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Developing a Geocultural Database of Quaternary Palaeoenvironmental Sites and Archaeological Sites in Southeast Arabia: Inventory, Endangerment Assessment, and a Roadmap for Conservation

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Abstract: Quaternary palaeoenvironmental (QP) sites in Southeast Arabia are important not only to understand the history of global climate change but also to study how ancient humans adapted to a changing natural environment. These sites, however, are currently missing from conservation frameworks despite reports of destroyed sites and sites under imminent threat. This study presents the Geocultural Database of Southeast Arabia, the first open-access database on QP sites in this region, created as a comprehensive inventory of regional QP sites and a tool to analyse QP records and archaeological records. The endangerment assessment of QP sites in this database reveals that 13% of QP sites have already been destroyed and 15% of them are under imminent threat of destruction, primarily due to urban development and infrastructure development. Chronological and spatial analyses of QP and archaeological sites and records highlight the intricate relationship between palaeoenvironment and archaeology and emphasise the need for sub-regional-scale studies to understand the variation of climatic conditions within the region, especially to study changes in the ancient human demography. This database illustrates the potential of a geocultural approach that combines archaeological heritage with Quaternary geoheritage as a way forward for the conservation of QP sites at risk.

Keywords: palaeoenvironment; quaternary; geoheritage; heritage conservation; Arabia; database; human dispersal; geochronology

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1. Introduction

Internationally, geoheritage conservation has advanced greatly in the past three decades, as is evident from the development of various international frameworks. Following the success of continental networks, such as the European Geoparks Network (established in 2000) and Asia-Pacific Geoparks Network (established in 2007), in promoting the protection of geological sites, UNESCO established its Global Geopark programme in 2015, overwriting its decision in 2001 to not pursue such a program for geoheritage sites [1]. Academically, the five key stages of geoheritage conservation have been identified as: inventory, quantitative assessment, conservation, interpretation and promotion, and monitoring [2]. The volume of research has grown significantly, especially for the first three stages [2–8].

Various quantitative evaluation methods have been created to assess geoheritage values (e.g., [9–14]). The most common criteria used for assessment in these methods include scientific value, aesthetic value, representativeness, rarity, integrity, extent of scientific knowledge, and geological diversity. In some studies, however, the need to consider the cultural relevance of geoheritage sites has been emphasised, especially as an antidote to the prioritisation of sites with high aesthetic values [15,16].

With growing interest and efforts, 169 geoparks from 44 countries have thus far been registered as UNESCO Global Geoparks [17]. Geographically, however, most of these geoparks are concentrated in Europe and East Asia, although a rapid growth is observed in Latin America. The lack of representation from African and Arab states, as well as Small Island Developing States, is evident and is highlighted by the fact that UNESCO has recently started offering grants to aid the establishment of geoparks in these regions [18,19].

In Southeast Arabia (i.e., the UAE and Oman), although no sites have yet been recognised in UNESCO frameworks, geoheritage conservation and geotourism are budding initiatives. In Oman, Al Hoota cave has been developed and promoted as a show cave [20], and in the UAE, Buhais Geological Park opened in 2020. Moreover, the Ministry of Tourism in Oman has developed a mobile app dedicated to promoting the geotourism resources of the country [21]. An inventory of regional geoheritage sites has been conducted by Searle [22] for the establishment of geoparks in the region. These inventories are extensive in their coverage of geological sites, especially those related to the Semail ophiolite, but apart from a few caves and wadis, Quaternary palaeoenvironmental (QP) sites lack representation.

Southeast Arabia boasts a wide variety of Quaternary landscapes that enables studies on Quaternary palaeoenvironments, the complexity of their variability over time, and their impact on the human demographics. Throughout the Quaternary, the landscape of this region alternated between wetter and drier conditions. Archaeological and palaeoclimatic evidence (e.g., [23–29]) has shown that early human settlement in the region is closely associated with environmental variability. This makes Quaternary palaeoenvironmental sites not only important as climatic archives, but also as “geocultural” sites that provide important lines of evidence for archaeological research. Indeed, many palaeoenvironmental studies from Arabia (e.g., [30–36]) include archaeological relevance as one of the main motives for the research.

Despite their scientific importance, only a few studies have considered QP sites in this region as heritage sites in need of conservation. A rare exception is the Abu Dhabi Sabkha, UAE, where Lokier [37] and Kirkham and Evans [38] have emphasised its unique heritage values, and reported how recent years have witnessed the destruction of this site due to petroleum and civil engineering activities. The loss of QP sites has also been reported in a few palaeoenvironmental studies, such as the sites studied by Atkinson, et al. [39] being destroyed by industrial development [33].

To draw attention to the heritage values of QP sites and to help prevent further loss, we present the Geocultural Database of Southeast Arabia (GDSA), the first database on QP sites in Southeast Arabia, designed to fulfil the first of the five stages of geoheritage conservation. The primary objectives of this database are to catalogue Southeast Arabian palaeoenvironmental archives and their endangerment status and to facilitate the identification of their scientific values, including their geocultural aspects. Additionally, it aims to help palaeoenvironmental scientists and archaeologists find relevant data from past research efficiently. To create such an inventory, it is considered a good practice to first define the database’s topic (type of heritage), scale, values (for what values these sites are evaluated), and use (goal), as outlined by De Lima, et al. [40] and Brilha [14]. Evidently, the topic of this database is QP sites, and its scale includes two countries: Oman and the UAE. The consideration of values for QP sites in Southeast Arabia is difficult, as most evaluation methods have been developed by researchers with experiences predominantly in Europe (e.g., [9–14]). In fact, an evaluation method does not yet exist for QP sites in arid regions. Therefore, this database collates available scientific data from each site as qualitative scientific values and does not attempt to quantify the data as relative values. The database also includes data on archaeological sites in the region as a response to the fact that connections with regional archaeology have been identified as a part of the scientific significance of palaeoenvironmental research in this region.

2. Regional Setting

Southeast Arabia is located in the arid subtropical climate belt, with the Rub'al Khali desert to the west and the Hajar Mountains to the east. Today, most of the region receives an annual rainfall below 100 mm except for the area around the Hajar Mountains, where it reaches up to 400 mm [41]. The main mechanisms producing precipitation are convective rainstorms, tropical cyclones, cold frontal troughs, and the southwesterly monsoon [41]. Rainfall occurs mainly in the winter for much of the region [42], but in the southern part, it occurs as monsoon rainfall in the summer months [43]. Geologically, about 44% of the land surface of this region is covered by Quaternary sediments (Figure 1). Quaternary landscapes in the region are divided into aeolian (57%), alluvium and gravel (24%), fluvial (14%), sabkha (5%), and others (>0.1%). The Rub'al Khali and the Wahiba sands are the main areas covered by aeolian sediments in this region. Both UAE and Oman have experienced major economic development over the past 20 years, with GDP growth of over 300% [44,45], boosted by the growth of the oil industry.

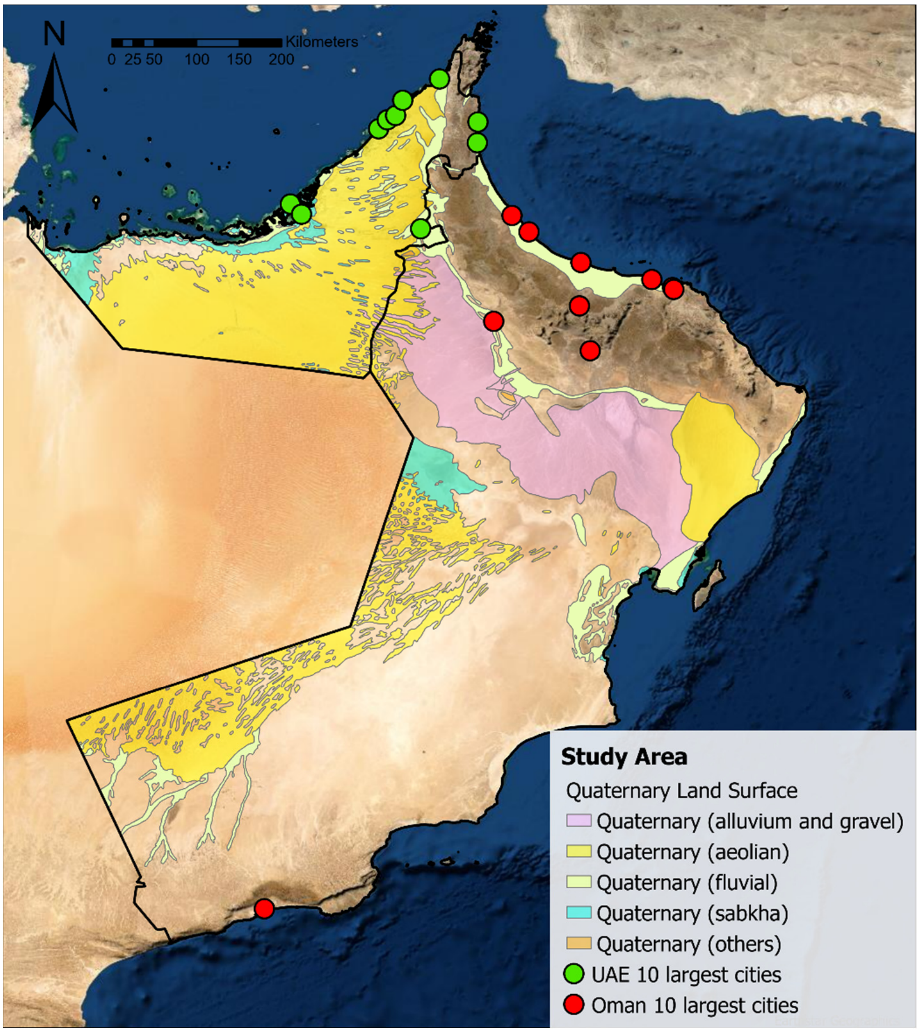

Figure 1. Satellite imagery of the study area and its Quaternary surface geology (geological data from Pollastro, et al. [46]). Satellite imagery from Esri, Maxar, Earthstar Geographics, and the GIS User Community. (Data on the largest cities in Oman are from the National Centre for Statistics & Information [21], and data on the largest cities in the UAE are from the Populated Places map by open-source data from Humanitarian OpenStreetMap).

3. Palaeoenvironment and Prehistoric Archaeology in Southeast Arabia

As the landscape of Southeast Arabia has periodically alternated between wetter and drier conditions throughout the Quaternary period, the region contains a wide variety of landforms that reflect regional and, by extension, global climate variability. These landforms provide records of changes in the regional climate, which is regulated by the interplay of several atmospheric systems, including the mid-latitude westerlies and the summer monsoon system. Palaeoenvironmental records from this region are also important for the understanding of global climate change, as the variability in the monsoon system has been considered as a teleconnective response to global climate variability [47].

A wide range of palaeoenvironmental studies has been undertaken across the region to establish the nature and timing of climatic changes and corresponding landscape responses, with chronologies derived from three main dating methods. Optically stimulated luminescence dating (OSL) has been used for sediment samples from sand dunes [36,48,49], palaeolakes [34], alluvial fans [29,50], and sabkhas [51,52]. For biological materials such as shell middens [53] and palaeomangroves [54], radiocarbon dating (^{14}C) has been used. Finally, uranium–thorium dating (U-Th) has been used to date the formation of speleothems [55,56]. In addition to the collection of chronometric data, recent projects such as the Palaeoenvironments and Archaeological Landscapes (PEARL) research project are attempting to apply new techniques, including the collection of palaeoecological data from the region using ancient sedimentary DNA [57], for a more holistic palaeoenvironmental reconstruction.

Palaeoenvironmental research in this region has a relatively short history. Most of the research has been conducted in the past 30 years, and it is only in the past 20 years that development and refinement in chronometric dating techniques have enabled the construction of a robust chronology of environmental changes (Figure 2).

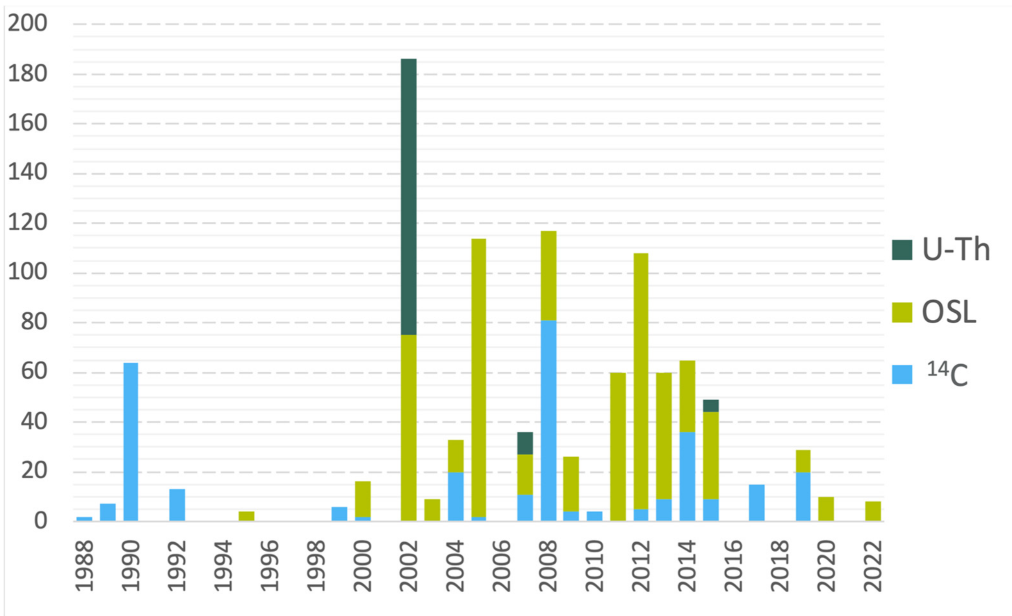

Figure 2. Number of published Quaternary palaeoenvironmental (QP) records and the dating method used in Southeast Arabia per year (data derived from the Geocultural Database of Southeast Arabia, GDSA).

The 30 years of research have elucidated the complexity of climatic fluctuation in this region. Until about 10 years ago, the palaeoenvironment of this region (especially wetter periods) was thought to be driven mostly in correspondence with the dominant forces that drive climate change at a global scale. In particular, climatic variability was attributed to eccentricity-paced northern hemispheric glaciation over a 100 k-year cycle [24,58]. Also, marine isotope stages (MISs) are commonly used as indicators of climatic variability over the Quaternary, in which odd numbers indicate periods with warmer, wetter climate with limited global ice volumes (interglacial periods) and even numbers indicate colder, drier periods with larger global ice volumes (glacial periods) [59]. More recently, however, it has been demonstrated that the nature and the timing of environmental change in Southeast Arabia are far more complex; alluvial fan records indicate a strong correspondence with the ca. 23 ka precessional cycle [28,32], while archaeological records suggest that human occupation was not strictly limited to strong "wet" phases (e.g., [60,61]). In addition, the broad heterogeneity of the Arabian landscape and the spatio-temporal variability of climate systems are becoming increasingly apparent. Regional complexity governed by localised geological and climatic factors is also considered a key component in understanding the history of regional climate change [62] and, by extension, human occupation.

Archaeologically, Southeast Arabia is a region of global interest for the study of the early development of modern human populations. The earliest evidence of anatomically modern human (AMH) dispersal out of Africa is recorded in Israel at around 194–177 ka [63]. In Al Wusta, Saudi Arabia, human fossil evidence has been identified in close association with lacustrine sediments and dated as older than 85 ka [64]. Beyond the Levant and Arabia, AMH fossils dated to 70–46 ka have been found in Southeast Asia [65], and human presence has been documented from lithics in Australia dated to ~65 ka [66]. However, the route that our ancestors took beyond the Levant is still contested due to the paucity of fossil evidence in Arabia [67].

For the past two decades, archaeologists have been debating over the routes that humans took out of Africa into Arabia and beyond [68,69]; two main hypotheses, involving a southern route and a northern route, have been proposed. Recently, however, this simplistic notion involving one route or the other is being called into question [70] with an acknowledgement that landscape heterogeneity plays an important role in ancient demographic change. In addition, it is important to note that the relationship between the environment and human settlement/migration is neither causal nor linear, but the role of the environment as an important contributing factor makes palaeoenvironmental studies highly relevant for studying archaeological hypotheses [23,24,27].

4. Materials and Methods

In discussing geoheritage, most terms lack an internationally recognised definition [71]. Table 1 presents definitions of geoheritage-related terms as used in this study. There is a need for a critical analysis of these and other terms within the geoheritage field, but the definitions presented here are well-established and well-cited definitions taken from the international literature.

Table 1. Definition of geoheritage-related terms used in this study.

Term	Definition
Geoheritage	The heritage or legacy of geological features on the Earth and recognises important or significant features of the Earth via a process of identification, categorisation, and evaluation, ultimately for their preservation for heritage, research, education, and tourism [5]
Geosite	A location, area, or territory in which it is possible to identify a geological or geomorphological interest for conservation [3]
Geopark	Well-defined territories with a development plan that aims to integrate the conservation of geological heritage (and other natural assets) with the preservation of the cultural identity of local communities [14]
Geodiversity	The natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landform, processes), and soil features. It includes their assemblages, relationships, properties, interpretations, and systems [7]
Geotourism	Tourism which sustains and enhances the identity of a territory, taking into consideration its geology, environment, culture, aesthetics, and heritage and the well-being of its residents [72]

4.1. Data Collection

Palaeoenvironmental records from Southeast Arabia which range from the present to approximately 934 ka, near the technical limitation of luminescence dating [73], were collected predominantly from published and unpublished articles. For unpublished sources, only those with clear metadata obtained by the authors (e.g., Stokes et al. [74]) were used. In addition, archaeological records from periods older than the Iron Age (~2200 BP) [75] were collected based on a literature review. However, due to the spatial nature of this database, archaeological sites without clear indications of their location (either in coordinates or in maps) in their publication are currently not included. Table 2 provide a breakdown of the types of information collected for palaeoenvironmental records and archaeological records. ^{14}C ages in the database have been calibrated using the latest IntCal20 and Marine20 calibration curves [76]. The database includes two inputs from the SCAPE database, a database on the chronological robustness of Holocene Quaternary palaeoenvironmental sites in Southeast Arabia [62]. The landform type classification has been developed to distinguish common types of geomorphological, sedimentological, and biological characteristics of Quaternary palaeoenvironmental sites for a nuanced analysis of their climatic implications. The robustness of chronology is a traffic light system that classifies the quality of the chronological data based on their data collection methods.

Table 2. Types of information collected for QP records and archaeological (Arch) records in the GDSA.

Information	Details	Information Available for
Location	Latitude and longitude of the site	QP, Arch
Precise location	Yes/no question of if the precise location of the site is provided	QP, Arch
Nearest populated place	Nearest populated place, derived from Thiessen polygons and populated place data from OpenStreetMaps	QP, Arch
Country	Country of the location	QP, Arch
Emirate/ governorate	Emirate (for UAE) and governorate (for Oman) where the site is located	QP, Arch
Wilayat	(Only for Oman) Wilayat (sub-region) where the site is located	QP
Protection status	Whether the site is protected under an established framework	QP
Protected area name	Name of the protected area	QP
Designation type	Type of designation that protects the site	QP
Landform type	Landform type (sensu) of the record	QP
Record type	What dating method was used to find the chronology of the QP record (QP) Type of archaeological record (Arch)	QP, Arch
Record information	Additional information on the setting of the record	QP
Record age	The age of the record in BP. (Mean of the upper and lower error range values)	QP, Arch
^{14}C 2 sigma old	The older of the 2 sigma range ages of the record in BP	QP, Arch
^{14}C 2 sigma new	The newer of the 2 sigma range ages of the record in BP	QP, Arch
OSL error range	The $\pm$ error range of the record in BP	QP
Archaeological period	Archaeological period to which the record belongs. Classification of periods based on [74]	Arch
Climatic implications	Climatic implications (wet, arid, transition, etc.) of the record as described in the source	QP
Robustness of chronology	Traffic light assessment system for the robustness of the chronological data (data available for records younger than 20 ka)	QP

4.2. Endangerment Assessment

An endangerment assessment for palaeoenvironmental sites in the database was conducted to understand the status quo of each site and as a first step to develop a list of endangered sites for conservation purposes.

Endangerment Criteria

The endangerment level of each site was evaluated based on a visual assessment of historic and current satellite imagery on Google Earth Pro and Bing Maps. These platforms were used because they provide free high-resolution colour imagery of the past 20 years [77], the period in which most palaeoenvironmental studies have been conducted in this region [62].

As the purpose of the assessment is to create a list of endangered sites, rather than to create a ranking of sites in the most danger, first, the types of disturbances were categorised. Then, a semi-quantitative scale was created to summarise the likelihood and the severity of disturbances. This approach allows a more nuanced, case-by-case comparison of sites in danger, compared to a fully numerical scale that appoints a definite value and ranking to each site, even if they are in similar conditions.

Disturbances to palaeoenvironmental sites can be either anthropogenic or natural. Anthropogenic disturbances were categorised based on the main types observed in the Endangered Archaeology in Middle East and North Africa (EAMENA) database [78], a database that documents archaeological sites in the Middle East and North Africa (MENA) region using satellite imagery. Quarrying was added as an additional type of disturbance, as many palaeoenvironmental records have been collected from quarries (e.g., [29,79,80]). Natural disturbances were categorised based on regional climatic factors and previous literature [81]. Table 3 summarises the categories of disturbances considered. To evaluate the likelihood and severity of natural disturbances, projections and hazard maps were used along with satellite imagery. For inland flooding, a MENA-scale hazard map [82] and a worldwide hazard map [83] were consulted. For coastal flooding, projections of sea-level rise and annual flooding by 2030 and 2050 [84] were used.

Table 3. Types of disturbances towards QP sites considered in this study.

Category	Disturbance Type	Likelihood Criteria
Anthropogenic Disturbance	Agricultural/Pastoral	Null: No recent activity/development observable around the site in the past 5 years Potential: Activity/development within 50 m of the site or rapid expansion of activity/development within 200 m of the site in the past 5 years Ascertained: Activity/development in the immediate vicinity of the site in the past 3 years
	Infrastructure/Transport	
	Industrial/Productive	
	Development (Construction, Urban Sprawl)	
	Quarrying	
Natural Disturbance	Dune Movement	Null: No signs of dunes moving towards the site Potential: Dune movement towards the site is visible Ascertained: Dune movement visible over the site
	Inland Flooding	Null: Site not located in flooding zone in either hazard map Potential: Site located in flooding zone for one hazard map Ascertained: Site located in immediate vicinity of a wadi or in flooding zone of both hazard maps
	Coastal Flooding	Null: Site not located in flooding projections Potential: Site located in annual flooding zone for 2030 or located in flooded zone for 2050 Ascertained: Site located in flooded zone for 2030

Severity is included to account for the differences in the gravity of disturbance based on its consequences. It is categorised into reversible, irreversible, and cumulative. If the outcome of the disturbance can easily be reversed (e.g., site being fenced off and used for pasture, without removal of the original Quaternary sediment), it is considered reversible. On the other hand, if the disturbance leads to permanent damage, or damage that would require considerable effort to reverse (e.g., site becoming a housing complex), it is considered irreversible. Cumulative disturbance refers to a disturbance that occurs continuously or intermittently [85], and it is relevant for natural disturbances, such as dune movement and annual flooding, in this study. Irreversible threats are considered the most severe threat, but the threat levels of reversible and cumulative threats are not ranked at the categorical level.

The likelihood considers the probability of the disturbance occurring. It is categorised as null, ascertained, or potential, following the assessment of World Heritage in Danger [86]. Each category of disturbance is listed with the criteria of likelihood, which is split into three categories, null, potential, and ascertained. Firstly, if a site meets the null criterion, it is considered that there is no evidence of that type of disturbance towards that site. Secondly, if a site meets the potential criterion, it means that a possibility for disturbance towards a site is detected, but at a lower certainty or in a longer timeframe. Finally, if a site meets the ascertained criteria, disturbance to the site is expected. For anthropogenic threat, a site would be placed into this category when the disturbance is likely to occur in the next 3–5 years based on its trajectory of development. This judgement will be made by analysing satellite imagery from previous years. The 3-to-5-year span is based on the definition of threat in the EAMENA database [78].

Each disturbance is summarised by combining its severity and its likelihood (e.g., irreversible ascertained, cumulative potential). The most severe level of the disturbance towards a site is used as its overall endangerment level unless it faces no observable disturbance or is already destroyed. For example, if a site faces irreversible ascertained danger due to development and cumulative potential danger due to coastal flooding, the overall endangerment level of the site will be represented as irreversible ascertained danger.

4.3. Geocultural database of Southeast Arabia

4.3.1. Compiling the Database

The collected data were compiled into an open-source database which is hosted at a free internet Cloud service for PostgreSQL databases. Instructions on how to access the database are included in the Supplementary Materials Document S2. It is most easily accessed via QGIS, which is a free GIS software, and it has been designed for use by anyone with basic skills in GIS software. GDSA was compiled to serve two purposes:

1. To provide a publicly available catalogue of palaeoenvironmental archives of Southeast Arabia and their endangerment status.
2. To provide a search engine that enables researchers to efficiently find relevant palaeoenvironmental and archaeological data from past research.

To serve these purposes, PostGIS was selected as the platform for this database. PostGIS is an extension of the PostgreSQL system, designed to process and analyse geospatial data [87]. PostGIS was deemed appropriate for this project as it can retrieve specified subsets of data chronologically and geographically using queries written with simple SQL code and can be disseminated easily without cost. The use of Arches Heritage Inventory and Management System, an open-source software platform designed for creating inventories of cultural heritage, used in many endangered archaeology databases was also considered [88]. However, its enterprise-level requirement for upkeep and maintenance was considered inappropriate for this stage of the project.

4.3.2. Search Functions

To facilitate the use of the query function of the database, template queries for anticipated uses of the database by researchers were created using the PostgreSQL coding language and included in the Supplementary Materials Document S1. With these template functions, users without knowledge of the PostgreSQL coding language can take advantage of the query functions, just by specifying the details in each query (e.g., chronological range, MIS, palaeoenvironmental/archaeological site of interest, radius), as guided by the instructions. Additional queries can be added to respond to the users' demands.

4.3.3. Additional Analysis

To analyse the geographical distribution of sites and records in the database, spatial data that are not included in the GDSA have been used. First, Woor et al.'s [62] map of the geomorphological sub-regions of Arabia (modified to include an Arabian Gulf Coast region) was added to analyse geographical distribution trends beyond legislative regions. This map enables a broad geomorphological and physiographic categorisation of the region and includes sub-regions such as the Arabian Sea Coast, the Arabian Gulf Coast, the Hajar Mountains, Northern Rub'al Khali (sub-coastal dune fields), Rub'al Khali (interior dune fields), and South Arabia (around the Hadramawt Plateau). In addition, shapefiles on roads in the region, from the open database provided by Humanitarian OpenStreetMaps, were used to conduct an analysis of the accessibility of QP sites. The proximity of QP sites to roads was analysed using buffers from roads. Finally, the location of potential geoparks in Oman, proposed by Searle [89], was used to consider the development of regional geoparks that combine QP sites with other geoheritage sites. In presenting geographical analyses, a technique called point displacement, which moves points in close proximity to form a circle surrounding their original location for enhanced visibility, is used to demonstrate multiple records from a single site.

5. Results

5.1. Overview of the Database

One thousand seventy-three chronological dates from 234 QP sites and 743 archaeological sites (44 with radiocarbon-dated artefacts) currently form the GDSA, as shown in Figures 3 and 4. The publication years of QP studies range from 1988 to 2022, with a rapid increase in the number of publications after 2001, whereas archaeological studies were published between 1994 and 2022, without a clear trend of increase or decrease. Eleven QP sites are located within protected natural areas.

5.2. Endangerment Assessment

Analysis of satellite imagery enabled an analysis of the overall conditions of QP sites in Southeast Arabia. Of the QP sites, 31 (13%) have been found to be destroyed, and 34 sites (15%) have been marked as under ascertained danger of destruction. Of the 31 destroyed sites, 3 are in Oman, whereas 28 are in the UAE. Conversely, no signs of threat were observed at 103 (47%) sites, and five sites were located within protected areas. In many cases, destroyed sites demonstrate clear signs of destruction, as shown in Figure 5.

As detailed in Figure 6, urban development and infrastructure development are the most prevalent causes of destruction for QP sites in Southeast Arabia, as these two threats are the causes for 13 and 8 sites being destroyed, respectively. Other causes of destroyed sites include quarrying (five sites), agriculture (four sites), and industrial productive activities (one site).

Of the sites under ascertained danger, 11 sites are under irreversible threat, 1 site is under reversible threat, and 25 sites are under continuous threat. Three sites face both irreversible and continuous ascertained danger. Of the 11 sites under irreversible ascertained danger, 9 are in the UAE and 2 are in Oman, with the most prevalent causes being development and quarrying, with 4 sites each.

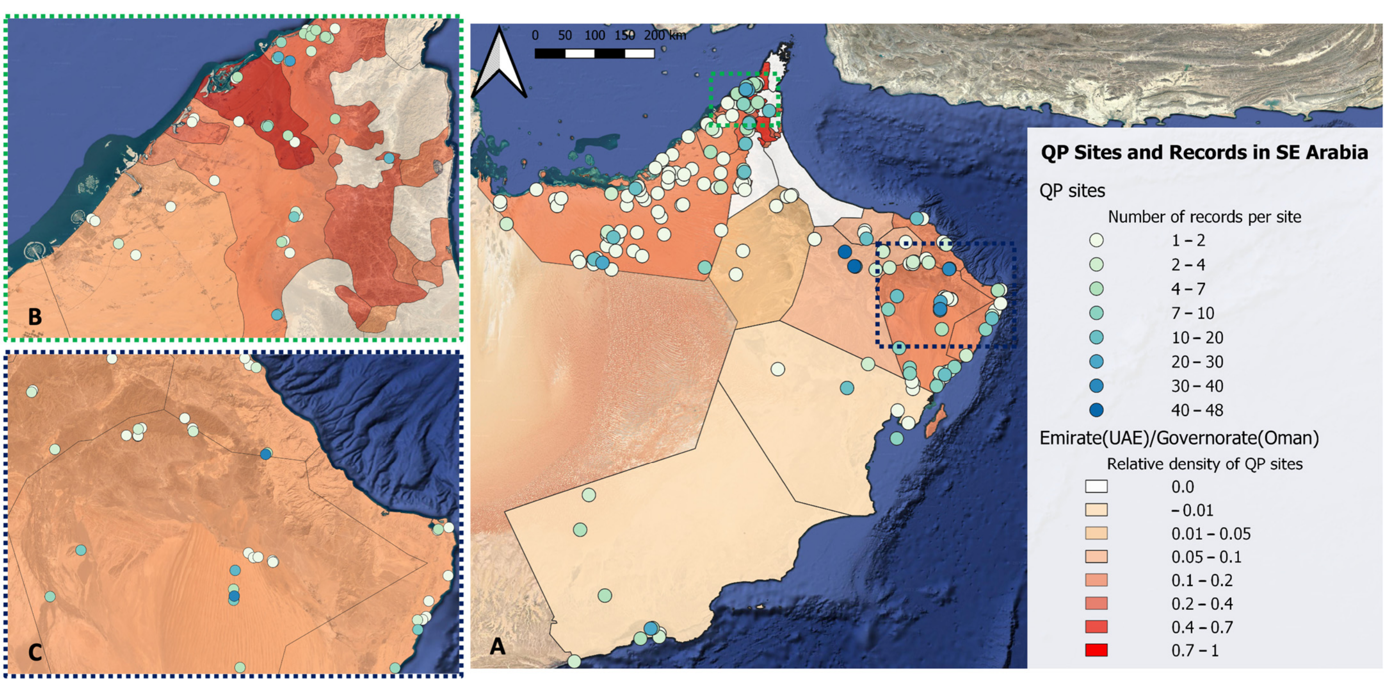

Figure 3. (**A**) QP sites in Southeast Arabia with an indication of the number of chronological records per site. The shaded background represents the relative density of QP sites per emirate/governorate. (**B**) An insert of Northeast UAE, an area with a high concentration of endangered QP sites. (**C**) An insert of Northeast Oman, an area with a high concentration of endangered QP sites.

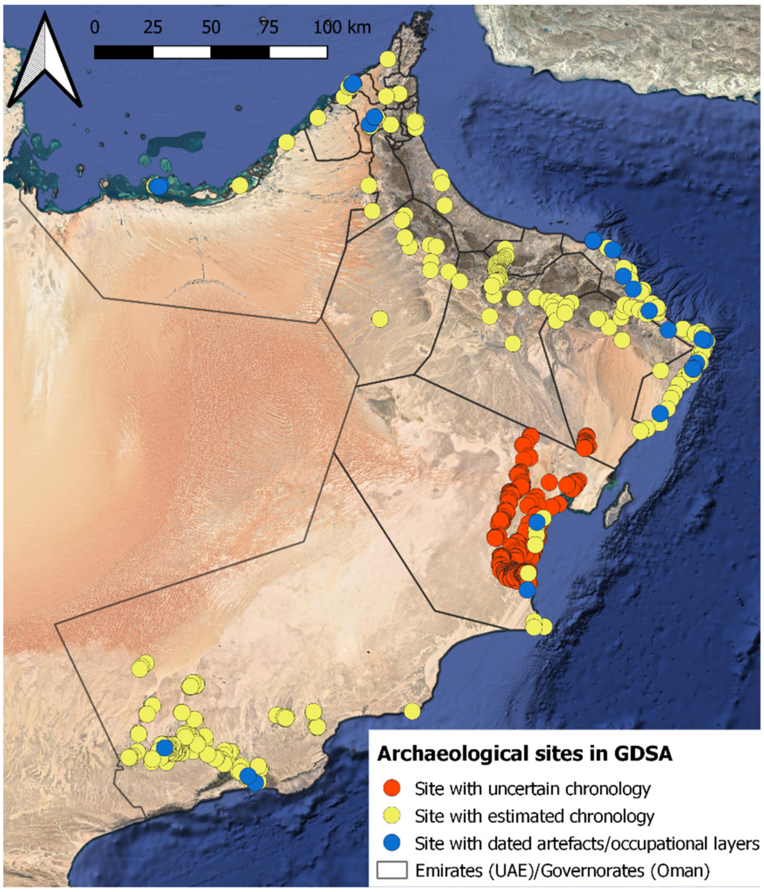

Figure 4. Archaeological sites included in the GDSA and the precision of the chronology at each site.

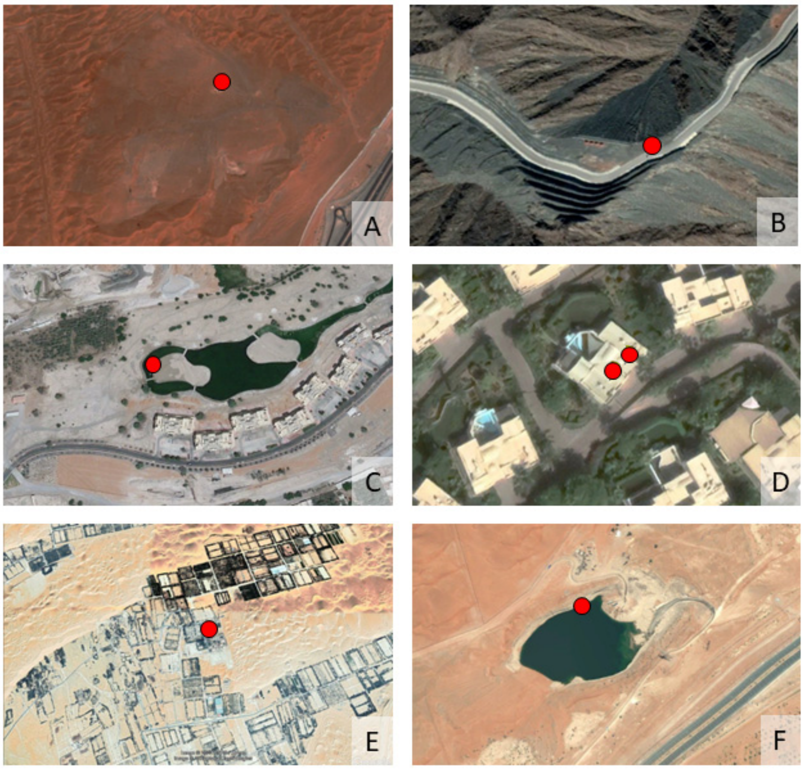

Figure 5. A composite of destroyed QP sites in Oman and the UAE (images from Google Earth): (**A**) outcrop from Atkinson et al. (2011) [39] destroyed by quarrying activities; (**B**) travertine site from Kelemen et al. (2008) [90] destroyed by the development of a road; (**C**) Hili Formation gravel site from Stokes et al. (nd) [74]. destroyed by construction of an artificial water body; (**D**) coastal dune sites from Stokes et al. (nd) [74] destroyed by housing development; (**E**) sub-sabkha dune site from Juyal et al. (1998) [91] destroyed by agricultural development; (**F**) aeolian and fluvial site from Parton et al. (2015) [29] turned into wastewater disposal site.

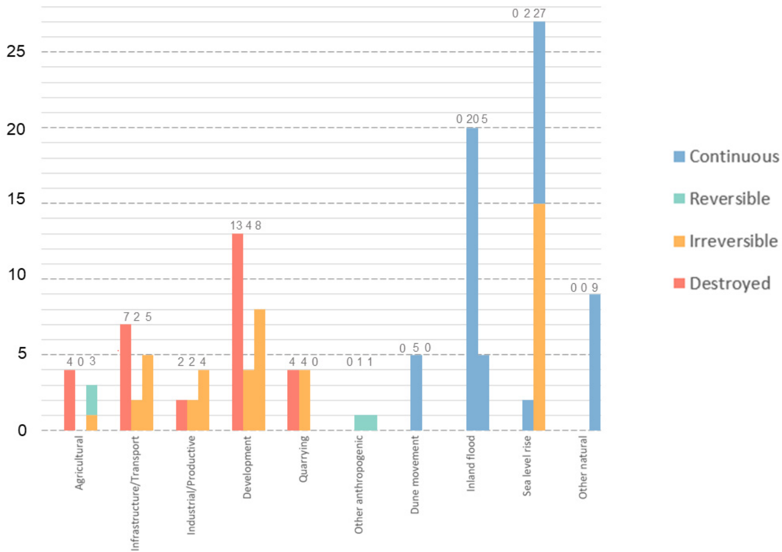

Figure 6. Types and gravity of threat towards Quaternary palaeoenvironmental sites in Southeast Arabia. The three bars for each type of threat represent different levels of its likelihood: the left bar indicates sites already destroyed, the centre bar indicates sites under ascertained danger, and the right bar indicates sites under potential danger. The colour of the bar indicates the severity of the threat, as shown in the legend. Numbers on top of each stacked bar demonstrate the total number of sites in each threat type and likelihood category.

For potential danger, sea level rise is the most prevalent cause, with 15 sites under irreversible threat, meaning they are projected to be under water permanently by 2050, while 12 sites are under continuous threat, meaning they may be in danger of being underwater during seasonal floods. It is closely followed by inland flooding, with 20 sites under ascertained danger and 6 sites under potential danger. Sea level rise and inland flooding are two of the most common types of disturbance in the database.

6. Discussion

6.1. Threats toward QP Sites

Compared to archaeological sites in the MENA region, as recorded by the EAMENA project, QP sites in Southeast Arabia demonstrate a greater proportion of disturbance and a different distribution in the type of threats. As of 2016, of the 180,000 sites registered in the EAMENA database, about 10% of them have been recorded as disturbed [92], which is less than the proportion of QP sites recorded as destroyed in the GDSA, which is at 13%. Although sites in the two databases cannot be compared directly, due to differences in the methodology and the sample size, it could be said that QP sites studied in Southeast Arabia are under at least as high a level of threat as archaeological sites in the MENA region.

In the EAMENA database, the five primary disturbance types are agricultural/pastoral, natural, infrastructure, looting, and industrial, with agricultural/pastoral threat affecting more than twice the number of sites disturbed by any single other type [78]. On the other hand, natural threat (i.e., dune movement, inland flood, and sea level rise), development, infrastructure/transport, quarrying, and industrial/productive are the five most common threat types in the GDSA. The relative abundance of sites under natural threat in the GDSA is most likely due to a combination of the coastal setting of sites, focus on water-related landscapes of QP research (e.g., wetlands, lakes, alluvial/fluvial systems), and the longer-term projection used for assessing natural threats. For anthropogenic threats, QP sites demonstrate a much higher level of endangerment due to development, infrastructure/transport, and quarrying, while demonstrating a lower level of impact from agriculture/pastoral activities. A possible reason for this difference could be the faster pace of economic development in Southeast Arabia compared to the rest of the MENA region, leading to more disturbances related to the secondary sector of the economy. Furthermore, the impact of quarrying must be noted and considered as a prevalent threat specific to QP sites. For QP sites, quarrying is the third most frequent anthropogenic cause for both destroyed and threatened statuses, whereas for archaeological sites in the EAMENA database, it is only the 11th most common cause of disturbance [78].

6.2. Geographical and Disturbance Type Trends

As can be seen in Figure 3, there is a similar number of QP sites in the UAE (119 sites, 51%) and in Oman (115 sites, 40%). Despite the slightly lower number of sites, the number of chronological records from Oman (618 records, 58%) exceeds that from the UAE (455 records, 42%). For archaeological sites, 94% of registered sites are in Oman. This is mostly due to the publication of large-scale surveys in Oman such as the Central Oman Palaeolithic Survey [93]. As archaeological sites without clear published indications of their location are currently not included in the database, the addition of such sites could change this distribution trend.

QP sites are concentrated in certain legislative regions (i.e., in the UAE, individual emirates; in Oman, regional governates). In the UAE, Abu Dhabi, the largest emirate with mostly Quaternary surface geology, hosts the highest number of recorded QP sites (n = 71), although the highest concentration of recorded QP sites per square kilometre is in Umm Al Quwain. In Oman, the highest number of recorded sites is in Ash Sharqiyah North (n = 40), while the highest concentration was found in Muscat, although the concentration is less than one-fifth of that of Umm Al Quwain, demonstrating that the studied QP sites in Oman are more widely dispersed. On the other hand, no QP sites have been studied or recorded in Fujairah (UAE), Al Batinah North, Al Buraymi, or Musandam (Oman). The distribution of sites does not seem to depend on the rural–urban classification, as 60% of the sites are located more than 50 km away from the centre of the 10 largest cities in either country, and 35% of sites are more than 100 km away.

On the other hand, proximity to roads has been identified as a strong influencing factor for the location of sites. Eighty-one sites (35%) are located within 200 m of major roads, along with 135 sites (58%) within 500 m, and 189 sites (81%) within 2 km, demonstrating that accessibility by car is a major factor in the location of QP research in Southeast Arabia. Proximity to roads also helps us understand the characteristics of QP sites under threat, as a much higher proportion of destroyed sites are in proximity to major roads (and, therefore, an increased likelihood of development), with 55% within 200 m, 87% within 500 m, and 94% within 2 km.

Another trend for sites under threat can be found when considering their geomorphological regions. As shown in Figure 7, destroyed sites are concentrated in three of the eight geomorphological regions: Northern Rub'al Khali (n = 13), Arabian Gulf Coast (n = 11), and Hajar Mountains (n = 7). The ratio of the number of QP sites in the Hajar Mountains region (n = 66, 28%) is proportionate with the ratio of destroyed sites (n = 7, 23%). On the other hand, although the sites in Northern Rub'al Khali (n = 67) and Arabian Gulf Coast (n = 41) make up 46% of all sites, these two regions host 77% of all destroyed sites. In addition, these two regions host 9 of the 11 sites (82%) under irreversible ascertained danger, demonstrating the highest need for conservation efforts. The endangerment of QP sites in the Arabian Gulf Coast is especially noticeable, with 71% of the sites in this geomorphological region considered to be under some level of endangerment.

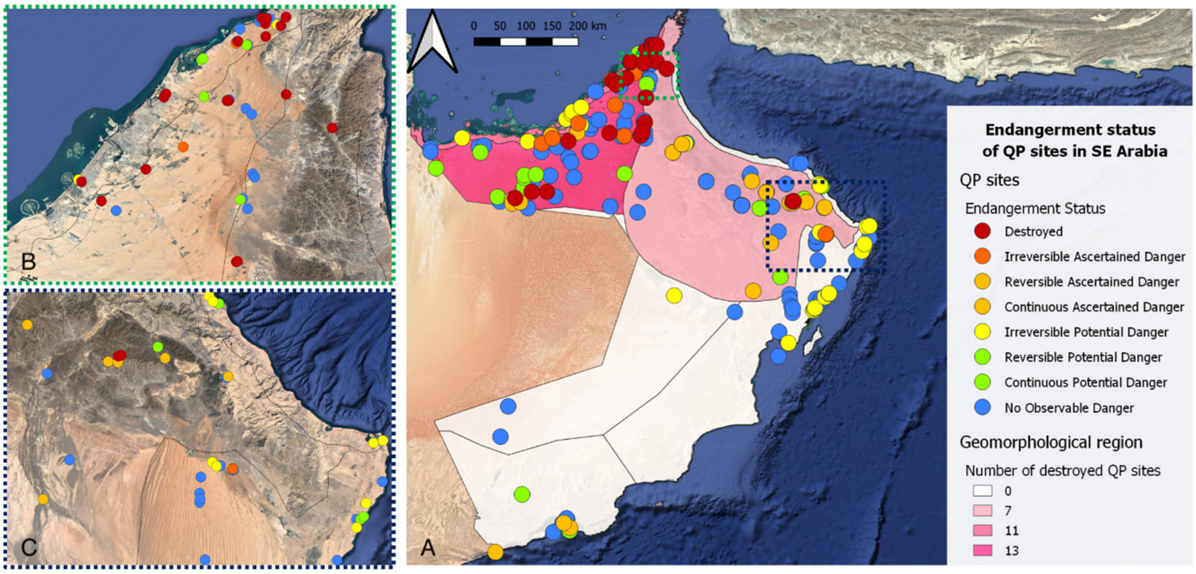

Figure 7. (**A**): The endangerment status of QP sites in Southeast Arabia. The base layer represents the number of destroyed sites in each geomorphological region. (**B**): Insert of an area in Northeast UAE with a high concentration of endangered sites. (**C**): Insert of an area in Northeast Oman with a high concentration of endangered sites.

Furthermore, an analysis of the cause of endangerment reveals that QP sites in each of these three geomorphological regions demonstrate distinct patterns. In the Arabian Gulf Coast, development and expansion of cities endanger QP sites, with development and infrastructure causing the destruction of nine sites and two sites, respectively. Descriptions of the cause of destruction include the construction of housing and the construction of man-made water features. In fact, all 11 destroyed sites are located within 25 km from the centre of the 10 largest cities in the UAE, such as Abu Dhabi, Sharjah, and Dubai, and 8 of them are within 10 km.

In the Hajar Mountains region, destruction of QP sites has mostly been due to the development of roads (n = 5) with some housing development (n = 2). With only two sites within 50 km from the centre of the 10 largest cities in either UAE or Oman, urban development does not explain the destruction of QP sites in this region. Beyond destroyed sites, there are no sites with irreversible ascertained danger in the Hajar Mountains region, but this region has the highest number of continuous ascertained danger (n = 13), due to the number of sites located within fluvial settings to study the chronology of hydrological processes in the area.

Finally, QP sites in the Northern Rub'al Khali region face the widest variety of threats. The two primary causes of destroyed QP sites in this region are quarrying (n = 5) and agriculture (n = 4). These two types of threats are almost exclusive to this geomorphological region at all levels of endangerment. All eight sites under threat or destroyed by quarrying are in this region, as well six out of seven sites endangered due to agriculture. In this region, quarrying activities provide materials such as rocks for land reclamation and aggregate for construction. Geographically, four of the five sites destroyed by quarrying are located within 20 km of the Arabian Gulf coast, where the largest cities are concentrated. Sites under irreversible ascertained threat due to quarrying are located further away from the coast, but with further economic development without conservation efforts, they will most likely be disturbed and lost. On the other hand, sites destroyed due to agriculture are located either in the Liwa Oasis (n = 3) or the Al Ain Oasis (n = 1), where arable land is limited.

Overall, although the location of the QP sites in Southeast Arabia does not seem to depend on the proximity to large urban areas, QP sites that are destroyed or are under irreversible threat are concentrated in urban areas or are related to industrial activities related to urban development (e.g., quarrying).

6.3. Landform Trends

The number of QP sites recorded from each type of landform is outlined in Figure 8 (some sites include records from more than one landform). With 108 sites (43%), aeolian records are the most common type of landform features represented in the database, followed by springs (n = 46, 18%) and fluvial (n = 40, 16%) records. Sites with aeolian records have been destroyed the most, at 16 sites. This could be because aeolian sites are also the most common type of chronological records in the database. Aeolian QP sites, however, are prone to quarrying. All eight QP sites in the database disturbed by quarrying contain aeolian records, of which four have been destroyed. At the sites destroyed by quarrying, satellite imagery shows the presence of cross sections suitable for palaeoenvironmental studies at some point over the last 20 years. In these cases, it is likely that the cause of the destruction of the site was the intervention that enabled the data to be collected in the first place. A similar trend can be observed in analysing the cause of destruction for QP sites with fluvial records. QP sites with fluvial records represent 24% of destroyed sites, although they are only found in 16% of sites in the database. This relatively high representation indicates that fluvial QP sites are more prone to disturbance than other types of sites. This could be attributed to the fact that sand and gravel present at fluvial QP sites are often quarried for aggregates and is evidenced by the fact that 4 out of 10 destroyed fluvial QP sites were destroyed due to quarrying.

Conversely, spring sites and mangrove sites in the database are less prone to disturbance. For spring sites, only 3 out of 46 sites have been destroyed, and most ascertained and potential dangers are natural threats due to proximity to water sources. The relative lack of anthropogenic threat towards these sites is likely because most of these sites are located in the Hajar Mountains, away from large urban areas, and because they are often too small for economic activities such as mineral extraction. For mangrove sites, 1 out of 16 sites has been destroyed, and none face irreversible ascertained danger. As 4 of these 16 sites are designated under protection, this result could be considered as an outcome of nature conservation efforts in this region since mangroves often benefit from ecological/biodiversity protective measures [94,95].

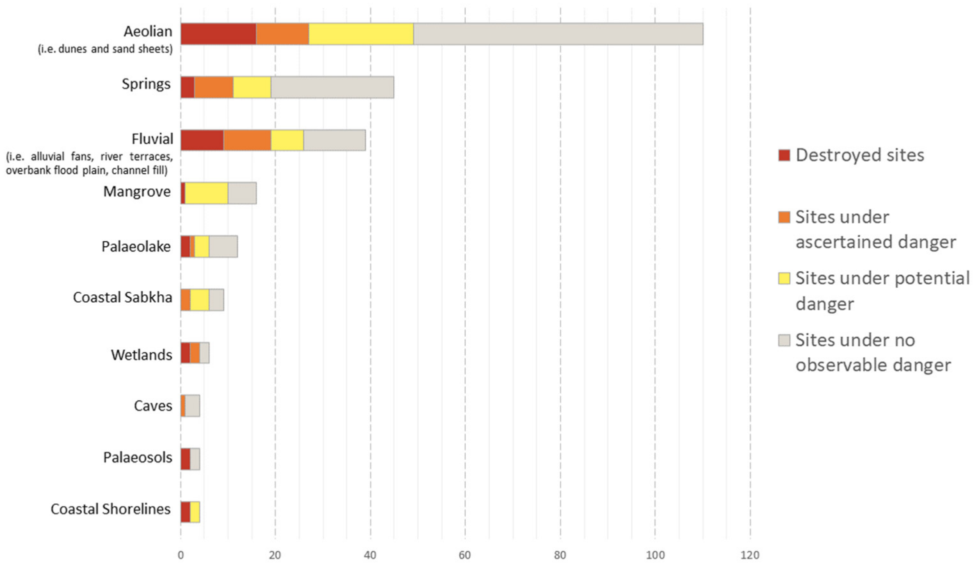

Figure 8. Endangerment status of QP sites in Southeast Arabia per landform type.

On the other hand, for coastal sabkha sites, although none of the nine sites are destroyed or under irreversible ascertained danger according to the criteria of this study, it has been reported that in the UAE, only 36% of the Abu Dhabi Sabkha has remained undisturbed since the 1960s [37]. This discrepancy demonstrates the limitation of the GDSA, as the sites recorded in this database are only sites documented by published sources and analyses of the changes only cover the last 20 years. To analyse larger areas or a longer timescale, it is necessary to combine the GDSA with other sources and/or field observations.

Of the less common types of landforms, some, such as palaeosols (two out of four), shorelines (two out of four), and wetlands (two out of six), have been destroyed proportionately more than others. However, due to the small sample size and the lack of a clear trend in the destruction cause or geographical location, it is unclear whether these sites face (or have faced) a greater level of threat than other types of sites.

7. Applications

7.1. Use of the Database for Archaeologists and Palaeoenvironmental Scientists

The strength of the GDSA database is that it is publicly available, and it allows both chronological and geographical analysis of QP data simultaneously. Furthermore, it allows an analysis not only of QP sites, but also of regional archaeological sites. Archaeologists, on the other side, can use the database to analyse the relationship between their archaeological site of interest and the regional palaeoenvironment. Furthermore, this database can be used in secondary or tertiary education for students studying geography, Earth sciences, and archaeology. The database will be updated on demand when provided with new data, and annually to include newly published data.

As shown in Figure 9, the database can demonstrate regional climatic transitions among marine isotope stages using data obtained from QP sites and the corresponding archaeological sites. Although Figure 9A shows MISs that are considered "wet", and Figure 9B shows MISs that are considered "dry" at the scale of the entire Arabian Peninsula, the palaeoenvironmental data from this region do not always correspond with this general trend. Instead, they demonstrate the spatio-temporal variability of climatic conditions within the region, reiterating the results of recent studies (e.g., [61,62]) that show evidence of increased sub-regional-scale precipitation, humidity, or water resources even in the supposedly dry periods. Furthermore, the database also provides a useful synthesis of a site's scientific attributes. As shown in Figure 10, all information regarding the record, such as the source, chronology, and data type, can be included in the attribute table of the maps, and be accessed with a few clicks. Researchers can use this database as a starting point to analyse their new data, to gain an overview of the regional palaeoenvironment, or to prioritise sites and/or regions on which to focus research.

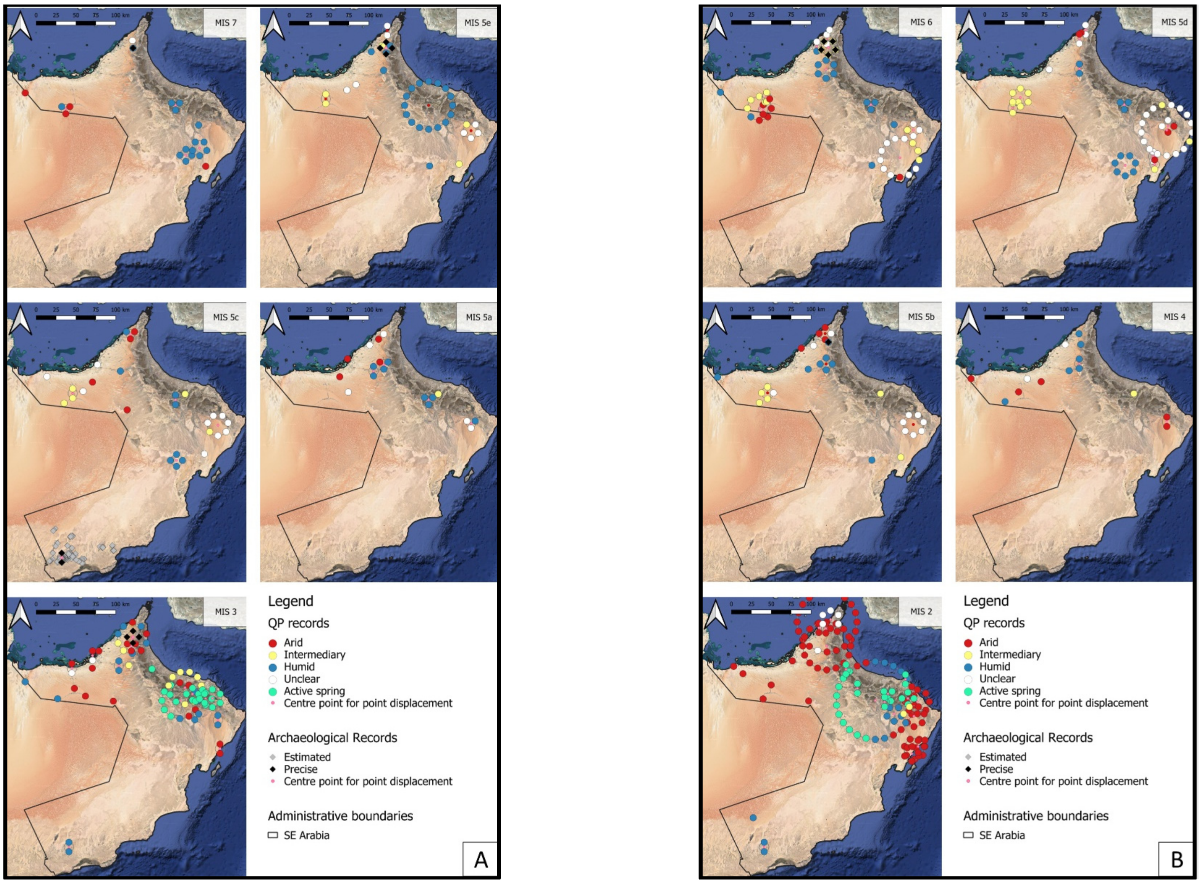

Figure 9. Maps demonstrating QP sites and archaeological sites in Southeast Arabia dated to MIS 7 to MIS 2. Point displacement is applied on the map to demonstrate multiple records from the same site. (**A**) MISs that are generally considered "wet"; (**B**): MISs that are generally considered "dry".

7.2. Case study: Relating Archaeological Records and QP Records at Jebel Faya, UAE

Jebel Faya, a site with the oldest evidence of human occupation beyond the Levant, is a rockshelter site located in the interior of the Emirate of Sharjah, with evidence of human occupation at around 210 ka (MIS 7), 170 ka (MIS 6), 135–120 ka (MIS 5e), 95 ka (MIS 5b), 40–38 ka (MIS 3), and 10–6 ka (MIS 1) [61,99]. This site has been occupied by humans due to its favourable geographical setting within a large alluvial plain situated between the mountains and the coast. The evidence of settlement at the site, however, indicates intermittent occupation. A hiatus in occupation from ca. 38 to 10 ka BP and possibly for a period after ca. 90 ka BP is evidenced by cultural discontinuities in the finds from each assemblage [100,101].

With queries set up alongside the database (see Supplementary Materials Document S2 for instructions), users can connect chronological data, their geographical location, and attributes such as climatic implications to archaeological records from this site, as shown in Figure 11. This figure shows all QP records in the database for which the error range of the chronology overlaps with the chronology archaeological records from Jebel Faya. Each map represents an MIS in which archaeological records from Jebel Fayahave been found. The distribution of QP sites for MIS 7 to MIS 5 is very similar to that of Figure 9 except for the speleothem data from Fleitmann et al. [98]. This is most likely due to the fact that the resolution of U-Th records in this region (e.g., those from Fleitmann et al. [98])

is relatively higher than the resolution of OSL records, especially when they are of older periods. Nevertheless, it shows the need for further palaeoenvironmental data from around the archaeological site (particularly for MIS 7) to better understand how the regional climatic setting may have facilitated the occupation of Jebel Faya. For MISs 1 and 3, the map allows a focused analysis of the palaeoenvironmental records related to the Jebel Faya site, showing a great variability in the regional climate, at periods in which evidence for human occupation is found.

	source_summary	recordid	mis	climatic_implications	easting	northing	type	agebp	osl_error	landform_type	record_information
1	Blechschmidt et al. (2009)	140	MIS7	Humid	57.718457	21.330856	OSL	233000	26000	Fluvial	Alluvial Fan sands
2	Blechschmidt et al. (2009)	141	MIS7	Humid	57.718457	21.330856	OSL	232000	21000	Fluvial	Alluvial Fan sands
3	Blechschmidt et al. (2009)	142	MIS7	Humid	57.718457	21.330856	OSL	225000	22000	Fluvial	Alluvial Fan sands
4	Blechschmidt et al. (2009)	143	MIS7	Humid	57.718457	21.330856	OSL	214000	19000	Fluvial	Alluvial Fan sands
5	Blechschmidt et al. (2009)	157	MIS7	Humid	58.206772	21.582674	OSL	229000	37000	Fluvial	Alluvial Fan sands
6	Blechschmidt et al. (2009)	158	MIS7	Humid	58.206772	21.582674	OSL	227000	27000	Fluvial	Alluvial Fan sands
7	Blechschmidt et al. (2009)	159	MIS7	Humid	58.206772	21.582674	OSL	220000	24000	Fluvial	Alluvial Fan sands
8	Blechschmidt et al. (2009)	160	MIS7	Humid	58.206772	21.582674	OSL	213000	46000	Fluvial	Alluvial Fan sands
9	Blechschmidt et al. (2009)	161	MIS7	Humid	58.206772	21.582674	OSL	194000	18000	Fluvial	Alluvial Fan sands
10	Goodall (1995) in Glennie and Singhvi (2002)	412	MIS7	Arid	52.033333	23.533333	OSL	208000	21000	Aeolian	Aeolian beneath duricrust
11	Immenhauser et al. (2007)	449	MIS7	Humid	58.171986	22.397347	U-Th	212402	NULL	Caves	NULL
12	Juyal et al. (1998) in Glennie and Singhvi (2002)	467	MIS7	Arid	58.423181	20.940241	IRSL	229000	19000	Aeolian	Aeolianite (miliolite)
13	Stokes and Bray (2005)	881	MIS7	Arid	53.411389	22.976944	OSL	209000	16000	Aeolian	Madinat Zayed Fm (Megabarchan)
14	Stokes and Bray (2005)	894	MIS7	Arid	53.542222	22.922778	OSL	188000	18000	Aeolian	Madinat Zayed Fm (Megabarchan)
15	Stokes et al. unpubl.	944	MIS7	Unclear	55.827234	25.388445	OSL	193110	30750	Palaeosols	Hili Fm
16	Wood et al. (2003)	966	MIS7	Humid	53.453791	22.996758	OSL	195000	27000	Fluvial	Palaeo interdunal sabkha - HUMID?
17	Bretzke et al. (2022)	976	MIS7	Humid	55.847519	25.118808	OSL	212000	19000	NULL	Occupational layer
18	Fleitmann et al. (2003)	1144	MIS7	Humid	57.353625	23.094827	U-Th	197000	7400	Caves	Speleothem Carbonate
19	Fleitmann et al. (2003)	1145	MIS7	Humid	57.353625	23.094827	U-Th	187000	9000	Caves	Speleothem Carbonate
20	Fleitmann et al. (2003)	1146	MIS7	Humid	57.353625	23.094827	U-Th	194000	6800	Caves	Speleothem Carbonate

Figure 10. Attribute table of QP records in Southeast Arabia from MIS 7 obtained from the GDSA. All mentioned references are Blechschmidt et al. (2009) [50], Goodall (1995) in Glennie and Sighvi (2002) [42], Immenhauser et al. (2007) [56], Juyal et al. (1998) in Glennie and Singhvi (2002) [42], Stoke and Bray (2005) [96], Stokes et al. (nd) [74], Wood et al. (2003) [97], Bretzke et al. (2022) [61], and Fleitmann et al. (2003) [98].

Users can generate these maps and tables for any archaeological site by changing the archaeological area and the timeframe (available in year BP or MIS) of interest. With the queries, users can further filter the data based on attributes such as landform type, geomorphological region, climatic implications, distance from the archaeological site, and the robustness of the chronology (for QP sites with ages younger than 20,000 BP). These queries facilitate the review of the connections between QP sites and archaeological sites. Similarly, palaeoenvironmental data can be compared to other palaeoenvironmental records in the database. Instructions for using these functions in the database are available as Supplementary Materials Document S2.

7.3. Use of the Database for Geocultural Conservation

The catalogue and endangerment status for each QP site in this database provide a baseline for initiating the conservation of QP sites in Southeast Arabia. The database can be used as a communication tool with local stakeholders to monitor and flag the destruction of sites, especially those that are under ascertained threat. In this regard, the endangerment status for registered QP sites is planned to be updated next year to remotely track changes in potential threats.

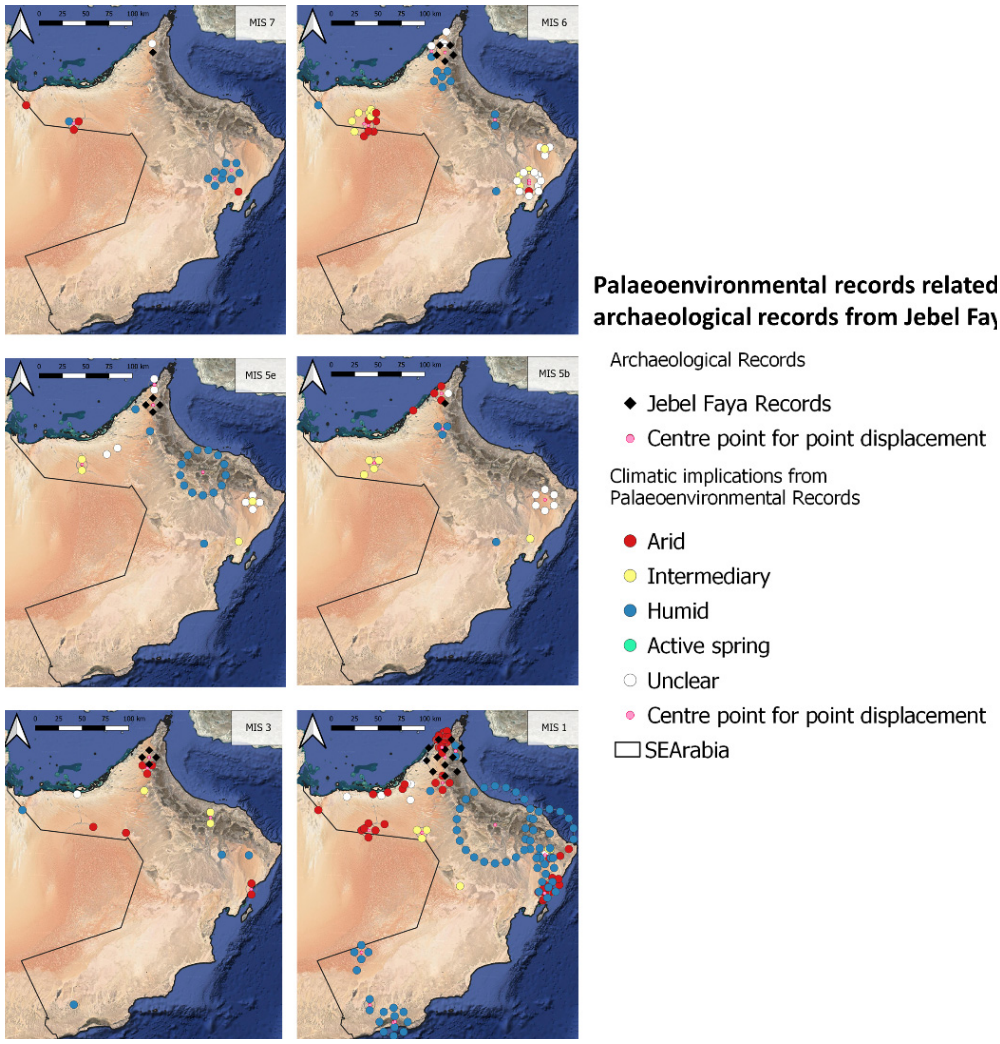

Figure 11. Map demonstrating archaeological records from Jebel Faya, UAE, per MIS, with chronologically corresponding QP records. Point displacement is applied on the map to demonstrate multiple records from the same site.

In promoting the conservation of QP sites, those located in quarries present a unique issue. Quarrying activities have provided opportunities for many QP studies (e.g., [27,39]) by providing human-made cross sections (e.g., through quarry face outcrops) suitable for investigation. For some former mining/quarrying geoheritage sites, such as the Mesel Pit Fossil Site in Germany, extraction activities have been stopped after the discovery of scientific findings (i.e., fossils) [102], but given the current lack of conservation measures for QP sites, such large interventions could be difficult in the near future. Nevertheless, with an inventory such as this database, a system of reporting similar to one employed in the UK [103] could be created to inform scientists and other stakeholders before destruction takes place, and to enable additional data collection if necessary.

In addition, the database facilitates a geocultural approach in promoting QP sites and other geoheritage sites in the region. By browsing and querying the database, users can easily find locations where archaeological sites and QP sites are concentrated in proximity and analyse the chronological relationship between the two types of sites. These data, combined with information on other types of regional geoheritage sites such as suggestions for geoparks by Searle [89], can be used to propose potential geoparks in the region, such as the one demonstrated in Figure 12. This demarcated area, in the north of Oman in the Hajar Mountains, includes archaeological findings from the Late Bronze Age, palaeoenvironmental data from springs between MIS 1 and early MIS 3, and speleothem data ranging from MIS 1 to MIS 11 that can be used to build a story of how the natural environment of the region changed throughout the Late Quaternary. The speleothem data from Al Hoota (or Hoti) Cave [98] are especially important as they provide a continuous high-resolution record of humid periods in this region. As Al Hoota Cave is already protected and developed as a tourist destination [104] with a museum, it could serve as the central area to introduce the entire geopark. Beyond the Quaternary, three geoheritage sites highlighted by Searle [89], Jebel al Akhdar, Jebel Shams, and Jebel Misht, with features from the Permian to the Cretaceous periods are located within the proposed geopark area. Jebel al Akhdar, in particular, is an important site for the study of Late Cretaceous thrust sheets and Permian–Cretaceous shelf carbonates, and it is suggested as a potential world heritage site by Searle [89]. Although primarily focused on the conservation of QP sites, this database can potentially contribute to the advancement of geoheritage conservation as well as archaeological conservation in this region.

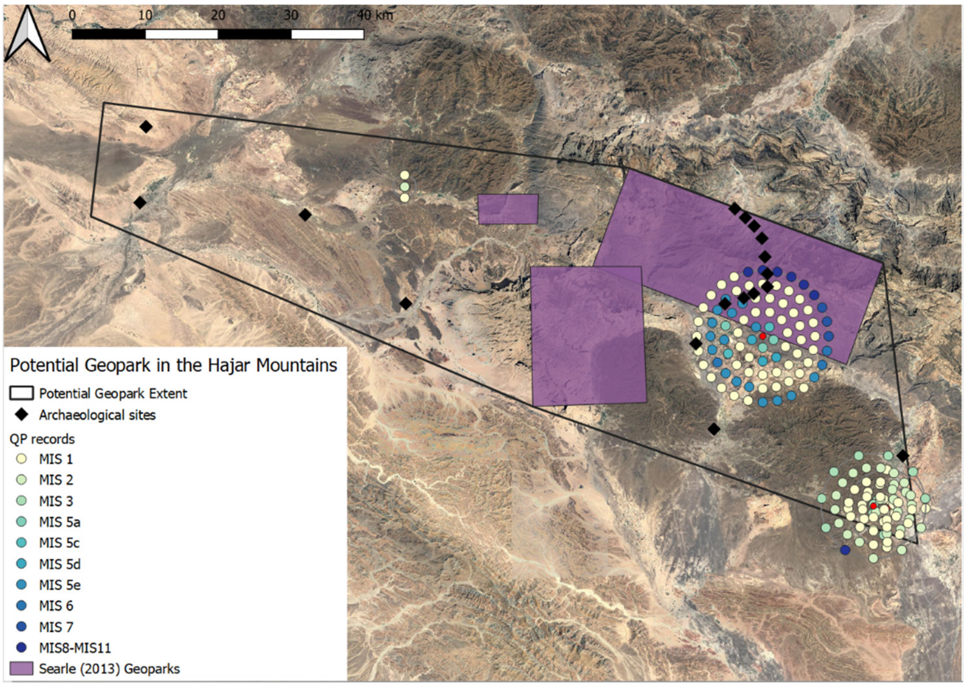

Figure 12. Potential area for a future geopark in Oman, in the Hajar Mountains. Point displacement is applied on the map to demonstrate multiple records from the same site.

8. Conclusions

Geoconservation is a budding initiative in Southeast Arabia and the broader MENA region, but the protection of Quaternary sites has not been a priority in most cases. The GDSA serves as the first step towards a systematic and scientific conservation of QP sites in Southeast Arabia. This study showed that an analysis of satellite imagery can provide an adequate endangerment assessment of the overall conditions of QP sites, using a methodology adopted from projects targeting archaeological sites in the MENA region [92]. The endangerment criteria created for this assessment reflect natural and anthropogenic threats specific to the regional natural environment, documented in heritage conservation literature. The approach can be adopted in other parts of the MENA region in the future, although the distinction between potential and ascertained threats may require adjustment based on factors such as data availability (e.g., sea level rise, flooding) or the speed of anthropogenic activities.

A need for protection of these sites is evident, with 13% of QP sites registered in the database found to be destroyed in the last two decades, along with more than 15% of sites considered to be under ascertained danger. Anthropogenic activities related to economic development are the main causes of endangerment for QP sites in this region, and sites in coastal areas and sites with fluvial landscape-related records face the highest level of endangerment. The need for the conservation of these sites is evident, with the proportion of destroyed QP sites in this region exceeding that of disturbed archaeological sites in the MENA region. As economic development continues in this region at a fast pace, monitoring of sites in these higher-risk settings should be considered a priority at this stage. Nonetheless, an evaluation of the values of QP sites from different perspectives, such as scientific values, touristic values, and educational values, is required to conduct a rigorous assessment to determine sites that should be prioritised for conservation or sites that are suitable for geotourism development.

The GDSA also functions as an open-access platform for researchers and other interested parties to obtain data on the palaeoenvironment of this region, along with studying their relevance for the regional archaeology. Its unique capability to conduct spatial and chronological analysis simultaneously should facilitate future research in this field, especially when comparing palaeoenvironmental data with archaeological data. Furthermore, it is hoped that the free access to these data, which have mostly been shared privately within research groups until now, will encourage more researchers to enter palaeoenvironmental and archaeological research in this region. The close relationship between the two disciplines, or the geocultural connection, should be explored as a strategy to protect both types of heritage sites.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142114096/s1, Document S1: Template codes for the GDSA; Document S2: Instructions to use the GDSA.

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Conflicts of Interest: The authors declare no conflict of interest regarding this research project.

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