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Inventory and Analysis of Quarries Using Geographic Information System and Remote Sensing Techniques for Eco-Friendly Quarrying Practices

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ABSTRACT

This study addressed the need for a more comprehensive inventory of pit and quarry operations in Tetouan province and M'diq-Fnideq prefecture. It employed a Geographic Information System (GIS) approach, integrating various spatial remote sensing (RS) and field data to identify suitable areas for extracting alluvial, rocky, and clay materials. The used data includes quarry inventory, geological information, hydrographic networks, slope, and land use. The finding revealed 72 quarries and assessed their suitability for resource extraction. Alluvial deposits, approximately 127 million m^3, were identified mainly in the primary wadis (river valley), including Oued Laou, Oued Amsa, Oued Mhajrate, and Oued Khemis. Massive rock deposits, consisting of limestone and sandstone, were estimated at 3.4 billion m^3. Clay deposits, suitable for various industrial applications, were also identified in significant quantities. In addition to confirming potential quarry deposits, our field surveys indicate that exploitation activities contribute to deforestation, and quarry waste often invades agricultural lands and forests. This information can facilitate sustainable resource management, environmental conservation, and informed policy and planning. The results highlighted the economic significance of geological resources in the study areas, contributing to various industries. Furthermore, by examining the relationship between quarries and the environment, including hydrographic networks, the study provides insights into eco-friendly quarrying practices. This methodology is expected to offer valuable insights into geological resources, guide sustainable resource management, and inform decision-making processes for regional development.

Keywords: quarry, geomaterials, remote sensing, GIS, sustainability, Morocco.

INTRODUCTION

The progress of any civilization is intricately tied to the field of civil engineering, which encompasses the construction of critical structures such as buildings, highways, dams, etc. This industry heavily relies on the extraction of various geomaterials, including rocks, sand, and gravel (Labi, 2014; Iodice et al., 2021; Bungau et al., 2022; Waqar et al., 2023; Sebbab et al., 2023).However, the expansion of the quarrying industry has brought forth a series of environmental challenges. Consequently, it has become imperative for both quarry operations and stone processing facilities to establish sustainable development plans that engage with the broader community and effectively address these environmental concerns (Careddu and Siotto, 2011; Akanwa and Ikegbuna, 2019; Gboe, 2023).

Construction materials sourced from quarries in Morocco are extensively utilized, driven by the region's substantial demographic and economic expansion (HCP, 2014). Given the rapid growth of the housing sector in the Tangier-Tetouan-Al Hoceima region, the demand for construction materials continues to surge. This increased demand aligns with overall economic growth, particularly in the construction and public works sector. The establishment and operation of new quarries are therefore essential to meet the requirements of these strategic construction projects, fostering regional and national development. Tetouan province and M'diq-Fnideq prefecture in the Tangier-Tetouan-Al Hoceima region of Northern Morocco boast a considerable abundance of quarries. However, it's crucial to recognize that quarrying activities exert pressure on the environment, potentially leading to significant and sometimes irreversible consequences. The nature and extent of these consequences depend on various factors, including preserving biodiversity within the natural environment and the specific geographical areas involved.

Alluvial, rocky, and clay materials, constituting fundamental geological resources, play pivotal roles in various industries, including construction and manufacturing (Bomeni et al., 2015; Salmasi and Abraham, 2022). The abundance of alluvial, rocky, and clay quarries in Northern Morocco has garnered increasing attention due to their economic significance and the potential environmental impact they may have. The geological diversity of this region presents a unique opportunity for conducting a comprehensive analysis of these quarries, encompassing assessments of geographical distribution through the utilization of Geographic Information Systems (GIS).

Comprehending the intricate aspects of quarries is vital for sustainable resource management, environmental preservation, and informed decision-making. Numerous authors have delved into sustainable quarry material resource management (Danielsen and Kuznetsova, 2016; Podimata and Yannopoulos, 2016). Some researchers have employed GIS methods to create predictive models, leveraging regional spatial characteristics to identify suitable areas for stone production. These models consider various factors, including land management, environmental considerations and marketplace constraints. Noteworthy contributions in this domain encompass the works of Karakas and Turner (2004) and Karakas (2014). In addition, Barakat et al. (2015) have explored the use of GIS techniques to inventory quarries for ornamental stone and aggregate, analyzing their spatial relations with geology, hydrographic and transportation networks, and consumption points in the Beni-Mellal Region (Morocco). Benbaqqal et al. (2016) applied a GIS approach to career development in building materials, focusing on a case study in the northern part of the former Region of Meknes-Tafilalet. Furthermore, Barakat et al. (2016) assessed aggregate rocks in the Tadla-Azilal region and delineated areas with aggregate resources, employing a GIS approach with weighted overlay analysis for suitable site selection.

This study addresses the gap in quarry census data within Tetouan province and the M'diq-Fnideq prefecture. Specifically, we employ remote sensing and GIS techniques and field investigation to conduct a comprehensive quarry inventory and investigate their spatial associations with the region's topography, geology, hydrology, hydrogeology, and land use. Using these spatial correlations, the GIS techniques identified specific regions up-and-coming for the building material industry, serving as potential quarry sites. This approach facilitates the efficient management of these mineral resources, ultimately ensuring a sustainable and reliable supply for the construction sector.

MATERIALS AND METHODS

Study area

The Tangier-Tetouan-Al Hoceima region is located in the extreme north-west of Morocco. It is bounded to the north by the Strait of Gibraltar and the Mediterranean Sea, to the west by the Atlantic Ocean, to the south-west by the Rabat-Salé-Kénitra region, to the south-east by the Fez-Meknes region and the Oriental region to the east. The surface area of the Tangier-Tetouan-Al Hoceima region is nearly 17,210 km², with an estimated population in 2022 of 3,900,365, representing 10.74% of Morocco's population. This research focuses on two contiguous administrative zones within this broader region: the Tetouan province and the M'diq-Fnideq prefecture. These zones, highlighted in Figure 1a, cover an area of 2542.51 km² and 178.21 km², respectively, within the Tangier-Tetouan-Al Hoceima region. These areas are exciting due to their concentration of open pit quarrying activities. Given its substantial

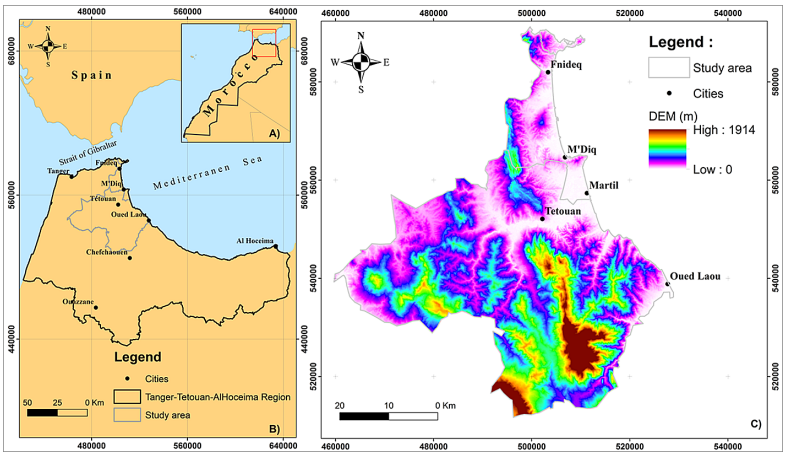

Figure 1. a) General location of Morocco, b) Location of the study area, c) DEM of the study area

environmental and economic significance, we contend that prioritizing this zone is essential.

Tetouan, the second-largest city in the region, boasts an industrial landscape dominated by sectors such as agri-food, chemicals, parachemicals, and garment manufacturing. Tetouan houses approximately 34% of the region's industrial facilities, while M'diq is renowned for its tourist attractions. Our comprehensive field survey encompassed all quarries within Tetouan province and the M'diq-Fnideq prefecture (Figure 1b). This survey unveiled 72 quarries, distributed as follows: 6 in M'diq-Fnideq and 66 in Tetouan. The active status of these quarries can be primarily attributed to the region's ongoing economic and industrial expansion, which has spurred increased activity across all sectors, including extraction. Geographically, most quarries are concentrated in the Tetouan province, spanning the Calcareous dorsal and flyschs nappes. Moving slightly northward, several quarries are situated within the M'diq-Fnideq prefecture.

The study area exhibits a varied altitude, ranging from 1914 m in the central south to sea level (0 m) on the Mediterranean coast. The coastal region has elevated hills and steep cliffs, occasionally yielding to limited pebble beaches and small alluvial plains. The Rif Mountain range rises to altitudes exceeding 1,000 m, extending from west to east, establishing a substantial impediment along most of the coastline. Most regional wadis are also frequently entrenched within deep, narrow valleys (Fig. 1c).

The study area is in the Rif mountain belt (Fig. 2). The Rif is an arc-shaped mountain range with a concavity facing north, made up of allochthonous units spilling outwards from the arc (towards the south), thrust onto the margin of the African plate, and presenting geosynclinal forms. The Rifan geosyncline was transformed into a complex orogen during Tertiary tectonic phases. The study area spans from Sebta in the north to Oued Laou in the east, encompassing continental units, the so-called internal domain that has pushed westward over a considerable distance on the Flyschs Nappes and the External Domain, presenting what can be described as an exotic terrane (Chalouan et al., 2008).

The internal domain corresponds to units originating from the northern paleo-margin of

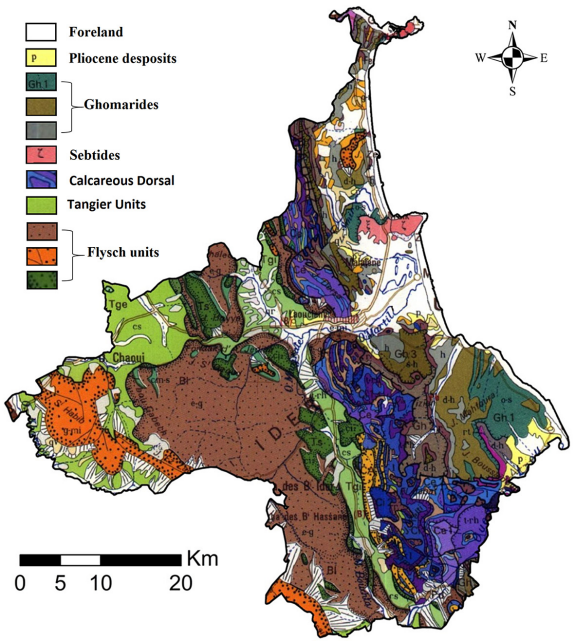

Figure 2. Geological map of the study area, modified from the 1:500,000 geological map of the Rif by Suter, 1980

the Maghrebian Tethys, specifically the eastern to southeast Iberian margin. It comprises a tectonic stack of metamorphic terrains from Variscan and Alpine ages and a non-metamorphic Mesozoic cover known as the "Dorsale Calcaire" (Durand Delga, 1969; Bouillin, 1986; Chalouan et al., 2008). This domain also encompasses the extended basement in the offshore Alboran basin (Comas et al., 1999; Do Couto et al., 2016), which developed from the Early Miocene onwards. The Flyschs Domain represents a nappe stack of Upper Jurassic pelagic sediments followed by Cretaceous to Early Miocene (Burdigalian) turbiditic sequences. These sediments accumulated over a highly thinned continental and oceanic crust, namely the Maghrebian Tethys (Belayouni et al., 2013; Vitale et al., 2014; Gimeno-Vives et al., 2020; Afiri et al., 2023).

The external domain, over-trusted by the Internal and flysch domains, signifies the former north African margin (Favre et al., 1991; Favre, 1992; Michard et al., 2014; Gimeno-Vives et al., 2019). Initially merged with the flyschs domain in a "Zone Marno-Schisteuse" (Fallot, 1937), it was later recognized as independent nappes, with the remaining "Zone Marno-Schisteuse" divided into two domains: the Rif s.s. and the PreRif (Durand Delga et al., 1960–1962). Subsequently, three paleogeographic-tectonic zones were distinguished-PreRif, MesoRif, and IntraRif (Suter, 1980), in which Gimeno-Vives et al. (2019) identified different domains of a magma-poor Rifted margin. As a characteristic of their Cenozoic evolution, PreRif and MesoRif exhibit a prominent unconformity termed the "MesoRif unconformity" which is well expressed in this domain. Notably, this unconformity needs to be present in the IntraRif and the Flyschs Domain.

In the study area, this latter measure no more than 10 kilometres in width and comprises three stacked structural complexes known as the Calcareous Dorsal Complex, Sebtide Complex, and Ghomaride Complex (Durand-Delga et al., 1960; Bouillin et al., 1970; Suter, 1980; Kornprobst and Durand-Delga, 1985). The Sebtide complex has experienced intense polyphase Alpine metamorphism, a feature that either needs to be present or better developed in the Dorsale Calcaire and Ghomaride nappes (Zaghloul et al., 2010). In the study area, the Sebtides are represented by two prominent headlands, 'Cabo Negro' (M'diq) and 'Monte Hacho' (Ceuta), flanking the bay on the eastern border of the study area. This complex primarily comprises deep-seated crustal rocks overlaid by the Ghomaride complex through a regional detachment. The Ghomaride complex forms a low mountain range characterized by gently rounded peaks, consisting of Paleozoic rocks affected by Variscan metamorphism, which is later overlain by relatively weak Alpine recrystallization (Chalouan et al., 2008). Additionally, remnants of their Mesozoic-Cenozoic covering can be observed. The "Calcareous Dorsal" is a complex assembly of thrust sheets dominated by Triassic-Liassic carbonates (Wildi, 1983), with local variations.

Sandstone facies, ghomarides, and flysch constitute the underlying geology for forested and shrubland areas (Fig. 2), with some regions experiencing significant degradation. In contrast, marl facies are primarily utilized for cultivation. Dense forests and open shrubland cover the upper elevations of the mountains and hills, while the lower regions are predominantly dedicated to agriculture. Here, cereals like wheat, barley, and oats are the predominant crops, occasionally grown in crop rotation with legumes such as chickpeas and beans or in conjunction with olive trees and various other fruit-bearing trees.

Quarries type

During our field survey, quarries were systematically classified into four distinct states of activity (Fig. 3):

1. Quarries in operation that refer to quarries actively involved in extraction and operational activities;
2. Closed quarries that have temporarily suspended their operations. This pause is often due to various factors such as administrative, economic, or social constraints;
3. Abandoned quarries that have permanently ceased their operations, signifying a complete halt in quarrying activities;
4. Under-construction quarries that are currently in the development phase or have received authorization to operate but have not yet commenced extraction activities (as outlined in Figure 3).

Furthermore, quarries are classified into distinct types based on the resources they extract, which include alluvial, rocky, and clay materials. Figure 3 shows the number of quarries within each of these specific categories. It is worth noting that all quarries within the public

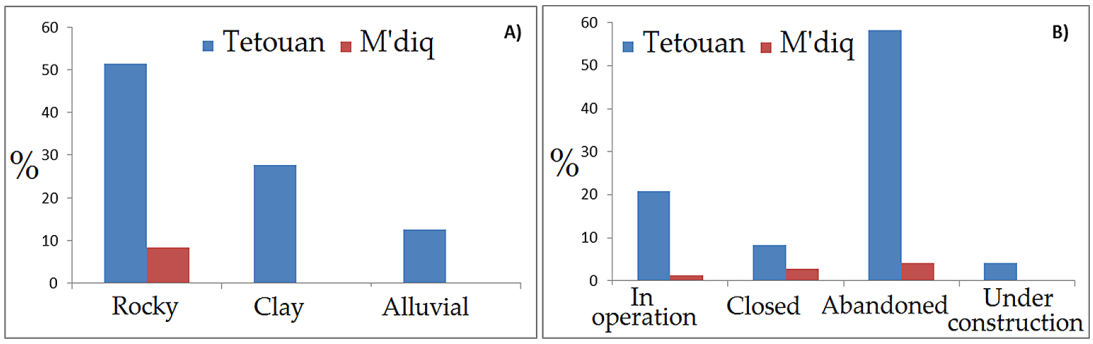

Figure 3. Distribution of quarries in the study area by (a) activity status and (b) operation type

hydraulic domain exclusively engage in extracting alluvial materials.

Among the four types of quarries (In operation, closed, abandoned, or under construction), abandoned quarries hold the highest significance, accounting for 62.50% of the total, followed by in operation quarries at 22.22%, closed quarries at 11.11%, and quarries under construction of being established at 4.17%. Regarding the primary resources extracted by quarries within the Tetouan province and the M'diq-Fnideq prefecture, rock extraction prevails as the most prominent category, constituting 59.72% of all surveyed quarries. Clay extraction follows at 27.78%, with alluvial quarries comprising 12.5% of the surveyed quarries across the study area.

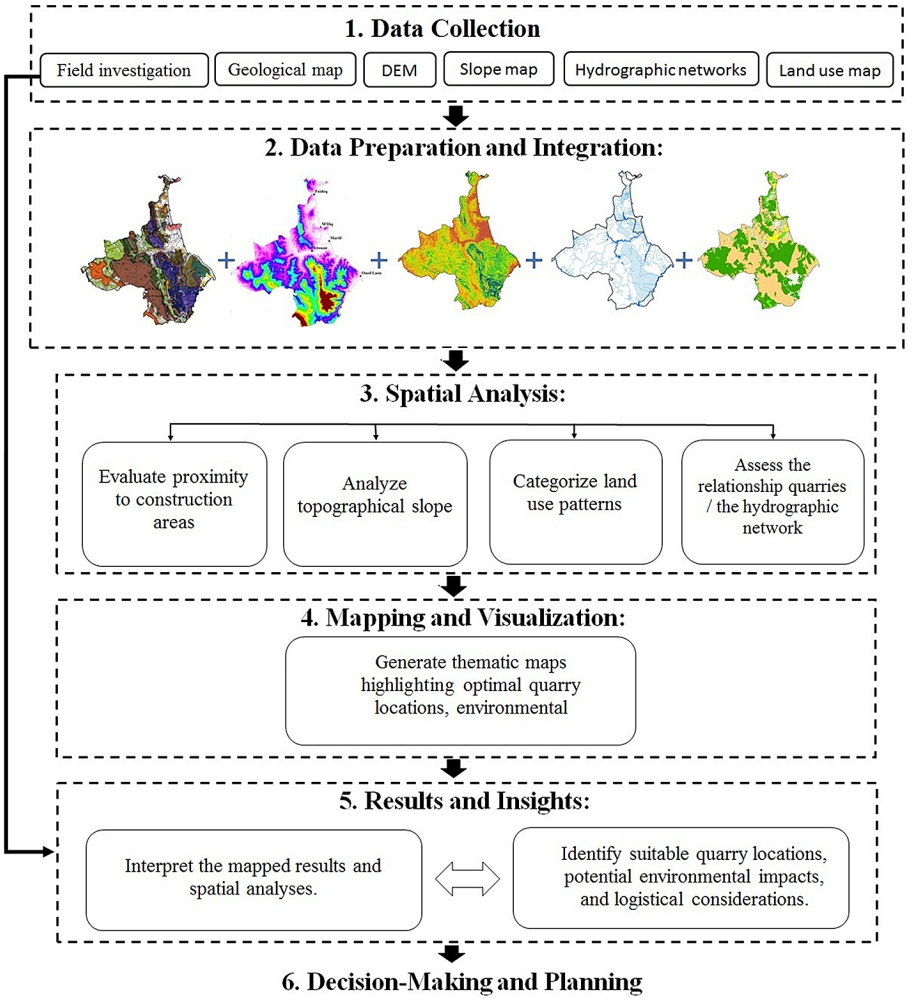

Figure 4. Flow chart of the used method

Methods

The present work has been carried out to overcome the lack of pit and quarry operation inventory at namely the Tetouan province and the M'diq-Fnideq prefecture level. Field and spatial data are used in the GIS approach to define the areas most likely to exploit alluvial, rocky and clay (Fig. 4). The used datasets include quarry locations, geological information, hydrographic networks, DEM, slope and land use data. The data analysis was conducted using ArcGIS 10.4, and five thematic layers were incorporated into the analysis:

1. Geologic map units featuring quarries: This layer provides information about the geological characteristics of the area, including the presence of quarries;
2. Proximity to construction and road: This layer assesses the distance between potential quarry sites, roads, and construction areas;
3. Slope: It includes data on the topographical slope of the land, which is relevant for quarry site selection;
4. Land use: This layer categorizes the land into different usage types, helping to identify suitable quarry locations;
5. Relationship between quarries and hydrographic network: This layer explores how quarries are situated around the hydrographic network, providing insights into potential environmental considerations. By integrating these five thematic layers, the study aims to comprehensively evaluate and identify optimal areas for quarrying activities within the region.

Numerous field investigations were carried out in 2022 to gather essential data. This data collection encompassed various details, such as the geographic coordinates of the quarries, the type of rock being quarried, and the intended applications or fields of use for the extracted materials. This collected data was organized and stored in Microsoft Excel spreadsheets for subsequent analysis and reference.

RESULTS AND DISCUSSION

Spatial analysis of thematic layers

A unique combination of morphological, climatic, hydrological, biological, and anthropogenic features characterizes tetouan province and the M'diq-Fnideq prefecture. These zones are situated along the Mediterranean coast, nestled within mountainous terrain, and encompass relatively confined, steeply sloping areas. The slope is a critical factor in mountainous regions when identifying appropriate locations for quarry operations. Terrain featuring steep slopes is generally considered less ideal for quarry locations due to the difficulties it presents for developing transportation infrastructure such as roads, highways, and rail tracks. The slope layer was created using data from the digital elevation model (DEM) and is represented in degrees (Fig. 5a). They are profoundly influenced by the Mediterranean climate, marked by a dense yet intermittent hydrographic network (Fig. 5b), characterized by swift responses to precipitation events owing to steep terrain and intense rainfall (Aqnouy et al., 2023; 2024).

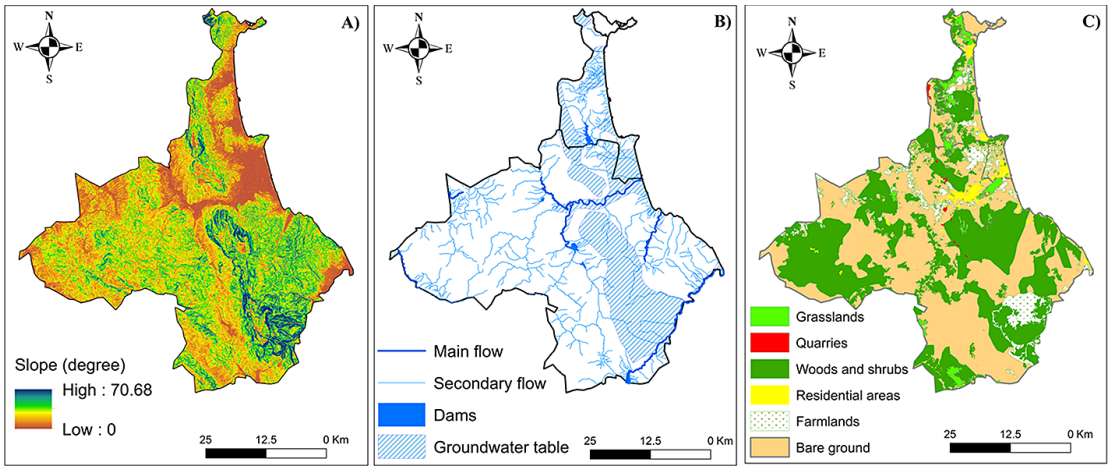

Figure 5. (a) slope map of the Tetouan province and the M'diq-Fnideq prefecture (b) hydrographic and groundwater map (c) land use map of the study area

These regions boast rich biodiversity, drawing from an intercontinental pool, and hold historical significance deeply rooted in human heritage.

In terms of hydrogeology (Fig. 5b), an intricate multilayered system is readily discernible, a common characteristic found in alluvial intramountainous Mediterranean aquifers. This complexity arises from various Quaternary phases of sedimentation, both marine and continental, as documented by Stitou El Messari (2002). This hydrogeological system comprises an upper layer composed of sand and gravel, overlaying a deeper layer primarily consisting of Plio-Quaternary conglomerates. The land-use criterion enables the differentiation of areas into grasslands, forests, bare land, agricultural zones, constructed areas, and quarries (Fig. 5c). Our field surveys, overall, indicate that exploitation activities contribute to deforestation, with quarry waste often tends to invade agricultural lands and forests

Comprehensive quarry inventory and suitability assessment

The identification of potential quarry deposits is contingent upon various criteria, primarily influenced by the spatial interplay between supply and demand. To ascertain prospective quarry deposits within the study area, several key parameters have been considered, including: resource Locations: evaluation of the locations of potential resources, encompassing considerations such as bedrock formations, alluvial deposits, and clays; Existing Quarry Status: assessment of the current status of quarries, including those in active operation and those that have been abandoned. In the ensuing sections, we present the outcomes of the analysis of these pivotal criteria and elucidate their influence on the selection of potential quarry deposits within Tetouan province and the M'diq-Fnideq prefecture.

The initial criterion for consideration involves the identification of geological resources that are both exploitable and readily accessible. This criterion was established through an analysis of existing geological maps and data, which facilitated the identification and delineation of areas rich in preferred geological resources such as limestone, sandstone, alluvium, clay, and more. Based on this assessment, three primary categories of potential resources have been identified; Alluvial Deposits: these are areas characterized by deposits of loose, sedimentary materials, often found along riverbanks and floodplains. Massive rock deposits: These refer to areas containing substantial, solid rock formations suitable for quarrying activities. Clay deposits: areas with significant clay deposits, which are valuable resources for various industries. Our investigation provides a detailed inventory of each resource type for a comprehensive overview of these diverse resources (Fig. 6).

The alluvial deposits, which are suitable for exploitation, are primarily concentrated within the major channels of the following wadis (seasonal riverbeds), Oued Amsa: Originating in and traversing the Ghomarides formations, this area is

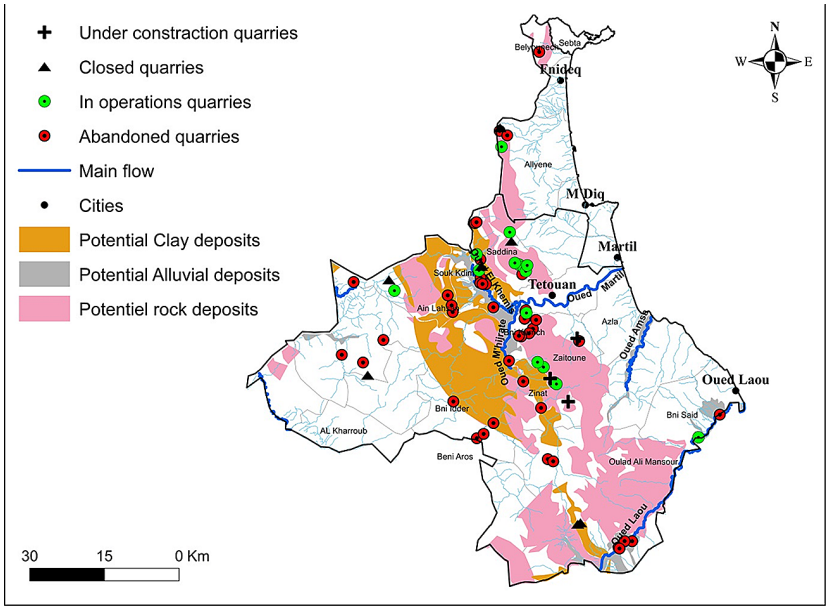

Figure 6. Potential quarries deposit in Tetouan province and the M'diq-Fnideq prefecture

situated at the mouth of the wadi. Access to this location is facilitated via National Road N°16, which connects the villages of Oued Laou and Bou Ahmed. Oued Laou: this wadi cuts across the limestone hinterland and intersects various geological formations, including Pliocene formations, the Ordo-Silurian ghomarides of Akaili, and the Devono-Dinantian ghomarids of Koudiat Tizian. Alluvial deposits are also located at the mouth of the Oued and can be accessed through National Road N°16, connecting the village of Oued Laou to Bou Ahmed. Oued M'hijrate: A tributary of Oued Martil, Oued M'hijrate originates in the elevated regions of the Beni Ider and internal Tangier formations.

The region boasts quarryable rock outcrops that span several geological units, including Triassic-Liassic Carbonate formations. These encompass the Calcareous dorsal. Aquitanian-Oligocene Sandstone formations: These belong to the Numidian sandstone nappe. Upper Cretaceous Clay formations: these are part of the Tangier unit. Oligocene-Aquitanian Sandstone Formations: these are associated with the Beni Ider nappe. Lower Cretaceous sandstone-detrital formations: these formations are characteristic of the Tisirene nappe. These diverse geological units contain rock formations suitable for quarrying activities, contributing to the availability of various quarry materials in the region.

Clay quarries are situated in several areas, including Melloussa Nappe. Clay quarries can be found within the Melloussa Nappe. Inner and Outer Tangier: Inner and outer regions have clay quarries. Tanger ("intraRifane" zone): Clay quarries are also located in the internal and external Tangier and outer Tanger ("intraRifane" zone). Outcrop of the Beni Ider Nappe: on the right bank of Oued Martil, there are clay quarries associated with the outcrop of the Beni Ider nappe. These areas serve as sources for clay materials used in various applications.

The present status of quarries, whether operational or abandoned, plays a crucial role in the criteria employed to refine the selection of potential deposits and establish their order of priority for exploitation (Agboola et al., 2020) (Fig. 6 and 7). This criterion is of significant importance as it allows for the identification of the following key aspects: Current state of exploitable material potential: it provides insights into the existing potential for material extraction within operational quarries and abandoned sites.

Location of areas offering optimal mining conditions: by assessing the operational and abandoned quarries, it aids in pinpointing locations where favourable mining conditions exist. Qualitative selection of materials: it helps make qualitative choices regarding the type and quality of materials available in operational and abandoned quarries. Identification of areas with minimal environmental constraints: Examining the status of quarries aids in the identification of areas with fewer environmental constraints, contributing to more sustainable quarrying practices. In summary, the current state of quarries is a pivotal criterion that guides the selection and prioritization of potential quarry deposits, focusing on operational feasibility, material quality, and environmental considerations.

The geological potential of the study area is circumscribed in the rock formations of the Calcareous dorsal in the Rif area, the power of which is significant. It is divided into three sections aligned between Jebha with the Haouz range in the northwest and the limestone ridge in the center. The units of the outer ridge are characterized by a thick series of Upper Triassic dolomite followed by alternating calcero-dolomite and Rhaetian marls, then by massive Hettangian limestones and Sinemurian flint limestones. Scales of the internal limestone ridge are characterized by a detrital Lower Triassic with red sandstones and clays, an Upper Triassic and Rhaetian with grey dolomites and a series with massive white limestones from the Hettangian – Sinemurian. Furthermore, limestone deposits have fascinating physico-mechanical characteristics (density, porosity, hardness, compressive resistance, etc.). They are widely exploited as blocks of these limestones used for public works (riprap, constructing piers, etc.).

Other limestones are crushed to produce gravel (ballast) for ballasting railway tracks and aggregate (gravel) for the preparation of hydraulic concrete. These formations are mainly exploited for their Triassic-Liassic carbonate material (limestones and dolomites).

In general, the study area is experiencing strong overexploitation of the limestone formations of the Calcareous dorsal" by existing quarries in the commune of Alliyine in the prefecture of M'diqFnideq, and the commune of Zinat province of Tetouan. The general landscape of the municipality of Taghramt and Alliyine is more industrialized by the presence of the first wind turbines in the region, pylons for high voltage lines, and

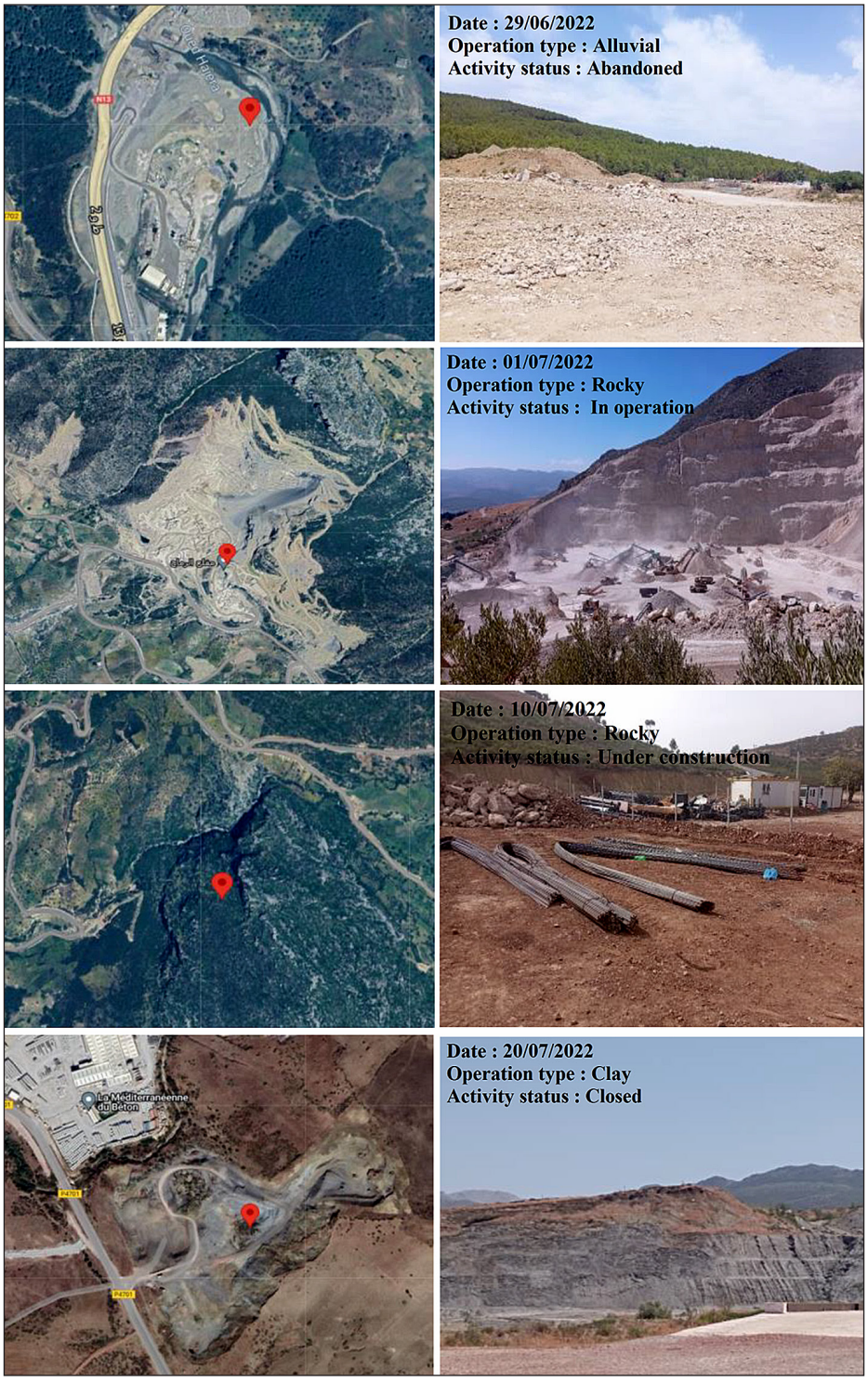

Figure 7. Photographs of the different types of quarries available in the study area.

several quarries to extract construction materials. The natural landscape is notably represented by the forest and maquis dominated by Mount Jbel Moussa and, in the background, the other shore of the Mediterranean, a natural system very threatened by the quarries in the area. For a power estimated at 10 m, the calculation of the reserves of this material in the prefecture of M'diq Fnideq and the province of Tetouan, and gives a potential with an estimated value of approximately 1 billion cubic meters, of which the more important is the limestone which characterizes the Calcareous dorsal of the prefecture of M'diq-Fnideq (Table 1).

The Rif chain is also characterized by the flysch layers made up of alternating large banks of coarse sandstone. It has significant areas in the

Table 1. Potential deposits of loose and massive rock

Specyfication	Deposits	Rocks	Total area (ha)	Workable area (ha)	Depth(m)	Product materials
Tetouan province	Massive rocks	Limestone	23115	12904	10	Gravel, Sand, All-venant, cement works
		Sandstone	52195	25501	8	All-rounder and ballast
	Loose rock	Clay	17116	14536	5	Stone and pottery, tile and cement industry
		Marl	8056	6119	5	Stone and pottery, tile and cement industry
M'diq-Fnideq prefecture	Massive rocks	Limestone	2046	1637	10	Gravel, Sand, All-venant, cement works
		Sandstone	668	591	8	All-rounder and ballast

Tangier-Tétouan-Al Hoceima region. Numidian sandstones of Aquitaine age continuously overlie versicolored clays of Oligocene age. The whole rests in thrust on the external Rif. The Beni Ider and Tisiren aquifers are exploited respectively for their sandstone material from the Oligocene – Aquitane and detrital sandstone from the Lower Cretaceous. The Numidian facies formation is primarily exploited for its sandstone material, which predominantly originates from the Aquitanian.

Clay deposits are abundantly present in the region, with some deposits reaching several tens of meters thick. Notably, the province of Tetouan hosts substantial deposits of gray pelites and phtanites, which are subjected to intensive exploitation. The potential deposits identified for potential expansion or the establishment of new clay quarries are primarily situated in the province of Tetouan and are associated with two distinct clay formations: internal Tangier unit: This formation comprises a series of marl-limestone layers overlying a clay-pelitic facies, with clay being the dominant component in certain areas. The primary exploitation focus in this formation is the Upper Cretaceous pelitic clays. External Tangier unit: this formation encompasses a series of marl-limestone clays, marls with fine sandy beds, and pelitic clays. The primary materials of interest in this formation are the Upper Cretaceous pelitic and marly clays.

These clay resources are integral to various industrial processes and significant economic importance in the region. Clays possess many valuable properties that render them suitable for diverse applications. They are classified as industrial minerals, which are minerals and rocks with economic significance, and their physical and chemical characteristics make them useful for various purposes. Thanks to their versatile physicochemical properties, clays can be directly employed in industrial processes following extraction. These substances encompass construction materials such as clay, sand, gravel, and rock aggregates, all contributing to various industries (Table 1).

The alluvial deposits within the wadi are primarily situated within the primary and secondary watercourses across the region. Based on the geological map and field assessments, these deposits are predominantly concentrated in the primary wadis, such as Oued Laou, Oued Amsa, Oued Mhajrate, and Oued Khemis. In the major watercourses, the alluvial deposits consist of silt-gravelly terraces and raw alluvium. These terraces are sometimes broad and extend along the right bank of the wadis, typically cutting into the marl-limestone formations. In contrast, the narrower valleys are filled with coarser alluvium and, on occasion, eroded alluvial terraces.

Notably, the alluvium in Wadi Laou is subject to exploitation, with operators confirming that the sand retained after sieving is high quality. Furthermore, the exploitation of alluvium from Wadi Mhajrate and Wadi Amsa holds significant importance within the study area. It's worth mentioning that this exploitation falls within the informal sector, where alluvium is sifted to extract sand. The alluvial quarries in the study area primarily yield raw materials (run-of-mine) and, upon request, sand. The exploitation areas occasionally align with basins of varying dimensions and depths.

Resource management and environmental considerations

The province of Tétouan is the most important area in the region of Tangier Tétouan Al Hoceima in terms of wealth and variety of deposits, which can largely meet the needs of the large communes of the province including the city of Tétouan, the coastal villages between the town of Martil and

the town of Oued Laou; and even export these aggregates to neighboring provinces. Massive rocks: manifested by carbonate, sandstone rocks with an estimated volume of 3.4 billion m^3, distributed regularly in the different municipalities of the province. These rocks represent the ideal source of good-quality aggregates for construction projects in the province and will largely meet the region's needs for aggregates in the next 20 years. Loose rocks: manifested by clays and marls with a potential volume of 1 billion m^3 (Table 1). These are the sources of raw material for manufacturing bricks and in the cement factory, which will subsequently be distributed in the province and neighboring provinces. Alluvium: located mainly in Wadi Amsa, Wadi Mhajrate, Wadi Azla Wadi Laou and other Wadis. With an estimated volume of 127 million m^3, these alluviums will provide the aggregates necessary for future construction projects in the province of Tetouan and its outskirts.

In the Prefecture of Mdiq-Fnideq, except for massive rocks and alluvium, there is a need for more quarry materials. This shortage explains why aggregates are imported from neighboring provinces like Fahs-Anjra, Tétouan, and Chefchaouen. Here is a more detailed breakdown: massive rocks: To the west of the Mdiq-Fnideq prefecture are limestone deposits with an estimated volume of 220 million m^3. These limestone resources can supply significant quantities of aggregates for local projects in the short and medium term. Alluvium: Alluvium, with an estimated volume of 21 million m^3, can provide sufficient aggregates in the short and medium term to meet the needs of the Mdiq-Fnideq prefecture. This information outlines the available quarry resources in the area and the reliance on neighboring provinces for aggregate supplies.

Preserving the broader environmental context of the areas under exploitation is a critical consideration. When identifying potentially exploitable deposits, it is essential to balance their proximity to presently exploited areas and the imperative of safeguarding these currently utilized resources and their surrounding environments. The primary objective is to achieve equilibrium by locating exploitable resources reasonably close to existing operational zones while avoiding areas that may already be overexploited. This equilibrium ensures that resource accessibility is optimized without detriment to the environment and the sustainability of currently utilized resources. In essence, this approach seeks to harmonize the efficient utilization of resources with the responsible preservation of the environment, fostering a sustainable balance in the exploitation of geological materials.

The extraction of limestone materials frequently leads to the exposure of the water table, resulting in water accumulation in low-lying areas, forming marshy regions. This resource is subject to overexploitation in the Tetouan province and the M'diqFnideq prefecture. In some exceptional cases, springs can emerge on slopes, particularly at the confluence of substantial fissures. The water table within these carbonate formations is susceptible to surface contamination, attributed to the prevalence of crack permeability and a surface layer in the local context. This configuration facilitates the rapid transmission of pollutants. Drilling, sieving, and crushing activities associated with quarry blasting generate dust clouds with varying particle sizes, elevated noise levels, and ground vibrations. This scenario is a source of discomfort for nearby residents, particularly when dust particles disperse over considerable distances in regions characterized by strong wind speeds.

An active quarry generates numerous immediate impacts associated with its ongoing operations. In contrast, a quarry that has been closed generates limited impacts, but it has the potential to impact the environment if its operations are resumed. An abandoned quarry, however, leaves behind residual impacts, typically necessitating rehabilitation measures.

Spatial data integration

Spatial data integration through GIS technology offers a comprehensive understanding of the geological resources in the study area. This holistic approach is expected to provide valuable insights into the distribution and characteristics of these resources, supporting sustainable resource management in Tetouan Province and M'diq-Fnideq Prefecture. Integrating quarry inventory data with geological, social, demographic, environmental, and administrative datasets using GIS techniques can yield important insights. These insights may involve zoning areas in land use plans for quarry operations or identifying priority zones for exploration by quarry companies, as demonstrated by López-Acevedo et al. (2022). GIS techniques and satellite remote sensing for spatial inventory and analysis of quarries have been recognized as potent tools for inventorying, monitoring, and managing natural resources and the environment, as Garg (2015) indicates.

The digital maps generated from this study can seamlessly integrate into GIS systems, enabling

the quantification of environmental attributes and tracking spatial changes. Our research lays the foundation for establishing a scalable, reproducible, and readily deployable workflow for monitoring quarry operations using remote sensing, GIS, and on-site investigations. Decision-makers and stakeholders can use this data to efficiently plan and manage quarry operations, ensuring a balance between economic benefits and environmental conservation.

CONCLUSIONS

This study employed a comprehensive approach to address the challenges of pit and quarry operation inventory in the Tetouan province and M'diq-Fnideq prefecture. By integrating GIS and conducting extensive field investigations, a detailed assessment of quarry resources and their spatial relations was achieved. The study gathered data on quarry locations, geological attributes, hydrographic networks, slope, and land use, all analyzed using ArcGIS 10.4. The analysis yielded several important findings and conclusions:

1. Inventory and suitability: the study successfully created an inventory of quarries and assessed their suitability for extracting alluvial, rocky, and clay materials. This information is essential for optimal utilization of geological resources in the region;
2. Thematic layers: the integration of thematic layers allowed for a comprehensive evaluation of potential quarrying areas. Geological, proximity, slope, land use, and environmental factors were considered in this assessment;
3. Field data collection: Extensive field investigations were conducted to collect valuable data. Information about quarry locations, the type of rock, and intended applications was systematically organized in Microsoft Excel spreadsheets, facilitating future analysis and reference;
4. Resource management: the study's results have implications for sustainable resource management. Identifying suitable quarry areas can help strike a balance between economic benefits and environmental preservation;
5. Environmental considerations: the relationship between quarries and ecological elements, such as hydrographic networks, was explored. This information can guide eco-friendly quarrying practices and minimize potential environmental impact;
6. Policy and planning: the findings can inform regional policies and planning efforts. Decision-makers can use this data to make informed choices regarding land use, resource allocation, and conservation;
7. Economic and industrial insights: the study underlined the economic significance of geological resources in the region. These resources are pivotal in various industries, contributing to the local economy. In essence, this study's methodology is expected to provide valuable insights into the Tetouan province's and M'diq-Fnideq prefecture's geological resources. It can guide sustainable resource management, environmental conservation, and informed decision-making to benefit the region's growth and development.

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