Hypogene karst associated with igneous intrusions and its influence on the subsequent karst evolution in high mountains (Central Andes, Peru)

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Accepted to: Proceedings of 21st Int. Congress of Speleology, France, 2021, 4 p.

Hypogene karst associated with igneous intrusions and its influence on the subsequent karst evolution in high mountains (Central Andes, Peru)

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Abstract

Carbonate rocks of Cretaceous age are wide spread in the Peruvian Andes. The studied area in the eastern part of the Cordillera Occidental, near a large igneous intrusion and a skarn deposit, exemplifies polygenetic and multi-phase karst development. Hypogene karstification is related to a hydrothermal activity associated with a magmatic event at ca. 11-9.7 Ma responsible for the emplacement of the nearby intrusion and related alteration of the carbonate rocks. It has resulted in deep-rooted, laterally isolated stair-case-rising shaft systems aligned to NE-trending sub-vertical fractures. These caves clearly exhibit a complete suite of remarkably well-preserved speleogens indicative of rising flow, standing as a foremost example of endogenous hypogene speleogenesis related to magmatic intrusions. Commencing in the Early Pleistocene, epigene karstification was strongly influenced by the presence of pre-formed hypogene caves that provided effective vertical drains across the vadose zone and defined hydraulic compartments. However, hypogene caves are largely isolated in the plan view, and lateral integration of the contemporary karst system by epigene karstification is incomplete, resulting in a complex flow system. The overprint of vadose features over hypogene morphologies is very distinct although local. Changes in the base-level position due to the landscape evolution and Pleistocene glaciations were further major factors that influenced epigene karst development.

1. Introduction and geological settings of the study area

In the Peruvian Andes, Cretaceous carbonate rocks cover about 13% of the total surface area and occur in two narrow, tectonized belts extending over 2,000 km long (EVANS, 2015; Fig. 1 A). Carbonate terrains, commonly karstified, host most of major metal ore deposits related to igneous intrusions and associated interactions between hydrothermal fluids and host rocks (LOVE, 2004; EVANS, 2015). Karst in the Andes is recognized in causing extreme hydrogeologic complexity and great challenges in mine dewatering and mine waste management (EVANS *et al.*, 2005; EVANS, 2015).

The orogeny that formed the Andes initiated in the Jurassic as crustal deformation due to a flat subduction of the oceanic Nazca Plate under the continental South American Plate. This caused crustal thickening of the overriding plate, the folding and faulting, uplift, volcanism, plutonism, hydrothermalism, and the formation of numerous mineral deposits in North Central Peru.

The study area lies ca. 30 km east of the crest of the Cordillera Blanca, within the belt of the Albian – Upper Cretaceous carbonates that stretches NW-SE in accordance with the regional framework. In the area, transverse (NE-trending) discontinuities are recognized at multiple scales, from regional basement structures (LOVE *et al.*, 2004) to faults and fractures cutting multiple rock packages. The latter are abundant in the study area (Fig. 2 B).

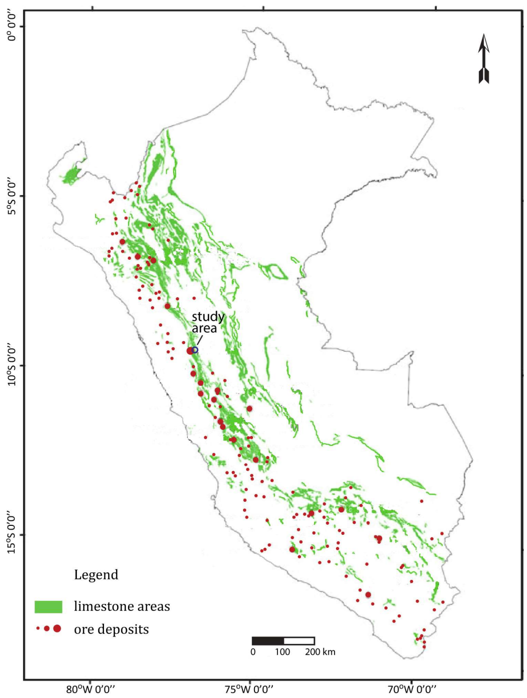

Figure 1 : Carbonate terrain and operating mines in the Peruvian Andes (from EVANS, 2015).

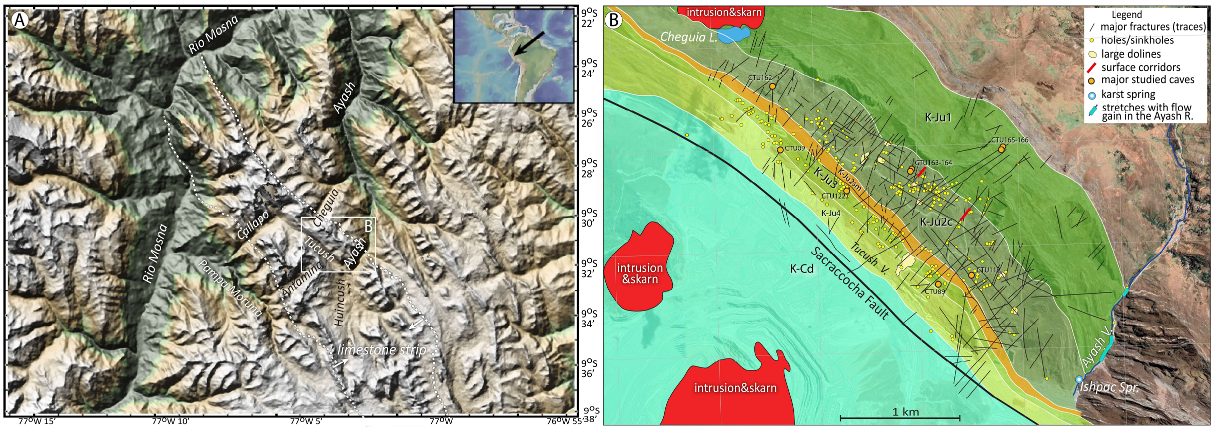

Figure 2 : A - Digital elevation model showing the outer limits of the steeply inclined Jumasha limestone (white dotted lines) and the location of the Tucush area within the wider physiographic context. B - Shaded geological map of the Tucush area showing traces of major fractures, distribution of major surface karst features, and locations of studied caves.

The study area encompasses the NW-trending Tucush glacial valley and the adjacent ridge, cut by the NE-trending Ayash valley (Fig. 2 A). The Jumasha Formation is intensely karstified and characterized by the rugged topography, with steep limestone slopes and peaks at altitudes ranging from 4,300 to over 5,000 m asl. The ridge is comprised by SW steeply dipping limestones (K-J1 to K-Ju4 units of Jumasha) bounded by marls and marly limestones of the Celendin Fm (Fig. 2 B). The carbonate sequence is pierced by one large and two smaller intrusions in the study area.

2. Results and discussion: The Tucush karst system

The contemporary karst hydrogeological system is recharged through the Tucush ridge and drained by the Ishpac Spring and smaller springs along the Ayash valley. Phreatic flow is mainly strike-parallel, whereas vadose flow is chiefly controlled by transverse fractures and associated karst shafts. Discharge variations show strong seasonality and rapid reaction to rain events, indicating low regulating and storage capacity of phreatic and epikarstic zones.

Epikarst in the Tucush area is young and immature. Most surface karst features show strong control by transverse fractures and are out of genetic/functional adjustment with the landscape, being formed through exhumation and destruction by the denudational surface of various elements of the void/conduit system (shafts, passages, chambers, enlarged fractures, etc.).

Twelve caves up to 160 m deep were investigated in detail and over 100 karst openings were documented. Vertical caves of hypogene origin dominate, typically consisting of shafts developed along *en echelon* fractures at different intervals and connected by bedding-controlled passages (Fig. 3). In some cases, large hypogene chambers are cut by vadose shafts. Caves have abundant hypogene speleogens organized in easily recognizable, spatially and functionally related assemblages that are shown (KLIMCHOUK, 2019) to be strong evidence of hypogene karstification. Vadose dissolution overprints hypogene morphologies in places, particularly in vertical shafts (Fig. 3; Fig. 4 a, b).

Hypogene karstification in the area is associated with the same multiphase magmatic event that resulted in the emplacement of the nearby intrusions (11 to 9.7 Ma; MROZEK *et al.*, 2017). Acidic magmatic and metamorphic fluids escaping the intrusion zone and partly recirculating beneath the Celendín Fm are capable to cause extensive hypogene karstification. During the hypogene stage, deep-seated cave systems were formed, with stair-case-rising patterns controlled by transverse fractures. Exhumation of the region through erosional and tectonic processes started 5–6 Ma (GARVER *et al.*, 2005), with the Jumasha Fm exposure by the beginning of the Pleistocene.

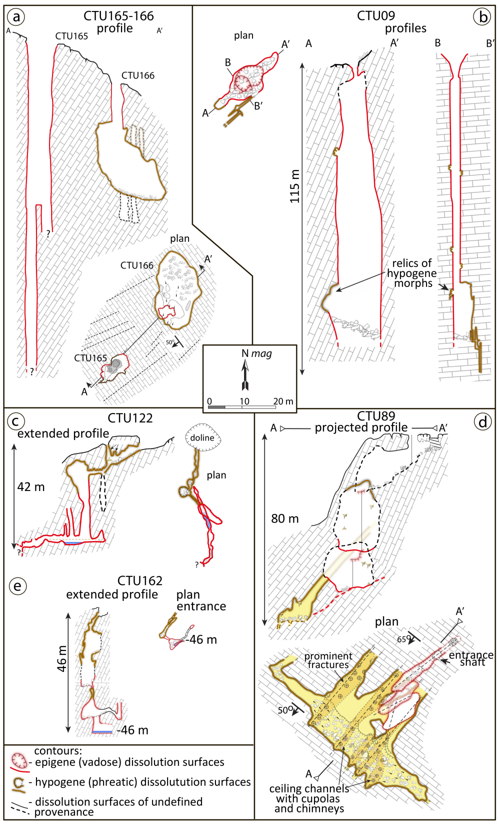

Figure 3 : Profiles and plans of vertical caves showing sections with prevalent epigene and hypogene morphs.

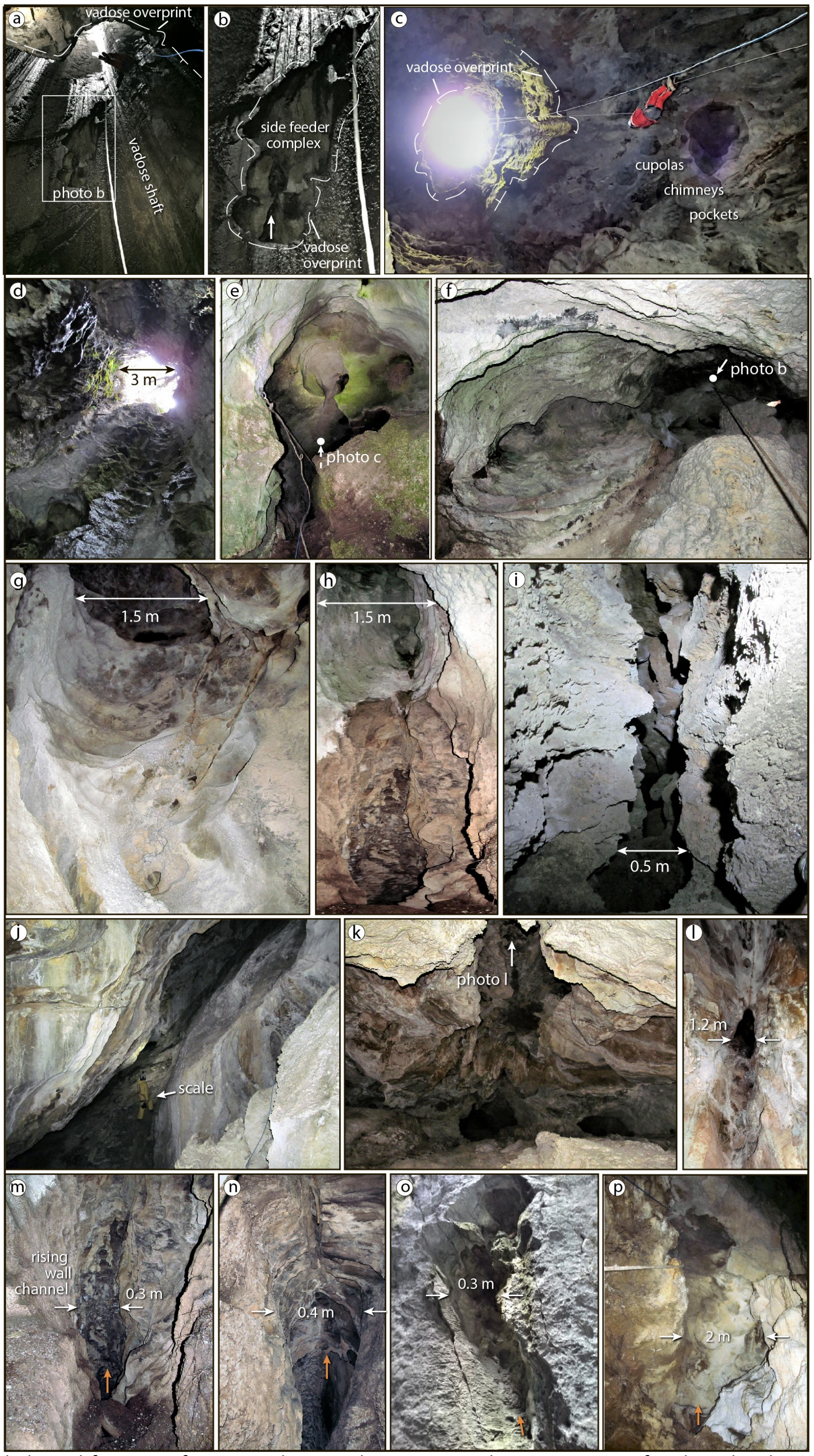

Figure 4 : Morphological features of caves in the Tucush area. a-c – the overprinting of vadose dissolution surfaces onto hypogene morphs ; d – hypogene shaft open to the surface ; e – the top of the internal shaft viewed from above ; f and h – features at the tops of internal shafts, viewed from below (f is the same shaft shown in e); i – rift-like passage ; j-l – inclined, bedding-controlled chamber (j – strike-parallel view ; k – updip view where the arrow points to a rising chimney/shaft shown in photo l as viewed from below) ; m-p – side feeders in the shaft walls. Caves : a, b, i – CTU09 ; c – CTU165, g, h, m, n – CTU162 ; j, k, l – CTU89 ; o, p – CTU164.

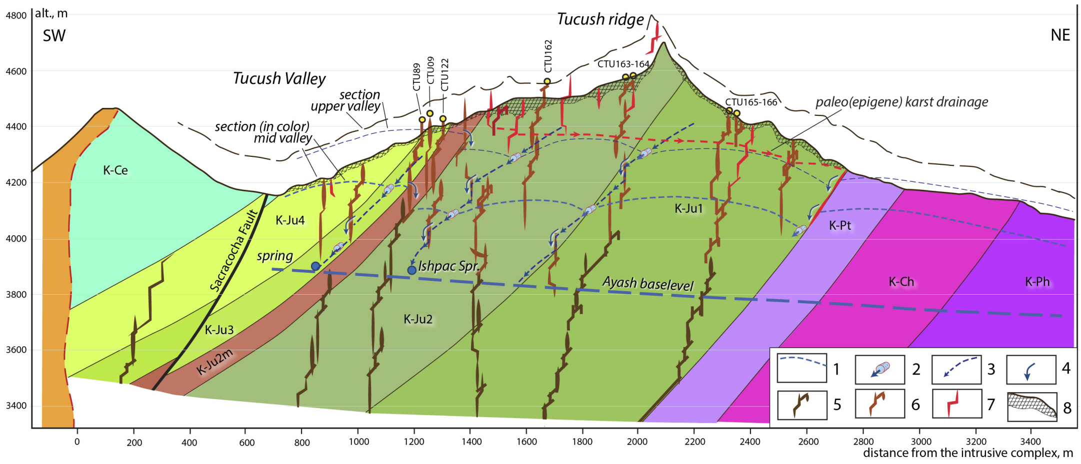

Figure 5 : A quasi-3D conceptual model of the contemporary Tukush karst hydrogeological system.

Since then, epigene karst developed with varying intensity, depending on climate and neotectonic/geomorphological factors. Extensive karst landscape with conduit systems likely formed during the Early to Middle Pleistocene. The karst system was likely drained to the NE along transverse fractures and associated hypogene caves.

Glaciations during the LGM greatly contributed to the geomorphogenesis of the Tucush area and exerted considerable effects on karst development including hindering karstification during progressive phases, glacial scouring of epikarst and upper pre-formed shafts, and massive recharge during the regressive phases that facilitated the development of existing cave systems.

Epigene karstification was strongly influenced by the presence of hypogene shaft systems which provided effective drains across the vadose zone, and facilitated rapid deepening of the vadose zone - depending on the outflow conditions varying in space and time. The presence of laterally isolated hypogene shaft systems determined a complex pattern of associated hydraulic compartments and their complex interplay in the course of the initiation and development of lateral phreatic conduits. The development of phreatic conduits during the main epigene phase was strongly favored along the NE trends. Rapid incision of the upper Ayash canyon along the NE-trending karstified zone in the end of the LGM began re-orienting the flow to the southeast along strike, thus intergrating previously independent transverse karst systems.

3. Conclusions

At least three major phases of karstification are identified in the Tucush area: (1) hypogene; (2) major epigene; and (3) current (post-glacial) epigene.

Carbonic acid hypogene karstification by thermal fluids resulted in the formation of laterally isolated shaft systems aligned to transverse throughgoing fractures. These caves are a foremost example of endogenous hypogene speleogenesis related to magmatic intrusions. The polygenetic and multi-phase nature of the Tucush karst system defines the complexity of the hydrogeologic system. The inheritance of hypogene caves strongly influences subsequent epigene karstification, groundwater flow, and geomorphogenesis in the vicinity of igneous intrusions. Understanding of the origin and evolution of karst is crucial for development of conceptual groundwater flow models for karst terrains and assessment of karst-related hazards and risks.

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