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Integrated Geotechnical Approach and GIS for Identification of Geological Resources Exploitable Quarries for Sustainable Development in Ifni Inlier and Lakhssas Plateau (Western Anti Atlas, Morocco)

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Abstract: The purpose of this paper is to identify, quantify and delineate the areas with suitable aggregate resources in the Precambrian massif of Ifni and the limestone plateau of Lakhssas (southwest Morocco). To fulfill this objective, a study was undertaken on the geotechnical parameters of the various geological outcrops of the region based on the analysis of 42 rock samples (carbonate, magmatic, detritic and volcano-detritic). Initially, we subjected these samples to a series of laboratory tests (impact resistance (L.A), wear resistance (MDE), density, porosity, absorption), to classify them according to geotechnical standards. Then, a geospatial database was created, to exploit these geotechnical data, from a geographical information system (GIS) to produce various thematic maps. Based on the results of this study, all geotechnical classes according to the standards (A to E for the European standard and 1A to 6D for the Moroccan standard) are present with good to very good geomechanical properties (L.A between 12% and 35%, MDE between 5% and 30%). This classification allowed us to use GIS to identify and quantify potential areas for exploitation by assigning five categories of geotechnical suitability levels (high (4), medium (3), low (2), very low (1) and others (0)) and to show that approximately 72% of the study area belongs to the categories high, medium and low. The combination of laboratory results and GIS has allowed us to carry out geotechnical mapping that will be used by regional authorities and actors for good management of the field of quarrying to rationalize the national natural heritage.

Keywords: GIS; geological resources; geotechnics; AFNOR; Moroccan standard; quarries

Citation: Sebbab, M.M.; El Ouahidi, A.; Ousbih, M.; Ouboulahcen, S.; Abdelrahman, K.; Abioui, M. Integrated Geotechnical Approach and GIS for Identification of Geological Resources Exploitable Quarries for Sustainable Development in Ifni Inlier and Lakhssas Plateau (Western Anti Atlas, Morocco). *Appl. Sci.* **2023**, *13*, 3932. https://doi.org/10.3390/app13063932

Academic Editors: Fabrizio Balsamo and Edoardo Rotigliano

Received: 11 December 2022
Revised: 5 March 2023
Accepted: 10 March 2023
Published: 20 March 2023

1. Introduction

The development of any modern society is proportionally linked to the field of civil engineering (construction of buildings, roads, dams, etc.) that make intensive use of materials from quarrying (e.g., rocks, sand, and gravel) [1]. However, like any industrial activity, the extraction of rocks in the area, the subject of this study, could surely have adverse impacts on the environment. Thus, any new study must explore the conditions of resource exploitation and its impact on ecosystem balances as well as the level of degradation of landscapes and the environment in a geographical area affected by the effects of climate change [2,3].

The demand for the aforementioned resources continues to increase globally, due to the rapid development of global socio-economic needs [4], which has pushed the reflection on how to manage the exploitation sites while valuing its natural resources. With the evolution of geographic information systems (GIS), which can perform multiple tasks of manipulation and analysis of geospatial data [5–7], decision-making in the field of natural resource management becomes more efficient and interactive. In this vein, several authors have addressed the issue of sustainable management of exploitable resources, using GIS to develop a predictive model based on geospatial data (rock geology, transport network, topography, and land use) to identify optimal areas for the installation of new quarries [8–11].

The choice of location of a quarry is directly related to the availability of data on lithology, petrographic, geochemical, and especially geotechnical properties [12]. Thus, the determination of the physico-mechanical characteristics of each rock unit, according to European (AFNOR) and Moroccan standards, by geotechnical tests is an essential step in identifying and classifying potential deposits.

The study area, which is part of the western Anti-Atlas (Morocco), has potential sources that have favored the opening of quarries without prior studies to optimize exploitation and that take into account the impact on the environment. In this context, our work is an attempt to map the geotechnical parameters favoring exploitation, by using the GIS, to identify and quantify resources and orient quarry operators toward the most suitable sites for the initiation of new quarries.

In this article, we will first address the geographical location and the geological and geomorphological framework of the study area, before proceeding to the determination of physical and mechanical parameters, which are intrinsic parameters of the rocks and not related to the production phase (crushing, washing . . .). The latter will be coupled with the spatial data from the GIS, thus allowing in the end the extraction of thematic maps informing decision-making and georeferenced databases useful for any planning in the future.

2. Study Area

The study concerns two geomorphological units that are part of the western Anti-Atlas, namely the limestone plateau of Lakhssas to the east and the Ifni inlier to the west. According to the new administrative division of Morocco in 2015 [13], they belong respectively to the regions of Souss Massa and Guelmim Oued Noun (Figure 1), with an area of about 2618.19 km^2. Geographically, the study area is bounded to the west by the Atlantic Ocean, to the south by the semi-desert plain of Guelmim, to the north by the limestone plateau of Tiznit, and to the east by the Paleozoic inlier of Kerdous.

The study area has three morphological domains (Figure 1):

- The Lakhssas plateau forms a rugged mountain barrier with an altitude of 1200 m between the Guelmim depression in the south (400 to 600 m) and the Tiznit plain in the north (100 to 400 m). The Lakhssas plateau is a complex anticline fold rising towards the west, overlooking the Ifni inlier with a slope of altitude of 300 to 500 m in the depressions [14]. The sedimentary cover of the border of the Ifni inlier, whose altitude varies between 400 and 700 m, is dominated by surface and underground karst phenomena.
- The Ifni inlier's altitudes reach 200 m in the central zone and approach 1100 m in areas with volcanic rocks, especially rhyolitic. It is dug in a depression compared to the Lakhssas plateau. The central zone with flattened relief is dominated by Paleoproterozoic granites covered in turn by Paleozoic and post-Paleozoic rocks, which form visible ridges [15].
- The coastal platform lies along the west coast of the Ifni inlier with an altitude between 30 and 100 m. The sharp cliff dominates the coastal fringe of 50 m and below the cliff, along the coast, we recognize dead cliffs of the Middle Quaternary and Flandrian [15].

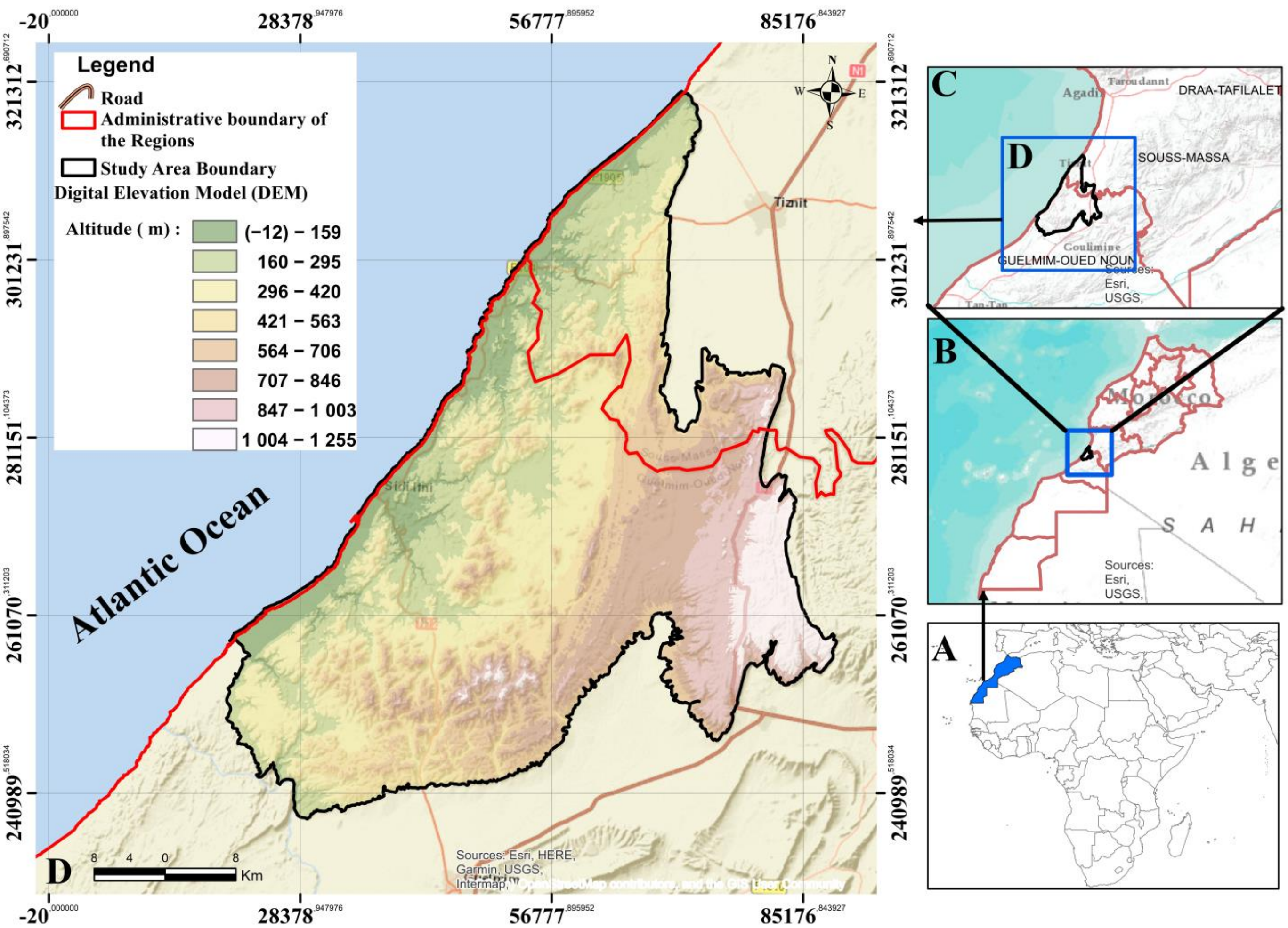

Figure 1. Geographical localisation of: (**A**) Morocco; (**B**–**D**) Ifni inlier and Lakhssas plateau.

On the structural and geological level, the study area belongs to the Anti-Atlas (Figure 2) [16] which is subdivided into three major structural areas [17]:

- The Central Anti-Atlas on both sides and along the major Anti-Atlas accident [18],
- The Eastern Anti-Atlas northeast of this accident,
- The Western Anti-Atlas to the southwest of this accident represents the frontal edge of the West African craton [19].

In Morocco, the Antecambrian inliers, where granitoids of the Proterozoic cover the Neoproterozoic terminal and Paleozoic, constitute the Anti-Atlas, especially the western Anti-Atlas, of which the Ifni inlier and the plateau of Lakhssas form a part.

The lfni inlier has a geological history that begins from the Paleoproterozoic to Cenozoic through the Neoproterozoic, Paleozoic, and Mesozoic [20–22]. It is formed by various granitoids surrounded by volcanic and volcano-sedimentary formations, which grow in the north, east, and south under the carbonate cover. The basement is formed exclusively by eburnean granites [20]. It outcrops to the east of the inlier, in the plain of Tioughza, in the Douar of Alouzad, showing a coarse texture, and to the north, in contact with the Neoproterozoic massif of the Sahel where it is finer. The Neoproterozoic cover is represented by quartzitic sandstones of the Lkst Group belonging to the Anti-Atlas Supergroup [21], and lower and upper volcano-sedimentary formations of the Ouarzazate Supergroup [22]. These formations are intersected by two groups of pan-African granitoids: Cryogenians represented in chronological order by the massif of Mesti then that of Ifni and those Ediacarian represented by the massifs of Taoulecht, Tioughza, and Mirleft. The limestones of the Lower Cambrian surmount this series.

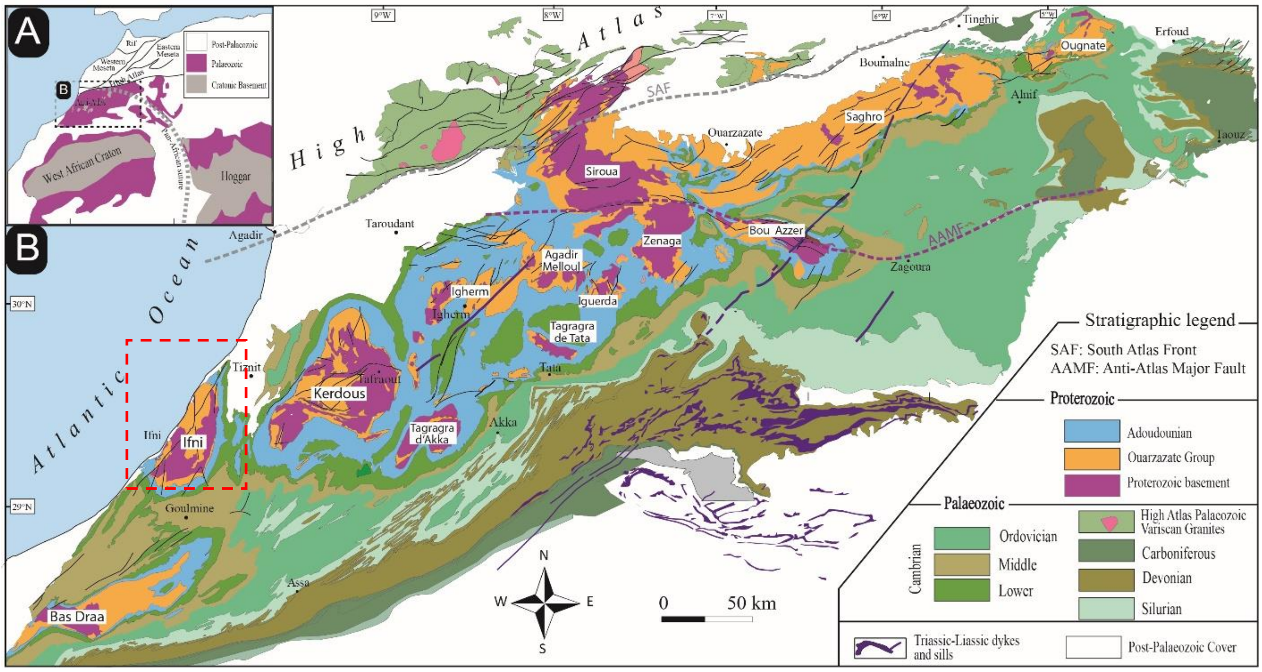

Figure 2. (**A**) The Anti–Atlas belt at the northern boundary of the West African Craton; (**B**) Schematic geological map of the Precambrian inliers of the Anti-Atlas range (modified after [16]).

On the other hand, the geological history of the Lakhssas plateau is limited to the Paleozoic and it is composed primarily of calcaro-dolomitic carbonate rocks of the Adoudounian period, from which an underground and surface karstic network develops. The Lakhssas plateau is located between the inliers of Ifni and Kerdous. It corresponds to a large synclinorium of Cambrian carbonate rocks showing an anticline structure in its core. In the central part of the plateau, the gravimetric and magnetic data suggest the presence of a block of basement raised under the massif of limestone. This structure is interpreted as a horst produced by the extension of the Upper Proterozoic and then reversed during the variscan compression.

3. Materials and Methods

The acquisition of data on potential resources and their location in any region has become an essential operation for land management, planning, and development. The development of GIS techniques, which give their users the ability to manage and analyze spatial data, offers the possibility for scientific researchers and technical operators to develop predictive maps of potential georesources, which offer the possibility of assessing the geotechnical quality of rock outcrops in any area.

In this study, to identify sites with geotechnically significant resources, we used GIS to combine field data, geotechnical test results, and classification standards and subsequently, extract the classification maps of the rock units according to their physical and mechanical characteristics, then deduce the results on the locations of the potential areas for exploitation. The steps followed to produce the geotechnical resource map are summarized by a conceptual diagram, shown in Figure 3.

The geotechnical tests required the realization of a sampling campaign from the most representative outcrops in terms of quantity in the study area. Table 1 and Figure 4 show the samples studied, their litho-stratigraphic classifications, and their geographical distribution in the geological map.

The samples were taken in triplicate and put in airtight plastic bags allowing a total backup and then transmitted to the laboratory to subject them to the various experimental protocols (Table 2).

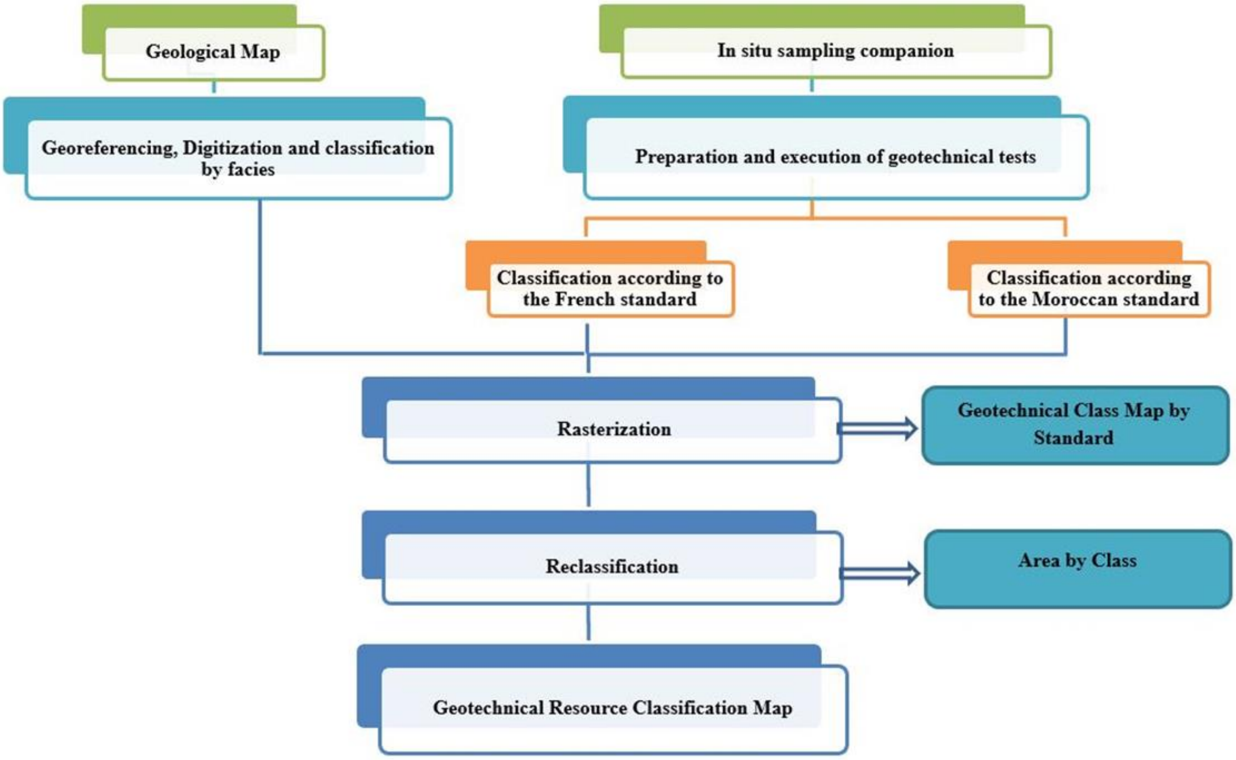

Figure 3. Conceptual diagram of the steps followed to produce the geotechnical resource map.

Table 1. Geological formations of samples.

Sample	Lithology	Geological Facies	Stratigraphy Unit
SC-1	Breccias and tuffs	Breccias and volcanic tuffs	NP3sv1
SC-2	Limestone	Black limestone with calcite nodules rich in Archaeocyathus	€i2c
SC-3	Quartz	Ferriferous quartz	QzF
SC-4	Dolomite	Pink dolomites with sandy pasts, bedded, alternating with pink marls	€iTw2-3
SC-5	Limestone	Dolomitic limestones, partly detrital	€i1a
SC-6	Dolomite	Blue dolomites	€iAd2b
SC-7	Limestone	Black limestone with calcite nodules rich in Archaeocyathus	€i2c
SC-8	Limestone	Blue-grey limestones with Archaeocyathids and siliceous beds	€i2a
SC-9	Limestone	Blue-grey limestones with Archaeocyathids and siliceous beds	€i2a
SC-10	Limestone	Blue-grey limestones with Archaeocyathids and siliceous beds	€i2a
SC-11	Limestone	White dolomitic limestones, bedded	€i1b
SC-12	Limestone	Blue-grey limestones with Archaeocyathids and siliceous beds	€i2a
SC-13	Diorite	Quartzitic diorite	NP3iδ
SC-14	Limestone	Blue-grey limestones with Archaeocyathids and siliceous beds	€i2a

Table 1. *Cont.*

Sample	Lithology	Geological Facies	Stratigraphy Unit
SC-15	Limestone	Blue-grey limestones with Archaeocyathids and siliceous beds	€i2a
SC-16	Limestone	Whitish nodulous limestones with Archaeocyathids and whitish pelitic intercalations	€i2b
SC-17	Limestone	Black limestone with calcite nodules rich in Archaeocyathus	€i2c
SC-18	Conglomerates	Basic conglomerates	€iAd1c
SC-19	Sandstone	Quartzitic sandstone complex	NP2iq1
SC-20	Limestone	Black limestone with calcite nodules rich in Archaeocyathus	€i2c
SC-21	Conglomerates and sandstones	Conglomerates and green sandstones with volcanic elements and acidic volcanic levels (rhyolites and dacites)	NP3ic
SC-22	Rhyolitic ignimbrites	Green rhyolitic ignimbrites	NP3ip2
SC-23	Rhyolitic ignimbrites	Ignimbrites and violet rhyolitic tuffs	NP3sp1
SC-24	Granodiorite	Red granitoid	NP3iγδ2
SC-25	Granite	Biotite monzogranite	PP3γ3
SC-26	Limestone	Gray limestone	€i2a
SC-27	Granite	Fine pink granite, compact (Leucocratic granite)	NP3iγ1
SC-28	rhyolite	pink rhyolite	NP3sv1
SC-29	Granodiorite	Coarse-grained granodiorite (Biotite granodiorite)	NP3iγδ3
SC-30	Granodiorite	Coarse-grained granite (Porphyroid granite)	NP3iγδ4
SC-31	Granite	Fine leucocratic granite	NP3iγ2
SC-32	Granite	Two-Micas granite (Muscovite granite)	PP3γ1
SC-33	Granodiorite	Biotite granite and dolerite enclave	NP3iγδ1
SC-34	Limestone, foliation	Metamorphic limestone with black veins	€i2a
SC-35	Limestone	Pink limestone well crystallized	€i2a
SC-36	Limestone	Black limestone, subhorizontal and metamorphic	€i2a
SC-37	Limestone	Purplish limestone	€i2d
SC-38	Limestone	Green limestone	€i2d
SC-39	Basalt	Olivine basalt	NP3sβ
SC-40	Dolomite	Pink dolomite	€iAd1
SC-41	Limestone	Black limestone with calcite nodules rich in Archaeocyathus	€i2c
SC-42	Granophyre and microgranite	Granophyre and microgranite dyke	NP3μγ

According to the requirements for concrete or road aggregates [23–25], it is clear that the intrinsic and manufacturing parameters are the basis of choice. However, the manufacturing parameters are controllable, and this work is limited to the identification of the intrinsic parameters according to the standards [26–31] (Table 2).

In this study, the geotechnical classification by standard [32,33] of the rock deposit in the study area is considered a factor. It was assessed using GIS [34,35] and its details are listed in Table 3.

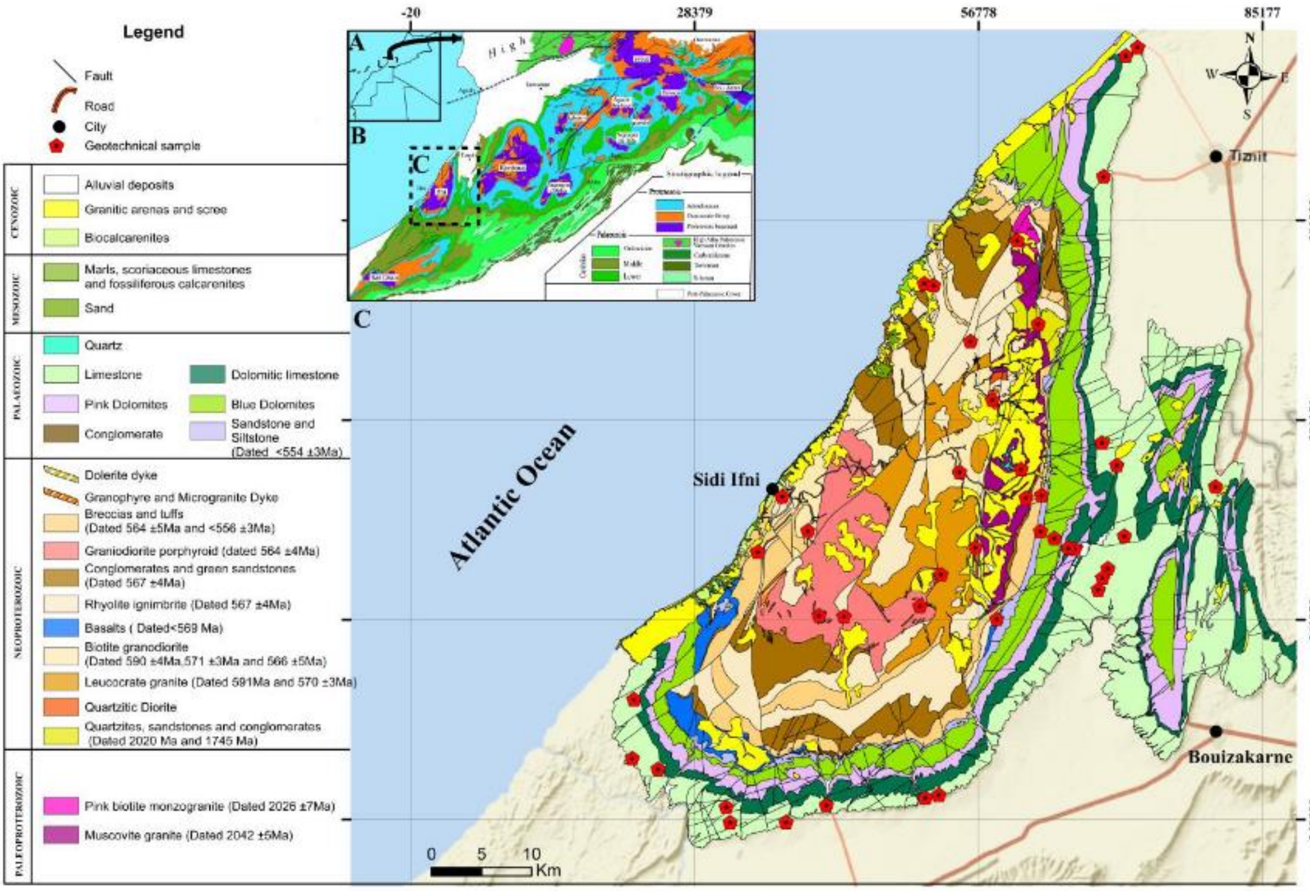

Figure 4. (**A**) Geographical localisation of Morocco, (**B**) Emplacement of the Ifni inlier and Lakhssas plateau in the Moroccan geological map and (**C**) Simplified geological map of the Ifni inlier and Lakhssas plateau.

Table 2. Geotechnical testing.

Parameter	Moroccan Standard	European Standard
Density (t/m^3)	NM 10.1.146	EN 1097-6
Porosity (%)		
Absorption (%)		
Los Angeles (L.A) (%)	NM EN 1097-2/2018	EN 1097-2/2010
Micro-Deval MDE (%)	NM EN 1097-1/2017	EN 1097-1/2011

Table 3. Classification scores of each sub-factor were used to select potential rock sites.

Factor	Suitability	Sub-Factors Geotechnical Classification Code According to		Classification Scores
		French Classification	Moroccan Classification	
Geotechnics	High	(A)	(1A)	4
	Medium	(B)-(A and B)-(A and C)	(2B)-(1A and 2B)-(1A and 3C)	3
	Low	(C)-(B and C)-(A, B, C, D and E)	(3C)-(2B and 3C)-(1A,2B,3C,4C,5D and 6D)	2
	Very Low	(D)-(E)-(F)-(C and D)	(4C)-(5D)-(6D)-(3C and 6D)	1
	Other	Unclassified rock		0

For this to happen, the analytical media and tools used in this study are:

- Seven geology maps 1: 50,000 (Moroccan Geological Survey) [36–42] were mosaiced, refined, and digitized to prepare the geological map and prepare the field mission in the study area.
- Digital Elevation Model (DEM) with a 30m resolution, published in September 2014, and downloaded from USGS Earth Explorer /SRTM 1 Arc-second Global (https://earthexplorer.usgs.gov/, accessed on 15 May 2022), is used to extract elevation [43].
- ArcGIS software was used to prepare the various maps used in this study.

Depending on the importance of each geotechnical class and the quality it offers, different class values were applied [44]. The values we propose for each class are summarized in Table 3.

The preparation of geotechnical class layers using the GIS environment required the digitization of all geological maps and the integration of field data. Then, all maps and vector data were converted to raster format [45] using the raster conversion option in the ArcGIS software. Subsequently, we classified them according to value using the "Reclassify" option to prepare the geotechnically significant resources map [46].

4. Results and Discussion

4.1. Analysis Results and Geotechnical Classification

The results of geotechnical analyses of the samples studied are tabulated in Table 4.

Table 4. Results of geotechnical analyses of the samples studied.

Sample	Density (t/m^3)	Porosity (%)	Absorption (%)	Los Angeles (%)	Micro-Deval (%)	French Classification Code	Moroccan Classification Code
SC-1	2.52	0.9	0.2	15	12	B	2B
SC-2	2.6	0.3	0.1	21	19	C	3C
SC-3	2.7	0.2	0.11	13	9	A	1A
SC-4	2.66	0.39	0.15	23	21	C	3C
SC-5	2.66	0.34	0.13	24	20	C	3C
SC-6	2.64	0.32	0.16	20	16	C	3C
SC-7	2.68	0.51	0.19	26	27	D	5D
SC-8	2.68	0.42	0.16	32	28	E	6D
SC-9	2.66	1.55	0.57	35	30	E	6D
SC-10	2.65	1.05	0.4	25	17	C	3C
SC-11	2.68	0.63	0.24	25	27	D	5D
SC-12	2.68	1.26	0.47	21	30	D	5D
SC-13	2.69	0.32	0.12	19	14	B	2B
SC-14	2.6	1.82	0.7	26	30	E	5D
SC-15	2.63	0.8	0.3	21	19	C	3C
SC-16	2.7	1.26	0.3	18	30	D	5D
SC-17	2.69	0.35	0.16	23	21	C	3C
SC-18	2.5	1.1	0.8	35	30	E	6D
SC-19	2.69	0.47	0.15	25	21	D	4C
SC-20	2.68	0.4	0.16	26	25	D	5D
SC-21	2.62	0.33	0.18	25	23	D	4C
SC-22	2.58	1	0.6	19	15	B	2B

Table 4. *Cont.*

Sample	Density (t/m^3)	Porosity (%)	Absorption (%)	Los Angeles (%)	Micro-Deval (%)	French Classification Code	Moroccan Classification Code
SC-23	2.64	1.61	0.61	20	17	C	3C
SC-24	2.67	1.15	0.53	18	6	A	1A
SC-25	2.7	3.1	1.2	17	7	A	1A
SC-26	2.69	2.3	0.74	25	16	C	3C
SC-27	2.8	1.5	0.58	19	5	A	1A
SC-28	2.6	1.2	0.42	14	7	A	1A
SC-29	2.75	1.54	0.58	16	6	A	1A
SC-30	2.65	1.59	0.62	18	6	A	1A
SC-31	2.62	3.1	1.2	19	5	A	1A
SC-32	2.66	1.83	0.69	15	8	A	1A
SC-33	2.59	2.7	1.16	30	11	C	3C
SC-34	2.74	0.74	0.25	19	12	B	2B
SC-35	2.73	1.85	0.65	12	8	A	1A
SC-36	2.69	1.46	0.58	25	21	D	4C
SC-37	2.69	1.55	0.4	13	6	A	1A
SC-38	2.65	2.8	1	12	8	A	1A
SC-39	2.75	0.33	0.2	12	9	A	1A
SC-40	2.67	3.5	0.9	16	12	B	2B
SC-41	2.65	1.8	0.46	22	19	C	3C
SC-42	2.63	1	0.8	18	14	B	2B

According to the results (Table 4), it is noted that the samples of carbonate rocks (limestone and dolomite) have a density between 2.6 t/m^3 and 2.74 t/m^3, with porosity and absorption that do not exceed 3.5% and 1%, respectively. These types of rocks show highly variable wear resistance (MDE) and impact resistance (L.A) values and do not exceed 30% for MDE and 35% for L.A.

For the samples of the magmatic rocks (granite, basalt, diorite, granodiorite, ignimbrite, and rhyolite), the results show that the density varies between 2.58 t/m^3 and 2.8 t/m^3, the porosity is between 0.3% and 3.1% and the absorption of 0.12% and 1.2%. In addition, they have a wear resistance (MDE) and impact resistance (L.A) that does not exceed 17% for MDE and 20% for L.A, except for the sample SC-33, which has a value of about 30%.

The detritic and volcano-detritic rock samples (breccia and tuff, conglomerate, sandstone) have a density between 2.5 t/m^3 and 2.69 t/m^3, a porosity between 0.33% and 1.1%, and an absorption range between 0.15% and 0.8%, except for the SC-18 sample, which is a conglomerate; the results show wear resistance (MDE) values ranging from 12% to 23% and impact resistance (L.A) from 15% to 25%.

From these results, it can be deduced that these rocky materials show very good physical characteristics with very high densities that vary between 2.5 t/m^3 and 2.8 t/m^3, low porosity that does not exceed 3.5%, and absorption of less than 1%.

On the other hand, the lower the Los Angeles (L.A) coefficient and the micro-Deval coefficient (MDE), the more it means that the rock material is excellent in terms of impact resistance and wear resistance [47]. According to the results, we can see that almost all the samples have good to very good mechanical characteristics with values of L.A between 12% and 35% and MDE between 5% and 30%. It is noted that the basalt (sample SC-39) has an L.A equal to 12% and the granite (sample SC-27, SC-31) has an MDE equal to 5%, and are the rocks which have respectively the highest impact resistance and wear resistance.

Furthermore, we used studies conducted by several authors on different types of rock to determine mechanical parameters (MDE and LA). Table 5 shows the L.A and MDE coefficients of the aggregates of different origins.

Table 5. Mechanical parameters of rocks according to the literature.

Lithology	Reference	Rock Type	Los Angeles (%)		Micro-Deval (%)		Number of Samples
			Min Value	Max Value	Min Value	Max Value	
Limestone	[48]	Carbonate rock	20.50	41.20	-	-	11
	[49]		21	49	11	60	17
	[50]		13	45	7.8	39.3	21
	[51]		18	51	22	45	3
Dolomites	[49]		18	31	9	52	9
Andesite	[48]	Magmatic rocks	15.40	18.90	-	-	10
Basalt	[52]		8	14	5	13	9
Granite	[53]		20	39	4	13	6
	[51]		28	35	11	11	2
	[50]		15	66	2	22.9	27
Meta-granite	[53]		21	30	6	9	2
Quartz	[53]		17	17	2	2	1
Granodiorite	[53]		21	23	5	6	2
	[51]		31	31	9	9	1
Meta-granodiorite	[53]		24	37	9	18	3
Sandstone	[54]	Detritic rock	17.7	51.7	22.1	24	27
	[50]		24	54	11.2	21.8	4

If we compare our results with those quoted above, we can see that:

- The carbonate rocks show very similar values of wear resistance (MDE) and impact resistance (L.A) according to the minimum values, with a slight difference of 1.8% for MDE and 1% for L.A. However, the maximum values in the literature [48–51] are almost double.
- The magmatic rocks have an almost similar wear resistance (MDE) and impact resistance (L.A) with a range of variation between 3% and 6% for both values (maximum and minimum) of the MDE and a difference of 4% for the minimum value of L.A. However, the maximum value of L.A, according to the authors, is almost double and even triple for some samples.
- The detrital and volcano-detrital rocks have almost similar wear resistance (MDE) and impact resistance (L.A) with a slight difference of 1.8% for both values (maximum and minimum) of the MDE and 3.7% for the minimum value of L.A. On the other hand, the maximum value of L.A according to the authors is almost double.

From this comparison, we can see that for the same type of rock, there is a difference in the value of the two mechanical parameters (MDE and L.A). This difference is explained, according to several authors [55–59], by the heterogeneity of geological parameters (including mineralogy, grain and crystal size, grain shape, and porosity).

To enhance and exploit the results of Table 4, we considered classifications [60] according to French [32] and Moroccan [33] standards (Figure 5), then we carried out a spatial analysis using the GIS to create thematic maps for each standard.

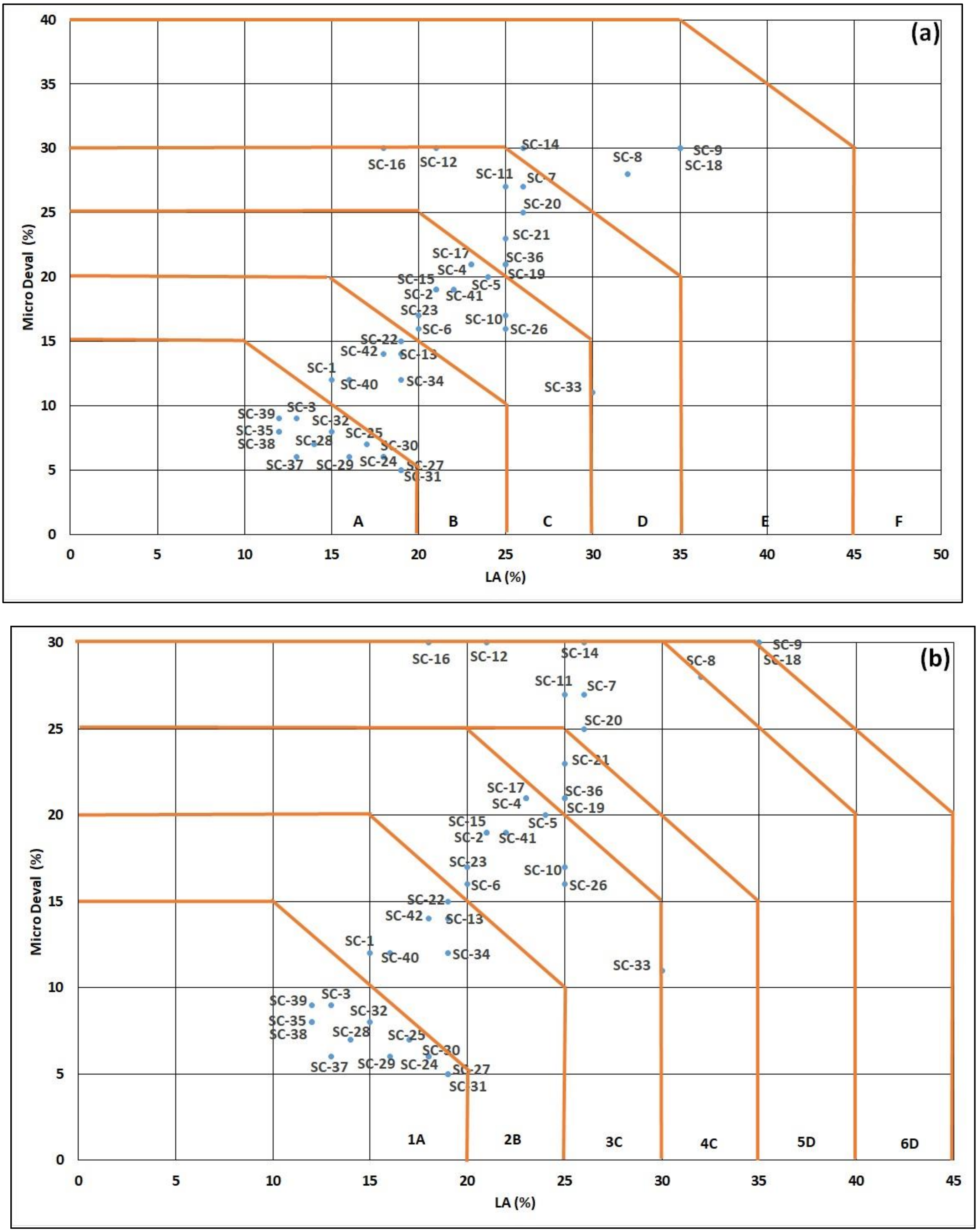

Figure 5. Diagram of mechanical parameters: (**a**) French standards; (**b**) Moroccan standards.

According to the French (Figure 5a) and Moroccan (Figure 5b) classifications, we can deduce that:

- The carbonate rocks are mainly between Classes A and E according to the French standard and Classes 1A and 6D for the Moroccan standards.
- The magmatic rocks are mainly divided between classes A and C for the French standard and classes 1A and 3C for the Moroccan standards.
- The detritic and volcano-detritic rocks fall between classes B and E according to the French standard and classes 2B and 6D for the Moroccan standards.
- There is a similarity between the two classifications, except that the denominations are particular at the level of the zones, and MDE is limited to 30% by Moroccan standards.

The intrinsic characteristics of the materials analyzed (Table 4) and the classification results (Figure 5) show that the fields of use of these materials are very wide, with very satisfactory quality.

The carbonate rocks represent a medium- to very high-quality material with a wide spectrum of use, especially for road aggregates and gravel used in the manufacture of any type of concrete, provided that a class higher than C or 3C is used according to the standard requirements.

The magmatic rocks have superior quality and highly solicited geomechanical characters (L.A and MDE around 20%, and a density greater than 2.58 t/m^3). These rocks can be considered noble materials whose use can go beyond simple road aggregates and be used as ballast for railway tracks as is the case for basalts (Class A or 1A) or rockfill used in port works in the case of rhyolite (Class A or 1A).

The detritic and volcano-detritic rocks represent a very high quality overall (except conglomerates), which can be used in several fields, especially in the road sector, and gravel is used in medium-quality concrete.

Furthermore, any exploitation of a deposit must be preceded by additional tests to have a very precise idea about the geochemical and geomechanical quality of the existing rocks, for example:

- Increase the number of samples to be analyzed over the entire surface of the deposit.
- Determine the geochemical and petrographic composition of the deposit facies.
- Carry out alkali-reaction tests for granites to verify the reactivity of these rocks with the binders.

4.2. Spatial Analysis

For each rock outcrop mapped and classified according to both standards (Figure 6A,B), we assigned one of four potential classifications (Figure 7). These classes have values of 4, 3, 2, 1, and 0, respectively, in the attribute table of the geotechnical potential map (Table 4). Table 6 presents the results of the calculation of the area by assigned classification for each rock outcrop in the study area.

Table 6. The assigned area by classification for each rock outcrop in the study area.

Classification Scores	Geotechnical Classification Code According to French Classification	Geotechnical Classification Code According to Moroccan Classification	Area (km^2)
4	(A)	(1A)	339.456
3	(B)-(A and B)-(A and C)	(2B)-(1A and 2B)-(1A and 3C)	264.469
2	(C)-(B and C)-(A, B, C, D and E)	(3C)-(2B and 3C)-(1A,2B,3C,4C,5D and 6D)	1276.1
1	(D)-(E)-(F)-(C and D)	(4C)-(5D)-(6D) -(3C and 6D)	422.629
0	Unclassified rock		315.54

According to the results, the following points can be deduced:

- This facilitates the identification of the classes for the two standards (French and Moroccan standards) for the appropriate area for any new quarries.
- The almost total similarity between the two classifications (French and Moroccan standards) is confirmed.
- The absence of classes 4 and 3 in the Lakhssas Plateau.
- The geotechnical class C or 3C, according to French and Moroccan standards, is the most dominant by an area of about 455.28Km^2; this class is composed of a majority of carbonate rocks concentrated around the Ifni inlier (Figure 6a,b) and some Ignimbrite.
- Class 2, which is assigned to a mixture of several geotechnical classes, is the most dominant by an area equal to 1276.1 Km^2, and according to Figure 7, this class is located at the plateau of Lakhssas and has an important presence at different parts around the Ifni inlier.
- Class 1, which is a very low geomechanical quality, has an area of about 422.29 km^2, and according to Figure 7, it is always glued to class 2.
- Class 4, which is assigned to geotechnical class 1A according to the Moroccan standard or A according to the French standard, is composed mainly of magmatic rocks. This class is favorable in all fields of use, has an equal area of 339.456 km^2, and is concentrated in the center of the study area with a slight presence in the north and south of the Ifni inlier.
- Class 3, which is assigned to a mixture of several geotechnical classes (Table 6), has an area of about 264.469 km^2 and is located around class 4.
- Class 0, which is assigned to unclassified rocks, has an area of 315.54 km^2. This class is mainly composed of quaternary rocks (biocalcarenite, alluvium, sand, etc.).

According to the spatial analysis, the compilation of the data of the results of geotechnical analysis and the geographical data made it possible to identify five classes of different qualities and to calculate their exact surface. In addition, high geotechnical quality rocks (Class 4) were found to be concentrated in the center of the study area (Figure 7) and this quality decreases when moving towards the four directions (east, west, north, and south).

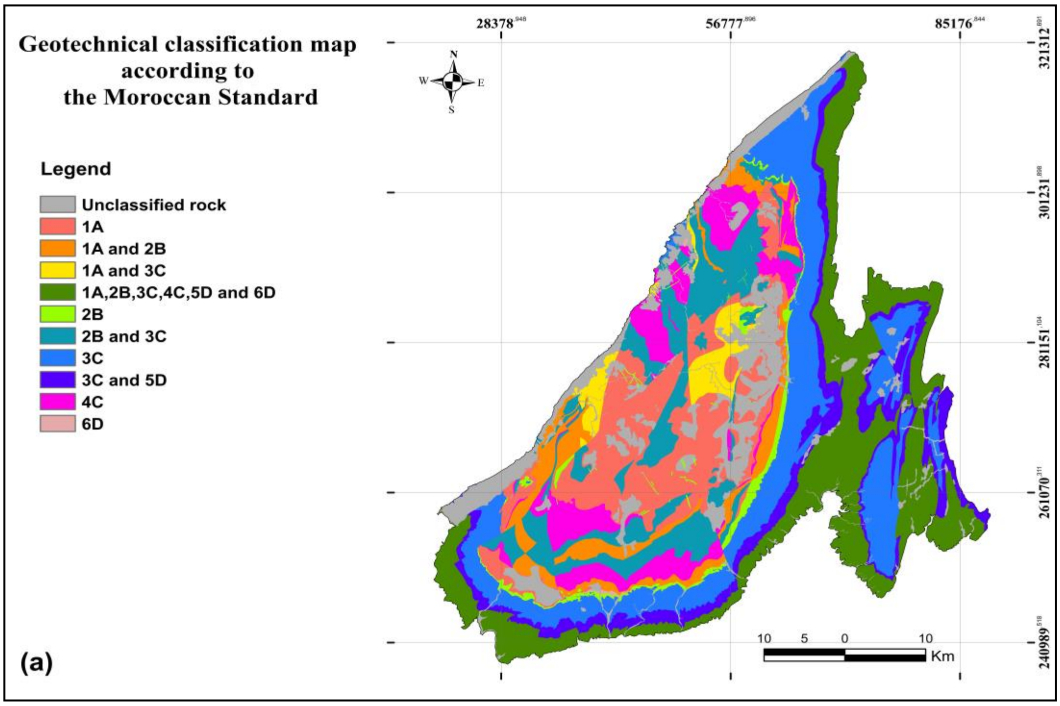

Figure 6. *Cont.*

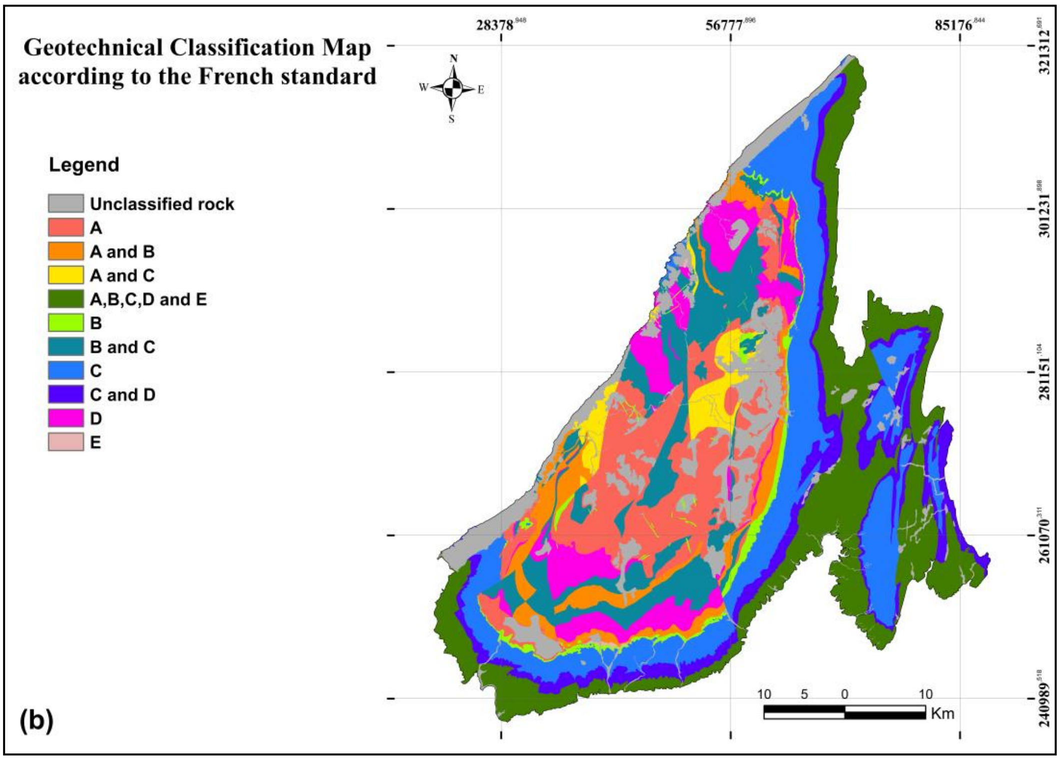

Figure 6. Geotechnical classification map: (**a**) According to the Moroccan standard. (**b**) According to the French standard.

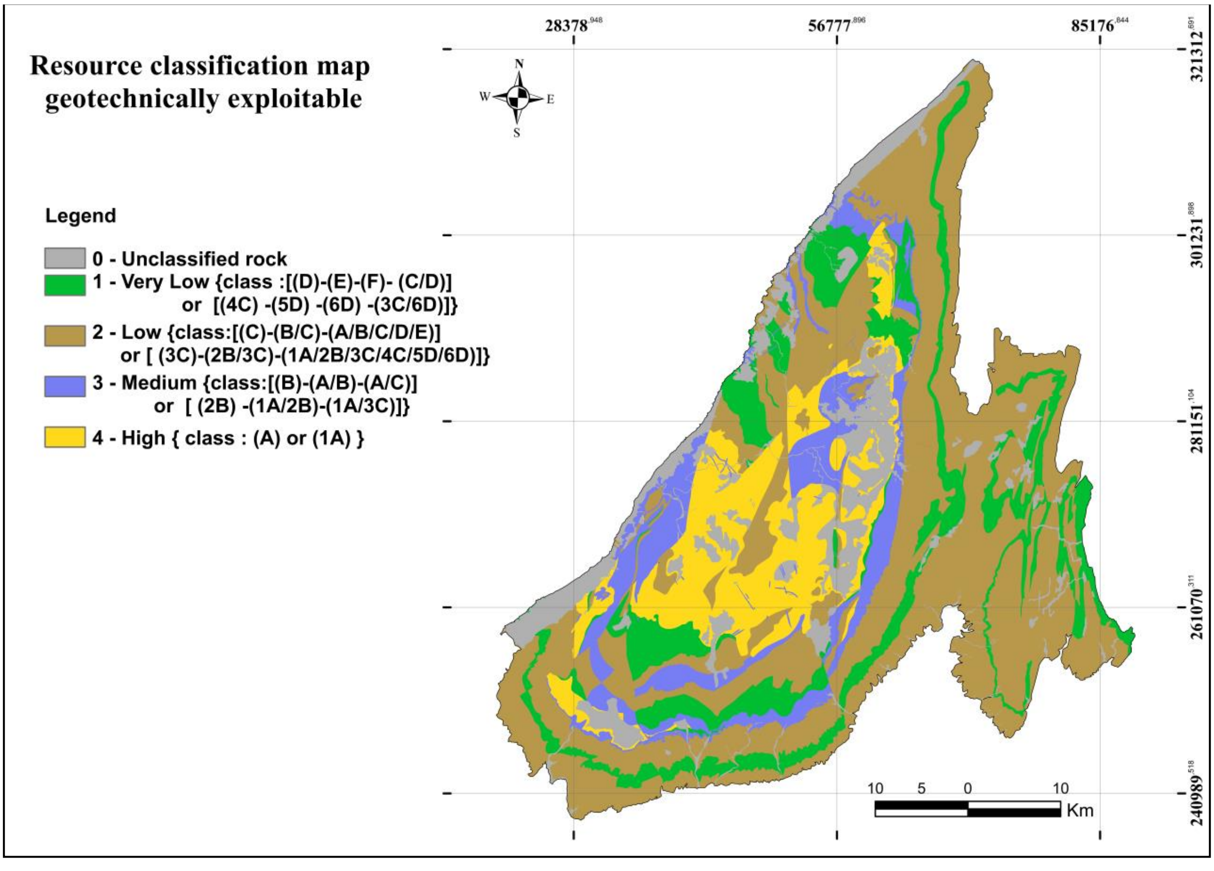

Figure 7. Geotechnical Resource Classification Map.

From the above, it can be seen that the choice of a site for the establishment of a new operation with well-determined requirements (quality and/or geotechnical class) for specific use (industrial exploitation, civil engineering, or aesthetic works . . .), has become very easy thanks to this geotechnical mapping. The latter requires a combination of field data, laboratory analysis, and spatial analysis. On the other hand, these results remain directly related to the characterization data applied to the various samples of the study area and must be validated by other geological data.

5. Conclusions

The identification of potential sites for quarrying in a developing country is a key task for the optimal and sustainable use of available resources. This study focuses on the selection of suitable geotechnical sites for the establishment of new quarries in the Ifni inlier and the Lakhssas plateau by combining field data with those acquired by the geotechnical tests in the laboratory in a GIS.

The suitable site locations are assessed considering the different geotechnical quality classes it proposes. Geotechnical laboratory tests were conducted on 42 samples of various rock outcrops, including carbonate, magmatic, detritic, and volcano-detritic rocks, to determine their geotechnical quality classes. Each geotechnical class or group was assigned a value between 0 and 4 based on their geotechnical suitability levels. All operations to create thematic maps were performed using ArcGIS software, such as digitization and rasterization. The final geotechnical suitability map was created using the reclassification function.

Based on geotechnical laboratory analyses and the geospatial analysis by GIS carried out on various outcrops of the Ifni inlier and the Lakhssas plateau, the following major points can be drawn:

- Laboratory testing indicated that most of the geotechnical properties determined do not vary significantly from one rock to another.
- The classification of rocks according to the European and Moroccan standards has shown that all classes (A to E for the European standard and 1A to 6D for the Moroccan standard) are present in our study area.
- Carbonate, detrital and volcano-detrital rocks (excluding the conglomerate's rocks) can be mined to produce high- to medium-quality aggregate thanks to their geotechnical classification (A to E for the European standard and 1A to 6D for the Moroccan standard) and their Los Angeles coefficient (L.A) and micro-Deval coefficient (MDE) values, which are less than 35%.
- Magmatic rocks can also be mined to produce high-quality aggregates thanks to their geotechnical classification (A to C for the European standard and 1A to 3C for the Moroccan standard) and their Los Angeles coefficient (L.A) and micro-Deval coefficient (MDE) values, which are less than 20%.
- The results of geotechnical analyses allowed us to consider basalts (L.A = 12 and MDE = 9) and rhyolites (L.A = 14 and MDE = 7) as excellent geotechnical materials due to their mechanical characteristics.
- The comparison of our results with previous work, carried out in other regions of the world, shows that the rocks in our study area have excellent geomechanical properties because, for the same type of rock, we have a difference in the value of the two mechanical parameters (MDE and LA) which reaches triple.
- Based on the spatial analysis, various suitable geotechnical sites in the study area are identified, classified as high (4), medium (3), low (2), very low (1) and others (0), and quantified.
- Categories 4 and 3 (high geotechnical quality rocks) are present only in the Ifni inlier, with an area of 339.456 km^2 for category 4 and 264.469 km^2 for category 3.
- The spatial analysis showed that geotechnical quality decreases in proportion to the distance from the center of the Ifni inlier towards the four directions (east, west, north and south).

- Spatial analysis showed that approximately 71.799% of the area of study area falls into the high, medium, and low categories and 28.201% falls into the very low and other zone categories.

According to these conclusions, there are suitable geotechnical sites with a very wide field of use. Nevertheless, for all source sites assessed in this study, we recommend requiring a detailed investigation with a very refined sampling mesh to validate the results.

Combining geotechnical results and GIS in this study generally gives satisfactory results for the geotechnical mapping of potentially suitable sites. Finally, we hope that the contribution of this work will serve the authorities and operators in the right choice of sites for the sustainable development of the geological heritage in the Ifni massif and the limestone plateau of Lakhssas.

Author Contributions: Conceptualization, M.M.S. and A.E.O.; methodology, M.M.S. and A.E.O.; software, M.M.S.; validation, A.E.O. and M.A.; formal analysis, M.M.S., A.E.O. and M.O.; investigation, M.M.S. and A.E.O.; resources, M.M.S.; data curation, M.M.S.; writing—original draft preparation, M.M.S., A.E.O. and M.O.; writing—review and editing, S.O., K.A. and M.A.; visualization, M.M.S.; supervision, A.E.O.; project administration, M.A.; funding acquisition, K.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Researchers Supporting Project number (RSP2023R351), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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