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INTEGRATION OF REGIONAL AND GLOBAL QUATERNARY DATA: A COMPREHENSIVE REVIEW TO ENHANCE UNDERSTANDING AND STRATEGIC PLANNING OF ENVIRONMENTAL FUTURES, CASE OF MOROCCO

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Abstract:
The Quaternary, a period spanning the last 2.58 million years, is crucial for understanding the climatic and environmental dynamics that have shaped the modern planet. This article explores how data specific to Morocco fit into the global context of Quaternary studies, drawing parallels between local and global information to reveal significant trends and features. By examining paleoclimatic, geomorphological, archaeological and palaeobotanical data, the analysis highlights similarities and differences between local and global observations. The results show that Moroccan data, although reflecting global trends, present specificities that enrich the understanding of climatic and environmental processes at the regional level. This integration not only makes it possible to complete global models but also to identify the local impacts of climate change, thus offering a more nuanced view of Quaternary dynamics and the challenges posed by current climate change.

Key words: Morocco; geomorphological data; archaeological data; palaeobotanical data; climate change.

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INTRODUCTION

The research was carried out in different regions of Morocco, including the Atlas Mountains, coastal plains, and Sahara deserts. Specific case studies included the analysis of sediments from Lakes Tislit and Ifni. The Quaternary, which covers the last 2.58 million years of Earth's history, is a pivotal period for understanding the climatic, environmental and biological developments that have shaped the modern planet. This period is marked by major climatic fluctuations, including glacial and interglacial periods, which have had profound im-pacts on ecosystems and human societies. The study of the Quaternary offers a unique perspective on the Earth's response to climatic variations and allows us to understand the processes that led to the current configuration of natural environments (Ehlers *et al.*, 2011; Campbell *et al.*, 2017; Kchikach *et al.*, 2024).

Morocco, with its diverse landscapes ranging from the Atlas Mountains to the coastal plains and the Sahara deserts, constitutes an exceptional study site for examining the impacts of the Quaternary. This geographic diversity generates a wealth of paleoclimatic, geomorphological, and archaeological data that provide valuable insights into environmental and human responses to past climate change (Burke *et al.*, 2021; Travelers, 2023).

Research on the Quaternary in Morocco has revealed interesting aspects which complement and enrich the global data. Lake sediments, alluvial deposits, and archaeological remains offer insights into local climatic variations and human adaptations to these changes (Burke *et al.*, 2021). For example, variations in Moroccan lake water levels and changes in vegetation reveal regional climate cycles that are often correlated with major global climate cycles (Rincón-Martínez *et al.*, 2010).

Global paleoclimatic studies, based on ice cores and marine sediments, have demonstrated significant oscilla-

tions in CO_2 concentrations and sea levels, providing a framework for understanding regional and local climate (Masson-Delmotte *et al.*, 2013). The integration of data specific to Morocco in this global context is essential to obtain a complete view of climatic and environmental dynamics during the Quaternary.

This analysis aims to explore how data from Morocco fit into the global framework of Quaternary studies by examining paleoclimatic, geomorphological, archaeological and palaeobotanical aspects. We will highlight similarities and differences between local and global observations, identifying the unique contributions and limitations of regional studies (Rousseau *et al.*, 2008; Raynal *et al.*, 2010; Charif *et al.*, 2014).

MOTIVATION OF THE STUDY

This study, on the integration of Quaternary data in Morocco, highlights the importance of combining regional and global perspectives for a more complete understanding of climatic and environmental dynamics. Although challenges exist, particularly in terms of regional variability and methodological uncertainties, the integration of local data enriches global models and provides valuable insights to anticipate the future impacts of climate change. Recommendations include improving analytical methods and an integrated multidisciplinary approach to overcome challenges and optimize understanding of interactions between global and regional climate drivers. The study of the integration of regional and global data from the Quaternary, with particular attention to the case of Morocco, is motivated by several essential reasons.

The Quaternary represents a key period for understanding the major climate changes that have shaped the current terrestrial environment. By integrating specific regional data from Morocco with those from global studies, we can obtain a more detailed view of climate variations and environmental processes at a local scale, thus enriching our understanding of global climate dynamics.

Morocco, with its diverse landscapes and varied environments (mountains, coastal plains, deserts), offers a unique study area to observe the local impacts of climate change during the Quaternary. The analysis of these local data makes it possible to better understand regional particularities and to complete global models.

Studying past responses to climate change provides valuable insights for understanding how local environments will respond to contemporary climate change. By examining how ecosystems and human societies have historically responded to climate variations, this research can help anticipate future impacts and formulate adaptation strategies.

By integrating data specific to Morocco, this study contributes to the enrichment of global climate models by adding crucial regional de-tails. Local particularities make it possible to refine climate projections and better understand regional variations and processes.

PROBLEMATIC

One of the main problems lies in the regional variability of the data. Differences in geomorphological, ecological and archaeological responses in Morocco can complicate direct comparison with global data. This variability can be attributed to local factors such as topography, atmospheric currents, and specific ecological conditions, which influence the observed processes. Discrepancies between regional and aggregate data may reflect methodological limitations or differences in analysis techniques. Local and global studies sometimes use different methods and scales of observation, which can lead to inconsistencies in results and complicate data integration.

The correlation between global climate trends and regional responses is often complex. Local data shows specific responses that are not always aligned with global trends due to factors unique to each region. This requires a more nuanced approach to understanding how global and local processes interact.

Another difficulty is the availability and quality of regional data. Palaeoclimatic, geomorphological, archaeological and palaeobotanical data may not be uniformly available or comparable, which may limit the scope of integrated analyses. Global climate models must be adapted to integrate local specificities. This requires not only a better understanding of regional variations but also a multidisciplinary collaboration to refine models, taking into account local data.

METHODOLOGY

This study is based on a comparative analysis of palaeoclimatic, geomorphological, archaeological and palaeobotanical data from both local and global sources. Local data comes from studies of lake sediments, geomorphological formations, archaeological sites and palaeobotanical remains in Morocco. Global data includes records from ice cores and marine sediments, as well as global climate models.

Paleoclimatic data

The analysis of ice core and marine sediment records aims to determine global variations in CO_2 and sea levels. These data provide insights into large-scale climatic fluctuations, allowing researchers to reconstruct past climatic conditions and understand the global impacts of climatic changes.

Geomorphological data

The study of geomorphological processes in Morocco, such as erosion and alluvial deposits, helps to understand how landscapes have been shaped by past climatic and environmental conditions. This analysis aids in reconstructing the evolution of terrain and geological formations in response to climatic variations over the centuries.

Archaeological data

The examination of human adaptations in response to climatic variations across Moroccan archaeological sites offers perspectives on how ancient societies reacted to environmental changes. This analysis provides clues about adaptation strategies and the impacts of climatic changes on the life styles and cultures of past populations.

Palaeobotanical data

The analysis of changes in flora and fauna in Morocco in relation to global climatic fluctuations helps trace modifications in plant and animal ecosystems over time. By examining palaeobotanical remains, researchers can establish connections between global climatic variations and local biodiversity changes.

By combining these diverse sources of data, the study aims to provide an integrated overview of the complex interactions between global climatic factors and local responses in Morocco. This comparative approach enhances the understanding of past environmental dynamics and provides crucial information for modeling future climatic and environmental changes.

ANALYSIS AND DISCUSSION

Paleoclimate data

The sediment records from Lakes Tislit and Ifni in Morocco are the examples that highlight specific cycles of humidity and drought. These cycles are influenced by local topographic and atmospheric conditions. During global interglacial periods, these lakes show heightened humidity, while glacial periods correlate with drought phases. These regional specifics align with global trends, but are shaped by Morocco's unique geography.

Global studies of the Quaternary rely on ice cores and marine sediments, providing detailed records of global climate conditions. Antarctic ice cores show oscillations in CO_2 concentrations, between approximately 180 ppm during glacial periods and 280 ppm during interglacials (Petit and Jouzel, 1999). Marine sediments indicate variations in sea levels and global temperatures (Houghton *et al.*, 2022).

Lake sediments in Morocco reveal significant regional climatic variations. For example, periods of increased humidity are correlated with global interglacial phases, while phases of drought are associated with global glacial periods (Rhoujjati *et al.*, 2010). Lake data from Lake Tislit and Lake Ifni show specific regional effects, such as a period of high humidity during the interglacial and dry phases during glaciations (Wanaim *et al.*, 2021).

Moroccan data show similar trends to global data, but with notable local specificities. Regional climatic variations in Morocco, such as more pronounced droughts, are influenced by global changes but also by local factors such as topography and atmospheric currents (Charif *et al.*, 2014; Wanaim *et al.*, 2021).

Geomorphological analysis

In Morocco, the Atlas Mountains experience distinct erosion patterns linked to prolonged droughts. This erosion results in alluvial deposits that reflect unique local hydrological variations. Such features differ from global geomorphological records due to Morocco's diverse topography, which modifies these processes regionally, enriching the global perspective on erosion and deposition.

Global geomorphological processes, such as glacial erosion and moraine deposition, are well documented. Glaciations sculpted landscapes with U-shaped valleys and moraines (Waitt, 1985). Deglaciation led to rapid changes in deposition and erosion regimes, observed particularly in North America (Barnosky, *et al.*, 1987; Carrivick and Tweed, 2021).

In Morocco, geomorphological processes are influenced by the diversity of environments. Periods of intense erosion in the Atlas Mountains are often associated with prolonged droughts (Parish and Funnell, 1999). Alluvial deposit formations and geomorphological processes reveal significant variations that do not always align with lacustrine paleoclimatic records due to differences in spatial and temporal scales (Peña-Monné *et al.*, 2022).

Moroccan geomorphological observations show responses to global climatic cycles, but with local particularities. The differences are due to topographic and hydrological variability which modifies the geomorphological processes observed globally (Lebamba *et al.*, 2009).

Archaeology and paleoanthropology

At the archaeological site of Jebel Irhoud, the Moroccan societies adapted to regional climatic changes by altering their tools and subsistence strategies. During periods of drought, specific adaptations such as changes in tool designs were made to cope with local environmental stressors, mirroring global trends but with distinct local innovations.

Global archaeological studies indicate that human societies developed technologies and lifestyles adapted to climatic variations. Human migrations, changes in lithic tools, and subsistence strategies are documented in response to glacial cycles (Mellars, 2006; Hudson *et al.*, 2012). Cultural adaptations are particularly notable in Europe, with innovations such as the evolution of hunting tools and strategies (Richter *et al.*, 2017).

Moroccan archaeological sites, such as those of Jebel Irhoud, show adaptations in lifestyles and technologies in response to climatic variations. Moroccan societies have modified their subsistence tools and strategies during periods of drought or humidity (Jeffrey, 2016). These adaptations reflect local responses to global climate change. The cultural adaptations observed in Morocco are consistent

Table 1. Comparative analysis of Quaternary climate and geomorphological data: global and regional perspectives in Morocco.

Section	Aspect	Global	In Morocco	Correlation
Paleoclimate data	Global data	Ice cores and marine sediments provide records of global climate; CO_2 variations between 180 ppm (glacial) and 280 ppm (interglacial)	Lake sediments show humidity and drought phases; data from Lake Tislit and Lake Ifni highlight specific regional effects	Moroccan data align with global trends but have local specifics influenced by topography and atmospheric currents
	Regional data	Variations in sea levels and temperatures observed globally	Increased humidity during interglacial and dry phases during glaciations	Regional trends in Morocco show similarities to global patterns with notable local variations
Geomorphological analysis	Global processes	Glacial erosion and moraine deposition; U-shaped valleys and rapid changes in deposition/erosion	Intense erosion in Atlas Mountains linked to droughts; alluvial deposits show significant local variations	Global geomorphological responses are evident but modified by local topo-graphic and hydrological factors
	Local processes		Geomorphological processes differ from lacustrine records due to spatial and temporal variations	Local processes in Morocco reflect global climatic cycles but with unique regional characteristics
Archaeology and palaeoanthropology	Global adaptations	Human societies adapted technologies and lifestyles to climatic variations; migrations and tool changes documented	Adaptations in Moroccan sites like Jebel Irhoud reflect local responses to climatic variations	Moroccan adaptations align with global trends but include unique local responses influenced by regional contexts
	Cultural changes	Innovations in Europe in response to climatic cycles	Tool and subsistence strategy modifications during droughts or humidity phases	Global cultural trends are mirrored in Morocco with specific local adaptations
Palaeobotany and palaeozoology	Global records	Changes in flora and fauna with species extinctions and migrations; notable changes in Europe and North America	Significant ecosystem changes in Moroccan Sa-hara; documented vegetation and desertification phases	Moroccan ecological changes align with global trends but show unique local responses, including endemic species
	Local records		Variations in plant and animal species composition reflect local ecological responses	Local ecological dynamics in Morocco provide additional details on global climatic influences

with global trends, but local specificities reveal unique cultural responses to local climatic conditions. Variations in technologies and lifestyles are influenced by regional contexts and available resources (Spaargaren and Van Vliet, 2000).

Palaeobotany and palaeozoology

Studies of the Moroccan Sahara reveal phases of dense vegetation and desertification influenced by local conditions. Endemic species show unique responses, such as resilience during desertification, which adds complexity to global records. This local biodiversity response offers a specific perspective on the effects of Quaternary climate changes.

Global palaeobotanical and palaeozoological records show changes in flora and fauna in response to climatic cycles. Species extinctions and migrations are well documented (DiMichele *et al.*, 2008). Changes in forests and faunas during glacial cycles are notable in Europe and North America (Davis, 1983; Prentice *et al.*, 2000).

Studies of plant and animal remains in the Moroccan Sahara reveal significant changes in ecosystems in response to climatic variations. Periods of dense vegetation and phases of desertification are well documented (McGregor *et al.*, 2009). Changes in plant and animal species composition show specific ecological responses, but regional particularities, such as the response of endemic species, some-times complicate direct correlation (Gasse, 2000). Ecological changes in Morocco are consistent with global trends, but regional specificities add important details about local ecological responses. Endemic species and variations in biodiversity reflect ecological dynamics influenced by global climatic conditions but modified by local factors (Saltré *et al.*, 2013).

The Table 1 summarizes a comparative analysis of Quaternary climate and geomorphological data, highlighting both global trends and regional specifics observed in Morocco. This table provides an overview of the similarities and differences between global data and those specific to Morocco, exploring the interactions between climate changes, geomorphological processes, and human and ecological adaptations.

CRITICAL ANALYSIS

This comparative study of palaeoclimatic, geomorphological, archaeological, and palaeobotanical data reveals both positive aspects and significant challenges in understanding the interactions between global trends and local specifics in Morocco.

Positive Points

The Moroccan data show significant conformity with global trends in climate and geomorphological changes. This alignment enriches our understanding of global processes by illustrating how universal climatic trends manifest on a local scale. For instance, variations in global CO_2 levels and temperatures observed in ice cores are echoed in changes detected in lake sediments in Morocco, highlighting the coherence of climatic processes across different scales.

Local studies provide precise regional data that are crucial details on impacts specific to Moroccan environments, offering a complementary perspective to global observations. These insights help refine global climate models by incorporating regional specifics, such as local variations in alluvial deposits or human adaptations to climatic changes. For example, analyzing palaeobotanical remains can reveal specific ecological responses not immediately apparent in global datasets.

Negative Points

Differences in geomorphological responses and cultural adaptations in Morocco complicate direct comparisons of regional variability with global data. Local variations, such as differences in ecological responses to climatic changes or specific human adaptations to Moroccan conditions, reflect the complexity of interactions between global and regional factors. This variability underscores the need to consider a local context for a more accurate interpretation of global data.

Methodological uncertainties caused by variations in analytic techniques and observation scales can lead to discrepancies in results. Contradictions between data may reflect methodological limitations or differences in geographic and temporal contexts studied. For example, methods used to analyze lake sediments may differ from those employed for ice cores, leading to divergences in interpretations. It is crucial to acknowledge these limitations and work towards harmonizing methodologies to reduce uncertainties.

Table 2. Comparative analysis of Quaternary palaeoclimatic and archaeological data in Morocco: insights, challenges, and methodological considerations

Category	Positive points	Negative points	Interpretation
Conformity to global trends	Moroccan data show significant conformity with global trends in climate and geomorphology, enriching our understanding of how universal processes manifest locally. Example: CO_2 levels and temperature variations observed in ice cores are reflected in Moroccan lake sediments.		
Precise regional data	Local studies provide crucial details on Moroccan-specific impacts, offering a complementary perspective to global observations. These insights help refine global climate models by incorporating regional specifics like local alluvial deposits or human adaptations to climatic changes. Example: Analyzing palaeobotanical remains can reveal specific ecological responses not im-mediately apparent in global datasets.		
Regional variability		Differences in geomorphological responses and cultural adaptations in Morocco complicate direct comparisons with global data. Local variations, such as differences in ecological responses to climatic changes or specific human adaptations to Moroccan conditions, reflect the complexity of interactions between global and regional factors.	Integrate local and global data to enhance understanding of interactions. Develop hybrid models that incorporate local variations into global climate forecasts for more accurate predictions.
Methodological uncertainties		Variations in analysis techniques and observation scales can lead to discrepancies in results. Contradictions between data may reflect methodological limitations or differences in geographic and temporal contexts studied. Example: Methods used to analyze lake sediments may differ from those employed for ice cores, leading to divergences in interpretations.	Standardize analysis methods to reduce un-certainties. Ensure consistency across studies to facilitate comparison of results and enable more reliable interpretation of data while accounting for specific geographic and temporal contexts.

Interpretation

To enhance the understanding of interactions between global trends and local specifics, it is recommended to develop integrated approaches that combine local and global data. This could include creating hybrid models that incorporate local variations into global climate forecasts, thus providing more accurate and context-specific predictions.

Continuing detailed regional studies is essential for better understanding local specifics and their impact on global climatic responses. Increasing the number and diversity of local studies will help capture the nuances of interactions between global and regional factors.

To reduce methodological uncertainties, it is advisable to standardize analysis techniques and ensure consistency in methods across different studies. This will facilitate the comparison of results and enable more reliable interpretation of data while accounting for specific geographic and temporal contexts.

By adopting these suggestions, we can improve the accuracy and relevance of the conclusions drawn from the comparative analysis of local and global data, thereby enriching our understanding of complex environmental dynamics. To provide a clear overview of the comparative study of Quaternary palaeoclimatic and archaeological data in Morocco, the Table 2 summarizes the identified positive and negative points along with their corresponding interpretations.

INTEGRATED STRATEGIES FOR MOROCCO'S ENVIRONMENTAL FUTURE: TOWARDS SUSTAINABLE AND INFORMED CLIMATE CHANGE MANAGEMENT

To ensure a robust and informed approach to managing Morocco's environmental future, it is essential to integrate a range of strategies that address both local and global perspectives. One key step is to standardize analytical methods across studies. Implementing uniform protocols for data collection and analysis ensures that information from various regions and scales can be accurately compared and integrated. This minimizes the risk of errors and enhances the reliability of data used to evaluate environmental and climatic changes.

An integrated approach that fosters collaboration among experts from diverse fields, such as climatology, geography, environmental sciences and anthropology – is crucial. This multidisciplinary cooperation provides a more comprehensive under-standing of the complex interactions between local and global data. By combining in-sights from climatological data with those from geomorphology and archaeology, we can better understand how historical climate changes have influenced human societies and landscape formation.

Conducting detailed regional studies is vital for refining global climate models. Exploring the specific climatic and environmental characteristics of Moroccan regions allows researchers to provide valuable data that improves the accuracy of global climate predictions. These studies reveal local climate patterns, ecological responses, and human adaptations that broader global models might miss, leading to more targeted and effective adaptation strategies.

Evaluating the impact of contemporary climate changes on Morocco's environmental dynamics is essential. Com_ paring current climatic trends with historical data from the Quaternary period helps assess how modern changes affect regional environments. Such analysis can uncover trends and anomalies in vegetation, soil composition, and erosion rates, offering valuable insights into the impacts of current climate changes.

Integrating contemporary climate impact data with historical records enhances our ability to forecast future trends and adjust strategies accordingly. Understanding past climates and their effects on environmental and human systems allows for better anticipation of current climate trends' potential consequences. This approach aids in refining climate models and developing resilient environmental and social systems to handle future climate variations.

Strengthening local research and environmental management capacities is crucial. Training local researchers and supporting sustainable management initiatives ensure that local knowledge is incorporated into development and conservation strategies. This approach leads to a better understanding of regional environments and more effective resource management.

The utilization of advanced technologies, such as Geographic Information Systems (GIS), environmental sensors and remote sensing tools, is essential for improving data collection and monitoring environmental changes. These technologies provide precise analysis and facilitate effective management of natural resources, enabling timely and adaptive responses to environmental shifts.

Engaging local communities in research and conservation efforts is fundamental. Community involvement offers unique perspectives on environmental changes and their impacts, promoting solutions tailored to local needs. Furthermore, community engagement ensures greater acceptance and successful implementation of environ-mental strategies.

Supporting and promoting environmental policies that are informed by scientific data is crucial for effective resource management. Policies based on reliable, up-to-date data enhance resource management and build resilience to climate change.

Conducting future scenario studies helps explore various potential trajectories based on climatic and environmental variables. These studies aid in anticipating the impacts of future changes and developing action plans to address them.

Finally, promoting international collaborative research enriches local studies with diverse perspectives and methodologies. This exchange of knowledge fosters best practices and contributes to a comprehensive and accurate understanding of environ-mental challenges.

By integrating these measures, a holistic and coordinated approach can be achieved to manage environmental

Table 3. Proposed strategies for managing Morocco's environmental future

Strategy	Description
Standardize analytical methods	Implement uniform protocols for data collection and analysis to ensure comparability and reliability
Foster multidisciplinary collaboration	Encourage cooperation among experts from various fields for a comprehensive understanding of local and global interactions
Conduct detailed regional studies	Perform specific studies to refine global climate models and provide valuable local data
Evaluate contemporary climate changes	Compare current climatic trends with historical data to assess the impact of modern changes on regional environments
Integrate historical and contemporary data	Combine past and present climate data to forecast future trends and adjust strategies accordingly
Strengthen local capacities	Train local researchers and support sustainable management initiatives to better understand and manage regional environments
Utilize advanced technologies	Use tools like GIS and environmental sensors to improve data collection and monitoring of environmental changes
Engage local communities	Involve local communities to gain unique perspectives and ensure the acceptance and effectiveness of environmental strategies
Support data-informed policies	Promote environmental policies based on reliable scientific data for better resource management and climate resilience
Conduct future scenario studies	Explore potential future trajectories to anticipate impacts and develop action plans
Promote international collaborative research	Encourage international collaboration to enrich local studies with diverse perspectives and methodologies

challenges in Morocco, enhance climate models, and develop effective strategies for adaptation and resource management. The Table 3 summarizes the key strategies for managing Morocco's environmental future.

CONCLUSIONS

The in-depth study of Quaternary data in Morocco reveals significant connections with global climate and environmental trends, while highlighting regional particularities that enrich our global understanding. By integrating palaeoclimatic, geomorphological, archaeological and palaeobotanical data, this article demonstrates that Morocco, with its geographic diversity, offers valuable insight into the local impacts of global climate change. Variations in lake water levels, distinctive geomorphological processes, as well as local archaeological and ecological adaptations illustrate how environmental responses in Morocco align with, but also diverge from global trends.

Data specific to Morocco, while reflecting major global climate cycles, show complex responses influenced by local factors such as topography, atmospheric currents and regional ecological conditions. These observations provide a better understanding of the nuances of climatic and environmental processes that cannot be understood solely from global data. For example, periods of prolonged drought observed in the Atlas Mountains and phases of desertification in the Moroccan Sahara reveal unique regional dynamics that complement trends observed on a global scale.

Additionally, integrating local data with global records provides a more comprehensive perspective on the historical impacts of climate change, highlighting specific ecological responses and cultural adaptations at the regional level. This integrated approach is crucial for future modeling of climate impacts, as it allows capturing not only general trends but also local variations that can influence climate predictions.

In conclusion, this study highlights the importance of continuing to combine regional and global data for a more in-depth understanding of Quaternary dynamics. Recommendations include improving analysis methods to strengthen data comparability and promoting a multidisciplinary approach for a more comprehensive assessment of interactions between global and local factors. Going forward, it is essential to continue detailed regional research and examine the impacts of modern climate change in comparison with historical data, in order to optimize preparation and adaptation to future climate challenges.

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Conflicts of interest

The authors declare no conflicts of interest.

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