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The Origin and Evolution of Endemic Birds in the Qinghai-Tibet Plateau

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Abstract The Tibetan Plateau is a unique region characterized by its high altitude, diverse habitats, and significant endemic biodiversity. This study systematically explores the origins and evolution of endemic bird species in this area, examining geological and climatic history, evolutionary adaptations, and current conservation challenges. The research identified the critical roles of plateau uplift and Quaternary climate changes in driving species formation and genetic differentiation. The endemic birds exhibit significant physiological, morphological, and behavioral adaptations to cope with the high-altitude environment. Despite ongoing conservation efforts, these species still face significant threats from climate change and human activities. The study emphasizes the importance of integrating phylogenetic, ecological, and behavioral research to guide conservation strategies. Longitudinal studies to monitor the impact of climate change and ensure the preservation of these unique bird populations are crucial. This study provides a comprehensive understanding of the evolutionary processes of biodiversity on the Tibetan Plateau, offering a scientific basis for future conservation efforts.
Keywords Qinghai-Tibet Plateau; Endemic birds; Evolutionary adaptations; Phylogenetics; Conservation strategies

1 Introduction

The Qinghai-Tibet Plateau, often referred to as the “Roof of the World”, is the highest and one of the most extensive plateaus on Earth. It spans over 2.5 million square kilometers and includes vast expanses of grasslands, mountain ranges, and diverse ecosystems. The plateau’s unique geographical and climatic conditions have created a distinct environment that supports a wide array of flora and fauna. The region is characterized by its high altitude, with an average elevation exceeding 4 500 meters above sea level, making it a unique natural laboratory for studying the effects of high-altitude environments on biodiversity and ecological processes.

The plateau’s formation is the result of complex geological processes, including the collision of the Indian and Eurasian tectonic plates, which has led to its continuous uplift over millions of years. This dynamic geological history, coupled with climatic fluctuations such as glacial and interglacial periods, has significantly influenced the region’s biodiversity. The Qinghai-Tibet Plateau serves as a critical biogeographic barrier and a corridor for species migration and evolution. It has become a hotspot for studying speciation, endemism, and ecological adaptations due to its isolation and varied habitats (Jiang et al., 2023). The plateau’s harsh environmental conditions, including low oxygen levels, extreme temperatures, and high UV radiation, have driven the evolution of unique physiological and behavioral traits in the resident species, making it an invaluable region for evolutionary and ecological research.

Endemic bird species of the Qinghai-Tibet Plateau hold significant ecological, evolutionary, and conservation value. These species have evolved unique adaptations to thrive in the high-altitude, harsh climatic conditions of the plateau. For instance, high-altitude passerine birds from this region have developed increased hemoglobin-oxygen affinity to cope with the low oxygen levels (Zhu et al., 2018). These adaptations are not only fascinating from an evolutionary biology perspective but also provide critical insights into the processes of speciation and adaptation. Furthermore, the Qinghai-Tibet Plateau acts as a natural laboratory for studying the impacts of geological and climatic changes on biodiversity, as demonstrated by the uplift of the plateau and glacial oscillations that triggered the diversification of bird species such as Tetraogallus.

Endemic birds are vital indicators of environmental health and play crucial roles in maintaining the ecological balance of the plateau's diverse habitats. The presence and behavior of these birds can reflect changes in the environment, such as climate change and human disturbance. Research has shown that suitable geographic ranges for most mammals, amphibians, and reptiles have increased over the past 40 years, while ranges for birds have generally decreased due to climate change (Jiang et al., 2023). This highlights the need for ongoing monitoring and conservation efforts. Furthermore, these birds contribute to the plateau's biodiversity and ecological functions, such as seed dispersal and pest control, which are crucial for the health and sustainability of the plateau's ecosystems (Wu et al., 2022).

This study systematically explores the origins and evolutionary history of endemic bird species on the Tibetan Plateau, providing a detailed analysis of the biogeographic patterns and adaptation mechanisms that allow these species to thrive in such a unique and harsh environment. The research highlights current knowledge gaps in this field and proposes directions for future studies, which will contribute to a more comprehensive understanding of the evolution and conservation of these region-specific birds.

2 Geological and Climatic History of the Qinghai-Tibet Plateau

2.1 Formation and uplift of the plateau

The Qinghai-Tibet Plateau, also known as the Tibetan Plateau, is the highest and largest plateau in the world, covering an area of approximately 2.5 million square kilometers (Figure 1). The formation of this geological marvel began around 50 million years ago, triggered by the collision between the Indian Plate and the Eurasian Plate. This tectonic activity initiated a series of complex geological processes that led to the gradual uplift of the region. Over millions of years, the continued convergence of these plates resulted in the elevation of the plateau to its current average height of over 4 500 meters. The initial phase of uplift during the Eocene epoch (around 40-50 million years ago) was followed by significant episodes of rapid elevation changes during the Miocene and Pliocene epochs, approximately 20 to 8 million years ago. These geological events have been instrumental in shaping the topography and climate of not only the plateau but also the surrounding regions.

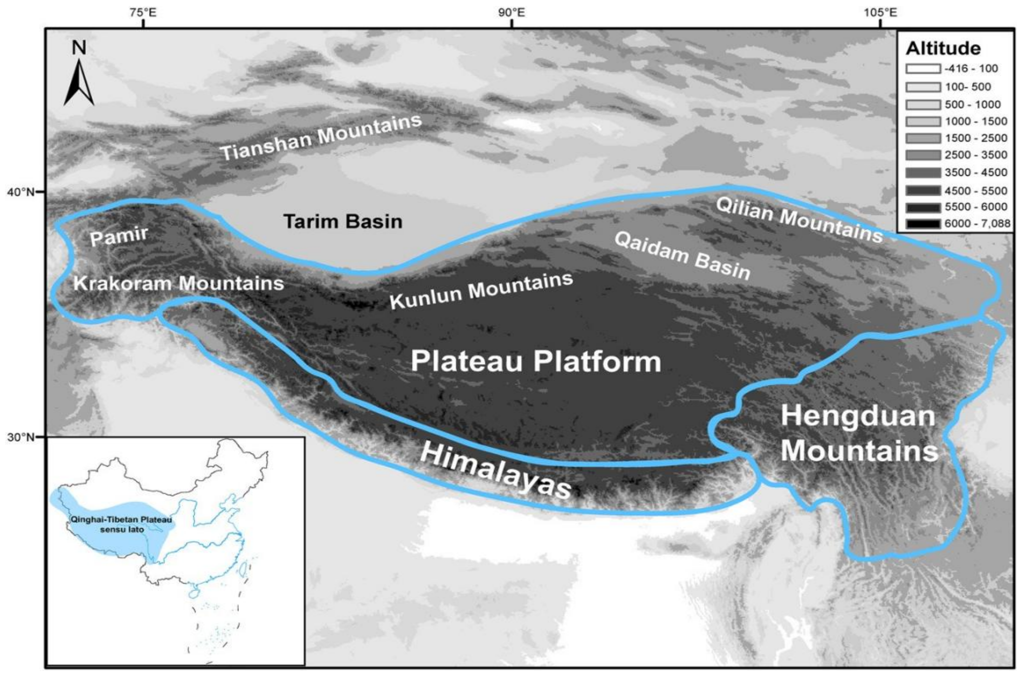

Figure 1 Geographic Scope of the Tibetan Plateau (Adapted from Mao et al., 2021)

Image caption: The image depicts the broad scope of the Tibetan Plateau (QTPsl), including the narrowly defined Tibetan Plateau proper (QTPss), the Himalayas, and the Hengduan Mountains. The regions within the plateau are distinguished by different colors, with the locations and boundaries of each major geographical unit clearly marked, providing a visual explanation of the geographical concept of the Tibetan Plateau and its complex topographic structure. The bottom left corner displays a detailed map downloaded from the Ministry of Natural Resources of the People's Republic of China (Adapted from Mao et al., 2021)

The uplift of the Qinghai-Tibet Plateau has had far-reaching implications for the global climate and the environment. The rise of the plateau significantly altered atmospheric circulation patterns, contributing to the development and intensification of the Asian monsoon system. This, in turn, affected precipitation patterns across Asia, influencing the hydrology and ecosystems of vast regions. The uplift also played a crucial role in the formation of the extensive river systems originating from the plateau, including major rivers such as the Yangtze, Yellow, Mekong, and Brahmaputra. These rivers have carved deep valleys and gorges, further shaping the plateau's rugged landscape. The combination of high elevation and varied topography has created a multitude of microclimates and ecological niches, fostering remarkable biodiversity. The ongoing tectonic activity and climatic impacts continue to influence the geological evolution and environmental dynamics of the Qinghai-Tibet Plateau (Guo et al., 2016).

2.2 Climatic changes and their impact on biodiversity

The uplift of the Qinghai-Tibet Plateau has had profound effects on global and regional climates, significantly altering atmospheric circulation patterns and contributing to the development of the Asian monsoon system. This monsoon system has had a crucial role in determining the climate of the plateau and its surrounding regions, resulting in distinct wet and dry seasons that have influenced the distribution and composition of local ecosystems. Additionally, the plateau's high altitude has caused it to act as a barrier to air masses, leading to unique climatic conditions such as cold temperatures and reduced oxygen levels, which have further impacted the flora and fauna of the region. These climatic changes have been particularly impactful during the Quaternary period, a time characterized by repeated glacial and interglacial cycles. These cycles have driven significant environmental changes, including alterations in temperature and precipitation patterns, which have had cascading effects on the plateau's biodiversity.

These climatic fluctuations have played a crucial role in shaping the biodiversity of the Qinghai-Tibet Plateau. During glacial periods, many species were forced to migrate to lower altitudes or to find refugia in areas with more stable climates. This has led to the formation of distinct genetic lineages and has promoted speciation as populations became isolated and adapted to different environmental conditions (Miao et al., 2021). For instance, the expansion and contraction of glaciers have repeatedly fragmented habitats, creating isolated populations that evolve independently. This isolation has facilitated the emergence of numerous endemic species, particularly among plants and animals with limited dispersal abilities. Moreover, as the glaciers retreated during interglacial periods, species recolonized the available habitats, often leading to secondary contact and hybridization events that further increased biodiversity. The combined effects of these climatic and geological processes have made the Qinghai-Tibet Plateau a hotspot of biodiversity and an excellent natural laboratory for studying the processes of speciation and adaptation (Guo et al., 2016).

2.3 Geological events and avian evolution

Geological events, particularly the uplift of the Qinghai-Tibet Plateau, have been pivotal in the evolution of avian species in the region. The uplift created diverse habitats and ecological niches, promoting speciation and diversification among bird populations. The rising plateau acted as a barrier and a corridor, leading to isolated populations and new evolutionary paths. This isolation, combined with varying environmental conditions, fostered the development of unique species adapted to specific niches. For instance, phylogeographic studies have shown that the uplift significantly contributed to the genetic divergence of avian species, with different lineages evolving in response to the new habitats and climatic conditions created by the uplift (Figure 2) (Lei et al., 2014). These evolutionary processes have resulted in a rich diversity of bird species, many of which are endemic to the plateau.

Furthermore, climatic fluctuations during the Quaternary have had a profound impact on avian evolution. The alternating glacial and interglacial periods caused shifts in habitats and resources, driving migration, population structure changes, and genetic diversity within bird species. As glaciers advanced and retreated, bird populations were forced to move and adapt, leading to periods of population expansion and contraction. These dynamic environmental conditions facilitated natural selection and adaptation, allowing birds to develop specialized traits for survival in the plateau's harsh climate (Gu et al., 2013). Additionally, the complex topography of the plateau provided refugia during adverse climatic conditions, helping preserve genetic diversity and enabling rapid post-glacial recolonization. These geological and climatic influences have collectively shaped the evolutionary history of the region's avian species, making the Qinghai-Tibet Plateau a hotspot for avian biodiversity and evolutionary studies.

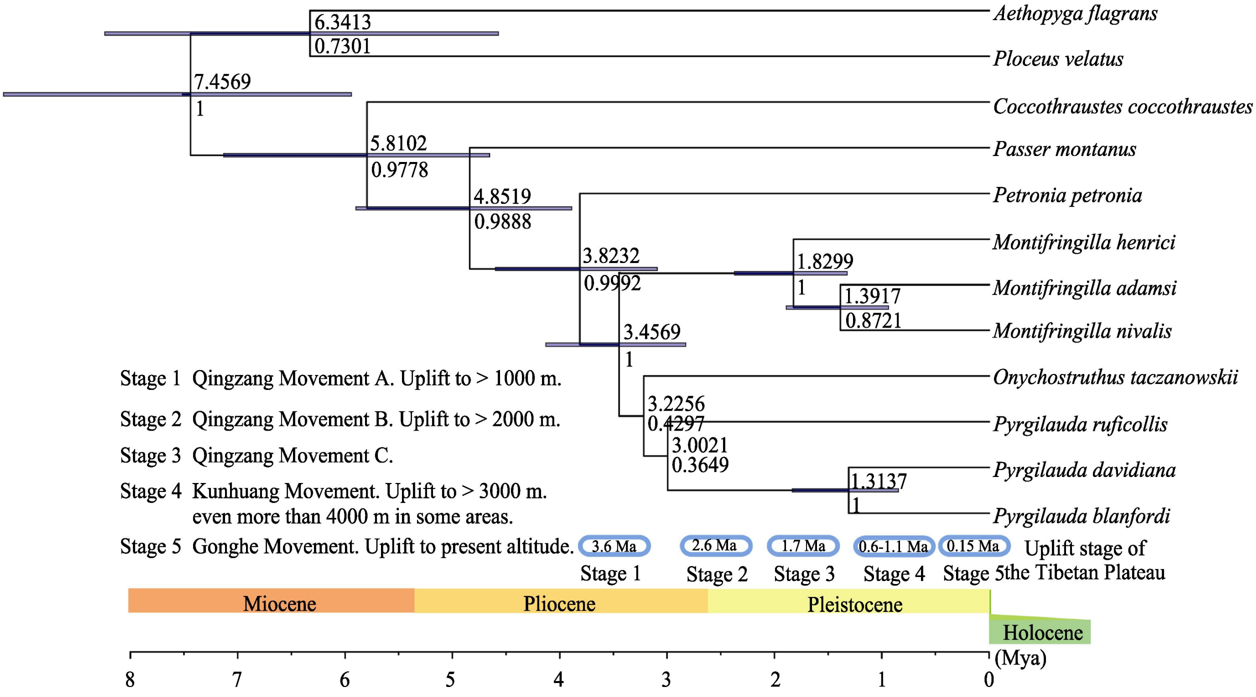

Figure 2 Phylogenetic Tree of Montifringilla Species at Different Altitudes (Adapted from Lei et al., 2014)

Image caption: The figure displays the divergence times of different Montifringilla species on the Tibetan Plateau, revealing the evolutionary history of these species under the influence of geological and climatic changes. The results support the significant role of the uplift of the Tibetan Plateau in driving avian species diversification (Adapted from Lei et al., 2014)

3 Historical Perspectives on Avian Endemism

3.1 Early studies and discoveries

The exploration of avian endemism on the Qinghai-Tibet Plateau can be traced back to the early 20th century when pioneering ornithologists began to document the unique bird species inhabiting this high-altitude region. The first comprehensive surveys were conducted by explorers and naturalists who braved the harsh conditions to collect specimens and record observations. These early studies revealed a striking level of avian diversity and endemism, with many species found nowhere else in the world. The harsh and isolated environment of the plateau was quickly recognized as a significant factor contributing to the development of unique species adapted to extreme conditions (Qu et al., 2010).

Among the first notable discoveries were species like the Tibetan snow finch (*Montifringilla adamsi*) and the blue eared pheasant (*Crossoptilon auritum*), which were distinguished by their morphological and behavioral adaptations to the high-altitude environment. These birds exhibited unique traits such as specialized feathers for insulation against the cold, and altered metabolic rates to cope with low oxygen levels. The documentation of these species provided crucial insights into how extreme environments drive evolutionary change, and spurred further interest in the region's avifauna (Gu et al., 2013). Initial findings indicated that the plateau's isolation acted as a natural laboratory for studying speciation and adaptation, laying the groundwork for future research.

The mid-20th century saw an expansion in avian research on the plateau as more systematic and methodical studies were undertaken. Researchers employed various techniques, including banding, nesting studies, and behavioral observations, to gather comprehensive data on the life history and ecology of endemic species. These studies were critical in understanding the ecological roles of these birds within their habitats and the evolutionary pressures they faced. Notably, the development of genetic analysis tools in the latter part of the century allowed scientists to delve deeper into the evolutionary history and genetic diversity of these species, confirming many hypotheses about their unique adaptations and evolutionary pathways. This period marked a significant advancement in the study of avian endemism on the Qinghai-Tibet Plateau, establishing it as a key area of interest for evolutionary biologists.

3.2 Evolutionary theories and hypotheses

One of the leading theories explaining avian endemism on the Qinghai-Tibet Plateau is the role of the region's significant geological events, particularly the plateau's uplift during the Miocene and Pliocene epochs. The uplift, which began around 50 million years ago and continued in phases, resulted in the creation of diverse and isolated habitats across different elevations and climatic zones. This geographic isolation acted as a catalyst for allopatric speciation, where populations of the same species diverge into new species due to physical separation (Liu et al., 2014). Phylogeographic studies support this theory, showing genetic divergence that corresponds with these geological events. The uplift created a variety of microhabitats, promoting niche differentiation and enabling the evolution of unique adaptations among avian species.

Another critical factor in the evolutionary history of the plateau's avian species is the impact of Quaternary climatic oscillations. The Quaternary period, spanning the last 2.6 million years, was marked by repeated glacial and interglacial cycles. These cycles dramatically altered the plateau's environment, leading to periods of both expansion and contraction of habitats. During glacial maxima, ice sheets and glaciers covered significant parts of the plateau, forcing species to retreat to refugia—areas where conditions remained habitable. As the glaciers receded during interglacial periods, these species re-colonized the plateau. This dynamic history of habitat fragmentation and expansion fostered genetic divergence and hybridization among isolated populations, further driving speciation and the development of unique genetic lineages (Lei et al., 2014).

Additionally, the plateau's extreme and varied climatic conditions have exerted strong selective pressures on avian populations, leading to significant physiological and ecological adaptations. The high altitude, intense solar radiation, low oxygen levels, and extreme temperature fluctuations have necessitated the evolution of specialized traits in endemic bird species. For example, some species have developed enhanced hemoglobin-oxygen affinity to cope with hypoxia, while others exhibit morphological and behavioral adaptations to survive the harsh winters. These adaptations have been critical for the survival and reproductive success of birds on the plateau, enabling them to exploit the unique ecological niches available. The combination of geological isolation, climatic fluctuations, and extreme environmental pressures has made the Qinghai-Tibet Plateau a natural laboratory for studying the processes of evolution and speciation (Zhu et al., 2018).

3.3 Important research progress

Lei et al. (2014) made substantial contributions to the understanding of avian endemism on the Qinghai-Tibet Plateau through his extensive research on the phylogeography and evolutionary history of bird species in this region. Their study highlighted how geological events, such as the uplift of the plateau and subsequent glaciations, have driven species diversification and adaptation. Another notable work examined the phylogeographical patterns of five avian species on the plateau, revealing distinct genetic lineages shaped by historical climate fluctuations (Lei et al., 2014; Qu et al., 2010). The work has been pivotal in demonstrating how these environmental changes have influenced avian speciation and distribution patterns.

Qu et al. (2010) significantly advanced the field with her research focusing on the genetic diversity and adaptation of plateau birds. Their comparative phylogeographic studies have provided insights into the evolutionary processes that have enabled these species to survive in high-altitude environments. For instance, the work on the genetic differentiation of the Tibetan snow finch and the blue eared pheasant has uncovered how climatic and geographical changes have shaped their population structures and evolutionary paths (Qu et al., 2010; Gu et al., 2013). The research has been essential in identifying the key genetic adaptations that allow these birds to thrive in one of the world's most challenging habitats.

Gu et al. (2013) contributed extensively to the conservation and genetic study of endemic bird species on the Qinghai-Tibet Plateau. Their research on the blue eared pheasant and other endemic birds has provided critical data on the population genetic structure and evolutionary history of these species. The work has emphasized the importance of understanding genetic diversity and demographic history for conservation efforts, highlighting how past climatic and environmental shifts have driven genetic differentiation and population divergence (Gu et al., 2013). The findings support the need for targeted conservation strategies that consider the unique evolutionary histories of these endemic species.

4 Modern Research Methods in Avian Evolution Studies

4.1 Molecular phylogenetics and genetic studies

Molecular phylogenetics has revolutionized the study of avian evolution on the Qinghai-Tibet Plateau by providing a detailed understanding of evolutionary relationships and lineage divergence. Researchers employ techniques such as DNA sequencing to analyze genetic material from various bird species, allowing them to construct phylogenetic trees that reveal the evolutionary history and genetic relatedness of these species. For instance, studies on the genetic diversity of plateau pika and multiple bird species have shown significant differentiation driven by historical climate changes and geographical barriers like mountains and rivers. These genetic analyses have been instrumental in identifying distinct genetic lineages and understanding how species have adapted to the unique environmental conditions of the plateau (Gu et al., 2013; Qi et al., 2023).

In addition to phylogenetic studies, whole-genome sequencing and transcriptomic analyses have provided deeper insights into the genetic adaptations of high-altitude species. By examining the complete genetic makeup of these birds, researchers can identify specific genes that contribute to their ability to survive in hypoxic conditions and extreme temperatures. Transcriptomic analyses, which study the expression of genes under different environmental conditions, have revealed how certain genes are upregulated to enhance metabolic efficiency and oxygen utilization. These studies have identified candidate genes associated with high-altitude adaptation, such as those involved in hemoglobin function and cellular respiration. For example, research on high-altitude passerines has identified genetic mechanisms underlying their adaptation to low oxygen levels, which include mutations that increase the affinity of hemoglobin for oxygen (Su et al., 2020). Such genetic insights are crucial for understanding the evolutionary success of avian species on the Qinghai-Tibet Plateau and can inform conservation strategies for preserving these unique genetic adaptations.

4.2 Paleontological evidence and fossil records

Fossil records play a crucial role in understanding the historical biogeography and evolutionary history of the Qinghai-Tibet Plateau. Paleontological studies have uncovered fossil leaves and remains of various flora and fauna, providing evidence for the plateau's historical climate and ecological conditions. For example, fossil leaves of the genus *Elaeagnus* have been found in the region, dating back to the late Miocene. These fossils suggest that the region once had a much warmer and more humid climate, which supported a diverse range of plant species. The well-preserved, densely packed stellate scales on the fossil leaf surfaces are diagnostic of the Elaeagnaceae family, and the discovery of these fossils has helped researchers understand the historical distribution and ecological adaptations of this plant family on the plateau (Su et al., 2014).

In addition to plant fossils, animal fossils have also provided significant insights into the plateau's past environments. For instance, paleontological evidence has been used to trace the diversification of species like the Tibetan snowcock, correlating their evolution with geological events such as the uplift of the plateau and Quaternary glaciations. The uplift of the plateau created new habitats and ecological niches, which promoted speciation and diversification among avian species. These geological and climatic changes are believed to have driven adaptive radiation, leading to the development of unique morphological and physiological traits in these birds. Such findings underscore the importance of paleontological studies in revealing how historical environmental changes have shaped the biodiversity and evolutionary trajectories of species on the Qinghai-Tibet Plateau (Lei et al., 2014).

4.3 Ecological and behavioral studies

Ecological and behavioral studies provide critical insights into how avian species interact with their environment and adapt to the extreme conditions of the Qinghai-Tibet Plateau. Researchers have investigated habitat preferences, territorial behavior, and diet to understand the adaptive strategies of species such as the white-rumped snow finch and the rufous-necked snow finch. These studies reveal that these species occupy distinct ecological niches and exhibit different resource utilization patterns, which help reduce competition and promote coexistence. For instance, the white-rumped snow finch is dominant in rural areas throughout the year, while the rufous-necked snow finch shifts to human-occupied areas during winter and spring. This spatial separation, coupled with differences in territorial aggression and diet - where the white-rumped snow finch consumes more seeds, and the rufous-necked snow finch relies more on human food waste - illustrates how behavioral adaptations mitigate interspecific competition and facilitate survival in the harsh winter months (Li et al., 2020).

Advanced technologies such as GPS tracking and remote sensing have significantly enhanced the ability to monitor migration patterns, habitat use, and other ecological dynamics of avian species on the plateau. For example, studies using these technologies have mapped the seasonal movements and breeding grounds of various bird species, providing data on how they navigate the challenging terrain and climate. This approach has also been instrumental in identifying critical habitats and migration corridors that are essential for conservation efforts. Additionally, ecological modeling and environmental DNA (eDNA) analyses are being used to assess the impacts of climate change and human activities on bird populations, furthering our understanding of their ecological requirements and resilience strategies (Zhang et al., 2017). These comprehensive ecological and behavioral studies are crucial for developing effective conservation strategies and ensuring the long-term survival of endemic bird species on the Qinghai-Tibet Plateau.

5 Origin of Endemic Birds in the Qinghai-Tibet Plateau

5.1 Biogeographical origins and migration patterns

The biogeographical origins of the endemic birds in the Qinghai-Tibet Plateau (QTP) are deeply rooted in the region’s complex geological and climatic history. The plateau has acted as both a cradle and a refuge for avian species over millions of years. Some bird species are believed to have originated in situ on the plateau, evolving unique adaptations to the high-altitude, harsh climatic conditions. The uplift of the plateau, which began around 50 million years ago, created isolated environments that promoted speciation. This uplift, coupled with climatic events such as the Miocene and Pliocene climatic oscillations, significantly influenced the distribution and diversification of bird species. For instance, studies have shown that several bird lineages diverged during these periods, leading to the current high levels of endemism observed on the plateau.

Migration patterns have also played a crucial role in shaping the avian biodiversity of the QTP. The plateau has served as a critical hub for avian migration, with species moving into and out of the region in response to climatic and environmental changes. During the glacial-interglacial cycles of the Quaternary period, the QTP provided refugia for many bird species, facilitating survival and subsequent dispersal during more favorable conditions. This bidirectional migration has resulted in a rich mosaic of genetic diversity within the avian populations of the plateau. For example, phylogeographic analyses have revealed that some species migrated into the plateau from adjacent regions, such as the Himalayas and the Palearctic, while others migrated outwards, spreading to distant areas like the Western Palearctic and the Nearctic (Gu et al., 2013). These movements have not only enriched the genetic pool but also facilitated the exchange of adaptive traits, contributing to the resilience and diversity of bird species in the QTP.

5.2 Speciation processes

Speciation processes on the Qinghai-Tibet Plateau have been driven primarily by geographic isolation, which is a direct result of the region’s dramatic uplift. The tectonic activity that raised the plateau created a variety of isolated habitats, such as mountain ranges, valleys, and isolated plateaus, which served as refugia during adverse climatic periods. These isolated habitats prevented gene flow between populations, leading to allopatric speciation. For example, the uplift of the plateau during the Miocene and Pliocene epochs created barriers that isolated populations of ancestral bird species, which over time diverged into distinct species due to the lack of interbreeding opportunities (Lei et al., 2014). This process is evident in the phylogeographic patterns observed in species such as the Tibetan snow finch and the Hume's ground tit, which show significant genetic divergence corresponding to the geological events of the plateau (Qu et al., 2009).

In addition to geographic isolation, climatic fluctuations during the Quaternary period have played a crucial role in driving speciation on the plateau. The repeated cycles of glaciation and deglaciation created dynamic environments that alternated between periods of isolation and secondary contact. During glacial periods, many species were forced into refugia, where isolated populations adapted to specific local conditions, leading to genetic divergence. When the glaciers retreated, some of these populations came into contact again, leading to hybridization and further diversification. This combination of isolation and hybridization has been a powerful driver of speciation in the region. For example, the Tibetan snowcock (*Tetraogallus tibetanus*) shows evidence of historical isolation during glacial periods followed by post-glacial range expansions and secondary contact, which have shaped its current genetic structure. These processes highlight the complex interplay between geological and climatic factors in shaping the unique avian diversity of the Qinghai-Tibet Plateau.

5.3 Factors driving endemism

Several factors drive the high level of endemism observed among birds in the Qinghai-Tibet Plateau. One of the primary factors is the geological history of the region, particularly the uplift of the plateau. This uplift, which began around 50 million years ago and has continued intermittently, created a variety of unique and isolated habitats. These isolated environments acted as refugia during adverse climatic conditions, providing safe havens for species to survive and evolve independently. The topographical complexity resulting from the uplift facilitated allopatric speciation, where species diverge due to geographical barriers. This process is evident in many avian species that show significant genetic divergence corresponding to their isolated habitats (Lei et al., 2014). Additionally, the climatic oscillations of the Quaternary period further influenced these patterns by periodically isolating populations during glacial periods and allowing secondary contact during interglacial periods, promoting both vicariance and hybridization-driven speciation.

Ecological factors also play a crucial role in driving endemism on the Qinghai-Tibet Plateau. The extreme and varied climatic conditions of the plateau have necessitated the development of unique adaptations among its avian species. This has led to niche specialization, where different species adapt to specific ecological niches, reducing competition and promoting coexistence. For example, the Tibetan snow finch and the rufous-necked snow finch exhibit distinct habitat preferences and dietary habits that allow them to coexist despite living in the same region (Li et al., 2020). Furthermore, the plateau's isolation from other regions has limited gene flow from external populations, maintaining genetic distinctiveness and enhancing local adaptation. Human activities and climate change have also begun to influence these dynamics, altering habitats and shifting the distribution and survival of endemic species. Studies have shown that climate change has already affected the ranges of several vertebrate species on the plateau, emphasizing the need for ongoing conservation efforts to protect these unique and diverse avian populations (Jiang et al., 2023).

6 Evolutionary Adaptations to High-Altitude Environments

6.1 Physiological adaptations

Birds inhabiting the high-altitude environments of the Qinghai-Tibet Plateau have developed several physiological adaptations to cope with hypoxia, extreme cold, and other harsh conditions. A key adaptation involves modifications in hemoglobin (Hb) function, which increases oxygen affinity and efficiency of oxygen transport. For instance, studies have shown that high-altitude passerine birds on the plateau have evolved increased Hb-O2 affinity through both parallel and divergent amino acid substitutions (Zhu et al., 2018). Additionally, genomic studies on Tibetan partridge have identified genes under positive selection related to hypoxia response, metabolism, and immune function, further highlighting the physiological adaptations to high-altitude living (Li et al., 2022).

6.2 Morphological adaptations

High-altitude birds exhibit distinct morphological traits that enhance their survival in extreme environments. Larger body size and specific anatomical features, such as increased wing length and tarsometatarsi length, are common among these birds. For example, snowfinches have evolved larger body sizes and exhibit variations in DNA repair mechanisms, which are crucial for coping with high UV radiation and cold temperatures. These morphological adaptations are accompanied by genetic changes that have been positively selected to support these traits.

6.3 Behavioral adaptations

Behavioral adaptations are critical for the survival of birds in high-altitude environments. These adaptations include changes in habitat use, feeding strategies, and territorial behaviors. High-altitude sparrows, for instance, exhibit enhanced metabolic and thermogenic capacities in their pectoralis muscles to maintain body temperature during cold conditions, while also showing shifts in habitat and dietary preferences during different seasons (Nabi et al., 2021). These behavioral adaptations reduce interspecific competition and allow efficient utilization of available resources, promoting coexistence in extreme environments.

These combined physiological, morphological, and behavioral adaptations underscore the complex and multifaceted strategies that high-altitude birds have developed to thrive on the Qinghai-Tibet Plateau.

7 Case Studies of Endemic Bird Species

7.1 Blue Eared Pheasant (*Crossoptilon auritum*)

The Blue Eared Pheasant (*Crossoptilon auritum*), an endemic bird species of the Qinghai-Tibet Plateau, exhibits significant genetic differentiation attributed to climatic oscillations during the Quaternary period. These climate changes have shaped the population genetic structure, leading to distinct subpopulations in different regions of the plateau (Gu et al., 2013).

By analyzing mitochondrial DNA sequences and eight autosomal microsatellite loci, the population genetic structure of the Blue Eared Pheasant was revealed, identifying four distinct subpopulations: the central Huzhu and Taizishan group, the southern Ruoergai group, the southernmost Wanglang group, and the northernmost Helanshan group (Figure 3). These subpopulations formed during the Pleistocene, corresponding to geological changes along the eastern edge of the Tibetan Plateau and climatic oscillations between interglacial and glacial periods. The findings indicate that these subpopulations constitute primary conservation units, particularly the isolated Helanshan subpopulation. Furthermore, the study explored how climatic and environmental changes drive population differentiation by comparing timelines of paleoclimate changes with species divergence times, underscoring the importance of phylogeographic studies for conservation efforts. This provides valuable information for understanding and preserving the biodiversity of the Tibetan Plateau's marginal areas (Gu et al., 2013).

7.2 Tibetan Bunting (*Emberiza koslowi*)

The Tibetan Bunting (*Emberiza koslowi*) displays unique phylogenetic relationships to other bunting species. Phylogenetic analyses have placed it within a distinct clade, illustrating its evolutionary divergence from related species.

The origin of the Tibetan Bunting can be traced back to the early Miocene, around 20 million years ago. During this period, multiple colonization events into and out of the Qinghai-Tibet Plateau have shaped its current distribution and genetic structure.

Intraspecific lineage separation and ecological segregation have further driven the diversification of the Tibetan Bunting. Different lineages have adapted to distinct ecological niches, leading to variations in habitat preference and resource utilization (Lei et al., 2014).

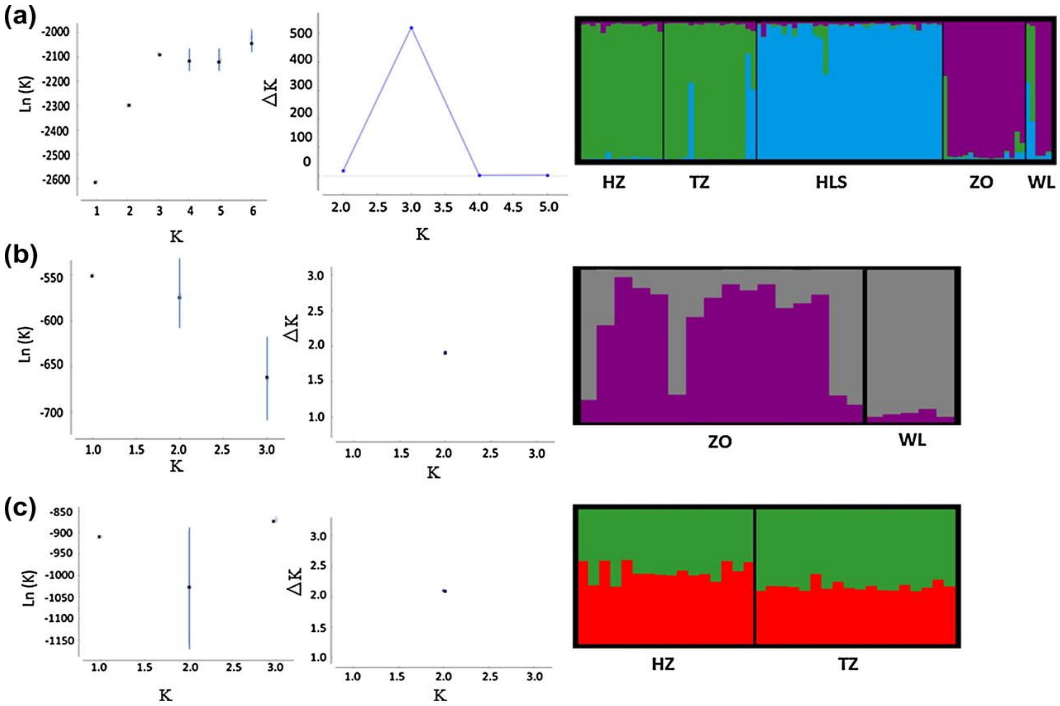

Figure 3 Bayesian STRUCTURE clustering results based on microsatellite genotypes of 91 individuals of blue eared pheasant *Crossoptilon auritum* from five populations(Adopted from Gu et al., 2013)

Image caption: (a) full data, indicating three genetic clusters (DK = 3); (b) samples of south of the low-elevation region, indicating two genetic clusters (DK = 2); (c) samples of north of the lowelevation region, indicating one genetic cluster (K = 1). Note that it is impossible to infer DK for K = 1 (Adopted from Gu et al., 2013)

7.3 Ground Tit (*Pseudopodoces humilis*)

The Ground Tit (*Pseudopodoces humilis*) exhibits significant genetic divergence between its central and eastern populations. This divergence is primarily driven by historical climatic changes and geographic barriers that have restricted gene flow between these populations (Zhu et al., 2018).

Habitat differentiation has led to distinct morphological traits between the central and eastern populations of the Ground Tit. These differences are adaptations to the specific environmental conditions of their respective habitats, including variations in body size and plumage characteristics (Li et al., 2020).

The isolation of populations in glacial refugia during the Pleistocene has driven incipient speciation in the Ground Tit. This process has resulted in genetic and morphological differentiation that could eventually lead to the emergence of new species (Lei et al., 2014).

8 Conservation Status and Challenges

8.1 Current conservation efforts and policies

Current conservation efforts on the Qinghai-Tibet Plateau focus on protecting endemic species and their habitats through the establishment of nature reserves and implementation of conservation policies. Approximately 80 nature reserves have been designated, covering about 22% of the plateau area, primarily located in the southeastern region. These reserves aim to mitigate the impact of human activities and climate change on biodiversity (Zhang et al., 2002). Additionally, the “Natural Forests Protection Project of China” aims to protect the upper reaches of the Yangtze and Yellow Rivers, implementing "no logging" policies to preserve the natural environment (Zhang et al., 2022).

8.2 Threats to endemic bird populations

Endemic bird populations on the Qinghai-Tibet Plateau face several significant threats, including climate change, habitat loss, and human activities. Climate change has caused shifts in species distributions, altering habitats and decreasing the suitable geographic range for birds (Jiang et al., 2023). Human activities, such as livestock grazing and infrastructure development, have led to habitat degradation and fragmentation, further threatening bird populations (Xia et al., 2007; Arthur et al., 2008). Additionally, the poisoning of plateau pikas, perceived as pests, has disrupted the ecosystem, reducing biodiversity and affecting bird species that rely on pika burrows for nesting (Lai and Smith, 2003).

8.3 Recommendations for future research and conservation strategies

To enhance conservation efforts and mitigate the threats facing endemic bird populations, future research and conservation strategies should focus on several key areas. Integrated conservation planning is essential, developing plans that consider both biodiversity and ecosystem services to balance conservation goals with human needs (Wang et al., 2021). Additionally, incorporating climate change projections into conservation planning will ensure that protected areas remain effective under future climate scenarios (Lu et al., 2022). Implementing habitat restoration projects that maintain the structural heterogeneity of landscapes will support a diverse range of species and ecological functions (Li et al., 2022). Finally, enhancing long-term monitoring programs and research to track changes in bird populations and habitats will inform adaptive management strategies (Jiang et al., 2023). By addressing these areas, conservation efforts can be more effective in protecting the unique avian biodiversity of the Qinghai-Tibet Plateau.

9 Future Directions and Research Needs

9.1 Areas for future phylogenetic and genetic studies

Future research should focus on expanding phylogenetic and genetic studies to encompass a broader range of endemic bird species in the Qinghai-Tibet Plateau. Utilizing advanced genomic technologies, such as whole-genome sequencing and transcriptomics, can provide deeper insights into the genetic adaptations and evolutionary histories of these birds. Such studies should also explore the role of hybridization and gene flow in speciation processes, particularly in response to historical climatic changes and geographical barriers (Li et al., 2014; Wu et al., 2022).

9.2 Importance of integrating ecological and behavioral data

Integrating ecological and behavioral data into phylogenetic and genetic studies is crucial for understanding how environmental factors influence the evolution of endemic birds. This includes examining habitat preferences, dietary habits, and reproductive behaviors. Research utilizing technologies such as GPS tracking, remote sensing, and UAV (Unmanned Aerial Vehicle) imagery can offer detailed insights into habitat use and migration patterns. Such integrative approaches will help elucidate the ecological niches and adaptive strategies of these birds, informing conservation efforts and ecological management (Li et al., 2022).

9.3 Need for longitudinal studies on climate change impacts

Longitudinal studies are needed to monitor the impacts of climate change on the distribution, population dynamics, and genetic diversity of endemic bird species over time. These studies should focus on how shifting climatic conditions affect habitat availability, migration routes, and interspecific interactions. Understanding these dynamics is essential for predicting future changes and developing adaptive conservation strategies. Collaborative efforts that combine field observations, climate modeling, and genetic analyses will be key to addressing these complex issues (Lei et al., 2014; Jiang et al., 2023).

By addressing these future research needs, we can gain a more comprehensive understanding of the origin, evolution, and conservation of endemic birds in the Qinghai-Tibet Plateau, ensuring their preservation in the face of environmental changes.

10 Concluding Remarks

The systematic review of the origin and evolution of endemic birds in the Qinghai-Tibet Plateau reveals the intricate interplay between geological, climatic, and ecological factors that have shaped these species. The uplift of the Qinghai-Tibet Plateau and Quaternary climate changes have been crucial in creating diverse habitats, promoting speciation, and driving genetic differentiation among bird populations. Endemic birds exhibit significant physiological, morphological, and behavioral adaptations to cope with the high-altitude environment of the plateau. These include genetic modifications for hypoxia tolerance, distinct morphological traits, and unique behavioral strategies. Despite ongoing conservation efforts, these birds face numerous threats, including climate change, habitat loss, and human activities. Current conservation strategies, while helpful, need to be enhanced and adapted to effectively mitigate these challenges.

Continued research is essential to deepen our understanding of the complex evolutionary processes and ecological dynamics that sustain the unique avian biodiversity of the Qinghai-Tibet Plateau. Future studies should focus on expanding genetic and phylogenetic research to uncover the evolutionary relationships and adaptive mechanisms of a broader range of species. Longitudinal studies are needed to monitor the impacts of climate change on bird populations, distribution, and habitat availability, providing crucial data for adaptive conservation strategies. Additionally, integrating ecological and behavioral data with genetic studies can offer a comprehensive understanding of how environmental factors shape species adaptation and interactions.

The Qinghai-Tibet Plateau represents a natural laboratory for studying the processes of speciation, adaptation, and ecological interaction in high-altitude environments. The unique evolutionary history of its endemic bird species underscores the importance of preserving this region’s biodiversity. Continued research and effective conservation strategies are crucial to safeguarding these species against the looming threats of climate change and habitat degradation. By advancing our scientific knowledge and implementing robust conservation measures, we can ensure the survival and thriving of these remarkable avian populations for future generations.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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