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Received: 18/04/2025

Revised: 28/06/2025

Accepted: 01/07/2025

Published: 04/07/2025

Academic Editor:
Dr. Alexandros Bartzokas-Tsiompras

DOI: 10.48088/ejg.p.jur.16.2.241.255

ISSN: 1792-1341

Research Article

Identification of Potential Paleoislands in the Mediterranean Sea During the Last Glacial Cycle

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Abstract: The Last Glacial Period (LGP) significantly altered sea levels and landscapes across the globe, with the Mediterranean Sea being no exception. During this period, fluctuating sea levels exposed numerous landmasses, some of which may have served as critical habitats for plants, animals, and even human populations. This study aims to identify and analyze the potential paleo-islands that were emerged in the Mediterranean Sea during the LGP (115,000 – 6,500 BP). Using high-resolution digital elevation models (DEMs) and bathymetric data, we reconstruct the Mediterranean's paleogeography, focusing on the periods of maximum sea-level regression. A novel methodological approach was applied to determine the duration and extent of these paleo-islands, while filtering out uncertainties related to their size and elevation. Results show the existence of hundreds of potential paleo-islands, including larger landmasses that significantly expanded during this period. This research highlights the critical role these islands played in biogeographical processes, such as species migration and dispersal, and possibly in the migration patterns of early humans. Future work will focus on refining the data with localized sea-level curves and incorporating sedimentary and erosion processes into the analysis, providing a more comprehensive understanding of the Mediterranean's geomorphological evolution

Keywords: Paleoislands; Last Glacial Period; Mediterranean Sea; Sea-level changes; Bathymetry; Paleogeography

Highlights:

- Sea-level fluctuations during the LGP significantly altered Mediterranean landmasses.
- Identification of paleo-islands in the Mediterranean during the Last Glacial Period.

1. Introduction

Glacial periods are remarkable climatic events characterized by extended periods of global cooling, resulting in the expansion of polar ice sheets and lower temperatures across the planet. The most recent glacial period, often referred to as the Last Glacial Period (LGP), represents a pivotal chapter in Earth's climatic history. As Clement and Peterson (2008) and Riechers et al. (2024) note, the LGP was the longest and coolest phase of the Quaternary Climate epoch, spanning from 115,000 to 9,700 years Before Present (BP). During this protracted glacial phase, global temperatures plummeted, reaching sea levels that witnessed significant fluctuations, as highlighted by Khan et al. (2019). However, simplifying a glacial period merely as a juxtaposition of high and low sea levels is a gross oversimplification, as the work of Dutton et al. (2022) underscores. The LGP was marked by a profound intricacy, with multiple temperature fluctuations and sea level variations, necessitating a detailed examination to comprehensively understand the environmental changes that unfolded during this era.

Despite the wealth of data and research available, it is remarkable that scientific analyses with territorial and cartographic components rarely delve into the comprehensive examination of sea-level changes during glacial periods. Many studies have traditionally focused on specific high or low points in sea level, typically represented by the maximum extent of subaerial lands during the Last Glacial Maximum around 18,000 BP, as noted in the works of Cooper et al. (2018), Khan et al. (2019), and Ishiwa et al. (2016). This reductionist approach often overlooks the dynamic and fluctuating nature of sea level changes during the LGP, as highlighted by Mann et al. (2019) and Björck et al. (2021). The intricacies of these fluctuations, shaped by factors like the continental shelf's shape and depth, underscore the need for a more comprehensive understanding of sea level changes over time, beyond the customary snapshots at single time points.

During the LGP, the intricate interplay between sea levels and the Earth's landmasses likely resulted in the existence of paleoislands. These landmasses would have been exposed during periods when sea levels were significantly lower than at present (Fraile-Jurado & Mejías-García, 2022). Given the extensive time frame of sea level changes during the LGP, it is reasonable to assume that a wide array of scenarios unfolded. Some presently emerged islands may have been considerably larger during certain periods, while other islands that once existed have since vanished beneath the rising sea levels. Additionally, there is the possibility that archipelagos, now dispersed, may have comprised larger, singular landmasses in the distant past.

Particularly, these paleoislands likely played a pivotal role in the distribution of animal and plant species during the LGP. They may have served as critical waypoints for migrations between Europe and Africa, and perhaps even as refuges for certain species and populations. Among the species under intensive investigation during this period are our ancient human ancestors, both Homo sapiens and Neanderthals. The movements and interactions of these early human populations have been extensively documented. However, what's often overlooked or simplistically addressed in these studies are the intricacies of sea level changes. Accurate information about the existence and transformations of these islands over time provides a powerful tool for enhancing our understanding of the paleoenvironments in which these human species thrived.

The objectives of this article are to identify the distinct periods during the Last Glacial Period (LGP) when various landmasses in the Mediterranean functioned as unique geographic entities, specifically as islands. This includes analyzing dynamic sea level changes to determine the specific timeframes when these areas were shaped as islands. Another key objective is to delineate the varying extents of currently emerged islands in the Mediterranean. By achieving these goals, the article aims to provide a detailed chronological account of the Mediterranean's paleogeography during the LGP.

2. Study area

The Mediterranean Sea, encompassing an expansive surface area of 2.51 million square kilometers and extending almost 4,000 kilometers in length, ranks as the second largest enclosed sea on the planet (Figure 1). Despite its significant dimensions, the Mediterranean exhibits a relatively deep average depth, averaging around 1,300 meters. However, what sets this region apart is its distinct topography, particularly concerning the continental shelf, which plays a pivotal role in this study.

Figure 1. Study Area. Major islands and bodies of water in the Mediterranean Sea.

For the purposes of this investigation, the study area encompasses the maximum extension of subaerial lands during the Last Glacial Period (LGP) when sea levels reached their lowest positions, approximately between -120 and -130 meters. The area is defined by the region between the -130 meters isobath and the present-day coastline. It is important to note that, from a geological perspective, the continental shelf could be more extensive than this delimited area.

A noteworthy characteristic of the Mediterranean's continental shelf is the diversity of its shape and development patterns. The shelf's depth distribution, as seen in the frequency histogram (figure 5), displays a relatively uniform pattern with a lower prevalence of both shallow and very deep areas, particularly those less than -100 meters.

The Spanish coastline along the Mediterranean Sea boasts a diverse and captivating continental shelf topography (subarea 1 in fig 2). In the extreme western Mediterranean, both the northern and northern shores of Andalusia and Morocco exhibit a relatively narrow continental shelf, as documented by Lafosse et al. (2018) and Lobo et al. (2006). Alboran Island, positioned between these coasts, while relatively small in size, features an exceptionally extensive continental shelf spanning approximately 60 kilometers. Moving towards the NE, the shelf gradually widens in the region between the cities of Melilla (Spain) and Oran (Algeria). In contrast, the northern coast of Spain maintains a narrow shelf until reaching the areas between the Capes of Palos and Cape of la Nao, where it expands to a width of around 40 kilometers. This expansion continues as we journey towards the Ebro Delta in Catalonia, where one of the broadest continental shelves in the Mediterranean Sea can be observed.

Furthermore, the Balearic Islands in the Spanish Mediterranean Sea (subarea 2 in Fig. 2) exhibit a distinct characteristic in terms of their bathymetry and geology. The presence of an almost continuous shore platform connecting the islands of Mallorca and Menorca, alongside Ibiza, Formentera, and Cabrera, adds to the overall complexity and diversity of the bathymetry within the Spanish Mediterranean continental shelf. This unique feature underscores the significance of further investigation and research within this region.

The central Mediterranean boasts a diverse range of continental shelf characteristics. In the Gulf of Liguria, a narrow shelf dominates, as indicated by Enrichetti et al. (2020), with a slight widening observed only between Livorno and Naples, influenced by the eastward rollback of the west-directed Apennine subduction. Corsica's narrow shelf merges with Sardinia (subarea 3 in fig. 2), where volcanic rocks and fossil paleo-valleys shape the shelf's contours (Deiana et al., 2021). Moving to the Adriatic Sea, its shelf stands out for its shallow depths and rich benthic communities, shaped by the interplay of deltaic areas and marine sediments. In contrast, the eastern coasts of Tunisia (subarea 4 in fig. 2) feature a wide shelf

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connecting various islands to Sicily, and the region is influenced by gradual NW-SE convergence and the North Africa collisional fold and thrust belt system. In Algeria and Morocco, the shelf remains largely underdeveloped due to the presence of mountain ranges that create a structurally-controlled edge and subduction contact (Domzig et al., 2012). These complex shelf characteristics contribute to the dynamic and diverse geological landscape of the central Mediterranean.

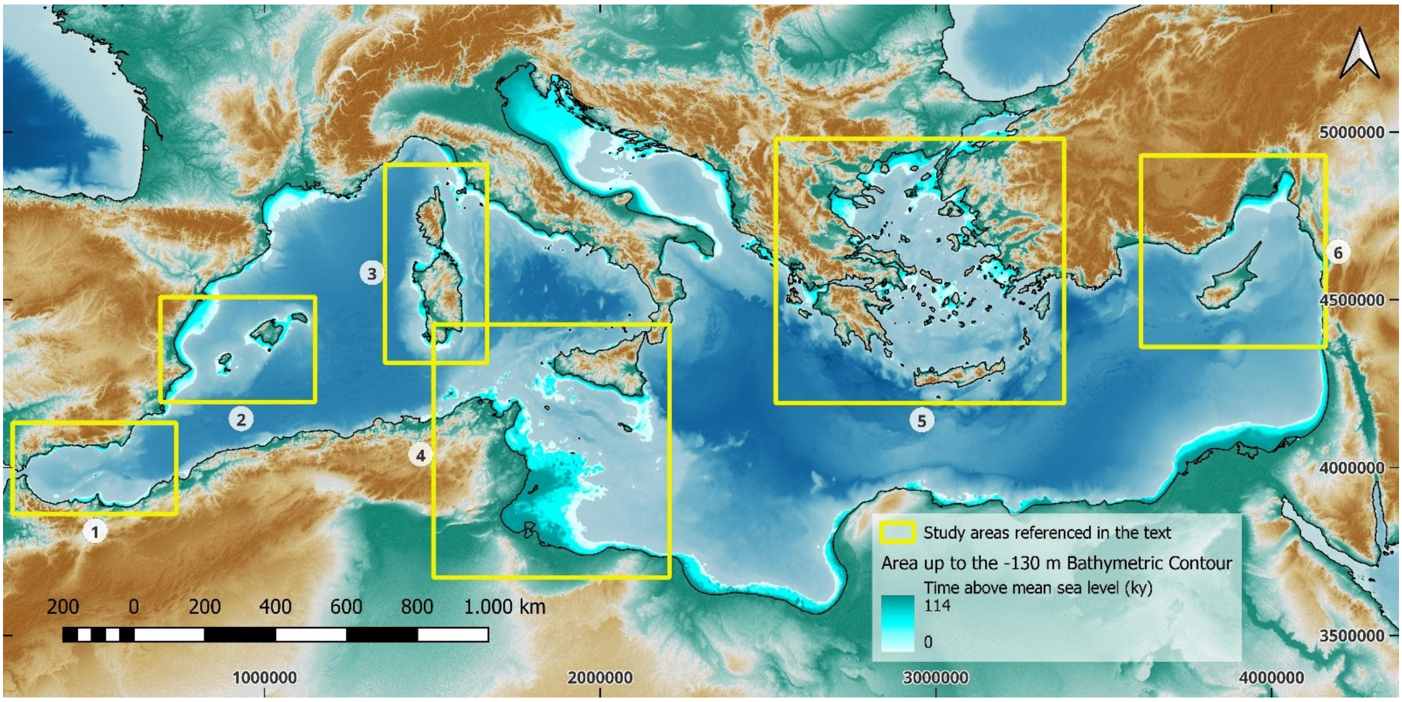

Figure 2. Subareas in the study area.

The eastern Mediterranean presents a diverse array of continental shelf features. Greece's continental shelf is notably influenced by the proximity of mountain ranges, resulting in a relatively narrow and coastline-parallel profile on its western side. In contrast, the Aegean Sea's continental shelf (subarea 5 in Fig. 2) is marked by complex and contentious maritime boundaries, subject to extensive studies due to territorial disputes between Greece and Turkey. This area exhibits remarkable tectonic complexity with multiple faults delineating basins of varying depths (Foutrakis & Anastasakis, 2020). Moving south along the Turkish coast, the shelf closely mirrors the existing coastline, particularly due to the presence of nearby mountain ranges. However, a significant exception can be observed between Mersin and the Gulf of Iskenderun, where the shelf widens substantially, characterized by thick sedimentary sequences resulting from prograding deltas (Ergin & Ediger, 1996).

In contrast, the coastlines of Cyprus, Lebanon, Syria, and Israel (subarea 6 in fig. 2) exhibit relatively narrow continental shelves, with a notable expansion occurring only in Egypt. Egypt's shelf showcases the presence of thick sedimentary facies located at considerable distances from the current Nile River delta, indicative of powerful accretion and erosion processes in the region (Kholeif & Ibrahim, 2010). Erosion has predominantly shaped this area in recent history, as revealed by Frihy et al. (1991). The coastal regions of Egypt and Lebanon feature narrow continental shelves extending toward the Gulf of Sidra and have been the subject of various legal studies regarding territorial waters (Leanza, 1993; McGinley, 1985; Roach & Smith, 1994). These regions exhibit relatively shallow shelf depths, and studies focusing on benthic habitats have uncovered diverse ecosystems within this unique eastern Mediterranean landscape (Gorgi et al., 1972).

3. Materials and Methods

This study employed a comprehensive methodological approach to map and analyze variations in the extent of the Mediterranean continental shelf during the Last Glacial Maximum (LGP). To facilitate this research, we utilized a continuous digital elevation model (DEM) with a spatial resolution of 110 x 95 meters, covering both exposed and submerged surfaces. This DEM was sourced from the European Marine Observation and Data Network (EMODnet) [emodnet.es.europa.eu/en/bathymetry]. The spatial precision of this model proved to be suitable for marine environmental investigations (Fraile-Jurado & Ojeda-Zújar, 2013), as the spatial heterogeneity of its morphologies is significantly lower compared to that of subaerial terrains.

In order to identify the most probable paleoislands in the Mediterranean, a spatial analysis was conducted. This methodology focused on variations in the extent of the continental shelf during the Last Glacial Maximum (LGM), using a series of analytical steps designed to isolate and characterize these ancient landforms.

1. Generation of Polygonal Entities: The EMODNET bathymetry raster, characterized by a resolution of 110 X 95 meters, was utilized to create depth contour lines at 1-meter intervals. From this comprehensive dataset, only the closed polylines were extracted, representing isolated polygons within the set of contour lines. These closed polylines were then converted into polygons, and any overlaps among polygons were dissolved, resulting in a singular entity for each distinct area. Additionally, four key parameters were attributed to these entities, encompassing the elevation of the shallowest level, the corresponding surface area, the elevation of the deepest level, and the surface area associated with the deepest level.

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2. Determination of Paleoislands: The identification of paleoislands was based on the analysis of concentric contour polygons derived from the bathymetric DEM. Only those polygons whose interior cells exhibited shallower depths (i.e., higher elevations) than those at the polygon edges were retained, indicating topographic highs that could have been emerged during sea-level lowstands. This criterion effectively excludes features whose interiors are deeper than their boundaries, which are more likely to represent submerged depressions or paleolakes, rather than true islands.
3. Calculation of Maximum Entity Existence Time: To ascertain the temporal aspect of these entities, a vectorized sea-level curve spanning from 120,000 BP to 6,500 BP. Although this article references that the Last Glacial Period (LGP) is generally considered to have ended around 9,700 years ago according to the literature, the date of 6,500 years ago was utilized as the point when sea levels approached (and according to some authors, possibly exceeded) current levels. This choice reflects that, despite atmospheric temperatures likely resembling current conditions from around 9,700 years ago, sea levels continued to rise beyond this date, adjusting the volume of oceanic waters to conditions warmer than those during the remainder of the LGP. A gridded dataset was constructed, featuring 1000-year intervals along the temporal axis and 1-meter increments along the elevation axis. By cross-referencing the surface and deep elevations of each entity with this temporal dataset, the initial and final dates of existence for every entity were determined (Fraile-Jurado & Mejías-García, 2022). Simple subtraction provided the total duration of their presence.
4. Determination of Entity Novelty: Entities present in the current Mediterranean landscape were classified as "existing at present," characterized by a shallowest elevation value of 0. Any other entities with a shallowest elevation value less than 0 were categorized as "new" underwater features.

The developed methodology underwent a selection process that excluded several islands into two steps for specific reasons:

1. Size Exclusion: Islands with a size smaller than 1 km^2 were excluded from the analysis due to uncertainties arising from the methodology itself, particularly concerning very tight isobaths, which might introduce errors. These errors could stem from interpolation processes in the Digital Elevation Model (DEM) that generalize curves around anomalous or erroneous data points, known as aberrations, or from interpolation processes carried out in seafloors with sparse data.
2. Altitudinal Differences Below 5 Meters: To improve the reliability of the results, features with less than 5 meters of altitudinal difference were excluded. This threshold accounts for several factors that may introduce vertical uncertainty: (1) the documented mean error in EMODnet bathymetric data, particularly between 0 and –130 meters; (2) wave action, with significant wave heights often exceeding 1.5 meters in the Mediterranean; and (3) local tidal ranges, which can reach 0.5 meters. Given these combined sources of potential distortion, a conservative 5-meter threshold was established to minimize false positives in the identification of paleo-islands.

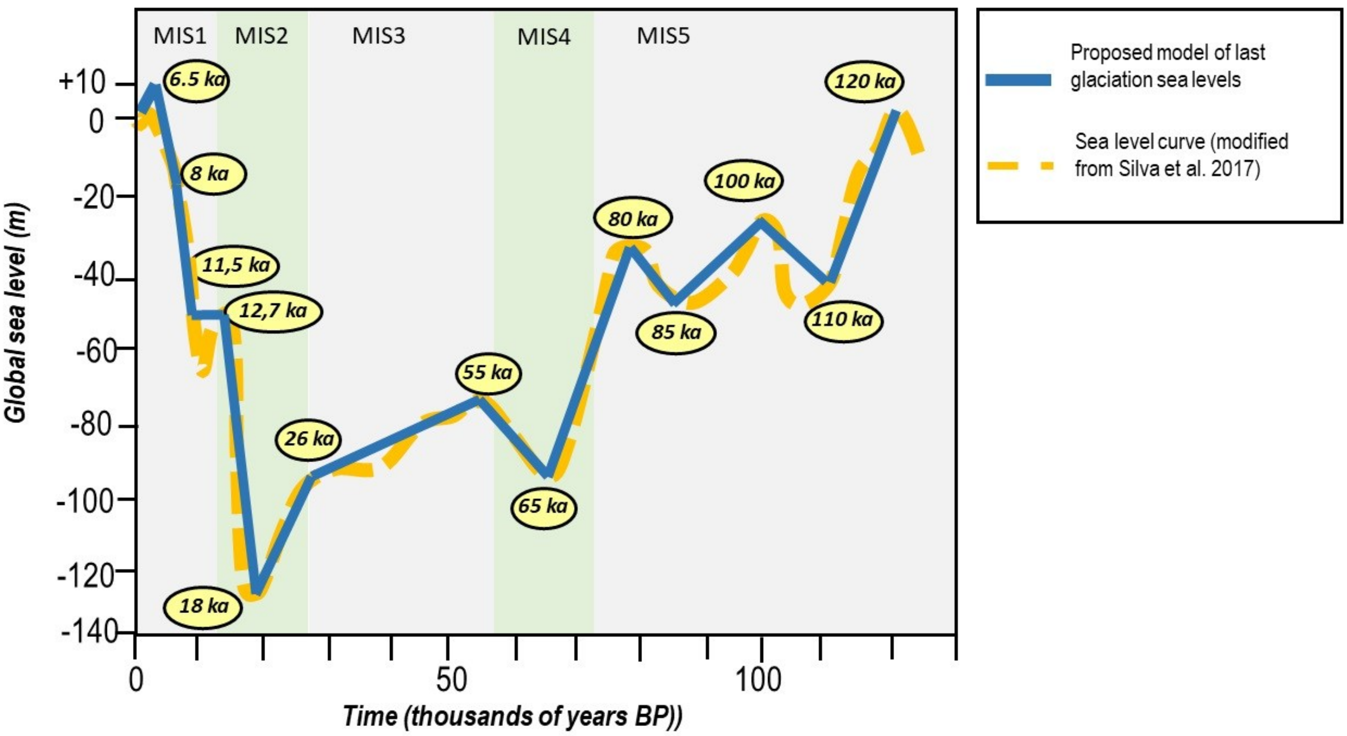

Figure 3. Simplified LGP sea level curve.

The analysis has identified three distinct types of insular spaces within the Mediterranean during the Last Glacial Maximum (LGM). The first type comprises individual islands that existed as separate landforms for varying durations throughout the LGM. These islands were significant in size and extent during specific periods when sea levels were lower, allowing them to remain exposed and distinct from other landmasses.

The second type includes currently emerged islands that, throughout the study period, had a larger extent than their present-day size. This is because the current sea level represents the most recent position during the LGM, and these islands would have been significantly larger in the past when the sea level was lower. Therefore, their historical extent was greater than their current dimensions, reflecting a larger land area that has since been submerged or eroded.

The third type involves islands that are currently subaerial but were part of larger landmasses during periods of lower sea levels. During these low sea level events, these islands were connected to other landmasses, forming a more extensive land area. However, during periods of intermediate sea levels within the LGM, these islands operated as individual entities, separated from the larger landmasses. Thus, their role and extent changed significantly depending on sea level fluctuations throughout the LGM.

4. Results

Initial analysis revealed a remarkably high number of potential paleoisland candidates within the Mediterranean Basin during the specified study period. A total of 8,662 entities were identified in raw results as potential paleoislands, exhibiting characteristics of a potential island formation at some point within the study period.

However, the filtering process led to the exclusion of 1,340 candidates solely due to their size being less than 1 km². An additional 848 candidates were excluded for having elevation differences of less than 5 meters, despite having an area greater than 1 km². Furthermore, 2,188 candidates were discarded as they met one of these criteria, although they were meeting the another criteria. The most rigorous filtering removed 5,670 candidates that failed to meet both criteria.

In total, 7,858 candidates were discarded, leaving 804 entities that fulfilled all criteria for identification as potential paleoislands. Notably, 84 of these candidates remain as present-day islands, albeit in a reduced form (Figure 4).

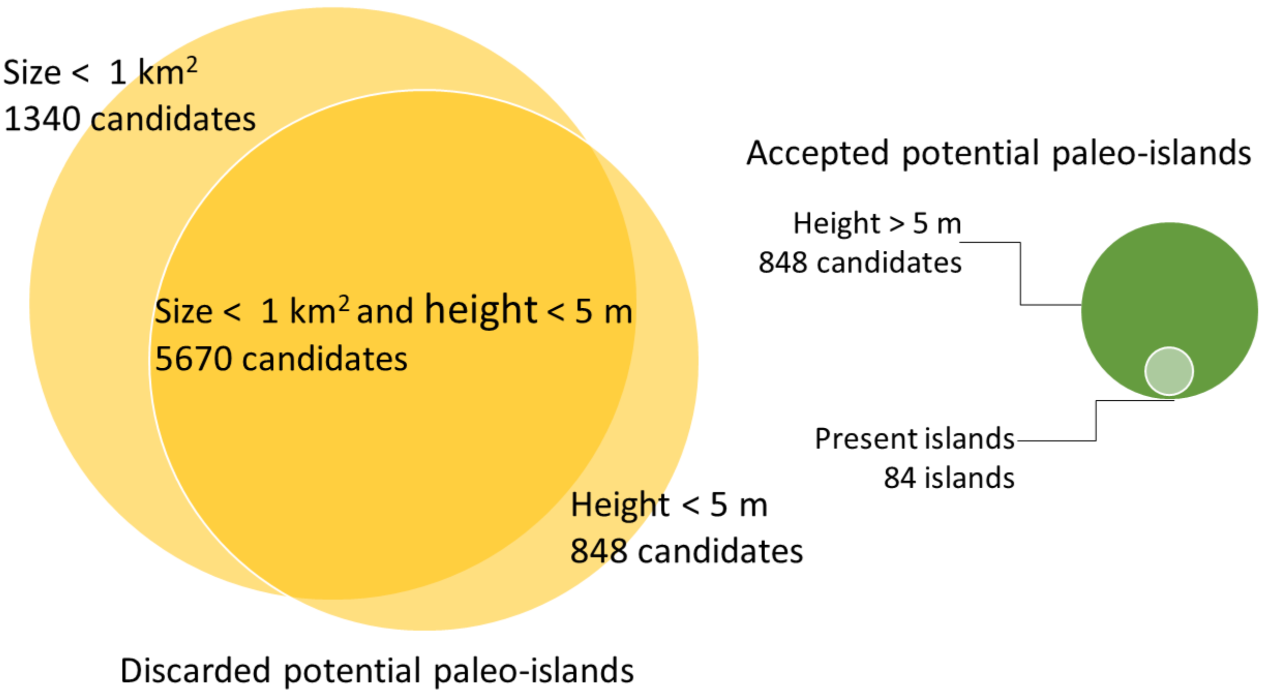

Figure 4. Venn Diagram showing the filtering process of potential paleo-islands based on size and elevation criteria.

The results underscore the lengthy and intricate history of islands and paleoislands within the Mediterranean Sea. Throughout time, there have been instances of large landmasses emerging for brief periods, contrasting with smaller islands enduring longer periods of emergence. Remarkably, some present-day islands experienced significant expansions, while others exhibited more moderate growth even during periods of lower sea levels. Additionally, significant geographical transformations, such as the narrowing of straits and the temporary unification of large islands like Corsica and Sardinia, further highlight the dynamic nature of the Mediterranean's landscape over time.

Figure 5 illustrates the distribution of potential paleoislands based on their maximum altitude during the Last Glacial Maximum (LGM). The data reveals that among the potential paleoislands, a total of 236 islands reached maximum altitudes between 5 and 10 meters at the lowest sea level during the LGM. The number of islands decreases progressively as the maximum altitude increases, with 129 islands reaching between 5 and 10 meters, and 77 islands between 10 and 15 meters. This downward trend continues, and the distribution becomes nearly random, with approximately 5 islands per category, for altitudes exceeding 60 meters.

A notable shift in the graph occurs in the category above 130 meters, where the number of identified islands increases to 84. This rise is attributed to the inclusion of currently emergent islands, some of which attain very high elevations. For example, islands such as Mount Ida in Crete, Mount Cinto in Corsica, and Mount Etna in Sicily, which exceed 2,000 meters and even 3,000 meters, respectively, are represented in this category (Figure 5).

Figure 5 displays the density percentage of the total subaerial surface area of potential paleo-islands during the Last Glaciation, based on the number of years they remained emerged. A notable number of islands were subaerial for relatively short periods, around 10,000 years, accounting for a little over 30% of the total surface area.

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Subaerial exposure lasting between 20,000 and 55,000 years is relatively less frequent. However, the graph shows that approximately 20% of areas were subaerial for 60,000 to 65,000 years, indicating a morphology that was relatively common throughout a significant portion of Mediterranean prehistory.

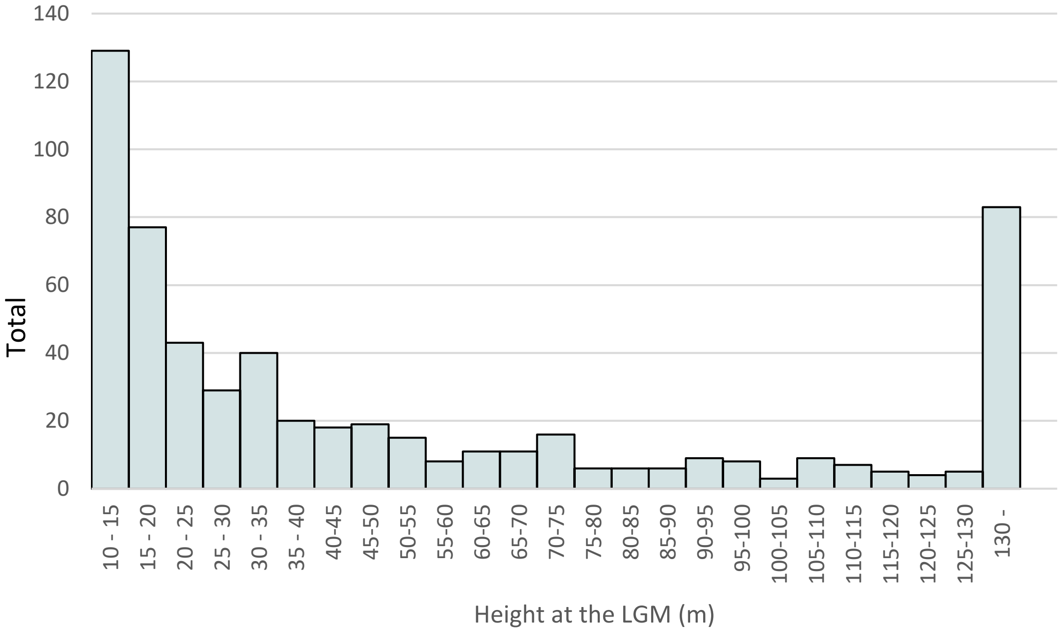

Figure 5. Histogram of paleoisland frequency based on their maximum height during the LGM.

The pattern recurs at values above 65,000 years, although such durations are less frequent, until reaching areas that remained subaerial for over 100,000 years. These account for approximately 14% of the total surface area and correspond to regions that were subaerial for nearly the entire duration of the Last Glaciation. They were only submerged during the initial stages of sea-level fall at the onset of the glaciation, and again in recent times as sea levels rose to their current position.

Results are shown in figure 4, distinguishing between paleoislands no longer above sea level, present-day islands, and present-day islands grouped into larger paleoislands.

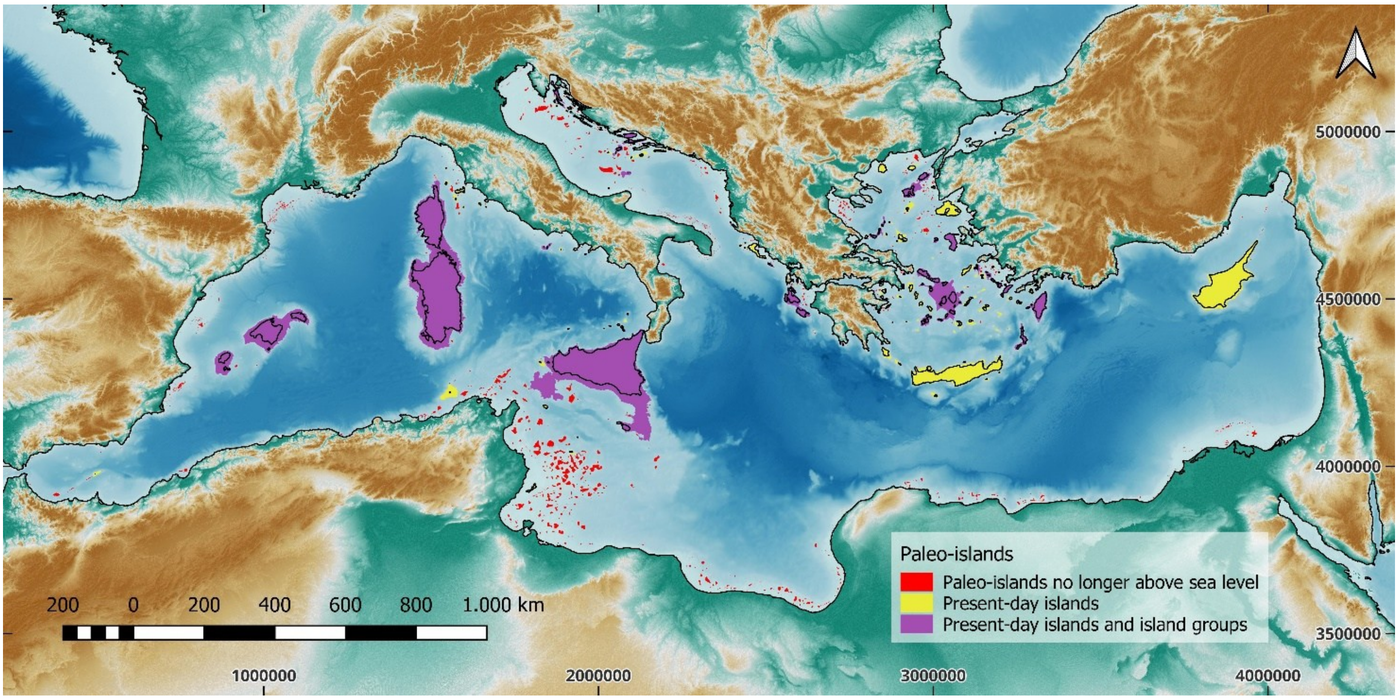

Figure 6. Distribution of potential subaerial landmasses during the LGP, interpreted as paleo-islands.

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In the western Mediterranean, the presence of identified paleoislands appears to be less common compared to other areas within the study region. Notably, the island of Alborán underwent significant changes, transitioning from its current size to an arc of islands spanning 40 km in length (fig. 7). Near the main island of Alborán, there is a notable arc of islands that emerged for periods shorter than 50,000 years, extending the NE-SW direction of this paleoarchipelago. Today, only the small island of Alborán remains as a remnant of this once extensive island chain.

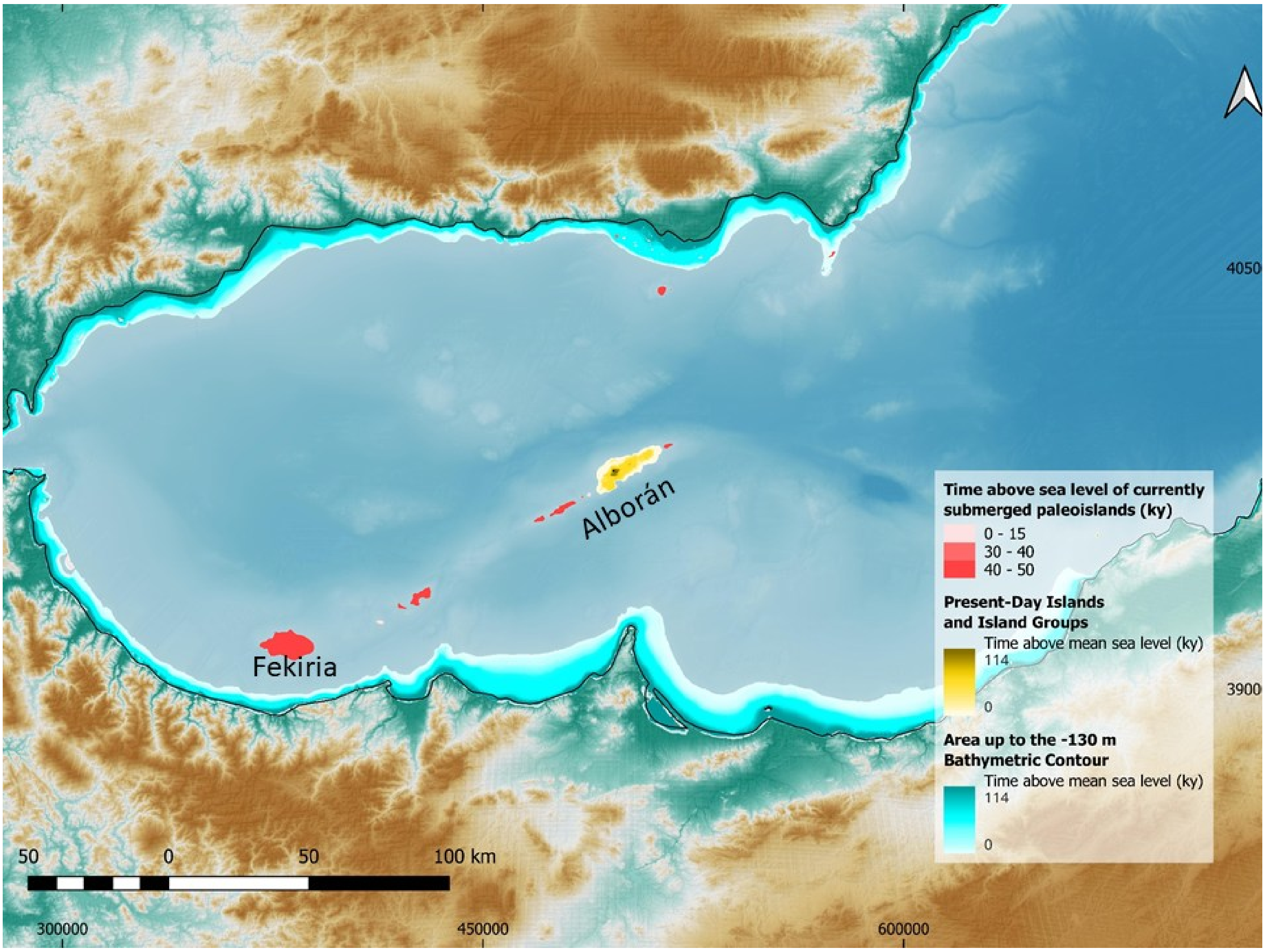

Figure 7. Alborán Sea area showing the NE-SW oriented archipelago over 100 km in length, with some islands emerged for up to 50,000 years.

Additionally, the islands of Mallorca and Menorca exhibited greater territorial extent in the past, forming a single landmass for approximately 60,000 years (fig. 8). The Ibiza-Formentera complex remained subaerial for the vast majority of the study period, approximately 111,000 years. Nevertheless, at its maximum extent, it covered approximately 3,000 km^2, contrasting with the current combined size of the two islands, which totals 650 km^2.

In the Central Mediterranean, two significant observations emerge. Firstly, the presence of the two largest paleoislands in the Mediterranean Sea: Sicily and the Corsica-Sardinia ensemble (fig. 9). The Corsica-Sardinia ensemble represents the largest Mediterranean paleoisland, spanning a maximum extent of 47,000 square kilometers during the LGM. This area corresponds to approximately 142% of the combined present-day surface area of Corsica and Sardinia. According to the findings, both islands were connected for periods exceeding 55,000 years, suggesting that during the Last Glacial Maximum (LGM), they were separate islands for approximately 62,000 years. The second-largest island identified is 'Greater Sicily', encompassing the current island of Sicily along with other smaller islands and islets such as Favignana and Marettimo. It covered an area of 44,000 km^2, marking a 76% increase compared to its current size of 25,000 km^2.

In the central sector of the Mediterranean (fig. 10), some of the largest currently submerged paleoislands have been identified (Table 3). For example, the island near the present-day coasts of Tunisia and south of Sardinia, referred to as Pandora for the descriptive purposes of this article to facilitate the identification of elements without current toponymy, reached a maximum area of over 1,200 km^2, making it one of the ten largest islands in the Mediterranean if it were emerged. It reached an altimetric difference of 36 m between its lowest point, at sea level during the last glaciation, and its highest point. It was only subaerial for 39,000 years. However, it should be noted as the largest island currently not above sea level. Under similar conditions, the island named Ruibalia remained subaerial for 51,000 years, although it reached an area of only 1,990 km^2. Similarly, the paleoislands Iscaria, with a maximum extent of 449 km^2, situated in what appears to be a large paleoarchipelago off the Tunisian coast, and Ruibalia, with a maximum extent of 447 km^2, belong to this central sector. Other smaller islands identified in this region include Saramagia and Gasolia, with decreasing sizes.

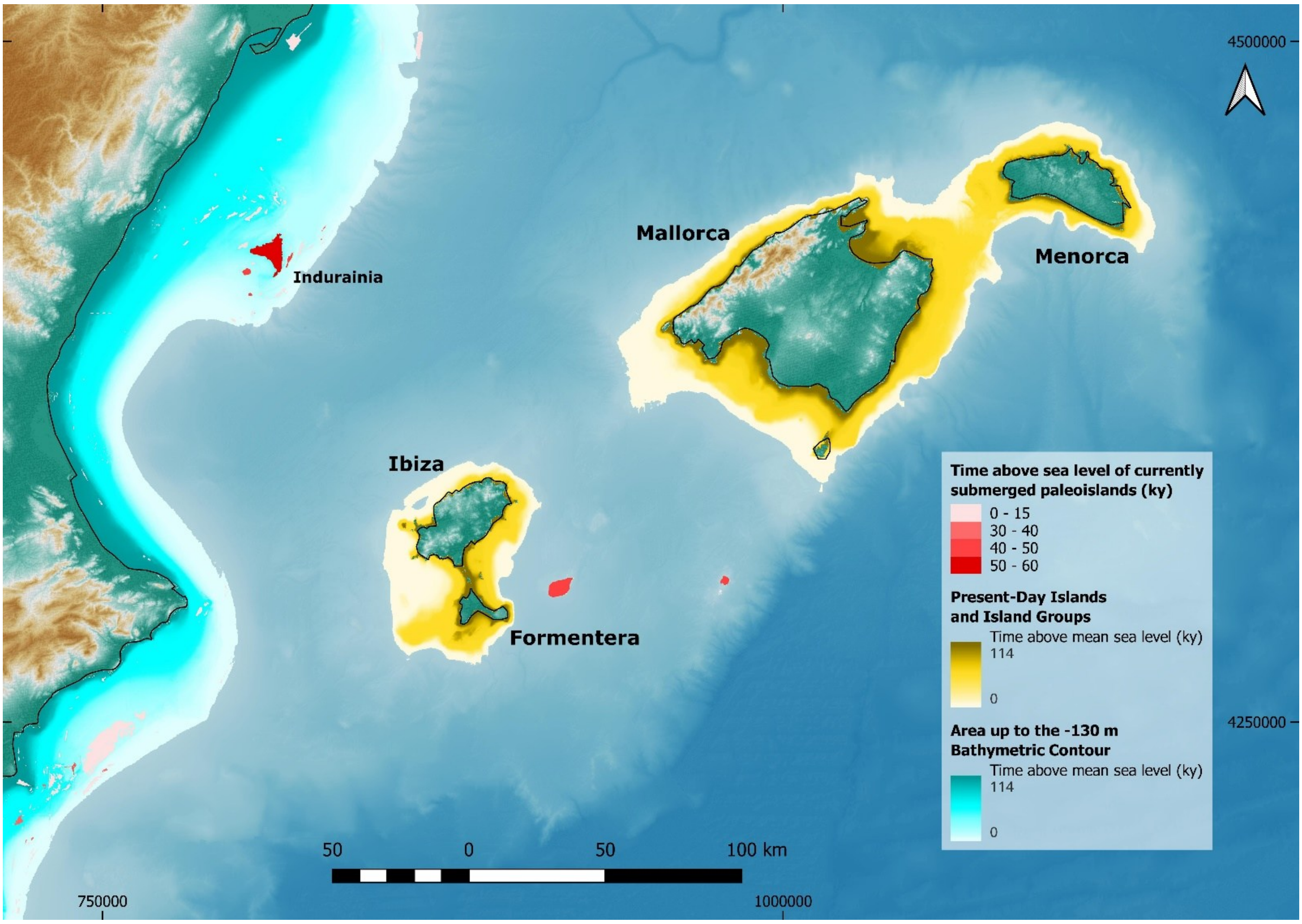

Figure 8. Paleoislands of the Balearic Archipelago, including land bridges between Mallorca and Menorca and between Ibiza and Formentera, as well as smaller subaerial islands that remained emerged for up to 40,000 years.

Ruibalia is particularly noteworthy due to its unique formation. This island was exposed above sea level for over 100,000 years but appears to have been composed of two mounds that were only connected for less than 15,000 years. As a result, Ruibalia functioned as two smaller independent islands for most of its existence. Additionally, within this sector, the island named Hectoria, with an area of 448 km², is another example of a currently submerged island located off the present-day coasts of Croatia. Similar analyses in this sector have identified the islands named Erasmia, with an area of 407 km², and Deferria, with an area of 338 km², both situated in the current Adriatic Sea, off the present-day coasts of Croatia.

Secondly, a significant number of identified paleoislands are noted north and northwest of Tunisia, primarily characterized by their small size and entity. However, their size is sufficient to warrant inclusion in the analysis, indicating a notable presence in the region. Considerably large groups of islands existed at various times during the last glacial period off the coasts of Croatia and Italy, in the Ionian Sea, as well as some smaller island arcs in the Tyrrhenian Sea.

In the eastern Mediterranean sector, notable is the presence of two large present-day islands (Cyprus and Crete), whose size increased by 15% and 23% respectively (Table 1), without including other currently subaerial islands or those that have been above sea level at any point during the study period.

The Aegean Sea stands out as the region with the highest presence of aggregated paleoislands once the analysis is completed and all potential candidates are filtered (fig. 11). The largest island that has not been above sea level in historical times in this region is located in the northeastern Aegean Sea, referred to as Socratia in this article. In the eastern sector, no significant large islands have been identified that, despite not existing in the present, functioned as unitary islands for extended periods in the past. However, as observed in Tables 1 and 2, this sector is highly relevant for the purposes of this investigation.

This area includes some of the unitary islands that have undergone the most substantial transformations in terms of their area while maintaining their status as individual islands, without merging with other currently subaerial islands. For instance, Cyprus experienced a 24.9% increase in area, reaching a maximum size of 11,550 km² (fig. 12) Crete saw a 25.4% increase, expanding to 10,454 km². Other islands such as Rhodes, with a 50% increase, Lesbos with a 28.6% increase, Chios with a 16.8% increase, and Corfu with a 23.4% increase, all demonstrate significant changes in their areas while remaining unitary islands.

In the eastern sector, the paleoislands that connected multiple currently subaerial islands, which remain separated by the present sea level, are particularly significant. The Andros-Syros-Mykonos-Paros-Antiparos-Naxos-Tinos (Table 3) system stands out, transitioning from a combined current area of 1,335 km² to 7,372 km² at the lowest sea level point, reflecting a 452% increase. This system functioned as a single landmass for

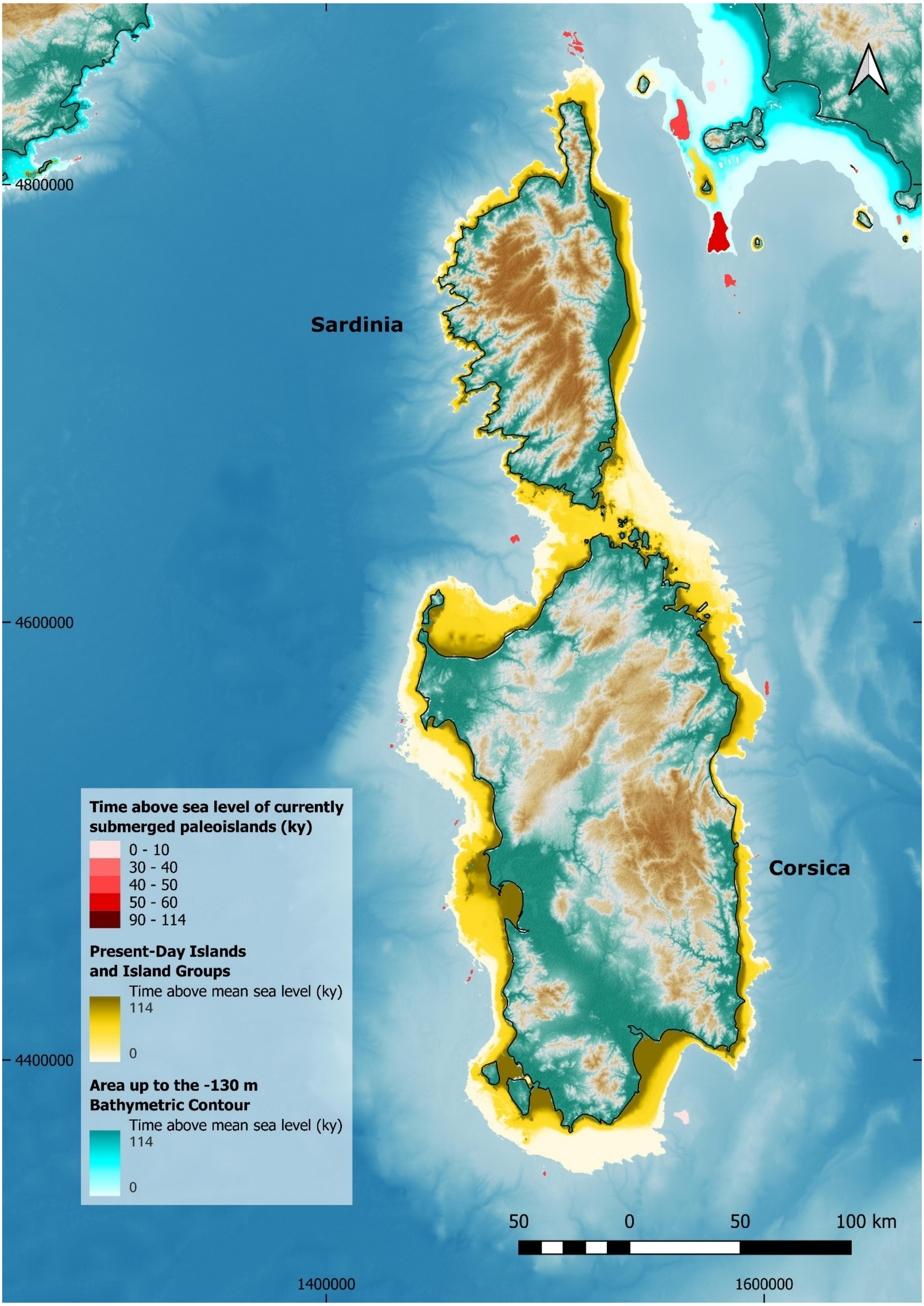

Figure 9. Corsica-Sardinia ensemble, connected as a single landmass for approximately 55,000 years.

periods less than 9,000 years, likely near the LGM, although it was probably composed of several smaller groups of two, three, or four large islands during the rest of the glacial period.

Other notable paleoislands in this sector include Kefalonia-Zakinthos, which expanded from 1,195 km² to 2,337 km², a 95.6% increase. Lemnos-Imbros showed a significant increase from 756 km² to 1,996 km², amounting to a 164.0% rise. The Karapathos-Kasos complex grew from 393 km² to 785 km², a 99.8% increase. Finally, the Milos-Kimolos-Poliegos group expanded from 231 km² to 658 km², reflecting an 184.9% increase.

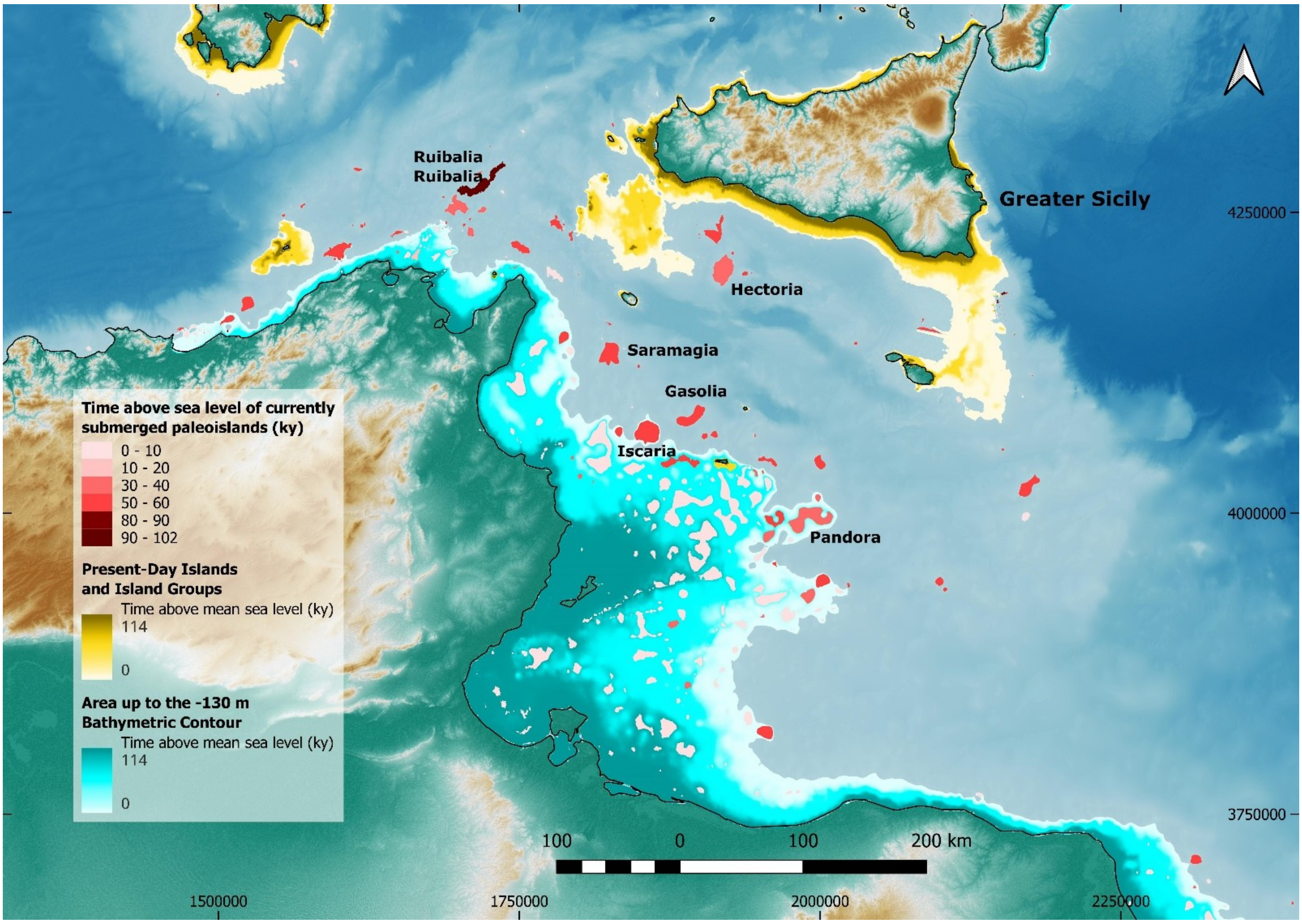

Figure 10. South-Central Mediterranean between Tunisia and the Greater Sicily paleoisland group, including Pandora, Iscaria, Ruibalia (emerged for over 90,000 years), Hectoria, Gasolia and Saramagia.

Table 1. Maximum extent reached during the Last Glacial Maximum by currently emerged individual islands, and their relative size increase in km².

Name	Present size	Largest area	Increase at the largest (%)
Cyprus	9,250	11,550	24.9
Crete	8,336	10,454	25.4
Rhodes	1,408	2,112	50.0
Lesbos	1,634	2,102	28.6
Chios	842	984	16.8
Corfu	585	722	23.4
Skyros	223	580	160.2
Hvar	297	574	93.3
Kythira	278	570	104.9
Thassos	380	483	27.1

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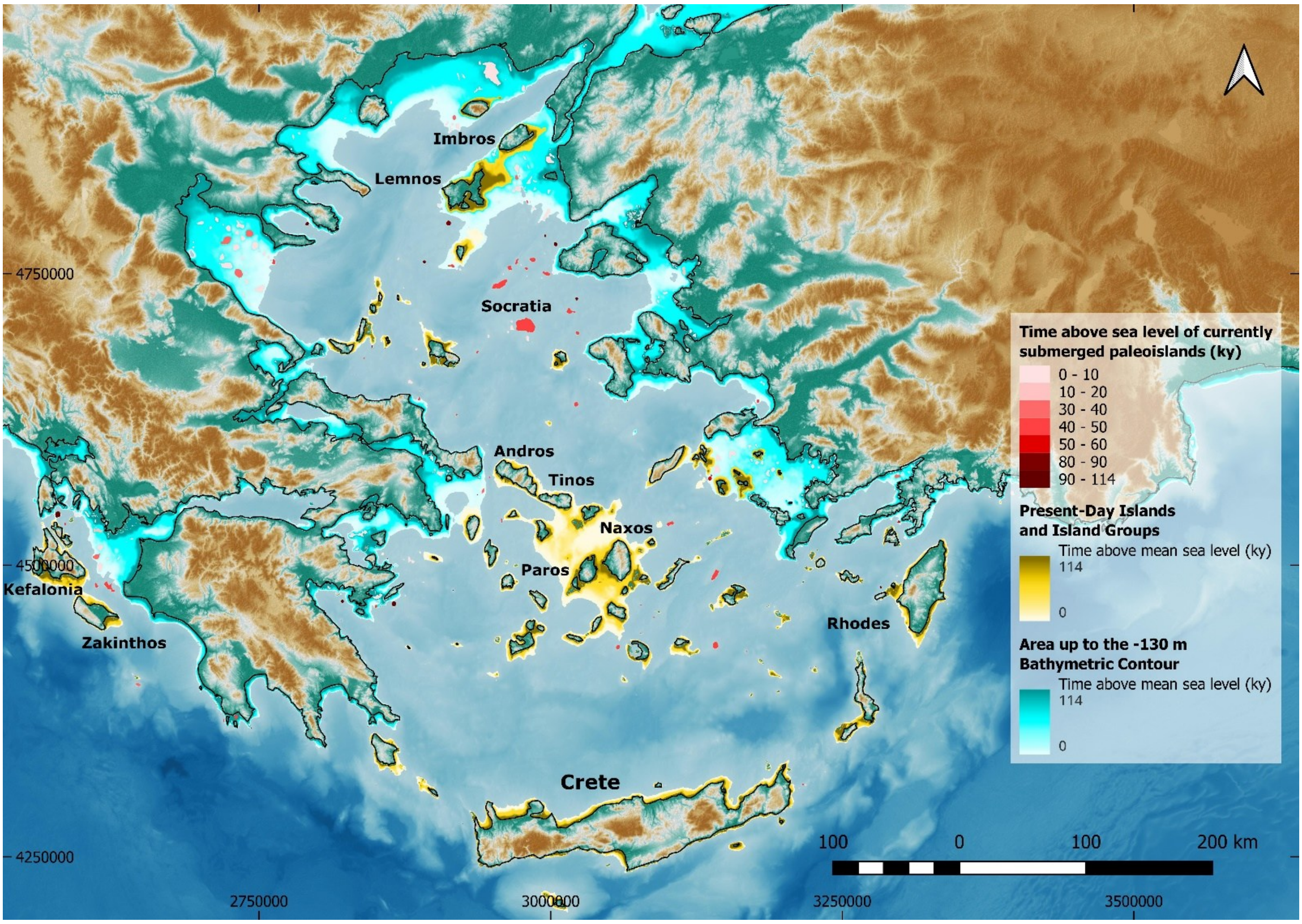

Figure 11. Islands and paleoislands of the Aegean Sea, showing some of the largest islands aggregations identified, like Andros-Syros-Mykonos-Paros-Antiparos-Naxos-Tinos and Lemnos-Imbros.

Table 2. Maximum size reached at the Last Glacial Maximum by aggregation of the largest potential paleoisland in km².

Name	Present size	Largest area	Increase at the largest (%)
Corsica-Sardinia	32,770	47,465	44.8
Greater Sicily	25,802	44,188	71.3
Mallorca-Menorca	4,342	10,929	151.7
Andros-Syros-Mykonos-Paros-Antiparos-Naxos-Tinos	1,335	7,372	452.2
Ibiza-Formentera	654	3,018	361.5
Kefalonia-Zakinthos	1,195	2,337	95.6
Lemnos-Imbros	756	1,996	164.0
Karapathos-Kasos	393	785	99.8
Cres	406	783	92.8
Milos-Kimolos-Poliegos	231	658	184.9

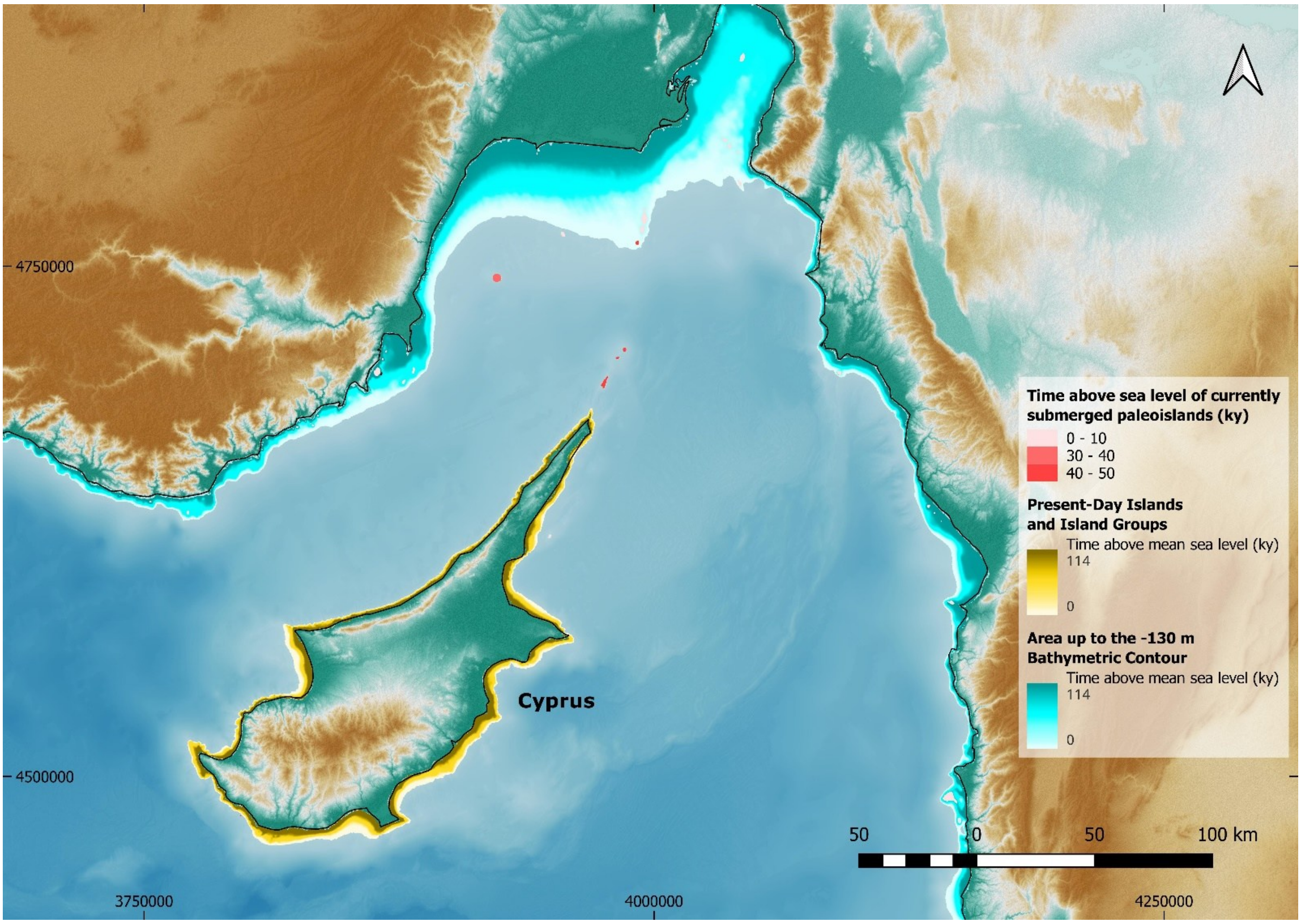

Figure 12. Relatively modest increase in the size of Cyprus during the study period.

Table 3. Maximum size reached at the Last Glacial Maximum by the largest potential paleoisland in km².

Name	Largest area
Pandora	1,293
Iscaria	449
Hectoria	448
Ruibalia	447
Saramagia	438
Socratia	407
Erasmia	386
Gasolia	376
Deferria	338

5. Discussion

The interpretation of the results requires cautious consideration, as a variety of limitations must be addressed, both methodological and data-related. These limitations, while important, do not diminish the overall reliability of the study but are essential for a comprehensive understanding of the findings.

One of the primary limitations is related to the use of a sea-level curve that, although a valid global simplification, may not account for localized variations. The Mediterranean region's complex geological history and local influences could lead to more intricate sea-level histories. This means that the sea-level data used in our study may not precisely represent regional fluctuations.

Although studies by Antonioli et al. (2007, 2021), Lambeck et al. (2004), and Vacchi et al. (2016)) provide valuable insights into sea level changes in the Mediterranean, it is important to note that the magnitude of the vertical changes identified in their research is significantly smaller than what would be implied by changes of approximately 5 meters over about 100,000 years. These figures are relevant as they represent the minimum threshold from which paleoislands have been identified in our study, suggesting that sea level changes in the Mediterranean during the last glacial period and the Holocene may not have been sufficient to account for the formation of these islands.

Additionally, the spatial resolution of the bathymetric model applied in this study is relatively coarse, resulting in vertical imprecision. The limited detail in the bathymetric data can influence the accuracy of depth measurements and, consequently, impact the representation of past landforms, including paleoislands.

The relative lack of vertical precision and spatial resolution in the employed bathymetric DEM has been recognized as relatively less critical in the submerged surface than in the subaerial surface. Studies such as Gao (2009) and Amante and Eakins (2016) have highlighted the limitations and accuracy of interpolated bathymetry in DEMs (Hojati & Mokarram, 2016), emphasizing the challenges associated with bathymetric mapping and the need for improved methods. Additionally, research by Siermann et al. (2014) underscores the significance of satellite-derived bathymetry and DEMs, particularly in marine environments. Based on the findings from Fraile-Jurado and Ojeda-Zújar (2013), it is evident that, unlike bathymetry (Sánchez-Carnero et al., 2012), vertical accuracy holds paramount importance in coastal areas.

Moreover, it is important to recognize the lack of continuous spatial data sources covering the entire Mediterranean region, particularly with regard to sedimentation and erosion rates (Roy et al., 2021; Díaz-Cuevas et al., 2020). These variables are critical for reconstructing the geological history of the Mediterranean seabed and understanding the evolution of submerged landforms. While some studies have contributed valuable localized insights into coastal erosion and sea level rise impacts (Fraile-Jurado et al., 2019; Ojeda-Zújar et al., 2021; Álvarez-Francoso et al., 2020), such detailed analyses remain spatially restricted. In addition, it must be acknowledged that processes such as sea-level rise can intensify erosion dynamics along the coast, potentially altering the sedimentary profile of shallow platforms and contributing to uncertainties in paleolandscape reconstructions (Martinez et al., 2022, Martinez et al., 2023). However, at the temporal scale considered in this study—spanning over 100,000 years—such processes can be regarded as negligible in the absence of more complete and regionally consistent data (Younes et al., 2023). Thus, while the influence of erosion and sedimentation cannot be fully quantified with current datasets (Bezinska & Stoyanov, 2019), their overall impact is assumed to be limited when assessing large-scale paleogeographic patterns. The robustness of the proposed methodology could be significantly enhanced by the incorporation of continuous data on tectonic activity and isostatic adjustments throughout the Mediterranean basin. Such information would allow for more precise estimations of vertical land movements, which in turn could refine the reconstruction of paleoshorelines and the timing of subaerial exposure. However, except for a few broad-scale global models, spatially and temporally detailed data on tectonic and isostatic processes remain largely unavailable across the Mediterranean region (Roy & Peltier, 2018).

Despite these limitations, this study offers valuable insights. The choice of scale and the size of the study area helps mitigate the impact of some limitations, particularly those associated with the bathymetric data. Focusing on elements of moderate size (larger than 1 km^2) enables a more robust analysis.

Similarly, the utilization of the sea-level curve, while potentially imprecise for specific time periods, is generally effective in identifying significant global sea-level changes. This approach provides a valuable approximation for describing the fundamental characteristics of potential Mediterranean paleoislands.

Considering the current scientific understanding of paleoanthropology, the approach employed in this article is indispensable for comprehending the probable migratory routes of various human species and communities. This methodology is particularly crucial in elucidating the migrations of Homo sapiens and the movements and final refuges of Neanderthals. Furthermore, this perspective allows for a more accurate interpretation of the colonization processes of many islands that are currently isolated, or more isolated than they were in the past. Historically, the main hypotheses for the settlement of these islands have often been attributed to phenomena such as chance. By integrating detailed paleogeographic data, this study provides a more robust framework for understanding the intentional and systematic aspects of ancient human migrations and settlements.

Despite the limitations outlined, it is highly probable that the overall distribution of Mediterranean islands during the Last Glacial Maximum closely resembles the results presented in this study. Significant errors may have occurred concerning smaller islands, particularly those very small identified islands that may not have existed. However, the methodology employed safeguards the validity of the results by eliminating very small or low-lying paleoislands. For the filtered islands, it is likely that the obtained extents and shapes do not precisely match the reality that existed throughout the study period, either overestimating or underestimating their true dimensions. Nevertheless, as an approximation of a phenomenon that influenced migratory routes and, in some cases, human settlement, this approach remains valid and insightful.

6. Conclusions

During the Last Glacial Period (LGP), hundreds, and possibly thousands, of islands, some of considerable size, emerged in the Mediterranean Sea, providing critical habitats for various plant and animal species and potentially serving as settlement sites for early humans. The complexity of the processes behind the emergence and submergence of these islands is key to understanding patterns of migration and settlement, both for humans and for other species.

The identification of paleoislands has significant paleoecological and biogeographical implications. These islands likely acted as refuges for flora and fauna during the LGP, influencing species' genetic diversity and evolutionary paths. Moreover, the dynamic sea-level changes would have opened and closed migratory routes between Europe, Africa, and Asia, shaping the biodiversity and distribution patterns we observe today. These islands may have also served as essential waypoints for ancient human populations, including both Neanderthals and Homo sapiens, highlighting the potential influence of these landmasses on human dispersal and settlement during prehistoric times.

The methodology employed in this study not only identifies the approximate shapes of these paleoislands but also provides a reasonable estimate of their duration above sea level. This temporal information is crucial for understanding how long these islands remained habitable or navigable for human and animal populations. However, future work could improve the precision of the analysis by employing more localized or recent sea-level curves and incorporating erosion and deposition data into the DEM, which are not currently available at this scale of study.

To further refine these findings, more precise spatial and temporal datasets are necessary, along with a broader analysis encompassing longer timeframes, such as the entirety of the Quaternary. Additionally, submerged paleoislands identified in this study could represent significant underwater archaeological sites, potentially holding artifacts or remains that provide new insights into prehistoric human occupation. As technology for underwater exploration advances, these areas could become focal points for archaeological research.

Finally, the geological and tectonic features of the Mediterranean played a pivotal role in the formation and evolution of these paleoislands. The interaction between sea level changes and tectonic processes helped shape the unique configuration of the Mediterranean basin, influencing the location and longevity of these ancient landmasses. The methodology developed in this study is not only valuable for understanding the Mediterranean but is also applicable to other regions of the world, offering a new perspective on the dynamic relationships between geology, sea levels, and landform evolution over time.

Funding: This research received no external funding.

Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: We gratefully acknowledge the editorial assistance provided by María Brey-Periáñez during the preparation of this manuscript.

Conflicts of Interest: The author declares no conflict of interest.

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