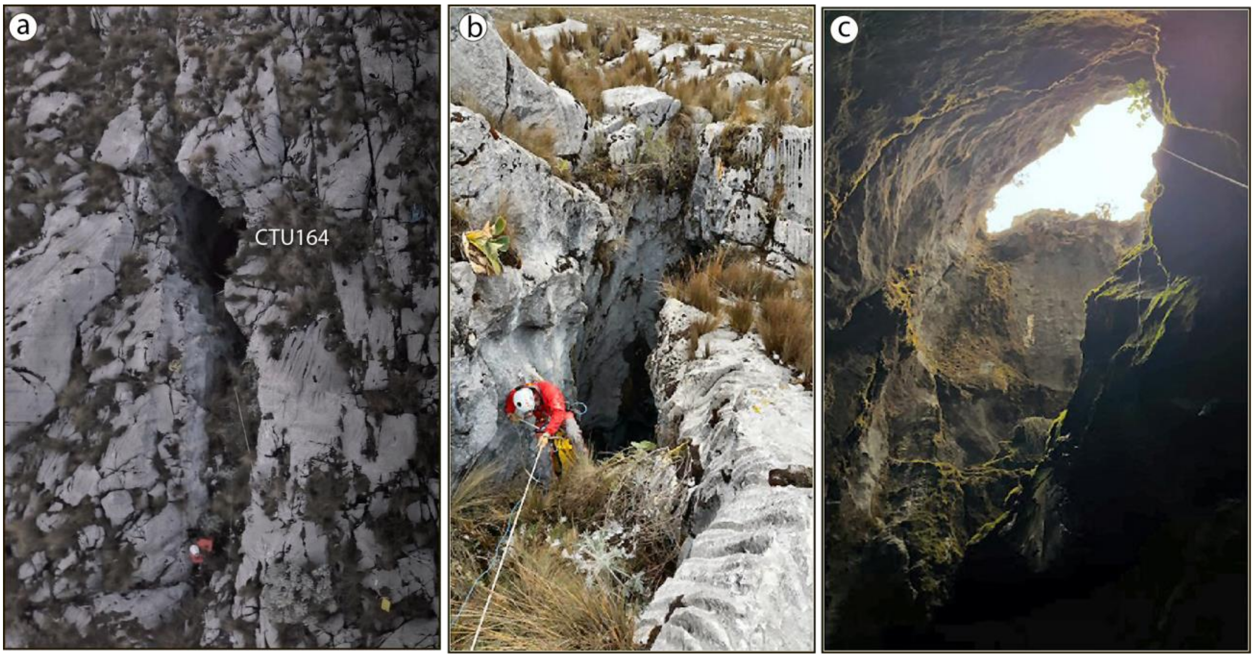

Fig. A1. CTU164 cave: a – a position of the shaft entrance in the NE-trending surface corridor; b – close-up view of the entrance; c – a chamber looking up.

CTU165 and CTU166

These two shafts are located close to each other (25 m) in the steep NE slope of the Tucush Ridge, within the K-Ju1 unit, at elevations 4,447 and 4,461 masl, respectively (Fig. 5). The CTU165 shaft opening is not associated with any surface catchment while CTU166 has a small doline around the entrance formed through degradation of the shaft mouth. The position of the entrances in the relief and the presence of remnants of almost completely removed shafts nearby (Fig. 7 b) indicate that a considerable thickness of the karstified limestone has been stripped off by glacial scouring. Both CTU165 and CTU166 are controlled by NE-trending fractures.

CTU165 is a deep shaft with a large opening, 8-shaped in plan view. In the main shaft, the NW wall has vadose morphology with vertical grooves, although cutting through pre-existing cavities of presumably hypogene origin. At a depth of ca. 60 m, the main shaft splits into two smaller shafts. Only one of them has been tested by exploration but the bottom has not been reached due to the rope length limitations, although it was observable at a total estimated depth of ca. 160 m. Despite the large dimensions of the shafts, considerable airflow toward the surface was observed, potentially indicative of a large and deep karstic system. The vadose overprint traces deeper into a lower shaft, but in the middle-deep sections the wall morphology is very irregular, with many pockets and small side conduits.

CTU166 starts with a vadose shaft with distinct vertical grooves, superimposed onto a large chamber, 15x25 m in plan dimensions and up to 20 m in height. The irregular morphology of the chamber, with numerous solution pockets, side alcoves, cupolas and high chimneys clearly attest its hypogene origin. Two more pits are located close to the wall of the chamber, one of which has been explored for 10 m to the blockage at the bottom.

CTU112

This cave is located in the middle slope of the Tucush lower sector at elevation 4,347 masl and developed in the K-Ju2 unit. It consists of an inclined (32^{o}) passage ca. 50 m long, developed at the intersection of the bedding and a fault trending at N47E (Fig. 9 a). A doline at the entrance is an exhumed part of this passage. The morphology is considerably reworked by gravitational processes such that breakout surfaces dominate in the cave ceiling and walls. However, several phreatic/hypogene features are clearly recognizable in the middle section, including a rising-flow wall channel, a chimney, and several cupolas. A large mass of finely laminated, dry grey clay with a minimal thickness of 0.5 m is found along the NW wall in the middle section. The clay deposit seems to be rather old, clearly unrelated to the vadose and active phreatic conditions. These sediments appear to be deposited by a slow moving or stagnant water. Pieces of the same clay, but almost lithified are found attached to the opposite wall. Spectrometry analysis by the

Terraspec instrument shows the mineral assemblage that consists of beidellite, quartz, opal, and siderite.

Large root-like deflected “stalactites” comprised of white porous calcite, apparently formed from lithification of moonmilk masses, with branches inclined at ca. 50-80^{o} toward the cave interior, occur in the sector at 10-20 m from the entrance.

CTU163

This cave is located at elevation of 4,566 masl in the upper slope of the Tucush middle sector and developed in the K-Ju2 unit (Fig. 5). The cave is a 35 m long inclined passage that stretches updip from a distinct 5-7 m deep surface corridor (Fig. 7 d); both the surface corridor and the passage are oriented at N50^{o}E (Fig. 9 b). A large part of the surface corridor has formed through unroofing of the passage, as evidenced by the presence of solution speleogens in the walls, although a distinct depression in the bottom of the SW part could suggest the presence of a shaft, now blocked by collapse material. Another shaft in the upper end of the passage is a rising chimney truncated by surface denudation (the upper entrance).

The passage demonstrates well-preserved solution morphology with distinct hypogene features: a rising wall channel above a blocked feeder (Fig. 11 c), several nested cupolas (Fig. 11 j), and rising-flow chimneys. The amount of the limestone rubble observed along the passage floor appears to be larger than it could be produced by the modest gravitational destruction of the solutional morphology in the passage. The limestone debris appears to be mainly produced by the collapse at the upper entrance and distributed downslope through the passage.

Speleogenetic analysis of CTU163 suggests that the inclined passage was likely formed as a connection between two shafts in the hypogene cave system, according to the conceptual model depicted in Fig. 9 c. The initial setting (I) shows two vertically extended fractures, occurring with the vertical and lateral offset (fractures 1 and 3), connected with laterally extended fractures (but still vertically orientated). Ascending hypogene flow formed shafts along fractures 1 and 3 and an inclined passage along the connecting fracture 2 (II). Denudational lowering of the surface and collapses of larger cavities led to the present-day configuration of the partly opened karst system (III).