# Extremophilic cave species: evolutionary relics of a hidden world

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**Abstract**. Cave ecosystems, characterized by constant temperature, high humidity, and absence of light, represent extreme and isolated environments that have driven significant evolutionary adaptations in species that inhabit them. This paper focuses on *Astyanax mexicanus* (De Filippi, 1853) (Mexican cavefish), a model organism for studying evolutionary biology, due to its remarkable adaptations to cave life. The Mexican cavefish exhibits two distinct forms: a surface-dwelling variety and a cave-dwelling variety that has lost pigment and functional eyes over thousands of generations. The adaptations of cave-dwelling *A. mexicanus*, such as heightened sensory systems and reduced metabolism, highlight the evolutionary strategies for survival in nutrient-scarce cave environments. This paper examines how caves act as natural laboratories for studying speciation and the process of evolutionary regression, shedding light on how organisms become highly specialized in response to extreme environments.
**Key Words**: *Astyanax mexicanus*, cave ecosystems, cavefish, evolutionary adaptations, speciation.

**Introduction**. Cave ecosystems, characterized by constant temperature, high humidity, and absence of light, represent some of the most extreme and isolated environments on Earth (Gavriloaie et al 2016; Salaga 2020). Species inhabiting caves have undergone extensive evolutionary adaptation to survive in these challenging conditions (Petrescu-Mag 2023). Among the most fascinating of these species are the cave-dwelling organisms, which can be considered phylogenetically aged and ultra-specialized - organisms that retreated into caves long before these subterranean spaces became their final refuges. One particularly intriguing group of species that embodies these traits are the cavefish, specifically those belonging to the family Amblyopsidae (the cave-dwelling members of the order Perciformes), which include species such as *Astyanax mexicanus* (De Filippi, 1853) (the Mexican cavefish). The purpose of this paper is to examine the evolutionary adaptations of cave-dwelling organisms, focusing on *A. mexicanus* as a model species. It explores how isolated cave environments lead to specialized traits such as loss of pigmentation and eyesight, and the development of heightened sensory systems. The paper aims to provide insights into the processes of evolutionary regression and adaptation in extreme environments, highlighting cave ecosystems as natural laboratories for studying speciation and survival strategies.

**Evolutionary recluses**: **the case of *A. mexicanus***. The Mexican cavefish, *A. mexicanus*, has become a model organism in studies of evolutionary biology due to its remarkable adaptations to cave life (Kowalko 2020; Ponnimbaduge Perera et al 2023). Found in the caves of northeastern Mexico, these fish are a prime example of how isolated environments, like caves, act as natural laboratories for evolutionary experimentation. *A. mexicanus* exists in two distinct forms: a surface-dwelling variety, which has retained its normal pigment and eyesight, and a cave-dwelling variety, which has lost both pigment and functional eyes over the course of thousands of generations (Figure 1) (Kowalko 2020).

Figure 1. Morphological variations in *A. mexicanus* (Hinaux et al 2015).

The transition of *A. mexicanus* into a cave-dwelling form is thought to have occurred over several million years, making it an example of a species that retreated into caves before these habitats became permanent evolutionary tombs. The cave-dwelling forms exhibit numerous unique adaptations: a loss of pigmentation due to the absence of sunlight, the development of heightened sensory systems such as enhanced lateral line detection (which allows the fish to sense vibrations in the water), and a reduced metabolism suited to the food-scarce cave environment. These traits suggest a long period of isolation and genetic divergence from their surface-dwelling ancestors.

One of the most striking features of cave-dwelling *A. mexicanus* is the loss of eyesight, which has been rendered obsolete in the dark cave environment. The eyes of cave-dwelling fish are either reduced to small, vestigial structures or entirely absent, a striking example of evolutionary regression - a process in which traits that are no longer beneficial to an organism’s survival are lost over time. This phenomenon was eloquently summarized by evolutionary biologist and geneticist Richard Dawkins, who once remarked, "The species that disappear from evolutionary time are not necessarily the weakest, but often the most highly specialized" (Dawkins 1986).

This highly specialized nature is evident in the cavefish's adaptations. The loss of vision is compensated by the development of more advanced mechanisms of sensory perception. For example, the fish’s lateral line system, which detects vibrations and changes in water pressure, has been fine-tuned to a high degree, allowing it to navigate through total darkness. This heightened sensitivity is a direct result of the pressures of living in an environment where food is scarce, and predation risks are minimal but still present in the form of cave-dwelling predators.

**An evolutionary escape from the surface**. The retreat into caves and the subsequent adaptations that followed also represent an intriguing story of evolutionary strategy. As cave environments are often nutrient-poor, species that thrive in them tend to evolve to be highly efficient in resource usage. The cavefish, for instance, exhibits a slow metabolic rate, which is another adaptation to the scarce food supply. The fish can survive on very little food, drawing on stored energy reserves and scavenging whatever small invertebrates might enter the cave waters (Cobham & Rohner 2024).

However, the life of these cave species is not without its risks. The caves themselves present a very delicate environment. Some cave systems have experienced human encroachment, which threatens the unique organisms within. Changes in water quality, the introduction of invasive species, or even climate change could disrupt the fragile ecosystems of caves and push these specialized species to the brink of extinction. This vulnerability to external threats is another reason why species like *A. mexicanus* and others are considered evolutionary recluses - species that may have retreated into the caves long before they became vulnerable.

**Caves as evolutionary hotbeds of specialization**. The cavefish *A. mexicanus* offers a compelling look into the evolutionary processes that occur in isolated environments, where species can become ultra-specialized and highly adapted to their niche (Wilson et al 2021). These species, having retreated into caves, offer an evolutionary narrative where the organisms' adaptations are seen as relics of an earlier, more active evolutionary time, before the cave became a metaphorical tomb. They serve as living records of a time when conditions on the surface forced species into subterranean refuges, leading to fascinating transformations that continue to challenge our understanding of evolution, adaptation, and survival in extreme environments.

By studying these cave-dwelling organisms, scientists are able to better understand the limits of evolutionary adaptation and the mechanisms behind speciation, showcasing the incredible diversity of life that can thrive in the most unexpected of environments. These ancient and specialized creatures continue to intrigue biologists, serving as a reminder of the adaptability and resilience of life in the face of extreme challenges.

**Conflict of interest**. The authors declare that there is no conflict of interest.

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Received: 26 October 2024. Accepted: 18 November 2024. Published online: 03 December 2024.
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How to cite this article:
Bordea D., Brașovean I., Gavriloaie C., 2024 Extremophilic cave species: evolutionary relics of a hidden world. ELBA Bioflux 16(1):7-9.