



The Karst of the Moroccan Atlas: A Tectono-Climatic Hybrid Model in a Global Comparative Context (Jura, Dinarides, South China) [†]

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Abstract

The karst of the Moroccan Atlas Mountains represents a strategic water resource and a paleo-environmental recorder of the first order for North Africa. However, despite its importance, it has not yet been the subject of a comparative synthesis positioning it within the global framework of karst systems worldwide. This study aims to fill this gap by providing (1) a critical synthesis of the state of the art on Atlas karst and (2) a rigorous comparative analysis with other reference mountain karsts (Jura, Dinarides) and a tropical analogue (Southern China) to identify specific features and universal principles. The methodology adopted consists of a systematic review (Scopus, Web of Science, Google Scholar) and analysis of karst systems according to a conceptual framework focused on the interaction between tectonic (orogenic style and history) and climatic (regime, gradients, Quaternary variations) controls. These comparison regions were chosen for their status as reference models: the Jura as a temperate folded model, the Dinarides as a Mediterranean holokarst model, and the karst of Southern China as a tropical model. The analysis is structured according to a ‘Tectonics-Climate’ conceptual framework, which systematically examines how the interaction of these two primary forces shapes the characteristics of each system. The analysis reveals that the Atlas karst is a unique ‘hybrid’ model, characterized by the combined influence of active and recent tectonic uplift and a very marked climatic gradient, ranging from sub-humid to semi-arid. This duality controls all of its characteristics, from the architecture of its aquifers to the precariousness of its water resources. It clearly distinguishes it from the temperate–humid karst of the Jura, the Mediterranean–humid karst of the Dinarides, and the tropical–humid karst of Southern China. By defining the place of the Atlas karst, we propose a priority research agenda for the coming decades, focused on process quantification, hydrosystem modeling, and high-resolution paleoclimate reconstruction.

Keywords: karst; Moroccan Atlas; hydrogeology; climate change; comparative study



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1. Introduction

Mountain karst systems, developed within soluble carbonate formations of orogenic belts, constitute a critical component of the Earth’s surface system. These environments

function as major natural “water towers,” supplying sustainable freshwater resources to a significant proportion of the global population, particularly in semi-arid regions [1]. Beyond their hydrological importance, karst systems represent exceptional continental environmental archives. Sedimentary deposits and speleothems preserved within endokarst networks provide high-resolution records of tectonic activity, climatic variability, and landscape evolution, often exceeding the temporal precision of other terrestrial archives [2].

Understanding karst genesis and evolution is therefore essential both for sustainable water-resource management and for reconstructing recent climatic and tectonic histories. The Moroccan Atlas Mountains represent a prime example of an intracontinental mountain belt hosting extensive and highly developed karst systems within thick Mesozoic carbonate platforms. These systems play a strategic hydrological role by regulating major river basins such as the Oum Er-Rbia and Moulouya and by sustaining agricultural production and urban water supply [3].

From a scientific perspective, the Atlas Mountains occupy a key climatic transition zone between North Atlantic and Saharan influences, making their paleoenvironmental archives fundamental for understanding regional climate dynamics, including African Humid Periods [4]. Despite an increasing number of localized studies addressing hydrogeology, geomorphology, and paleoclimate, a comprehensive synthesis positioning Atlas karst system within a global comparative framework remains lacking.

Most existing investigations focus on individual massifs or thematic approaches, leaving unresolved a fundamental question: does the Atlas karst merely represent a regional Mediterranean variant or does the interaction between active tectonics and strong arid-to-humid climatic gradients generate a distinct karst system type?

This review argues that systematic comparison with established global analogues such as the temperate folded Jura karst and the classical holokarst of the Dinarides is necessary to define a specific “Atlas Karst Model.”

2. Objectives and Methodology

The primary objective of this review is to address the following question:

To achieve this objective, the study aims to accomplish the following:

1. Provide a critical synthesis of current knowledge regarding the geology, geomorphology, hydrogeology, and paleo-environmental evolution of Moroccan Atlas karst systems;
2. Conduct a rigorous comparative analysis between the Atlas system and major global karst analogues (Jura, Dinarides, South China) using a tectono-climatic analytical framework;
3. Propose an integrated conceptual model for Atlas karst evolution and define priority directions for future research.

The review is based on a systematic literature survey conducted through Scopus, Web of Science, and Google Scholar databases. These comparative regions were selected as reference end-member models:

- The Jura Mountains (temperate folded karst);
- The Dinarides (Mediterranean holokarst);
- South China karst (tropical karst system).

3. Moroccan Atlas Karst: State-of-the-Art Synthesis

3.1. Geological and Tectonic Framework

Karstifiable formations of the Moroccan Atlas (Figure 1) are predominantly hosted within extensive Jurassic carbonate successions, particularly Liassic limestones forming the structural backbone of the High and Middle Atlas [5]. Mountain building resulted

from Cenozoic intracontinental orogenesis related to convergence between the African and Eurasian plates.

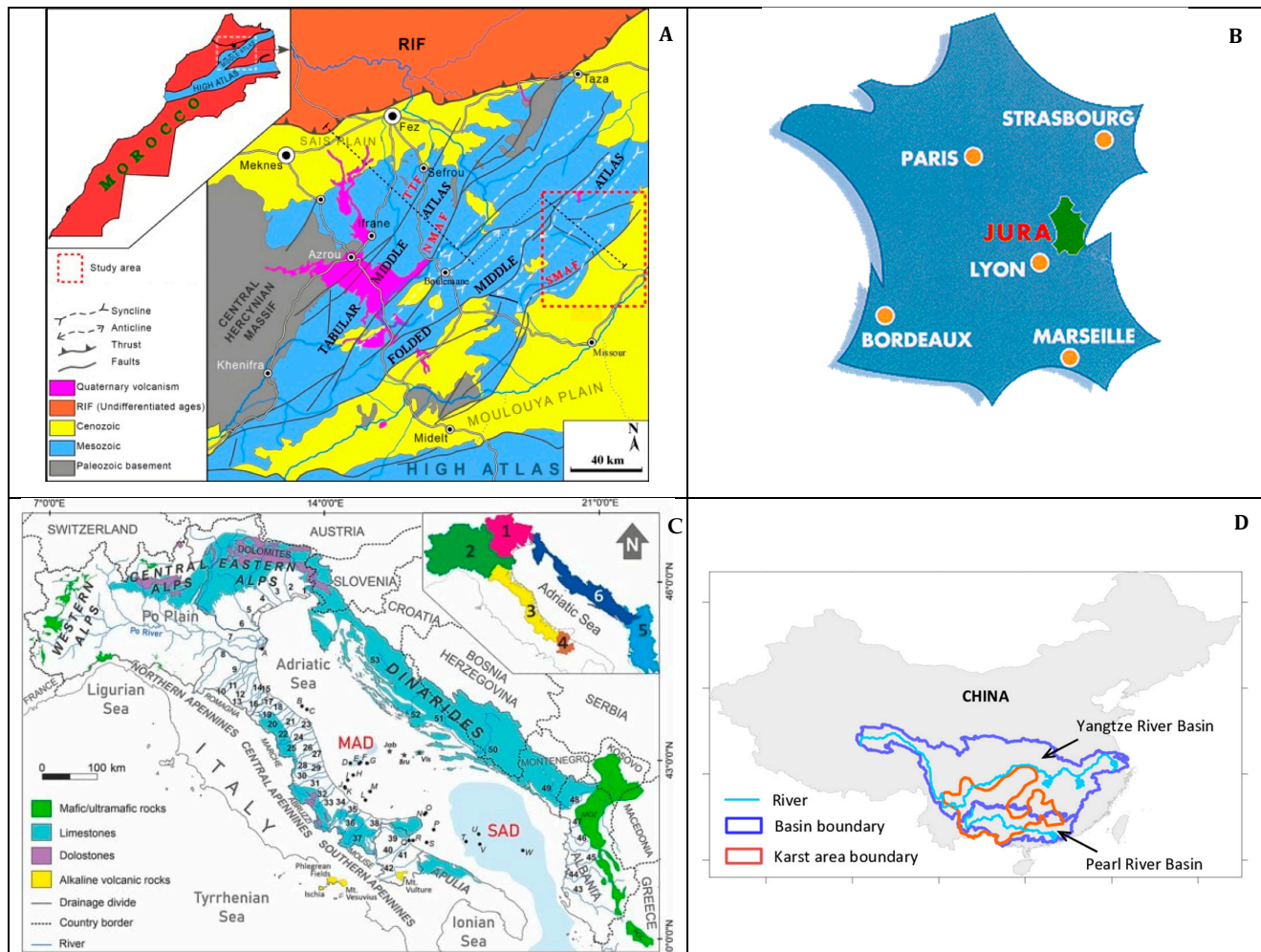


Figure 1. Geographic location of the study area and comparison regions. (A) Morocco showing the Atlas Mountains and the study area; (B) Jura Mountains (France) [6]; (C) Dinarides (Croatia–Slovenia) [7]; (D) South China karst [8].

This tectonic context generates several key characteristics, listed as follows:

- Persistent tectonic activity involving uplift and seismic deformation;
- Maintenance of steep hydraulic gradients;
- Continuous landscape rejuvenation;
- And enhanced secondary permeability through faulting and fracturing [6].

Large-scale folding and major thrust structures, notably the South Atlas Front, exert strong structural control on karst aquifer geometry and regional drainage organization.

3.2. Climatic and Paleoclimatic Context

The modern Atlas climate exhibits a pronounced NW–SE gradient ranging from sub-humid Mediterranean conditions (>800 mm/year) to semi-arid and arid environments (<300 mm/year). This gradient directly controls present-day karstification intensity.

However, Quaternary climatic oscillations played an even more decisive role in large-scale karst development. High-resolution speleothem records demonstrate recurrent African Humid Periods characterized by significantly wetter conditions than today, promoting intense carbonate dissolution and speleogenesis [4].

Alternation between humid and prolonged arid phases produced a polygenetic karst landscape, where active processes overprint relict morphologies inherited from contrasting paleoclimatic regimes. Speleothem archives further reveal strongly nonlinear responses to orbital forcing, highlighting regional sensitivity to climatic thresholds [9].

3.3. Characteristic Geomorphology

Atlas karst geomorphology reflects polygenetic evolution (Figure 2). Exokarst landscapes include inherited doline fields, structurally controlled sharp lapiaz, and deeply incised gorges linked to tectonic uplift [10]. Endokarst development is characterized by multi-level cave systems structurally guided by tectonic discontinuities, where speleothem growth episodically records favorable climatic phases [4].

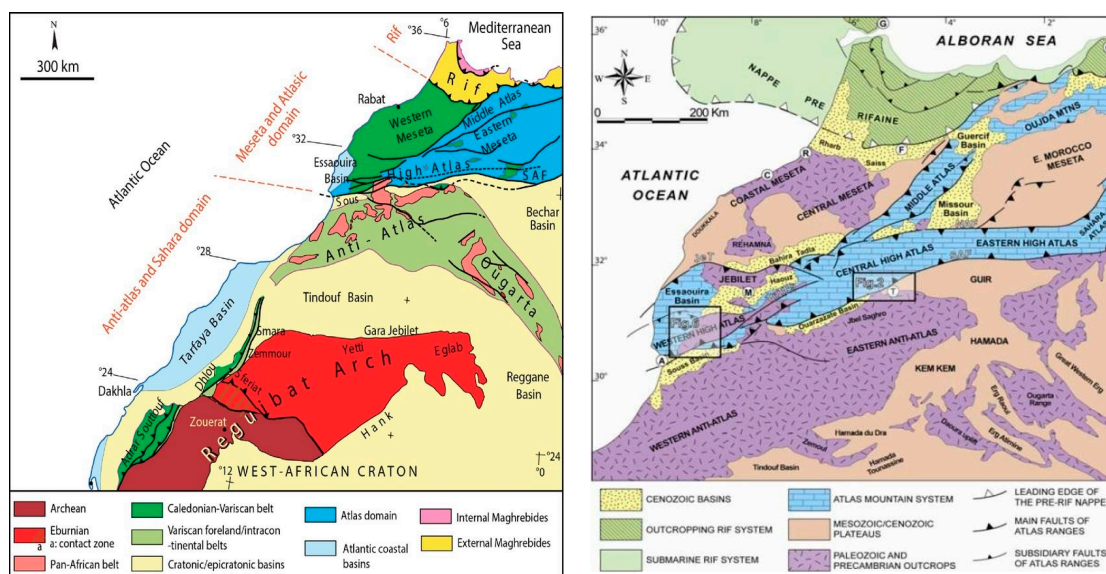


Figure 2. Simplified geological and structural map of the Atlas Mountains illustrating the main carbonate outcrops and major tectonic structures.

3.4. Hydrogeology

Atlas hydrogeology is controlled by dual recharge mechanisms involving rainfall and snowmelt, resulting in strong seasonal and interannual variability. Large Middle Atlas aquifers contrast with more compartmentalized High Atlas systems.

A central issue concerns the contribution of fossil groundwater, inherited from paleo-recharge during humid periods, raising critical questions regarding long-term resource sustainability [11].

4. Moroccan Atlas Karst: State-of-the-Art Synthesis

4.1. Tectonic Control on Karst Architecture

The Atlas karst represents a hybrid tectonic model. While sharing folded structural organization with the Jura [12], ongoing uplift and active deformation resemble younger mountain belts such as the Dinarides. Nevertheless, nappe-scale tectonics remain less developed, resulting in comparatively smaller aquifer systems [13].

4.2. Climatic Imprint on Karst Processes

The defining climatic signature of the Atlas is pulsed karstification, alternating between arid phases—during which dissolution nearly ceases—and intensely humid episodes activating rapid karst development.

This contrasts with the following:

- Continuous dissolution under humid temperate Jura climates [14];
- Extreme tropical dissolution rates producing tower karst landscapes in South China [15], absent in the Atlas region.

4.3. *Speleothem Records as Paleoclimate Archives*

Atlas speleothems function as threshold recorders, displaying discontinuous growth interrupted by arid-period hiatuses [4]. This differs markedly from the more continuous climatic archives observed in temperate Jura [16] and tropical Chinese karsts [17], making Atlas karst uniquely sensitive to North African aridity dynamics.

4.4. *Hydrosystem Typology*

Atlas karst hydrosystems are characterized by hydrological fragility, marked by highly variable recharge and dependence on inherited groundwater reserves. In contrast, Jura and Dinaric systems benefit from abundant renewable recharge, although they exhibit greater pollution vulnerability due to rapid flow transfer (Table 1) [13].

Table 1. Tectonic, climatic, hydrogeological, and sedimentary characteristics of the Atlas karst system compared with major global karst analogues (Jura Mountains, Dinarides, and South China).

Parameter	Atlas Mountains	Jura Mountains	Dinarides	South China
Tectonic Setting	Hybrid tectonic model	Folded structural belt	Rapid tectonic uplift	Stable platform with long-term karst evolution
Climatic Context	Alternation between arid phases (near cessation of karst processes) and very humid periods	Humid temperate climate	Mediterranean humid climate	Tropical climate
Aquifer Architecture	Hydrologically fragile system with limited and variable recharge	Abundant and largely renewable recharge	Abundant and largely renewable recharge	Highly developed and continuously recharged systems
Sedimentary Record (Speleothems)	Threshold-controlled archives with discontinuous growth	More continuous sedimentary records	Relatively continuous records	Tropical-type continuous records

5. Discussion: Toward a Unified Atlas Karst Model

5.1. *Atlas Specificity: A Hybrid Karst Under Dual Control*

Comparative analysis demonstrates that Atlas karst constitutes a unique hybrid system governed by the interaction between fold tectonics, active uplift, and a pulsed climatic regime oscillating around an aridity threshold. This synergy produces a highly sensitive polygenetic karst system.

5.2. *Universal Principles and Regional Contingencies*

The Atlas example confirms universal geomorphological principles, including tectonic uplift as a primary driver of incision and the palimpsest nature of karst landscapes. It also highlights the dominant role of climatic thresholds in activating or suppressing karst processes.

5.3. *Implications for Sustainable Management and Risk Assessment*

Recognition of this model has direct implications for water-resource management, requiring integration of non-renewable groundwater storage concepts. It is equally critical

for assessing natural hazards such as seismic activity and karst collapse while supporting the valorization of a unique geoheritage system.

6. Conclusions

The Moroccan Atlas karst represents a distinctive mountain karst system shaped by the combined influence of tectonic activity and climatic variability. Unlike the more continuous karst development observed in humid regions such as the Jura, the Dinarides, or South China, karstification in the Atlas has evolved in a discontinuous manner, controlled by alternating humid and arid phases. This has produced a complex and heterogeneous karst landscape, with direct implications for aquifer functioning and water availability.

Beyond its regional significance, the Atlas provides an important example of karst evolution in a semi-arid tectonically active setting. Understanding this interaction is essential not only for improving karst science but also for supporting sustainable groundwater management in the context of ongoing climate change.

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References

1. Viviroli, D.; Kummu, M.; Meybeck, M.; Kallio, M.; Wada, Y. A global-scale assessment of mountain systems and their water resources. *Nature* **2020**, *586*, 742–747.
2. Fairchild, I.J.; Baker, A. *Speleothem Science: From Process to Past Environments*; John Wiley & Sons: Hoboken, NJ, USA, 2012.
3. Howell, B.A.; Fryar, A.E.; Benaabidate, L.; Bouchaou, L.; Farhaoui, M. Variable responses of karst springs to recharge in the Middle Atlas region of Morocco. *Hydrogeol. J.* **2019**, *27*, 1693–1710. [CrossRef]
4. Ait Brahim, Y.; Wassenburg, J.A.; Sha, L.; Cruz, F.W., Sr.; Deininger, M.; Sifeddine, A.; Cheng, H. North Atlantic ice-rafting and implications on the Western Mediterranean climate: A perspective from speleothem records. In Proceedings of the AGU Fall Meeting, San Francisco, CA, USA, 9–13 December 2019.
5. Frizon de Lamotte, D.; Michard, A.; Saddiqi, O. The geology of Morocco: A synthesis. In *Continental Evolution: The Geology of Morocco*; Michard, A., Saddiqi, O., Chalouan, A., de Lamotte, D.F., Eds.; Springer: Berlin/Heidelberg, Germany, 2008; pp. 315–401.
6. Gibout, L. LE JURA. Available online: <http://laetitiagibout.chez.com/Jura.htm> (accessed on 5 January 2026).
7. Amorosi, A.; Sammartino, I.; Dinelli, E.; Campo, B.; Guercia, T.; Trincardi, F.; Pellegrini, C. Provenance and sediment dispersal in the Po-Adriatic source-to-sink system unraveled by bulk-sediment geochemistry and its linkage to catchment geology. *Earth-Sci. Rev.* **2022**, *234*, 104202. [CrossRef]
8. Yao, C.; Luo, Z. Karstic water storage response to the recent droughts in Southwest China estimated from satellite gravimetry. In Proceedings of the International Conference on Intelligent Earth Observing and Applications, Guilin, China, 23–24 October 2015; pp. 334–339.

9. Sha, L.; Ait Brahim, Y.; Wassenburg, J.A.; Yin, J.; Peros, M.; Cruz, F.W.; Cai, Y.; Li, H.; Du, W.; Zhang, H.; et al. How far north did the African Monsoon fringe expand during the African Humid Period? Insights from Southwest Moroccan speleothems. *Geophys. Res. Lett.* **2019**, *46*, 14093–14102. [[CrossRef](#)]
10. Ballesteros, D.; Pérez-Mejías, C.; Moreno, D.; Moreno-Sánchez, M.; Reyes-Carmona, C.; Alfonso-Jorde, D.; Azañón, J.M.; Booth-Rea, G.; Torre, D.; Jerez-Longres, P.S.; et al. Unveiling the potential of karst vadose deposits in constraining Quaternary tectonic subsidence. *Earth Surf. Process. Landf.* **2024**, *49*, 3437–3455. [[CrossRef](#)]
11. Bakalowicz, M. Karst groundwater: A challenge for new resources. *Environ. Earth Sci.* **2015**, *74*, 517–529. [[CrossRef](#)]
12. Király, L. Karstification and groundwater flow. *Speleogenes. Evol. Karst Aquifers* **2003**, *1*, 1–13.
13. Stevanović, Z. *Karst Aquifers of the Dinaric Chain*; Springer: Berlin/Heidelberg, Germany, 2015.
14. De Waele, J.; Plan, L.; Audra, P. Recent developments in surface and subsurface karst geomorphology: An introduction. *Geomorphol.* **2009**, *106*, 1–8. [[CrossRef](#)]
15. Zhang, C.; Qi, X.; Wang, K.; Zhang, M.; Yue, Y. The application of geospatial techniques in monitoring karst vegetation recovery in southwest China: A review. *Prog. Phys. Geogr.* **2017**, *41*, 450–477. [[CrossRef](#)]
16. Genty, D.; Blamart, D.; Ouahdi, R.; Gilmour, M.; Baker, A.; Jouzel, J.; Van-Exter, S. Precise dating of Dansgaard–Oeschger climate oscillations in western Europe from stalagmite data. *Nature* **2003**, *421*, 833–837. [[CrossRef](#)]
17. Wang, Y.J.; Cheng, H.; Edwards, R.L.; An, Z.S.; Wu, J.Y.; Shen, C.C.; Dorale, J.A. A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China. *Science* **2001**, *294*, 2345–2348. [[CrossRef](#)]

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