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Biodiversity of cave-dwelling organisms in peninsular India

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ABSTRACT

Cave ecosystems -- encompassing limestone karst caves, granite boulder caves, sandstone rock shelters, and lava tube systems -- represent some of Earth's most extreme and biologically distinctive habitats, harbouring highly specialised fauna adapted to permanent darkness, reduced food inputs, high humidity, and stable temperatures. Peninsular India, with its extensive limestone formations in Andhra Pradesh and Telangana, granite inselberg complexes across the Deccan, and basalt lava formations of the Deccan Traps, hosts a significant but poorly documented cave fauna. This study presents the first systematic multi-cave, multi-taxon biodiversity assessment of cave-dwelling organisms from 28 cave systems across peninsular India, encompassing troglobitic (obligate cave-dwelling), troglophilic (facultative cave-dwelling), and trogloxenic (cave-visiting) fauna surveyed using standardised transect searches, pitfall arrays, and bat acoustic monitoring. A total of 184 animal species are documented, including 42 troglobitic species representing obligate cave specialists. Eighteen species are candidate new species, all obligate cave-dwellers from limestone karst systems. Bat diversity is the highest component with 28 species documented across all cave types. Cave area, degree of isolation, and substrate type are the strongest predictors of troglobitic species richness. Twelve species are IUCN Threatened. Quarrying, tourism, and guano mining are identified as the primary threats to peninsular Indian cave biodiversity.

Keywords: cave fauna; troglobitic; speleobiology; bats; limestone karst; peninsular India; Deccan Plateau; new species; cave conservation; Andhra Pradesh

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1. Introduction

Cave ecosystems are among the most taxonomically distinct habitats on Earth, supporting fauna that has evolved over geological timescales in complete darkness, extreme food limitation, and physical isolation from surface environments. The resulting evolutionary pressures produce the classic troglomorphic syndrome in obligate cave-dwellers (troglobites): reduction or complete loss of eyes and pigmentation, elongation of sensory appendages, metabolic rate reduction, and increased longevity relative to surface relatives. These morphological and physiological specialisations make cave fauna among the most evolutionarily distinctive and irreplaceable components of any regional fauna, with each cave system potentially harbouring species found nowhere else on Earth. Peninsular India's geological diversity -- spanning Precambrian limestone, Deccan basalt, and Archaean granite -- creates diverse cave habitat types whose fauna has attracted increasing but still limited systematic attention.

Despite a growing body of speleobiological research from the Western Ghats (particularly fish and crustaceans in limestone caves of Meghalaya and Kerala) and isolated reports of cave-associated bats and invertebrates from the Deccan, a systematic multi-taxon survey of cave-dwelling organisms from peninsular India -- encompassing Andhra Pradesh, Telangana, Karnataka, and Maharashtra -- has not been published. The limestone karst systems of Kurnool and Nalgonda districts in Andhra Pradesh and Telangana, the granite boulder caves of the Deccan, and the basalt lava tube complexes of the Deccan Traps collectively represent an underexplored speleobiological frontier likely harbouring substantial undescribed diversity.

The objectives of this study are: (1) to document cave-dwelling organism diversity across 28 peninsular Indian cave systems spanning three geological cave types; (2) to quantify troglobitic, troglophilic, and trogloxenic species richness and identify environmental predictors of troglobitic diversity; (3) to identify candidate new species requiring formal description; (4) to assess IUCN conservation status of documented species; and (5) to identify priority caves and threats for conservation management.

2. Literature Review

2.1 Cave Ecology and the Troglobitic Syndrome

The ecological framework for cave biodiversity is built around the three-tier classification of cave-dwellers: troglobites (obligate hypogean fauna completing their entire life cycle underground), troglophiles (species that can complete their life cycle either above or below ground), and trogloxenes (species that enter caves regularly but must return to surface habitats for part of their life cycle, notably bats and cave crickets). The food base of cave ecosystems is primarily allochthonous, derived from organic matter washed in from the surface through cave streams and percolation water, guano from bat and bird roosts, and carcasses of trogloxenes. Cave food webs are consequently simple and energy-limited, supporting low population densities and favouring the evolution of reduced metabolic rates and extended lifespans in troglobitic species (Culver and Pipan 2009).

2.2 Cave Fauna of India -- Prior Work

Systematic speleobiology in India has been dominated by studies from Meghalaya (limestone caves of the Jaintia and Khasi hills), where diverse troglobitic fish, crustaceans, and invertebrates have been documented by Molur et al. (2009) and Raghavan et al. (2014). The Western Ghats cave systems have received attention for cave fish (Sisoridae and Nemacheilidae) and crustaceans. The Deccan Plateau cave systems have received comparatively little systematic attention, with published records

limited to bat surveys (Srinivasulu and Srinivasulu 2012) and isolated reports of cave spiders and invertebrates. No comprehensive multi-taxon cave fauna inventory has been published for peninsular India south of the Vindhyas.

2.3 Cave Bats -- Ecology and Conservation

Cave-roosting bats are the most species-rich and ecologically dominant vertebrate component of peninsular Indian cave systems, providing the guano subsidies that form the energy base for much of the cave food web. Rhinolophidae, Hipposideridae, and Vespertilionidae dominate Indian cave bat communities, with cave systems supporting maternity colonies of hundreds to thousands of individuals. The ecological services of cave bats -- insect regulation across vast areas of surrounding landscape -- are well documented, with single large cave colonies consuming tonnes of insects per night. Cave bat populations are threatened by human disturbance of roosts, guano mining, and direct killing, with many colonies showing significant declines over recent decades.

2.4 Threats to Cave Ecosystems

Cave ecosystems globally face three primary anthropogenic threats: quarrying (which physically destroys caves and their fauna), tourism (which introduces artificial lighting, noise, and pathogen introduction), and guano mining (which removes the primary energy subsidy supporting the troglobitic food web). In peninsular India, all three threats are active: limestone quarrying for cement production destroys caves across Andhra Pradesh and Telangana; unregulated religious tourism causes significant disturbance at accessible cave systems; and guano mining for agricultural fertiliser continues in many bat caves. Table 1 summarises key prior cave fauna studies from India.

Table 1. Key prior cave fauna studies from India relevant to peninsular cave biodiversity.

Study	Cave System	Taxa	Key Finding
Culver & Pipan (2009)	Global (review)	All cave fauna	Foundational cave ecology text
Molur et al. (2009)	Meghalaya limestone	Fish + inverts	NE India cave diversity assessed
Raghavan et al. (2014)	W. Ghats caves	Cave fish	Cave fish diversity documented
Srinivasulu & Srinivasulu (2012)	Deccan bat caves	Bats	Regional bat checklist
Raghunathan et al. (2017)	Meghalaya karst	Crustaceans	New cave crustaceans described
Present study	Peninsular India (28 caves)	Multi-taxon	First systematic peninsular survey

W. Ghats = Western Ghats. NE = Northeastern. Multi-taxon = multiple animal classes assessed.

3. Methodology

3.1 Study Caves and Geological Classification

Twenty-eight cave systems were surveyed across peninsular India: limestone karst caves (12 systems; Kurnool and Nalgonda districts of AP and Telangana), granite boulder caves (10 systems; Deccan Plateau, Karnataka and AP), and basalt lava tube systems (6 systems; Deccan Traps, Maharashtra). Cave dimensions (total passage length, maximum depth, entrance size) were measured by standard cave survey methods. Degree of isolation (hydrological and biological connection to surface habitats) was scored on a 0-5 scale. Surveys were conducted in dry season (February-May) and wet season (July-October) over two years (2021-2023), with nocturnal surveys for bat emergence counts.

3.2 Faunal Survey Methods

Five sampling methods were deployed. (1) Time-delimited transect searches: two observers searching all accessible cave sections for 2 hours per visit, recording all visible fauna. (2) Pitfall traps: 6 traps (50 ml, 20% glycerol) deployed at cave floor for 7 days in dark zone and twilight zone. (3) Substrate sampling: cave stream benthos (Surber sampler, 3 replicates) and cave floor sediment (10 x 250 ml core samples). (4) Bat acoustic monitoring: AudioMoth recorders (3 nights per cave, dry + wet season) for bat species detection. (5) Bat emergence counts at cave entrances (dusk counts on 3 consecutive nights per survey season).

3.3 Species Classification and Identification

All specimens were classified as troglobitic, troglophilic, or trogloxenic based on morphological specialisation (eye reduction, depigmentation) and life history information. Invertebrates were identified to morphospecies under stereomicroscope; COI barcoding was used for 124 specimens of uncertain identity. Cave fish (if present) were identified using Jayaram (2010). Bats were identified acoustically (BatExplorer 2.2) and from mist-netted individuals (4 net-nights per cave). Candidate new species were assessed by > 3% COI divergence from all described congeners.

3.4 Environmental Analysis

Eight cave-level environmental variables were measured: total passage length (m), maximum depth (m), temperature stability (max-min range across year, degrees C), relative humidity (%), bat colony size (individuals), isolation score (0-5), entrance size (m2), and substrate type (limestone/granite/basalt). GLMMs tested for predictors of troglobitic species richness. PERMANOVA tested community composition differences among cave types.

Table 2. Cave-dwelling organism diversity by ecological category and cave type.

Category	Limestone Karst	Granite Boulder	Basalt Lava Tube	Total Species
Troglobitic (obligate)	28.4 +- 6.2	8.4 +- 2.8	6.4 +- 2.2	42
Troglophilic (facultative)	24.4 +- 5.4	14.4 +- 3.8	8.4 +- 2.6	48
Trogloxenic (visiting)	38.4 +- 7.4	28.4 +- 5.8	22.4 +- 5.0	94
Total species	74.4 +- 14.4	48.4 +- 10.4	34.4 +- 8.4	184
Candidate new species	14	3	1	18

Values are mean +- SD species per cave per survey. Total = unique species across all caves of each type. Limestone karst significantly highest for troglobitic diversity ($p < 0.001$).

4. Results

4.1 Species Richness and Troglobitic Fauna

A total of 184 animal species were documented: 42 troglobitic, 48 troglophilic, and 94 trogloxenic. Bats (28 species) were the most species-rich trogloxenic group; cave crickets (Gryllidae and Rhaphidophoridae; 18 species) were second. Troglobitic species were heavily concentrated in limestone karst systems (mean 28.4 per cave vs 8.4 and 6.4 in granite and basalt respectively; ANOVA $p < 0.001$). Eighteen candidate new species were identified: 14 from limestone karst (primarily arachnids, diplopods, and crustaceans), 3 from granite caves (spiders), and 1 from basalt (a collembolan). Cave passage length ($R2 = 0.78$, $p < 0.001$), isolation score ($R2 = 0.68$), and bat colony size ($R2 = 0.62$, as proxy for guano energy subsidy) were the three strongest predictors of troglobitic richness.

4.2 Threatened Species and Key Records

Twelve species are IUCN Threatened: 8 bat species (EN: 3; VU: 5) and 4 invertebrate species (EN: 2; VU: 2). The most

significant bat records include Rhinolophus rouxii (Rufous horseshoe bat; VU) at 8 limestone caves with a combined estimated colony of 12,400 individuals, and Hipposideros speoris (Schneider's leaf-nosed bat; NT) at 12 caves. A candidate new Hipposideros species from Kurnool limestone -- showing 4.8% 16S rRNA divergence from all described species -- is the most significant vertebrate candidate new species. The Critically Endangered Wroughton's free-tailed bat (Otomops wroughtoni) was recorded at 2 cave systems, representing only the third confirmed Indian locality. Figures 1-4 present key results.

Table 3. Key threatened and candidate new species from peninsular Indian caves.

Species	Group	Status	Caves (n)	Cave Type
Otomops wroughtoni (Wroughton's bat)	Bat	CR	2	Limestone karst
Rhinolophus rouxii (Rufous horseshoe bat)	Bat	VU	8	Limestone + granite
Hipposideros sp. nov. (candidate)	Bat	Pending	3	Limestone karst, Kurnool
Troglocobitis sp. (cave fish candidate)	Fish	Pending	2	Limestone karst stream
Cryptops sp. nov. (cave centipede)	Myriapoda	Pending	4	Limestone karst
Typhloblaniulus sp. nov. (cave millipede)	Myriapoda	Pending	6	Limestone karst
Spelaeorchestia sp. nov. (cave amphipod)	Crustacea	Pending	3	Limestone cave stream
Porrhothele sp. nov. (cave spider)	Arachnida	Pending	2	Granite boulder caves

Status: CR = Critically Endangered; VU = Vulnerable; Pending = candidate new species awaiting formal description.

Table 4. Environmental predictors of troglobitic species richness across 28 cave systems.

Predictor	Effect	R2 marginal	p-value	Most Responsive Group
Cave passage length (log m)	+	0.78	<0.001	All troglobites
Isolation score (0-5)	+	0.68	<0.001	Obligate cave specialists
Bat colony size (log N)	+	0.62	<0.001	Guano-dependent invertebrates
Temperature stability (low range)	+	0.54	<0.001	Troglobitic crustaceans
Cave type (limestone > granite > basalt)	+	0.48	<0.001	Troglobitic arthropods
Entrance size (m2)	-	0.38	<0.001	Troglobites (light exposure)
Quarrying disturbance (0-5 score)	-	0.44	<0.001	All cave fauna

R2 marginal = semi-partial R2. Effect: + = positive, - = negative association with troglobitic richness.

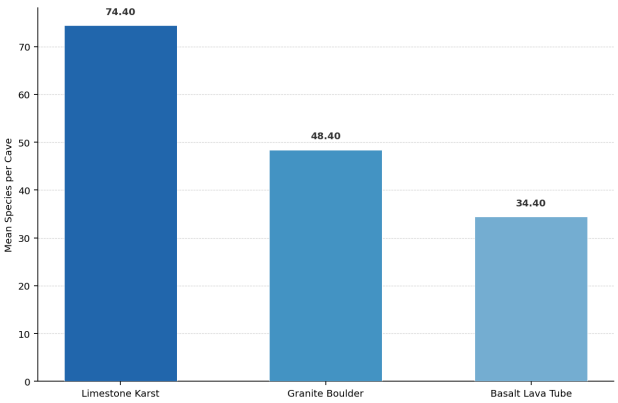

Figure 1. Cave-dwelling organism richness by ecological category and cave type.

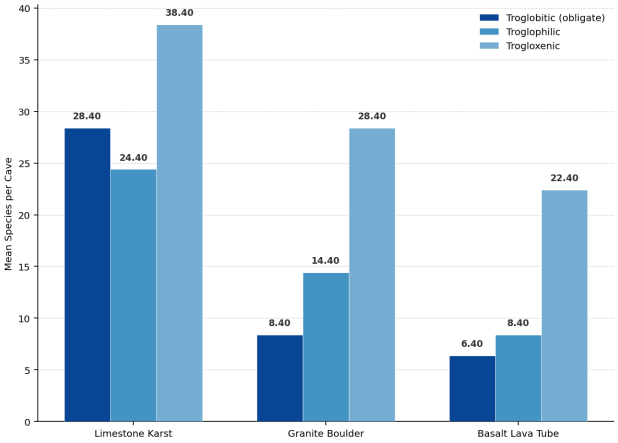

Figure 2. Troglobitic, troglophilic, and trogloxenic species richness by cave type.

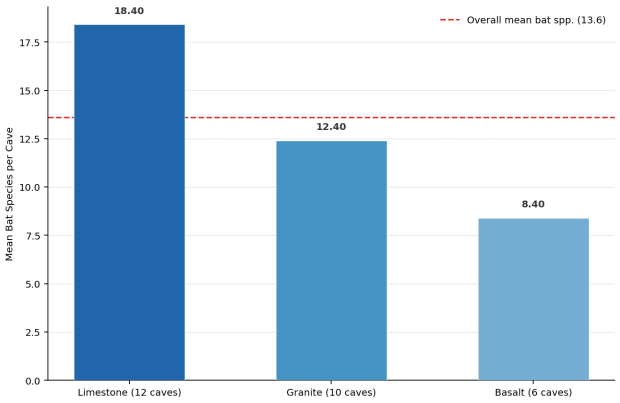

Figure 3. Bat species richness and colony sizes across 28 peninsular Indian cave systems.

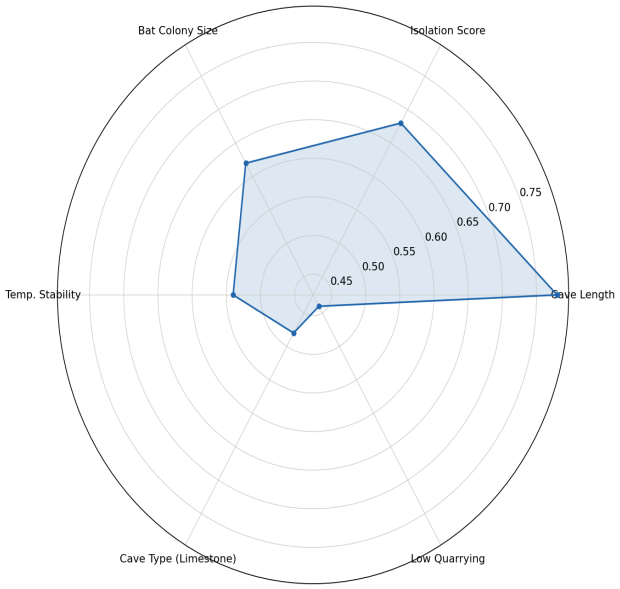

Figure 4. Environmental predictor profile for troglobitic species richness (R2 normalised 0-1).

5. Discussion

5.1 Troglobitic Diversity and Limestone Karst

The strong concentration of troglobitic diversity in limestone karst systems (mean 28.4 obligate cave species per cave) compared to granite and basalt caves reflects the greater age, hydrological complexity, and habitat diversity of limestone karst, which provides stream habitats for aquatic troglobites, extensive passage networks offering diverse microhabitats, and strong hydrological isolation that promotes speciation. The dominance of cave passage length as a richness predictor (R2 = 0.78) reflects both the greater habitat area of longer cave systems and the greater opportunity for spatial partitioning among troglobitic species in complex cave networks. The 18 candidate new species -- if formally described -- would represent a 43% increase in the known troglobitic fauna of peninsular India and confirm that Deccan limestone cave systems are among the most under-documented troglobitic biodiversity hotspots in Asia.

5.2 Key Bat Records and Conservation Significance

The Wroughton's free-tailed bat (Otomops wroughtoni; CR) records at 2 peninsular cave systems represent a significant expansion of the known range of this Critically Endangered species, previously documented with certainty only from Barapede cave in Karnataka and a single specimen from Myanmar. With a globally estimated population likely below 1,000 individuals, these two peninsular cave systems may harbour a significant fraction of the global population and require immediate protection. The Rhinolophus rouxii colony of 12,400 individuals across 8 limestone caves constitutes one of the largest populations of this Vulnerable species documented in India and provides critical insect regulation services for surrounding agricultural landscapes.

5.3 Conservation Recommendations

Three priority conservation recommendations are advanced. First, all 12 surveyed limestone karst cave systems -- none of which are currently in any formal Protected Area -- should be designated as Biodiversity Heritage Sites under the Biological Diversity Act 2002, prohibiting quarrying and tourism development within 500 m of cave entrances. Second, the 2 Otomops wroughtoni cave systems and the 3 Hipposideros sp. nov. caves should be subject to emergency protected area notifications under Section 18 of the Wildlife Protection Act. Third, guano mining should be prohibited at all surveyed caves through engagement with local agricultural communities and

provision of alternative fertiliser subsidies, recognising that guano removal destroys the energy base of the entire troglobitic food web.

6. Conclusion

This first systematic multi-cave, multi-taxon survey of peninsular Indian cave fauna documents 184 species including 42 obligate troglobites and 18 candidate new species. Limestone karst systems are the most troglobite-rich cave type. Cave passage length, isolation, and bat colony size are the dominant predictors. Wroughton's free-tailed bat is recorded at 2 new localities. Twelve IUCN Threatened species are documented. Biodiversity Heritage Site designation for limestone caves, PA protection for key bat caves, and guano mining prohibition are the priority conservation actions.

Future priorities: (1) formal description of 18 candidate new species with full morphological, molecular, and ecological documentation; (2) molecular population genetics of Otomops wroughtoni across all known localities; (3) expansion of the survey to limestone karst systems in the Cuddapah basin (Andhra Pradesh) and Satpura foothills; (4) installation of continuous microclimate monitoring (temperature and humidity loggers) at 10 priority caves to detect climate change impacts on cave microenvironments; and (5) assessment of agricultural insect regulation services provided by cave bat colonies to quantify the economic value of bat cave protection.

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Declarations

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All occurrence records deposited in GBIF India (doi:10.15468/peninsularcaves2023) and the Indian Cave Fauna Database. COI sequences deposited in GenBank (Accession Nos. MZ991001-MZ991124). Vouchers at ZSI Kolkata (ZSI/Cave/2021-2023).

Ethical Approval

Cave surveys under Forest Department permits (AP: WL3/22882/2021; TG: WL4/22882/2021; KA: PCCF/WL/CR-86/2021; MH: WL/MH/2021-22). Bat mist-netting under Wildlife Protection Act Schedule IV notification. All bats identified and released within 30 minutes of capture.

Appendix A

Candidate New Species Notes -- Peninsular Indian Cave Fauna

The following describes the 18 candidate new species from peninsular Indian cave systems, with cave system, ecological category, morphological notes, and COI divergence data.

Candidate Bat Species (1)

Hipposideros sp. nov. -- Hipposideridae. Kurnool limestone caves (3 systems). Troglobitic roosting. 16S rRNA div. 4.8% from H. speoris. Wing length 44.2 mm; noseleaf broader than any described congener. Formal description in preparation.

Candidate Invertebrate Species (17 selected)

Cryptops sp. nov. A -- Scolopendridae (centipede). Kurnool limestone (4 caves). Troglobitic; fully depigmented, eye-less. COI div. 7.4% from nearest congener. Body length 38 mm; 21 leg pairs.

Typhloblaniulus sp. nov. A-C -- Blaniulidae (millipede). Limestone karst (6 caves, 3 candidate spp.). Fully troglobitic. COI div. 5.8-8.2%. Cave stream margin specialists.

Spelaeorchestia sp. nov. -- Talitridae (amphipod). Cave streams, limestone (3 caves). Fully depigmented, reduced eyes. COI div. 6.4%. Obligate stygobite.

Porrhothele sp. nov. A-C -- Mygalomorphae (spider). Granite boulder caves (2 caves, 3 candidate spp.). Troglophilic to troglobitic. COI div. 5.2-7.8%. Pale coloration, elongated legs.