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Potential Economic Sources of Rare Earth Elements in Libya: Evidence from the Al Uwaynat–Kufra Region

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Abstract

Various studies indicate that Libya possesses a wide range of geology with potential areas for discovering rare earth elements (REEs). However, until now, no REE resources have been identified in the country. In this regard, this study was conducted to examine the prospectivity for REE mineralization in Libya using remote sensing and GIS. The study found that the southeastern part of Libya, specifically the Al Uwaynat crystalline massif and the Al Uwaynat–Kufra corridor, had the highest prospectivity for REEs. The results showed that the area had favorable spectral, alteration mineralization, lithology, and carbonatite anomalies with significant lineament density. Consequently, the research recommended detailed follow-up geological, mineralogical, and geochemical surveys to confirm the initial findings. Generally, the produced prospectivity map can only be used for regional exploration and should not be used to estimate potential resources or economically viable mineralization.

المصادر الاقتصادية المحتملة للعناصر الأرضية النادرة في ليبيا: أدلة من منطقة العوينات-الكفرة

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الكلمات المفتاحية
العناصر الارضية النادرة، الاستشعار عن بُعد، نظم المعلومات الجغرافية، العوينات، حوض الكفرة، ليبيا.

الملخص

تشير دراسات متعددة إلى أن ليبيا تتمتع بخصائص جيولوجية متنوعة تتضمن مناطق واعدة لاحتمالية وجود العناصر الأرضية النادرة؛ ومع ذلك، لم يتم حتى الآن تحديد أي موارد لهذه العناصر في البلاد. وفي هذا السياق، أُجريت هذه الدراسة لتقييم احتمالية وجود تمعدنات للعناصر الأرضية النادرة في ليبيا باستخدام تقنيات الاستشعار عن بُعد ونظم المعلومات الجغرافية. وقد خلصت الدراسة إلى أن الجزء الجنوبي الشرقي من ليبيا - وتحديداً كتلة العوينات الصخرية البلورية والممر الرابط بين العوينات والكفرة - يُعد المنطقة الأكثر واعدية لوجود هذه العناصر. وأظهرت النتائج تمتع المنطقة بخصائص مواتية تشمل السمات الطيفية، ومؤشرات التمعدن المرتبط بعمليات التغير الصخري وشذوذات صخور الكربوناتيت، فضلاً عن كثافة ملحوظة في الخطيات الجيولوجية. وبناءً على ذلك، أوصى البحث بإجراء مسوحات جيولوجية ومعدنية وجيوكيميائية تفصيلية لاحقة للتحقق من النتائج الأولية. وبشكل عام، فإن خريطة الاحتمالية المُنتجة تصلح لأغراض الاستكشاف الإقليمي فقط، ولا ينبغي استخدامها لتقدير الموارد المحتملة أو تقييم الجدوى الاقتصادية للتمعدنات.

1. INTRODUCTION

The lanthanides (elements 57-71 in the periodic table), with the exception of the extremely unstable promethium (Pm, atomic number 61), are referred to as rare earth elements (REEs). Lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu) are the 14 elements that make up REEs. They can be divided into two categories: (1) Light rare earth elements (LREEs, La-Eu); and (2) Heavy rare earth elements (HREEs, Gd-Lu). Yttrium (Y) and scandium (Sc) are geochemically similar to REEs and are classified as part of the HREEs. REEs are important because of their unique magnetic, electrical, optical, and catalytic properties and are widely used in technologies such as permanent magnets, batteries, electronics, wind turbines, electric vehicles, and renewable-energy systems. REEs are generally not rare in the Earth's crust, but they are rarely concentrated enough

to form economically exploitable deposits. They commonly occur in minerals such as monazite, bastnäsite, xenotime, and allanite and are associated with geological environments including carbonatites (Kim et al., 2005; Xu et al., 2010; Doucelance et al., 2014; Mitchell and Smith, 2017; Decrée et al., 2020; Ford et al., 2023; Almohammed et al., 2026), alkaline igneous rocks (Romanova et al., 2012; Benaouda et al., 2017; Muavhi et al., 2021; Fu et al., 2025), granite (El-Taher, 2007; Huang et al., 2012; Yang et al., 2018; Liu et al., 2022; Zou et al., 2026), pegmatite (Habler et al., 2007; Eberle et al., 2012; Mohammedyasin et al., 2017; Amigun et al., 2022; Tende and Clark, 2026), phosphate deposits (Ounis et al., 2008; Khan et al., 2012; Auer et al., 2017; Karimzadeh and Tangestani, 2022; Hassan et al., 2026), and heavy-mineral sands (El-Kammar et al., 2007; Abdel-Karim et al., 2016; Veerasamy et al., 2021; Morin-Ka et al., 2025).

Compared to research on other mineral deposits, the earlier studies on REE resources in Libya are limited. The available information is mainly regional or focused on geology relevant to potential REE occurrences rather than describing REE resources. According to Dhahri et al. (2023), Libya is characterized by a wide range of rock types. Thus, the country has an excellent potential for containing various mineral resources. On the other hand, the researchers note that there are currently no confirmed REE resources in the country. Nevertheless, they assume that unexplored areas, mainly in southern and eastern Libya, could contain undiscovered mineral resources. Further geological, geochemical, and geophysical studies and even remote sensing via satellite could help assess the potential of these regions. Accordingly, the research highlights the potential for REE exploration in Libya, but it does not show any confirmed REE resources. Ren et al. (2025) reviewed the distribution of REE deposits in Africa. In this regard, Libya differs fundamentally from countries such as Tanzania, Malawi, South Africa, Angola, Namibia, and Madagascar, which are characterized by a significant number of REE deposits. According to Rare Earth Exchanges (2026), Libya possesses significant potential reserves of REE and some strategically essential minerals currently unexploited in the south of the country. The article mentions two particular areas – the Murzuq and Tibesti corridors – which are believed to hold reserves of REE, gold, and other resources. In particular, Libya has actively engaged the U.S. Geological Survey (USGS) to conduct geological mapping and research to identify the unexploited resources. Nevertheless, the country's potential in REE remains understudied and requires further assessment and exploration efforts to define its volume, quality, and economic feasibility.

The geological framework map (Fig. 1) indicates that Libya is a region with a considerable variability in geological development. The crystalline basement is mainly developed in the southern and southeastern part of the country, including Al Uwaynat. In different parts of the country there is an exposure of alkaline and igneous complexes and large-scale structural features that provide potential areas for mineralization. In particular, the concentration of carbonatite occurrences is obvious in the southeast of Libya (Al Uwaynat–Kufra Region), which suggests that this area has the best potential for exploring REE deposits.

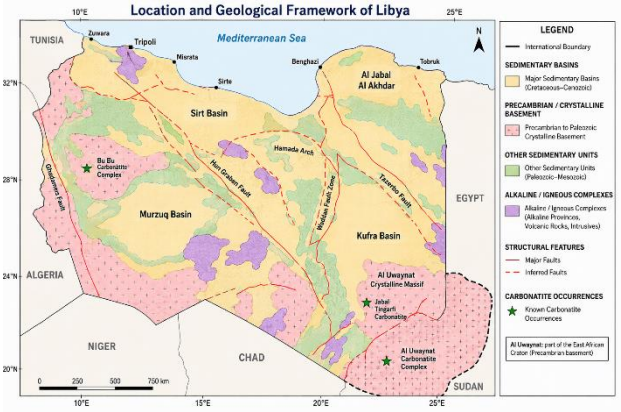


Figure 1: Location and geological framework of Libya.

2. OBJECTIVE

The main goal of the present study is to evaluate and prioritize REE mineralization potential in Libya using a remote sensing and GIS-based approach. Specifically, the study focuses on the Al Uwaynat-Kufra Region and aims to:

(1) Understanding the geology of Libya and identifying potential REE mineralization zones.
(2) Using Sentinel-2 MSI to determine spectral signatures and improve the lithology separation of carbonates/carbonatites, ferric-iron oxides, and hydroxyl alteration anomalies.
(3) Utilizing DEM, to delineate lineaments, circular features, lineament density, and other structural controls.
(4) Using a GIS-based weighted-overlay analysis to combine the evidence layers, including geological, spectral, alteration, and structural, together with carbonate occurrences.
(5) Producing a prospectivity map of REE mineralization potential in the study area classified into very low, low, moderate, high, and very high categories.
(6) Recommending areas for follow-up geochemical and geological surveys.
(7) Presenting a vision for sustainable exploration and development that would diversify Libya's economy and contribute to economic growth by 2040.

3. METHODOLOGY

The authors used remote sensing and GIS-based methodology to assess the geological setting and REE exploration potential of Libya. First, the authors gathered geological and structural data to create the location and geological framework map. Then, the authors analyzed the Sentinel-2 MSI data using false-color band combinations (B12–B11–B4) to enhance the spectral contrast and delineate lithology and surface materials. Such combinations were used to identify carbonate/carbonatite, ferric-iron, and hydroxyl alteration mineral occurrences in the Al Uwaynat–Kufra area. The authors processed the digital elevation model (DEM) to extract the hillshade,

lineaments, circular features, and lineament-density polygons to identify structural controls on mineralization. Finally, the authors combined the geological, spectral, alteration mineral, and structural data with carbonatite occurrences using the GIS-based weighted-overlay analysis. This analysis produced the REE prospectivity map, which was classified into very low, low, moderate, high, and very high classes. The final 2040 conceptual predictive map used the prospectivity areas as a basis, while sustainable exploration, infrastructure, employment, downstream processing, investment, and economic diversification scenarios highlighted the potential contribution of REEs to the economy of Libya by 2040.

4. RESULTS AND DISCUSSION

The B12–B11–B4 Sentinel-2 composite (Fig. 2) demonstrates the region's compositional variability, as seen in the wide range of spectral responses from different materials and lithologies. Southern Libya is highly variable in its surficial sediments, ranging from exposed bedrock, sand seas, weathered sediments, and different lithologic types. The Murzuq and Kufra basins are underlain by broad expanses of various sedimentary rocks and sands, whereas the Al Uwaynat crystalline massif has a distinct spectral response. Similar trends can be seen throughout the study area, suggesting that delineation of different lithologic units using Sentinel-2 imagery has potential to identify areas of interest for further mineralogical assessment.

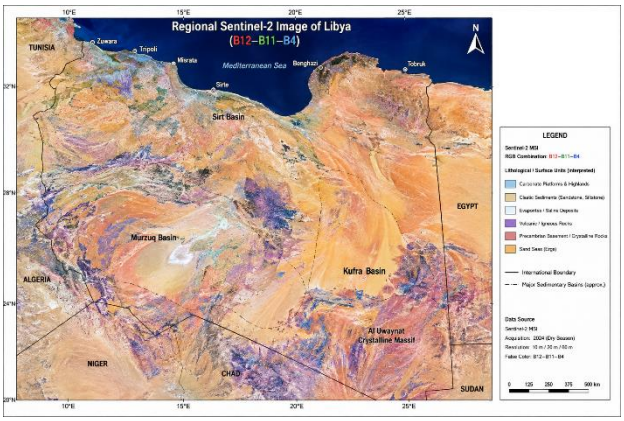


Figure 2: Regional Sentinel-2 image of Libya.

The detailed image (Fig. 3) allows one to discern geological units in the southeastern study area more clearly than in the previous case. The Al Uwaynat crystalline massif, which is enveloped by the sedimentary rocks of the Kufra Basin, appears as a region of distinct spectral heterogeneity. The ground covered with carbonatite deposits and other rocks of a complex structural history is also of interest within the studied area. Thus, the figure indicates areas containing various types of rocks, their transformations, and associated surface materials that can be of interest to conduct further multi-spectral mineral exploration. The Al Uwaynat–Kufra Region can be regarded as a priority for further geological and geochemical investigations.

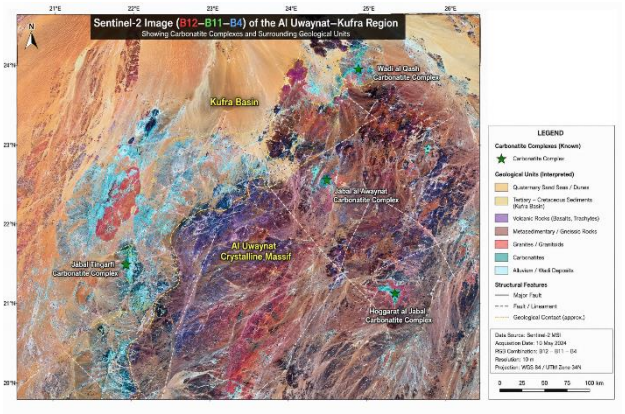


Figure 3: Sentinel-2 image of the Al Uwaynat–Kufra Region.

The carbonate/carbonatite anomaly map (Fig. 4) indicates zones with anomalous spectral response related to carbonate minerals. Moderate to very high carbonate anomalies are associated with various locations in Libya, but most prominent is the southeast part of the country around Al Uwaynat and the Kufra Basin. Carbonatites were reported from the regions associated with anomalous spectral response, suggesting that carbonatite occurrences could be found in the proximity of carbonate anomalies. Nevertheless, it should be noted that the detected carbonate anomalies should not be confused with carbonatites. There is a possibility that limestone or other rock types could exhibit a similar spectral response on the satellite imagery.

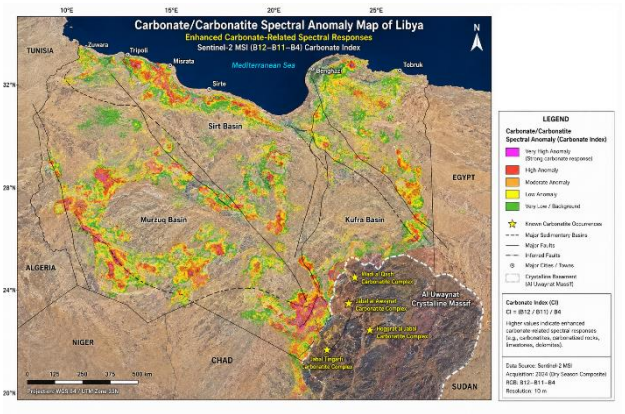


Figure 4: Carbonate/carbonatite spectral anomaly map of Libya.

The integrated alteration map (Fig. 5) highlights the spectral response variability of ferric-iron, hydroxyl and carbonate minerals, which are found in various locations in Libya. Strong anomalies were detected along several structural lineaments, and around outcrops, which were especially evident in zones of the southeastern part of the country. The occurrence of alteration minerals is associated with faults, crystalline rocks, and previously identified carbonatite deposits. This fact adds importance to the detected zones, especially those related to Al Uwaynat, as zones of probable magmatic-hydrothermal impact, which requires further mineralogical and geochemical analyses.

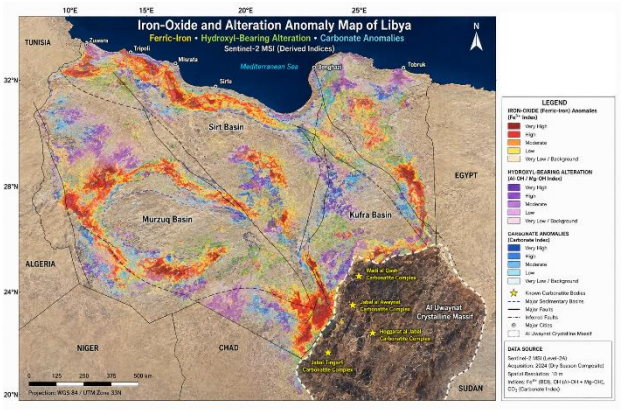


Figure 5: Iron-oxide and alteration anomaly map of Libya.

The DEM-derived hillshade (Fig. 6) highlights the regional pattern and structural architecture of Libya. The extracted lineaments exhibit several dominant trend directions, outlining major structural provinces in the sedimentary basins and crystalline basement areas. Circular and ring-shaped lineament patterns are common in the south and southeast of Libya, and they might indicate intrusion, volcanic centers, or dome structures. Furthermore, the analysis shows that lineaments are concentrated in specific regions with a significant number of circular structures, such as in the Al Uwaynat–Kufra Region. In general, the association of structural intersections and circular features with REE anomalies suggests the importance of considering structural controls on REE prospectivity in the study area.

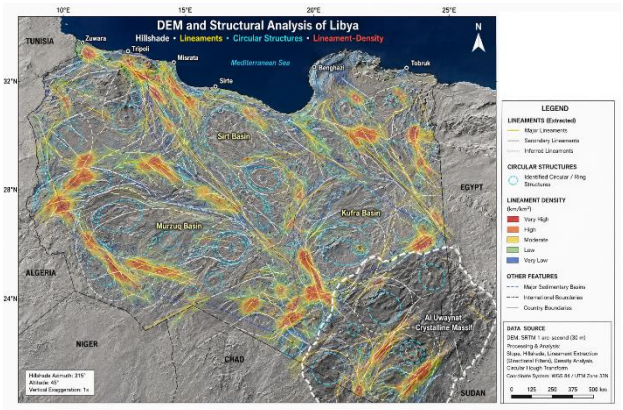


Figure 6: DEM-derived structural analysis showing lineaments and circular/ring-shaped features in Libya.

The integrated REE prospectivity map is presented in Fig. 7. It combines the available geological information, Sentinel-2 spectral anomalies, indicators of alteration, DEM-derived lineaments, and carbonatite occurrences into five classes that represent the areas of very low, low, moderate, high, and very high potential. The highest prospectivity was found to be associated with the southeastern part of the country, including the Al Uwaynat crystalline massif and the Al Uwaynat–Kufra corridor. This area has a significant number of the mentioned REE indicators, which are favorable for carbonatite-related mineralization. Other areas with moderate to high prospectivity were found to be related to particular linear structural zones while most of the sedimentary basins have low prospectivity. The presented map should be primarily used for the exploration prioritization at the regional scale and not as a quantitative assessment of REE mineralization potential.

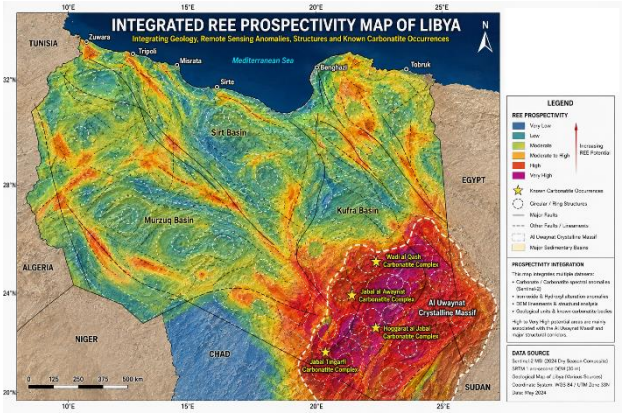


Figure 7: Integrated REE prospectivity map of Libya showing very low to very high prospectivity classes.

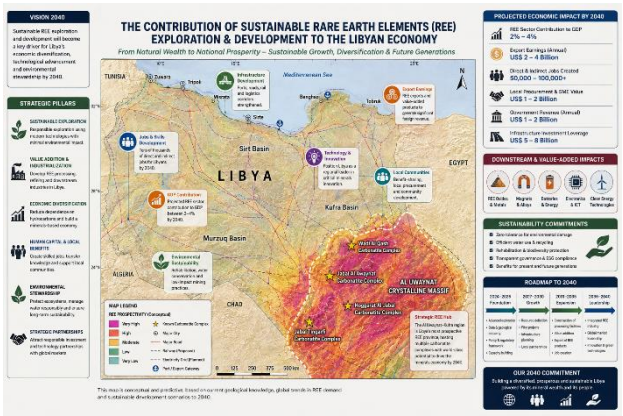


Figure 8: Conceptual map for sustainable REE exploration and development toward Libya's economic diversification by 2040.

The conceptual predictive map (Fig. 8) suggests that successful, responsible REE exploration can significantly contribute to Libya's economic development by 2040. The Al Uwaynat–Kufra Region is considered a priority for further exploration to create an REE province for resource assessment, mining, processing, and value addition. It is assumed that the area will undergo integrated development: improving infrastructure, securing employment and training, sourcing materials locally, innovating, expanding export opportunities, and diversifying the economy. The figure should be treated as a conceptual and predictive model rather than a realistic economic forecast. In reality, it is intended to illustrate the example of resource development for the country by focusing on natural wealth, preserving biodiversity, restoring ecosystems, and protecting water resources.

5. Conclusions and Recommendations

This study highlights the possibility of using remote sensing, DEM analysis, geological information, and GIS for a regional assessment of REE prospectivity in Libya. The geological structure is quite diverse, with various crystalline basement rocks, alkaline and igneous complexes, large-scale fault structures, and carbonatites described, particularly in the southeast part of the country. The study shows significant spectral diversity in Libya based on Sentinel-2 analysis. In particular, the Al Uwaynat crystalline massif demonstrates a clearly distinct and diverse spectral response to the sedimentary rocks of the Kufra Basin, thus being a promising target for further analysis in a broader multiband spectral study. The carbonate/carbonatite spectral analysis detected moderate to very high anomalies in the presented data. The strongest anomalies were associated with the Al Uwaynat location and the Kufra Basin. Some of the discovered anomalies are found in proximity to carbonatite occurrences reported in the literature. Thus, their presence adds credibility to the potential of the area to host carbonatites. Nevertheless, the detected spectral anomalies cannot be used as a reliable indicator of the presence of carbonatites since their presence can be explained by the presence of limestone and other rocks. The alteration analysis revealed that ferric-iron, hydroxyl, and carbonate anomalies are distributed along several structural lineaments and around the crystalline outcrops in the southeast of Libya. Due to their association with faults, crystalline rocks, and carbonatite occurrences, some of the detected anomalies should be given priority. DEM-based structural analysis detected distinct linear trends and numerous circular or ring-shaped features in the southern and southeast of Libya. The large number of identified lineaments combined with the high number of REE-related anomalies found in the Al Uwaynat–Kufra region and the association of anomalies with structures indicate the role of tectonic controls in REE mineralization. The prospectivity analysis revealed that the Al Uwaynat crystalline massif and Al Uwaynat–Kufra corridor are the most promising areas for further exploration activities. This conclusion is based on the coincidence of several spectral, geological, and structural anomalies detected in these regions. Other prospective areas with predicted moderate- to high-grade REE mineralization were found along the structural corridors. In contrast, the wide sedimentary-basin areas were predicted to have low prospectivity. Thus, the obtained results may help in the selection of priority areas for exploration. However, the detected anomalies should not be considered as deposits with a specific grade, tonnage, or economic viability, requiring each anomaly to undergo detailed geological assessment.

The proposed recommendations include the following:
(1) The Al Uwaynat – Kufra Region should be prioritized for further REE exploration due to the highest possible geological, spectral, alteration, structural, and carbonatite indicators.
(2) The most promising areas in terms of REE prospectivity should be prioritized for field geological mapping to confirm the predicted spectral lithology, structural observations, and carbonatite occurrences.
(3) Geochemical surveys, including rock, soil, stream-sediment, and regolith sampling, and analysis, should be conducted to confirm REE contents in the targeted areas with potential mineralization anomalies.
(4) Mineralogical and petrological methods, such as XRF, SEM, and other appropriate geochemical tests, should be used to identify REE mineral assemblages and confirm the presence of carbonatites in the targeted area.
(5) The most prospective regions should be surveyed using airborne or ground geophysics, including radiometric, magnetic, and gravity methods, to identify buried alkaline and carbonatite complexes.
(6) Higher-resolution and multi-temporal satellite imagery should be acquired and analyzed to refine the spectral-et al anomalies and eliminate areal cover, illumination, and spectral confusion effects.
(7) The results of field and laboratory investigations should be integrated into the GIS-based weighted overlay model to update the prospectivity map, which will allow for continuously incorporating new data.
(8) Water conservation, biodiversity, and environmental protection, including mine-site rehabilitation and responsible waste disposal, should be considered in any future exploration and mining activities, which are particularly relevant for the fragile desert ecosystem.
(9) Future economic evaluations should be based on actual REE resources, including their grade, recovery, metallurgical, and infrastructure characteristics, rather than the proposed 2040 scenario.
(10) The 2040 scenario should be considered as the conceptual model for the development of the region, which includes REE mining, processing, and associated infrastructure, as well as job creation, training programs, and economic diversification. The article specifically highlights the potential of the Al Uwaynat – Kufra Region as a future REE province.

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