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Systematic search of circular structures using satellite imagery to identify potential new impact structures in Mauritania

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ABSTRACT

Mauritania, with its ancient (Archean to Paleoproterozoic) and desertic terrains and gentle relief, has been under-explored in terms of impact structures. To date, two confirmed impact craters, namely Tenoumer and Aouelloul, and four circular structures for which an impact origin has been suggested, are known in Mauritania. This work aims at a systematic exploration of circular structures in Mauritania and provide a comprehensive database to support their exploration and elucidate their origin. This approach includes multi-scale search on Google Earth images, and a preliminary assessment of their origin using available geological, geophysical, and geochemical data as well as Digital Elevation Models. A total of 50 new circular structures were detected during our survey, adding to four candidates previously identified. They are distributed throughout the territory with an important fraction of them being located in the Taoudeni basin. The diameters of these structures vary from 60 m to 7.5 km with a right-skewed distribution. A preliminary assessment of the possible origins of these circular structures is proposed and the most promising candidates for potential meteoritic impact sites are listed for future investigations.

1. Introduction

The formation of impact craters is a major geological process, which affects rocky and icy bodies (planets, moons, asteroids) populating the solar system (Melosh, 1989). Meteorite impacts affects planetary evolution in multiple, sometimes opposite, aspects, leading to chaos and destruction or enabling the emergence of habitable environments. They deliver energy and chemical elements that are incorporated in planetary envelopes. These collisions also shape the relief of planetary surface. They modify planetary material from atomic/mineral scales (vaporization, melting, shock metamorphism) to macroscopic scales (fractures, structural deformation, crater excavation, ejecta) and even to crustal scales, in the case of large impact basins (French and Koeberl, 2010; Osinski and Pierazzo, 2012). Largest collisions in the Solar System are invoked as possible explanations for the formation of the Moon (Benz et al., 1986; Cameron and Ward, 1976) and of the Martian dichotomy (Watters et al., 2007). Parts of the impactor that created the Moon are considered as a possible source of the Earth's mantle basal heterogeneities (Yuan et al., 2023). Asteroid and cometary collisions also affect the evolution of planetary atmospheres, through the addition of volatile elements (Zahnle et al., 1992) or by eroding the atmosphere (Melosh and Vickery, 1989; Pham et al., 2011). Like major volcanic events, large impact may induce climate change by loading large amounts of dust and climatic active gases into the atmosphere (Pollack et al., 1983). On Earth, large events may have been responsible for climate change and mass extinction, such as that of the K/T boundary contemporaneous to the Chixculub event (Schulte et al., 2010) or dust produced by the same event that changed the climate during several years (Senel et al., 2023).

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Impact craters may have also provided aqueous environment and energy favorable to the development of life on Earth, and may be elsewhere (Osinski et al., 2020). It was recognized that about 1/3rd of the >200 recognized impact structures on Earth are associated with natural resources, such as ore-deposits, water or hydrocarbon reservoirs (Reimold et al., 2005; James et al., 2022). Impact craters form spectacular landscapes that represent inspiring geosites for public outreach, and for the dissemination of scientific knowledge (e.g., Chandran et al., 2022). A number of impact structures host museums and attract thousands of visitors (Meteor Crater in USA, Ries in Germany, Rochechouart with its Centre International de Recherche & Restitution sur les Impacts et sur Rochechouart - (https://cirir-edu.org) CIRIR - in France). The Vredefort dome, the largest impact structure on Earth (Osinski et al., 2022), is listed on the UNESCO World Heritage site, whereas the Araguainha impact structure is listed as one of the first hundred IUGS (International Union of Geological Sciences) Geological Heritage sites (see https://iugs-geoheritage.org/geoheritage_sites/domo-de-araguainha-impact-structure/).

The impact crater record is however incomplete and discoveries remain to be made (Hergarten and Kenkmann, 2015). The search of impact structures on Earth is justified by the need to complete the knowledge gap on the terrestrial impact record. This knowledge is useful to decipher the geological history at the regional or global scales (including global/regional changes, mass extinctions). It is also useful to provide independent constrains to the current rate of collisions and to quantify the hazard associated by meteoritic impact for the humankind, in addition to the data provided by the monitoring programs of near-Earth asteroids, or small objects colliding the Earth and the Moon (Brown et al., 2002; Colas et al., 2020; Devillepoix et al., 2019; Liakos et al., 2020; Nesvorný et al., 2023; Tonry et al., 2018). The association of impact structures with mineral, or more generally economic resources is another source of motivation to search for impact structures (Reimold et al., 2005; James et al., 2022).

The knowledge of the terrestrial impact record is heterogeneous and there is a clear deficit of impact structures on the African continent. No new confirmations have been made since the last comprehensive review by Reimold and Koeberl (2014). Hergarten and Kenkmann (2015), considered 128 known exposed impact craters, at the timing of writing of their study, and found, using erosion modeling that there was no evidence for missing craters larger than 6 km in diameter. These authors claimed that more than 90 exposed craters in the range from 1 to 6 km remained to be discovered worldwide. The discovery of several impact structures larger than 6 km since 2015, including Cerro do Jarau, Pantasma, Ramagrh, and Jeokjung-Chogye Basin, somehow invalidates their conclusion. There are actually two caveats in the study of Hergarten and Kenkmann (2015). The approach assumes completeness above a certain diameter (90 km) and cannot rule out systematic incompleteness of the terrestrial record. The equations are also solved for a constant and homogeneous erosion rate, whereas it can vary by several orders of magnitude depending on geological contexts and climates. Considering the relative density of exposed and buried impact structures on the different continents, Rochette et al. (2019) predicted an important deficit of craters in Asia, Africa, and South America, and suggested that the number of craters above 10 km awaiting discovery in Africa could be about 20. We follow a simple approach implemented initially for the prospection of impact structures in Morocco (Chaabout et al., 2015). It relies on a systematic exploration of circular structures by using satellite images, using the Google Earth on-line interface, which allows to easily navigate between various scales. The search of circular structures was also achieved on shaded relief images. The first section briefly reviews the origin of this research that was encouraged in the wake of the organization of the series of AICAC conferences (Arab Impact Cratering and Astrogeology Conference). This section also presents a brief overview of the current knowledge about impact craters in Arab countries. The second section presents an overview of the geology of Mauritania and perspectives for the search of impact structures. The third section describes in detail the methodology, and is followed by the result section. The global analysis of the distribution of the circular structures and relationships with geology and topography is followed by a preliminary assessment of the possible origins of these circular structures. The most promising candidates for future investigations are presented.

2. The emergence of impact science in the Arab countries

The heterogenous knowledge of the terrestrial impact record on Earth is largely influenced by the knowledge and training of local geologists in impact science, and of their capacity to identify in the field and document in the laboratory the macroscopic and microscopic evidence of impacts. This effect is well illustrated when one examines the rate of discoveries in various regions of the globe, with a sharp increase of discoveries in USA in the sixties, followed rapidly by Europe, Australia and South America (Baratoux and Folco, 2023). In Africa, the number of discoveries is lower per surface unit, compared to all other regions of the globe. The search and study of impact craters in Africa and in the Arab world remains indeed a real challenge due to the lack of training in this domain, in addition with lack of funding and accessibility of areas with limited infrastructure and safety issues. However, one should mention a few milestones in the development of impact science in this region. One should recognize the pioneering work of impact scientists based in South Africa, and their intensive research on the oldest and largest impact structure on earth, the Vredefort dome (Reimold and Gibson, 1996). The drilling of the Bosumtwi impact crater in Ghana, is another milestone (Koeberl et al., 2007), although there is an under-representation of local scientists in this large international project and, in general, in the scientific exploration of the crater (Boateng et al., 2023). There is, however, the notable exceptions of D. Boamah, who was the first Ghanian citizen to achieve a PhD in impact science, and who wrote several first-authored publication in this domain (Boamah and Koeberl, 2003, 2006, 2007), and more recently, the participation of M.S. Sapah, the first cosmochimist in Ghana who contributed to a field study of the ejecta of lake Bosumtwi (Baratoux et al., 2019). The AICAC conferences series (Arab Impact Cratering and Astrogeology Conference) in Jordan in 2009 (Reimold, 2010), in Morocco in 2011 and 2014 (Baratoux et al., 2012) and 2017 in Algeria (Belhaï et al., 2017) contributed to connect impact scientists in African and Arab countries with international partners. New PhD students were trained in impact science in the last 5 years, in particular in the framework of the African Initiative for Planetary and Space Science and of the ATTARIK Foundation in Morocco (Baratoux et al., 2017; Chennaoui et al., 2022). In detail, the discovery of the first impact structure in Morocco, named Agoudal, led to the training in impact science of a PhD student in Morocco (El Kerni et al., 2019), whereas research programs were carried at Algerian craters in the framework of another PhD thesis (Sahoui, 2017) as well as on the geophysical aspects of one Algerian impact crater (Lamali et al., 2016, 2020, 2022). Training in impact science of PhD students and young scientists are also in progress in Senegal, Côte d'Ivoire and Cameroun with significant achievements on Bosumtwi (Niang et al., 2022), on the potential impact structure of Velingara in Casamance (Quesnel et al., 2024), and on the Mora Ring in Cameroun (Temenou et al., 2019).

The focus of this review section is placed here on the Arab world, comprising the following 22 countries: Algeria, Bahrain, Comoros, Djibouti, Egypt, Iraq, Jordan, Kuwait, Lebanon, Lybia, Mauritania, Morocco, Oman, Palestine, Qatar, Saudi Arabia, Somalia, Sudan, Syria, Tunisia, United Arab Emirates, and Yemen. The last comprehensive review of impact structures in the Arab world was achieved 4 years ago (Chabou, 2019). There are 13 recognized impact craters and structures in the Arab countries, which are listed in Table 1 and presented as a function of age and diameter in Fig. 1. The diameters and ages represented in Fig. 1 are the maximum value of the possible range of values, listed in Table 1, with error bars. Note that there are considerable error

Table 1
List of impact craters and impact structures in the Arab countries, by alphabetical order.

Name	Country	Latitude	Longitude	Diameter (km)	Age (My)	Year of confirmation	Selected bibliographic references
Agoudal	Morocco	31.988°N	5.514°W	<3	<4	2013	Sadilenko et al. (2013); Chennaoui Aoudjehane et al. (2016); El Kerni et al. (2019); Lorenz et al. (2015)
Amguid	Algeria	26.087°N	4.395°E	0.45	0.01–0.1	1980	Lambert et al. (1980); Mchone et al. (2002); Sighinolfi et al. (2020)
Aouelloul	Mauritania	20.241°N	12.674°W	0.39	3.1 ± 0.3	1966	Chao et al. (1966); Koeberl et al. (1998); Monod and Pourquié (1951); Ould Mohamed Navee et al. (2024)
BP structure	Libya	25.32°N	23.31°E	3.2	<120	1974	French et al. (1974); Koeberl et al. (2005); Martin (1969)
Jebel Waqf as Suwwan	Jordan	31.049°N	36.806°E	5.5	2.6–30	2008	Kenkmann et al. (2017); Salameh et al. (2008); Schmieder et al. (2011)
Kamil	Egypt	22.018°N	26.087°E	0.045	≤0.004	2010	Fazio et al. (2014); Folco et al. (2011, 2010)
Oasis	Egypt	24.573°N	24.41°E	15.6	<120	1974	French et al. (1974); Koeberl et al. (2005); van Gasselt et al. (2017)
Ouarkziz	Algeria	29.012°N	7°551°W	3	65–345	1970[a]	Fabre et al. (1970); Reimold and Koeberl (2014)
Saqqar	Saudi Arabia	29.583°N	38.7°E	34	70–410	2015	Kenkmann et al. (2015)
Talemzane	Algeria	33.315°N	3.034°E	1.75	≤3	1980	Karpoff and Brady (1953); Lamali et al. (2022, 2020, 2016); Lambert et al. (1980); Mchone et al. (2002)
Tenoumer	Mauritania	22.918°N	10.406°W	1.0	1.57 ± 0.14	1970	French et al. (1970); Fudali (1974); Fudali and Cassidy (1972); Jaret et al. (2014); Pratesi et al. (2005); Schultze et al. (2016)
Tin Bider	Algeria	27.6°N	5.111°E	6	<66	1981	Kassab et al. (2021); Lambert et al. (1981)
Wabar	Saudi Arabia	21.503°N	50.473°E	0.11, 0.64, 0.116	0.0003	1933	Chao et al. (1961); Gnos et al. (2013); Hanafy et al. (2021); Prescott (2004)

[a] Ouarkziz is currently listed as a confirmed impact structure, ever since the report by Fabre et al. (1970), but further work is necessary to provide evidence for shock metamorphism.

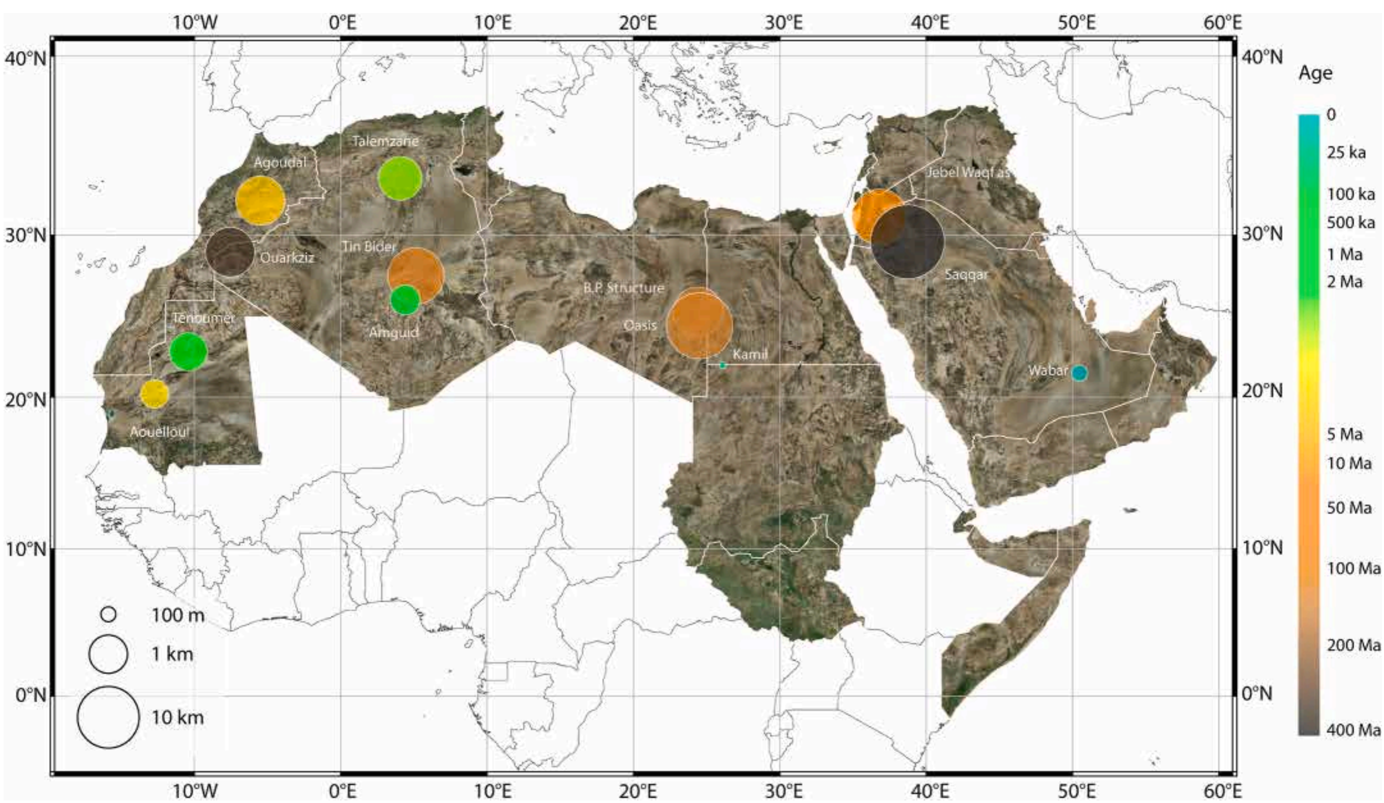

Fig. 1. Map of impact craters and impact structures in the Arab world. Color-code ages and diameters correspond to the maximum values of the possible range listed in Table 1. The data were extracted from Kenkmann (2021) and Osinski et al. (2022). Bing imagery is used as a background for Arab countries.

bars when the diameter is unknown, and inferred from indirect observations, as in the case of Agoudal (Morroco), or when the age is indirectly constrainted by the age of the deformed rocks, and not directy using isotopic systems on impact melts. There are no new confirmed impact structures in the Arab world since the review of Chabou (2019), whereas several impact structures outside the Arab world were confirmed during this period of time. Chabou (2019) listed 33 circular stuctures, including three candidates impact structures in Mauritania, Gogui, El-Mrayer and Temimichat-Ghallaman (see Table 2 for their coordinates, and diameters). Dietz et al. (1969) mentioned the Semsiyat dome, in the vicinity of the Richat dome, as a circular structure. However, the authors did not favor an impact origin, based on collected chert

Table 2
List of circular structures identified in Mauritania (complete information is available in supplementary material (Baratoux, 2023, file: Mauritania_Circular_Structures.xlsx), including semi-axes lengths for elliptical structures and additional geological unit). D: diameter (km), E: elevation (m), taken from the mean values of several points (5–10) in the vicinity of the circular structure (within 3 radii).

Name	Latitude	Longitude	E (m)	D (km)	Unit	Age	Group	Lithology	Unit	Age	Group	Lithology
Akjoujt	19°45′13.25″N	14°27′20.59″W	100	1.40	OcMg	Paleoproterozoic Neoproterozoic	Neoproterozoic Intrusive Rocks	Gabbro and microgabbro	Oci	Paleoproterozoic Neoproterozoic	Neoproterozoic Supracrustal Rocks	Basal quartzose metasandstone with local migmatite, tourmalinite, and marble; phyllite, slate, pelitic schist, and metagraywacke
Bassikounou 1	15°33′10.76″N	5°53′38.46″W	288	1.94	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover				
Bassikounou 2	15°39′10.45″N	5°55′45.55″W	282	0.40	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover				
Bassikounou 3	15°37′09.99″N	5°54′01.00″W	279	3.02	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover	TIM	Upper Tertiary	Cenozoic Supracrustal Rocks	Sandstone and clayey sand, kaolinitic clay, iron pan
Bassikounou 4	15°33′01.13″N	5°48′05.92″W	281	3.91	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover	TIM	Upper Tertiary	Cenozoic Supracrustal Rocks	Sandstone and clayey sand, kaolinitic clay, iron pan
Bir Moghrein	25°48′26.73″N	11°41′37.71″W	407	0.23	Zm1	Devonian	Paleozoic Supracrustal Rocks	Unfossiliferous argillite, marly limestone, brachiopod coquina				
Bou Jertala 1	21°40′45.80″N	9°29′33.11″W	380	1.70	Oj	Cambrian to Ordovician	Paleozoic Supracrustal Rocks	Predominantly red and pink quartzose sandstone, also feldspathic sandstone, microconglomerate, micaceous siltstone, and mudstone				
Bou Jertala 2	21°44′11.33″N	9°21′34.78″W	380	1.65	Oj	Cambrian to Ordovician	Paleozoic Supracrustal Rocks	Predominantly red and pink quartzose sandstone, also feldspathic sandstone, microconglomerate, micaceous siltstone, and mudstone	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover
Bou Jertala 3	21°44′38.72″N	9°19′59.63″W	380	1.34	Oj	Cambrian to Ordovician	Paleozoic Supracrustal Rocks	Predominantly red and pink quartzose sandstone, also feldspathic sandstone, microconglomerate, micaceous siltstone, and mudstone	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover
Chegga 1	25°37′50.34″N	6°30′50.40″W	440	0.80	Qca	Quaternary	Quaternary Sediments and Sedimentary Rocks	Calcrete and silcrete (hamada)	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover
Chegga 2	25°43′44.69″N	7°36′27.68″W	410	2.94	Yg	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granite				
Chegga 3	25°37′38.86″N	8°23′15.58″W	380	1.60	TBg	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granodiorite to tonalite	Qz	Unknown	Quartz	Quartz and (or) carbonate veins

(*continued on next page*)

Table 2 (*continued*)

Name	Latitude	Longitude	E	D	Unit	Age	Group	Lithology	Unit	Age	Group	Lithology
Chegga 4	25°16′42.89″N	8°13′5.18″W	390	0.45	TBg	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granodiorite to tonalite	Qz	Unknown	Quartz	Quartz and (or) carbonate veins
Chegga 5	25°16′09.44″N	8°12′30.60″W	390	0.65	TBg	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granodiorite to tonalite	Qz	Unknown	Quartz	Quartz and (or) carbonate veins
Chegga 6	25°16′04.80″N	8°12′07.88″W	390	0.28	0.28	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granodiorite to tonalite	Qz	Unknown	Quartz	Quartz and (or) carbonate veins
Chegga 7	25°16′14.12″N	8°11′58.56″W	390	0.70	0.70	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granodiorite to tonalite	Qz	Unknown	Quartz	Quartz and (or) carbonate veins
Chegga 8	25°15′32.29″N	8°10′35.88″W	385	0.76	0.76	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granodiorite to tonalite	Qz	Unknown	Quartz	Quartz and (or) carbonate veins
Chegga 9	25°14′26.52″N	8°11′26.52″W	390	1	1	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granodiorite to tonalite	Qz	Unknown	Quartz	Quartz and (or) carbonate veins
Dio Bou Guedra	18°54′42.66″N	13°42′55.40″W	80	4.27	Qr	Quaternary	Quaternary Sediments and Sedimentary Rocks	Desert pavement gravel (reg)	Agt	Paleoproterozoic to Neoproterozoic	Neoproterozoic Supracrustal Rocks	Quartz mica schist, pelitic schist and metasedimentary rocks
El Hank 1	24°17′09.57″N	6°46′28.87″W	360	0.42	Em1	Mesoproterozoic	Mesoproterozoic Supracrustal Rocks	Basal sandstone, pelite, laminated dolostones, stromatolite biostromes				
El Hank 2	24°08′57.41″N	6°42′52.78″W	320	0.88	Md	Mesozoic	Mesozoic Intrusive Rocks	Gabbro, diorite, dolerite, and microgabbro				

Name	Latitude	Longitude	E	D	Unit	Age	Group	Lithology	Unit	Age	Group	Lithology
El Mrayer	22°43′20.6″N	7°18′43.3″W	330	3.50	Ec	Ordovician	Paleozoic Supracrustal Rocks	Large-scale cross-stratified quartzose sandstone	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover
El Mreiti 01	22°45′18.00″N	6°38′17.00″W	319	1.39	Md	Jurassic	Mesozoic Intrusive Rocks	Gabbro, diorite, dolerite, and microgabbro	Id	Devonian	Paleozoic Supracrustal Rocks	Fine-grained sandstone with brachiopods and trilobites, fossiliferous claystone, coralline limestone
El Mreiti 02	23°28′04.91″N	7°47′35.90″W	316	0.72	Em1	Mesoproterozoic	Mesoproterozoic Supracrustal Rocks	Basal sandstone, pelite, laminated dolostones, stromatolite biostromes	Jb	Neoproterozoic	Neoproterozoic Supracrustal Rocks	Green mudstone and diamictite, interbedded with mauve to red, parallel laminated mudstones and grey sandstones.
El Mreiti 03	23°29′16.70″N	7°48′21.27″W	329	0.65	Md	Mesozoic	Mesozoic Intrusive Rocks	Gabbro, diorite, dolerite, and microgabbro	Em1	Mesoproterozoic	Mesoproterozoic Supracrustal Rocks	Basal sandstone, pelite, laminated dolostones, stromatolite biostromes
El Mreiti 04	23°29′44.15″N	7°48′51.90″W	325	0.60	Md	Mesozoic	Mesozoic Intrusive Rocks	Gabbro, diorite, dolerite, and microgabbro	Em1	Mesoproterozoic	Mesoproterozoic Supracrustal Rocks	Basal sandstone, pelite, laminated dolostones, stromatolite biostromes
El Mreiti 05	22°45′11.83″N	7°30′05.67″W	302	0.35	Ec	Ordovician	Paleozoic Supracrustal Rocks	Large-scale cross-stratified quartzose sandstone	Kn	Paleozoic	Paleozoic Supracrustal Rocks	Coarse-grained sandstone, red pelite, and calcareous mudstone; minor bioclastic limestone with brachiopods
El Mreiti 06	22°45′01.32″N	7°29′12.61″W	322	0.16	Kn	Paleozoic	Paleozoic Supracrustal Rocks	Coarse-grained sandstone, red pelite, and calcareous mudstone; minor bioclastic limestone with brachiopods				
El Mreiti 07	22°45′17.82″N	7°29′00.53″W	321	0.42	Ec	Ordovician	Paleozoic Supracrustal Rocks	Large-scale cross-stratified quartzose sandstone				
El Mreiti 08	22°46′09.78″N	7°29′26.57″W	297	0.06	Kn	Paleozoic	Paleozoic Supracrustal Rocks	Coarse-grained sandstone, red pelite, and calcareous mudstone; minor bioclastic limestone with brachiopods				

(*continued on next page*)

Table 2 (*continued*)

Name	Latitude	Longitude	E	D	Unit	Age	Group	Lithology	Unit	Age	Group	Lithology
Name	Latitude	Longitude	E	D	Unit	Age	Group	Lithology	Unit	Age	Group	Lithology
El Mreiti 09	22°46′13.33″N	7°29′26.08″W	300	0.10	Kn	Paleozoic	Paleozoic Supracrustal Rocks	Coarse-grained sandstone, red pelite, and calcareous mudstone; minor bioclastic limestone with brachiopods				
El Mreiti 10	23°29′37.80″N	7°48′41.55″W	311	0.12	Md	Mesozoic	Mesozoic Intrusive Rocks	Gabbro, diorite, dolerite, and microgabbro	Em1	Mesoproterozoic	Mesoproterozoic Supracrustal Rocks	Basal sandstone, pelite, laminated dolostones, stromatolite biostromes
El Mreiti 11	22°45′05.76″N	8°08′34.12″W	310	3.40	Az	Upper Neoproterozoic	Neoproterozoic Supracrustal Rocks	Blackish laminated, silicified pelites grading to multicolored, poorly indurated pelites	Qca	Quaternary	Quaternary Sediments and Sedimentary Rocks	Calcrete and silcrete (hamada)
El Mreiti 12	23°00′09.76″N	6°43′26.08″W	300	1.55	Ec	Ordovician	Paleozoic Supracrustal Rocks	Large-scale cross-stratified quartzose sandstone	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover
El Mreiti 13	23°00′57.49″N	6°35′41.10″W	295	2.18	Ec	Ordovician	Paleozoic Supracrustal Rocks	Large-scale cross-stratified quartzose sandstone	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover
Ghallamane 1	23°01′16.32″N	9°54′19.44″W	240	2.84	ZDmy	Mesoarchean	Archean Intrusive Rocks	Charnockite, foliated to mylonitic	Ql	Quaternary	Quaternary Sediments and Sedimentary Rocks	Lacustrine deposits
Ghallamane 2	23°04′17.40″N	9°53′44.88″W	235	3.70	ZDmy	Mesoarchean	Archean Intrusive Rocks	Charnockite, foliated to mylonitic	Ql	Quaternary	Quaternary Sediments and Sedimentary Rocks	Lacustrine deposits
Gogui	15°33′27″N	11°18′28.7″W	180	0.44	So	Mesoproterozoic	Mesoproterozoic Supracrustal Rocks	Fine- to medium-grained feldspathic, micaceous, and glauconitic sandstone-quartzite				
Gourfafié	15°54′46.26″N	7°11′41.57″W	300	0.95	Qr	Quaternary	Quaternary Sediments and Sedimentary Rocks	Desert pavement gravel (reg)	Ql	Quaternary	Quaternary Sediments and Sedimentary Rocks	Lacustrine deposits
Guelb et Tikit	22°56′32.00″N	13°03′50.00″W	388	1.24	TRf	Neoarchean	Archean Supracrustal Rocks	Banded iron formation and ferruginous quartzite	Qa	Quaternary	Quaternary Sediments and Sedimentary Rocks	Alluvial fans, cones, and talus, undifferentiated
Guelb Zouéouga	22°45′25.16″N	12°53′15.24″W	359	1.35	TRf	Neoarchean	Archean Supracrustal Rocks	Banded iron formation and ferruginous quartzite	Qa	Quaternary	Quaternary Sediments and Sedimentary Rocks	Alluvial fans, cones, and talus, undifferentiated
Name	Latitude	Longitude	E	D	Unit	Age	Group	Lithology	Unit	Age	Group	Lithology
Hassi Djebilet 1	26°46′05.47″	7°59′06.11″W	376	0.84	Zm2	Devonian	Paleozoic Supracrustal Rocks	Phosphate-pebble conglomerate, limestone with orthoceras and brachiopods, sandstone, siltstone, and claystone				
Hassi Djebilet 2	26°04′41.77″N	7°34′23.99″W	413	2.10	Qca	Quaternary	Quaternary Sediments and Sedimentary Rocks	Calcrete and silcrete (hamada)	Yg	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granite
Koumbi Saleh	15°53′19.32″N	9°55′04.73″W	160	1.30	Qf	Quaternary	Quaternary Sediments and Sedimentary Rocks	Fluvial deposits, alluvium	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover
Mdeinet el Beida	25°22′34.10″N	8°12′20.16″W	370	1.70	TBg	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granodiorite to tonalite	Qz	Unknown	Quartz	Quartz and (or) carbonate veins
Ntakat	16°54′01.96″N	11°42′39.15″W	547	7.98	Ti	Upper Ordovician	Paleozoic Supracrustal Rocks	Quartzose cross-bedded sandstone; argillaceous microconglomerate and micaceous siltstone; argillaceous sandstone with boulders; quartzite; argillaceous	Qa	Quaternary	Quaternary Sediments and Sedimentary Rocks	Alluvial fans, cones, and talus, undifferentiated

(*continued on next page*)

Table 2 (*continued*)

Name	Latitude	Longitude	E	D	Unit	Age	Group	Lithology	Unit	Age	Group	Lithology
								sandstone and microconglomerate with Skolithos				
Rachid	18°57′06.91″N	11°39′10.58″W	270	1.50	Ti	Upper Ordovician	Paleozoic Supracrustal Rocks	Quartzose cross-bedded sandstone; argillaceous microconglomerate and micaceous siltstone; argillaceous sandstone with boulders; quartzite; argillaceous sandstone and microconglomerate with Skolithos	Qd	Quaternary	Quaternary Sediments and Sedimentary Rocks	Dunes and sand cover
Semsiyat Dome	21°00′48.24″N	11°49′58.08″W	600	4.35	Oj	Cambrian to Ordovician	Paleozoic Supracrustal Rocks	Predominantly red and pink quartzose sandstone, also feldspathic sandstone, microconglomerate, micaceous siltstone, and mudstone	Ql	Quaternary	Quaternary Sediments and Sedimentary Rocks	Lacustrine deposits
Taghader	16°57′42.84″N	11°45′04.53″W	589	7.50	Ti	Upper Ordovician	Paleozoic Supracrustal Rocks	Sandstone Quartzite	Qa	Quaternary	Quaternary Sediments and Sedimentary Rocks	Alluvial fans, cones, and talus, undifferentiated

Name	Latitude	Longitude	E	D	Unit	Age	Group	Lithology	Unit	Age	Group	Lithology
Temimichat-Ghallaman	24°14′54.4″N	9°38′59.1″W	265	0.70	TGp	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Granite to granodiorite	TGg	Paleoproterozoic	Paleoproterozoic Intrusive Rocks	Biotite leucogranite with tourmaline pegmatite dikes
Tergit 1	20°05′31.99″N	12°58′04.73″W	410	1.34	Oj	Cambrian to Ordovician	Paleozoic Supracrustal Rocks	Predominantly red and pink quartzose sandstone, also feldspathic sandstone, microconglomerate, micaceous siltstone, and mudstone				
Tergit 2	20°04′32.48″N	12°57′38.12″W	450	1.54	Oj	Cambrian to Ordovician	Paleozoic Supracrustal Rocks	Predominantly red and pink quartzose sandstone, also feldspathic sandstone, microconglomerate, micaceous siltstone, and mudstone	Qn	Quaternary	Quaternary Sediments and Sedimentary Rocks	Sand over desert pavement and calcrete
Tichit	18°29′20.40″N	9°08′48.12″W	365	5.40	Ti	Upper Ordovician	Paleozoic Supracrustal Rocks	Quartzose cross-bedded sandstone; argillaceous microconglomerate and micaceous siltstone; argillaceous sandstone with boulders; quartzite; argillaceous sandstone and microconglomerate with Skolithos	Oj	Cambrian to Ordovician	Paleozoic Supracrustal Rocks	Predominantly red and pink quartzose sandstone; feldspathic sandstone, microconglomerate, micaceous siltstone, and mudstone
Tourne	22°28′37.37″N	11°51′51.88″W	333	0.33	At2	Mesoproterozoic	Mesoproterozoic Supracrustal Rocks	Dolostone and dolomitic limestone including stromatolitic, microcrystalline, macrocrystalline, ferruginous, and carbonate-conglomerate facies; minor sandstone, shale, and glauconitic shale				

breccia in the innermost area that do not show any indication of shocks. They concluded on the basis of similarity and proximity to Richat that Semsiyat was also of endogenous origin. Here we chose to include the Semsiyat dome in the list of potential impact structures as it was apparently visited only once by an impact specialist, more than 50 years ago, and the proximity argument with the Richat, much larger than the Semsiyat dome, remains insufficient to settle the debate. To our knowledge, only one of the four potential impact structures in Mauritania was visited by a group of scientists since 2019, namely, Temimichat-Ghallaman (24°15′N, 9°39′W, 750 m in diameter) (in 2016, by E. Ould Mohamed Navee, along with M. S. Ould Sabar, a geologist from the University of Nouakchott). Structural observations and sample were collected during this visit, but there was no report of evidence of shock metamorphism, and the origin of this structure remains to be elucidated (Ould Mohamed Navee et al., 2024). It should also be noted that Gnos et al. (2018) published new analyses of sandstones collected 7 years before publication on the Jabal Rayah structure (28°40′N, 37°11′E, 5 km in diameter) in Saudi Arabia, but did not report evidence of shock metamorphism.

Therefore, the efforts should be channellized in two directions: 1) search of new circular structures through satellite imageries to enrich the current database of potential impact structures in the Arab world and provide preliminary assesments of their origin, based on available data, to help determining the priorities for future field work, and 2) field expeditions to potential impact structures, which requires financial support and participation of scientists with sufficient expertise in impact science, structural geology and petrology (to be able to examine macroscopic and microscopic pieces of evidence of shock and perspectives of alternative origins). Identification of circular structures may lead to contributions in the understanding of magmatic and tectonic history, and might also lead to discovery of economically viable structures such as kimberlite pipes, known to be the main host matrix for diamonds (Ringwood et al., 1992). For instance, the Richat dome, forming a spectacular circular structure in the Mauritanian part of the Sahara Desert, and informally called *The eye of Africa*, which has been once proposed as a potential impact structure (Cailleux et al., 1964), is now considered as an isolated Cretaceous alkaline-hydrothermal complex, including a kimberlite plug (Matton and Jébrak, 2014).

3. Climatic and geological contexts

Mauritania has two main assets for the potential discoveries of impact structures: its geology and its arid climate. The present/recent arid climate of the country is favorable to the preservation of small and recent impact structures. Most rain falls during the short rainy season from July to September. The average annual precipitation varies from 500 to 600 mm in the far south and decreases northward. The precipitation is lower than 100 mm in the two third of the country.

As for the geology, the country comprises four provinces: the Reguibat Shield, the Taoudeni Basin, the Mauritanides Range, and the coastal sedimentary Basin (Fig. 2). The Reguibat Shield is composed of Archean and Paleoproterozoic groups and granitoids. The Taoudeni Basin consists of Neoproterozoic and Palaeozoic sedimentary rocks intruded by Mesozoic mafic sills and dikes of the Central Atlantic Magmatic Province (CAMP) and is often covered by Quaternary sediments. The Mauritanides range formed as a result of orogenic events during the late Proterozoic and Paleozoic. The Atlantic Coastal Sedimentary Basin is composed of Cenozoic sedimentary rocks and is covered by Quaternary sediments.

4. Data and methods

4.1. Identification of circular structures

The approach follows that of Chaabout et al. (2015) for the exploration of circular structures in Morocco and was directly applied to Mauritania. Our methodology relies on the use of high-resolution Google Earth images. To facilitate and monitor the progress of the tedious survey of the vast surface area of Mauritania (1 030 700 km^2), which is larger than Morocco (710 850 km^2), the country was divided in more than 400 parcels of 50 km $\times$ 50 km. The google Earth software was used to fly over the parcels at different altitudes. The parcels were then examined from the highest altitude (global view of the parcel) to the lowest altitude (corresponding to the highest resolution available). Shaded relief images overlaid on color-coded topography were also used to check the validity of circular features observed in satellite imagery or to search for additional circular objects. For this purpose, we have used FABDEM (Forest And Buildings removed Copernicus 30 m DEM) (Hawker et al., 2022). FABDEM is the most recent publicly available topographic data covering the entire Earth surface at a resolution of 30 m/pixel. This approach enabled us to detect circular features from a few tens of meters to a few tens of kilometers. Any detected circular structure is delineated by the coordinates of its center and a polygon defining its outer limits. Urban areas have been avoided.

4.2. Analysis of the finding and preliminary assesment of circular structures

It is expected that most of the detected circular structures have a non-impact origin, as shown by the previous systematic search in Morocco (Chaabout et al., 2015). Magmatic, tectonic and superficial processes (erosion, weathering) or a combination of these processes should be responsible for most of the circular features detected in the satellite imagery. Some circular features may be the result of human activities. We present first a global analysis, that is intended to detect outliers in possible global trends that could result for the magmatic/tectonic or superficial processes responsible for most of the circular structures. We investigate the spatial distribution of these circular structures with respect to relief, lithology and ages of lithological units. All circular stuctures are considered in this analysis, independently of their diverse origins. FABDEM is used for topographic analysis. The most recent geological map of Mauritania (Bradley et al., 2015) is used to record geological units within the perimeters of the circular structures, ordered by surface area of exposure within two radii of each circular structure.

The analysis of the spatial distribution of these circular structures addresses the following questions: are they homogeneously distributed ? Do they form cluster ? Alignments ? What is the proportion of circular structures occurring on the different geological units ? For this purpose, the circular features are overlaid on available geological and topographic maps to extract lithology, ages of geological units, and elevations. The results of this analysis are also motivated by the possible extension of this approach to other countries, in particular in North and West Africa. Extrapolation of these results may be useful to predict the number of circular structures that can be detected, and that would need to be examined individually to elucidate their origin, according to age of geological units or elevations. Lessons may also be learned from these results to optimize more sophisticated detection algorithms.

The second level of the analysis focuses on the individual examination of each circular structure. For each circular structure, we have produced three maps: a map based on Bing imagery using the Bing plugins in QGIS, a map of color-coded elevations with an optimum stretch to reveal the circular structure, overlaid on a shaded relief, and a close-up view of geological map for the same area, overlaid on a shaded relief. The morphology and the local and regional geology in the neighboring of each structure are discussed, to form a first assessment of possible origin. The following questions serve as criteria to assess plausible alternatives to the impact origin, including magmatic intrusion/volcanic or hydrothermal features: is there any evidence for volcanic activity near the structure? Is there any evidence for regional deformation? Is it a karstic region? Are there indications of anthropic activity. This preliminary assessment leads us to propose a list of circular features with the best prospect for an impact origin that should be prioritized targets for field work in Mauritania.

5. - results

Fifty-four circular/elliptical structures have been detected in satellite imagery, and correspond either to positive (cones, domes), or negative (depressions with or without raised rims) topographic expressions. The complete list of these features with coordinates, diameters, elevations, and up to two dominant geological units occurring at the structure is given in Table 2. More complete information is provided in supplementary material (Baratoux, 2023, file: Mauritania_Circular_Structures.xlsx), including other minor geological units noted at each structure, and axes lengths for the elongated (elliptical) structures. For elliptical structures, the diameters correspond to the diameter of a circle having the same surface area as the ellipse (the square root of the product of the length of the major and minor axes). The circular features are reported on the geological map of Mauritania (Fig. 2) and are also shown on aerial imagery (Fig. 3) and on the topographic map (Fig. 4).

5.1. Spatial distributions and sizes

Circular structures have been identified on a large proportion of the Mauritanian territory, with the exception of the southwestern and southeast parts of the country. To the first order, the distribution is readily explained by the occurrence of Quaternary deposits in these two regions (see section 5.2). Some objects form clusters, such as the group of structures labelled "El Mreiti" in the northeastern part of the country, or the ones labelled Bassikounou in the southern part of the country (see Figs. 3 and 4). In terms of diameter, the distribution ranges from 60 m to 7.5 km with most frequent diameters smaller than 2 km, despite a potential for large impact structures in the Proterozoic and Archean domains of Mauritania. It is of note that size frequency distribution of the circular structures is right-skewed (Fig. 5), as is the size frequency distribution of the ~200 impact structures on Earth. Other geological processes, such as tectonic and magmatic processes, do not necessarily produce right-skewed size frequency distribution, as for instance plutons smaller than a given size may not be able to ascent through the crust before cooling and emplace at a shallow depth. Since most of the circular structures are expected to result from non-impact processes, a right-skewed size frequency distribution of circular structures,

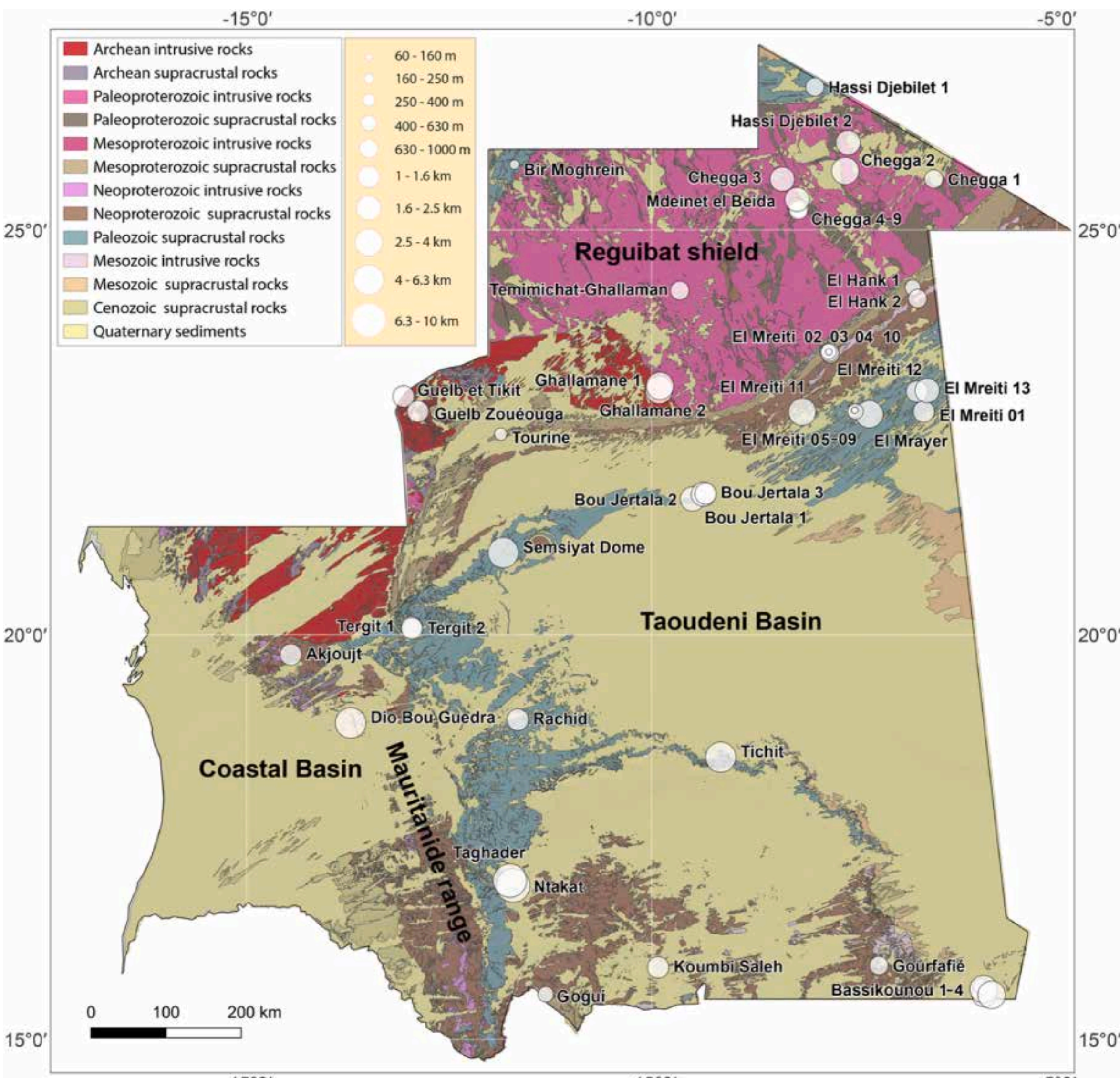

Fig. 2. Geological map of Mauritania with the different geological units, redrawn from the shape files provided by Bradley et al. (2015) (simplified version) showing the locations of circular structures detected in this study. The size of each circle is related to the diameter of the structure (not to scale, see legend).

independently of their origin, is a surprising result, which shall be confirmed or infirmed based on the extension of this study to a larger territory and to a wider range of diameters. The absence of circular structures larger than 8 km in our list of detections reflects a possible caveat of our approach for the search of the remnants of large and ancient impact structures. Other approaches, based for instance on geophysical data may be more appropriate than satellite imagery for this purpose.

5.2. Relationships with geological units

This section describes the proportion of circular structures associated with geological units. The geological units have been grouped into 13 categories based on lithology (supracrustal rocks, including sediments, metasediments, and volcanic rocks, versus intrusive bodies), and ages (Archean, Paleoproterozoic, Mesoproterozoic, Neoproterozoic, Paleozoic, Mesozoic, Cenozoic, and Quaternary). A 14th lithological category has been added that corresponds to very minor occurrences on the map of quartz or carbonate veins of unknown ages, as two circular structures intersect with this unit. The proportion of circular structures as a function of each group is presented in Fig. 6a, which can be compared with the proportion of surface area of exposure of each unit, based on the geological map (Fig. 6b). This figure was achieved to see if circular structures were associated more frequently with a given geological era. The two charts would show similar proportion if the distribution of circular structures as a function of geological unit was statistical random. The first result is the fact that circular structures are rarely found in Quaternary sediments, as already noted from their spatial distribution. In Archean and Proterozoic units, circular structures are more frequent in supracrustal rocks than in association with intrusions. The Neoproterozoic, Paleozoic and Mesozoic periods are over-represented in the circular structure pie charts. There is also a remarkable proportion of circular objects associated with Mesozoic intrusions, suggesting that these objects are not impact structures but likely related to magmatic processes.

5.3. Relationships with topography

Finally, we have examined the distribution of circular structures as a function of elevations. A comparison of the distribution of elevations of circular structures (using the kernel density method) with the distribution of elevations of Mauritania (histogram with bins of 1 m) is given in Fig. 7. The comparison shows that the distribution of circular features is parallel to the distribution of elevations of the country with an exception for the lowest elevations (<200 m) that correspond to areas eroded and covered by Quaternary sediments. Note that the global distributions have two peaks, which may also explain the two clusters of circular structures around 300 m and 400 m, respectively (see red circles in Fig. 7), though this is considered as statistical noise by the kernel density estimator. Elevations above 500 m are slightly over represented in the distribution of circular structures with respect to the frequency distribution of country-wide elevations (the three structures above 500 m are Semsiyat Dome, Ntakat and Taghader).

Finally, it is possible to examine the relationships between diameters, elevations and geological age (Fig. 8). This figure indicates that small circular structures occur in a narrow range of elevation. It reveals that the three features at the highest elevations identified in Fig. 7 are also the larger objects and are associated with Paleozoic supracrustal rocks. It also shows the relative paucity of circular features smaller than 1 km for areas entirely covered by Quaternary sediments, indicating the difficulty to detect small and buried circular structures using satellite imagery and/or topographic data.

The main results of these global analyses may be summarized as follows: the Neoproterozoic supracrustal unit, the Paleozoic supracrustal and the Mesozoic intrusive units are particularly "productive" of circular structures. It is likely that the features associated with Mesozoic units are in fact magmatic intrusions. Circular structures are found at all elevation with no particular bias, except in the lowest parts of Mauritania, which are covered by Quaternary sediments and lack circular features. Three circular structures have been identified in the highest regions of Mauritania, in association with Paleozoic crustal rocks.

6. Preliminary assessment of each circular structure

All lithological information provided below are based on the examination of the geological maps. The three maps for the 6 most promising structures, based on the individual assessment presented below, are provided in Fig. 9 (Chegga 2, Dio Bou Guedra, Hassi Djebilet 2, Temimichat-Ghallaman, Rachid, and Tichit). The selection also considers the conditions for exploration in the field. The complete set of maps for the 54 circular structures, which also include candidate impact craters, are provided as supplementary material (Baratoux, 2023).

6.1. Circular structures in Archean units

Guelb et Tikit (1.24 km) and Guelb Zouéouga (1.35 km) were named after the maps of Bronner (1978) and Institut Géographique National, Annexe, Centre de l'Afrique Occidental, 1970. They are located in the Reguibat shield. They appear as two dark circular features in satellite imagery, but the topography reveals that they are eroded hills. The circular features correspond to the talus formed by the material eroded away from the slopes of the hills. The central part of the hill associated with Guelb et Tikit 1 is mapped as Banded Iron Formation and ferruginous quartzite. This formation is commonly observed in this region, and is generally mapped as curvi-linear features. One of these linear features intersects the hill corresponding to Guelb Zouéouga 2. The hills are surrounded by Archean intrusive. These features are therefore likely the results of sedimentary and superficial processes.

Ghallamane 1 (2.84 km) and Ghallamane 2 (3.70 km) are two small circular gentle and flat-floor depressions also located in the Reguibat shield. They were noted on the Rhall Amane topographic map as depressions with well-marked drainage patterns (Institut Géographique National, Annexe, Centre de l'Afrique Occidentale, 1968). They are formed in the TT unit, described as "serpentinized metadunite, metagabbro, amphibolite, anorthosite, and quartzo-feldspathic gneiss". This unit is locally covered by Quaternary sediments in lower elevation areas, and is exposed as irregular shapes. These structures deserve further attention, as they could be small and recent impact craters, but the sediment cover is an obstacle for direct exploration in the field (without shallow drilling).

6.2. Circular structures in Proterozoic units

The site of Akjoujt includes one circular and deep pit (100 m) and two circular features visible in satellite imagery, but barely distinguishable on the topographic data. The site has been readily identified as a mining site where Cu is extracted (open pit) from Neoproterozoic intrusive rocks. It illustrates that our approach may detect circular features of anthropic origin as it was already the case with (Chaabout et al., 2015).

Chegga 2 (2.94 km) is a shallow elongated depression occurring in a Paleoproterozoic granite (Fig. 9a). Satellite imagery reveals centripetal drainage pattern (Fig. 9a). There is no other similar depression in this geological unit. A 3 km-wide uranium anomaly, centered at 25°44′N, 7°37′W (see Fig1 2, Ishagh et al., 2021) corresponds to the depression. This circular feature deserves further attention.

Chegga 3 (2.40 km), Chegga 4 (1.60 km), Mdeinet el Beida (0.4 km), Chegga 5 (0.65 km), Chegga 6 (0.28 km), Chegga 7 (0.7 km), Chegga 8 (0.76 km), and Chegga 9 (1.0 km) are circular domes with well-marked radial drainage patterns in satellite imagery. Mdeinet el Beida was noted on topographic map of Institut Géographique National Service

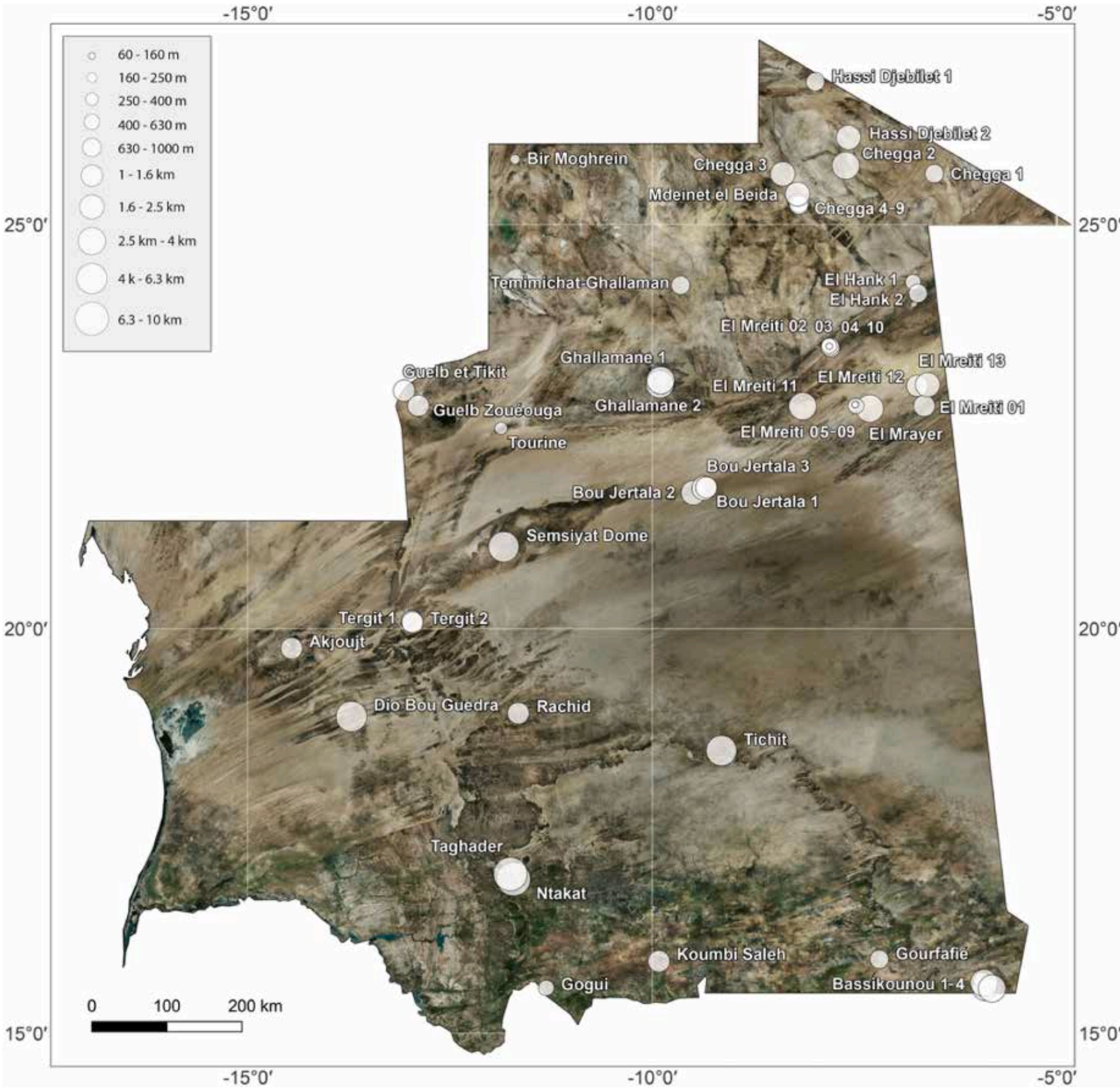

Fig. 3. Map of all circular features on the Bing imagery for Mauritania.

géographique, 1960. They occur on a granodiorite to tonalite Proterozoic unit, but the domes are notably associated with the map unit "Quartz and (or) carbonate veins". They are located between two hyper-alkaline magmatic intrusions (Hassi el Fogra to the north and Tigsmat el Khadra to the south). A magmatic origin appears to be the most plausible explanation for these structures.

Dio Bou Guedra (4.27 km) may be described as a series of concentric rings largely covered by Quaternary deposits (Fig. 9b). The rings, lying a few tens of meters above the Quaternary sediments, are associated with map unit Agt described as "quartz micaschist, pelitic schist and metasedimentary rocks". The arcuate relief of the structure was noted in the Bir Allah topographic map (Institut Géographique National, Annexe, Centre de l'Afrique Occidentale, 1969). Tectonic deformation of the metasediments may explain the occurrence of these arcuate rock exposures (e.g., Foum Taguentour in Algeria, see Chabou, 2019 for details). However, the same unit, exposed elsewhere in the area, form linear ridges and is, according to our observation of the geological map, never associated with concentric outcrops. These concentric rings may correspond to the rim and central peak or peak ring of a small but complex impact structure. The structure deserves further attention.

Hank 1 (420 m) is a small and shallow depression barely visible in the topographic data, but well visible in satellite imagery. It occurs in Mesoproterozoic sediments. There is no obvious explanation for this feature, which therefore deserves further attention.

El Mreiti 02 (720 m) is another circular feature located in the same unit as Hank 1, about 150 km to the south-west. Its topography is composed of a shallow depression with a central hill and pit. On satellite imagery, the rim appears to be irregular, the inner moat shows concentric lineaments and the central mound is also marked by concentric lineaments. The presence of Mesozoic intrusive rocks, including gabbro, diorite, diorite and microgabbro (Md unit, see for instance El Mreiti 03, 04 and 10) and in the immediate vicinity argues for a magmatic origin for this feature (a magmatic intrusion that has probably not been properly mapped).

El Mreiti 11 (3.40 km) is an incomplete circular feature forming a 30 m deep depression, and open to south-west. The region is largely covered by Quaternary sediments, but the floor of the structure is composed of pelites of the Adrar Group (Proterozoic). It lacks any central mound that could suggest a complex impact structure. The structure may be the result of erosional/superficial processes.

Gogui (440 m) was already mentioned in a previous survey of satellite imagery (Rossi, 2002). It was described as a dark circular feature surrounded by an annulus of lighter-tone material. The drainage pattern appears to be influenced by its presence, but the morphology of the

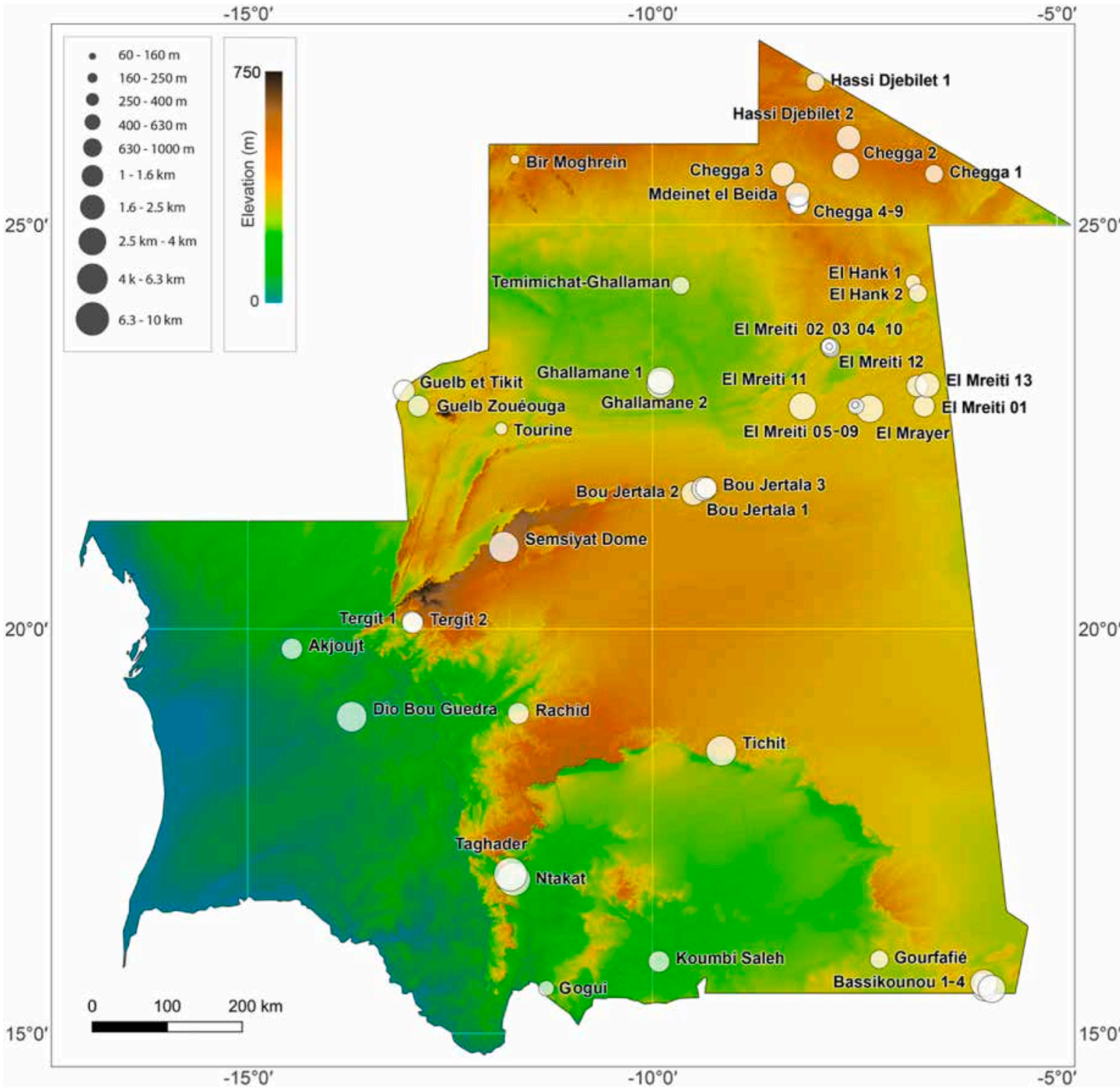

Fig. 4. Map of all circular features on the global FABDEM of Mauritania.

feature is difficult to define from satellite imagery (it could be either a mound or a depression). In fact, the topographic data reveal that this feature is not a depression, but a near-perfect cone. It is composed of Mesoproterozoic fine-to-medium-grained feldspathic, micaceous, and glauconitic sandstone-quartzite. A few other elongated mounds may be observed on the same unit. This feature is most likely the result of the erosion of the sandstone-quartzite unit.

Temimichat-Ghallaman forms a topographic depression with raised rims. It was well represented on the Temimichat Rhall Amane topographic map (Institut géographique national, annexe, centre de l'Afrique occidentale and Mauritanie, 1965). It occurs in Paleoproterozoic granite to granodiorite (TGp unit) (Fig. 9d). No such other depression is observed in the TGp unit. Pomerol (1967) reported the presence of basalt within the crater and argued in favor of a magmatic origin. Rossi et al. (2003) reported the occurrence of pseudotachylites-bearing rocks at the rim and considered that this structure remains a good candidate for a simple crater on a crystalline target. Though a magmatic origin may be possible, its morphology, with raised rims, makes it one of the most promising candidates for an impact origin.

Tourine (330 m) is a small circular mound occurring in Mesoproterozoic limestone. It appears as a dark circular feature in satellite imagery, with several concentric features. The color contrast suggests that the lithology may be different, but the small feature was likely not mapped at the resolution of the geological map. There are no known exposures of volcanic or magmatic units near the Tourine feature, and no other circular or elongated mounds in this unit. Given the lack of sufficient information, we prefer not to speculate on the origin of this circular mound.

6.3. *Circular structures in Phanerozoic (except quaternary)*

Bir Moghrein (230 m) is a very small circular mound composed of Devonian argillite or marly limestone (Zm1 unit). More or less elongated similar landforms occur on another argillite unit (Gb) of Silurian age a few km north-east of Bir Moghrein. It is therefore reasonable here to exclude an impact origin.

The four Bassikounou structures are named after the small city located about 30 km of the cluster. Bassikounou 01 and Bassikounou 03 were noted as depressions in the topographic map of the Nampala map of the Institut Géographique National, Annexe, Centre de Dakar, 1977. Bassikounou 3 is an elliptical depression (2.40 × 3.80 km) that is essentially covered by Quaternary sediments. On satellite imagery the interior of the depression appears as darker material. The map mentions an exposure of "sandstone and clayey sand, kaolinitic clay, iron pan"

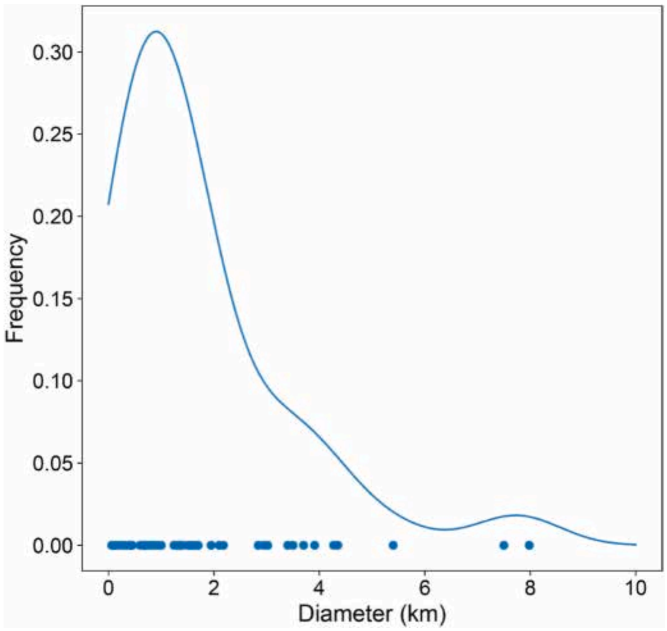

Fig. 5. Size frequency distributions of the 54 circular structures identified in Mauritania, including the four structures previously identified and the 50 circular features discovered in this study. The diameter of each structure is noted by a blue circle above the x-axis. The size-frequency distribution is right-skewed.

(unit TIM) on the south-eastern part of the depression. Bassikounou 4 is another elliptical depression (3.0 × 5.10 km) with similar characteristics, including Quaternary cover and limited exposure of the Cenozoic sandstone unit. The proximity, the similarity and elongation of Bassikounou 1, Bassikounou 2, Bassikounou 3, Bassikounou 4 features (see 5.4 for Bassikounou 1, Bassikounou 2) are strong arguments against an impact origin and in favor of a superficial process.

Hank 2 is a small and elliptical depression (1.10 × 0.770 km) occurring in the Jurassic Md unit described as "gabbro, diorite, dolerite, and microgabbro". There are two more irregular depressions a few km to the north-east of this feature with similar dimensions and amplitudes in relief. This depression is likely to be the result of superficial/erosional processes.

El-Mrayer (3.50 km) appears as a series of concentric features in satellite imagery, with two lineaments, that are oriented NNE-SSW and NEE-SWW. Radial and concentric features were already reported on the Mejaouda topographic map (Institut Géographique National, Annexe, Centre de l'Afrique Occidental, 1972). The albedo circular feature corresponds to an incomplete circular plateau with a central depression of about 1 km in diameter. The structure affects Ordovician sandstones of the Adrar Supergroup. It was initially noted by Rossi (2002). Orti et al. (2008) visited this structure in the field and found no evidence of shock metamorphism. Despite the fact that no intrusive bodies have been mapped in this region, the feature has typical characteristics of a shallow buried laccolith.

El Mreiti 03 (650 m), El Mreiti 04 (600 m) and El Mreiti 10 (120 m) are similar features, each of them appearing as a circular plateau culminating about 30 m above the surrounding terrain. They are clearly mapped as magmatic intrusions, and correspond to the map unit Md, mapped as "Jurassic gabbro, diorite, dolerite, and microgabbro". The

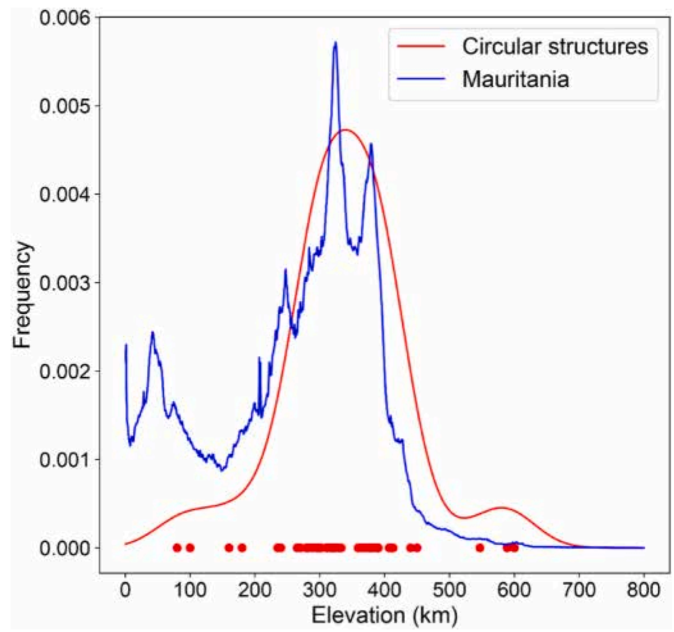

Fig. 7. Frequency distribution of the 54 circular structures obtained from kernel density estimation (red curve), compared to the frequency distribution of elevations of the entire country (blue curve), calculated from the FABDEM shown in Fig. 4. The elevations of circular features are also reported with red circles above the x-axis.

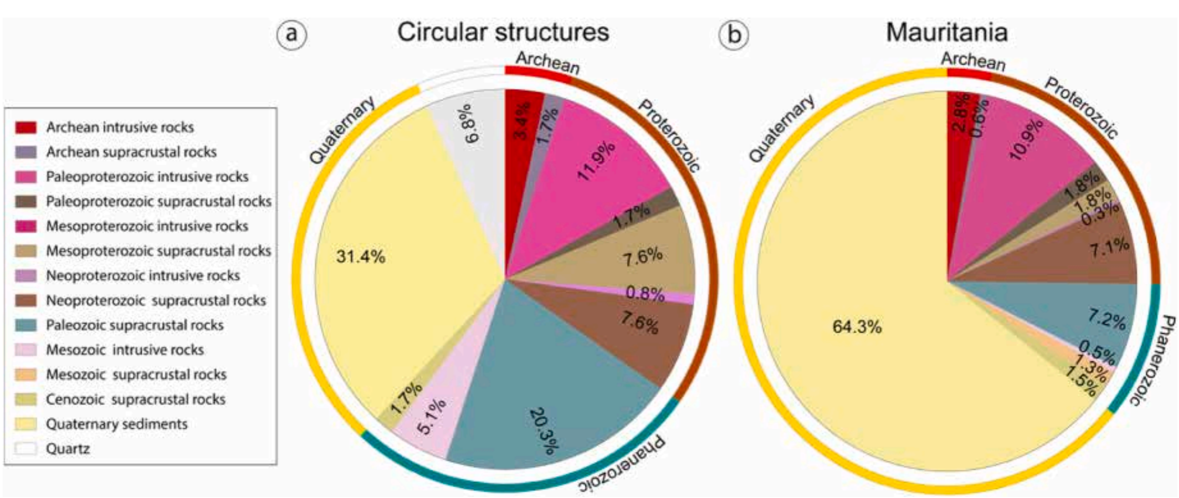

Fig. 6. a) Pie charts of the proportion of circular structures grouped as a function of geological units; b) Pie charts of the proportion of surface area of exposure of geological units.

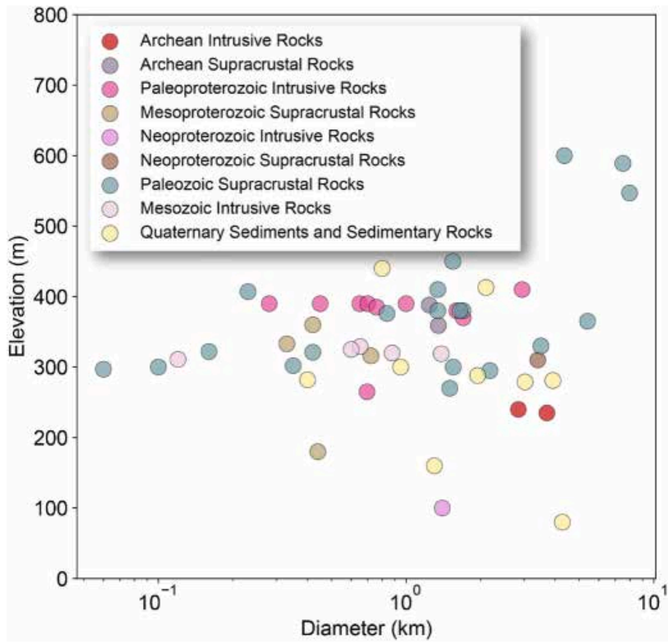

Fig. 8. Diameter versus elevation and geological units of the circular structures.

circular structures were already noted and considered to be dolerite pipes by Villemur (1967). The magmatic origins of these features, and of El-Mreiti 02, not recognized on the map, are clear. 140 km to the south-east of this group of circular objects, the El Mreiti 01, forms an elliptical structure (1.60 km × 1.20 km) with a raised rim, and is also associated with the Md unit. An arcuate, incomplete ring was aleady noted on the Oglat Hameïdnat topographic map (nstitut Géographique National, Annexe, Centre de l'Afrique Occidental, 1972). It is likely that this feature shares a common origin with the El Mreiti structures mentioned in the paragraph.

El Mreiti 05 (350 m), El Mreiti 06 (160 m) and El Mreiti 07 (60 m) form another cluster of circular features sharing similar morphological characteristics. They appear as a positive relief in the topographic map, that can be described as a roughly circular region of hills. They all occur in the Ec map unit, defined as Ordovican sandstones and quartzites. They are likely erosional features.

El Mreiti 08 (100 m) and El Mreiti 09 (60 m) are a group of two small conical features both occurring in the Kn unit, described as Cambrian sandstones or pelites. They are likely erosional features.

El Mreiti 12 (1.55 km) and El Mreiti 13 (2.18 km) are roughly circular depressions formed in Ordovician sandstones. Considering the fact that close depressions, more irregular in shapes, are very common in this unit and region of Mauritania, the impact hypothesis can be excluded here.

Hassi Djebilet 1 is an elongated plateau (1.0 × 0.7 km) of Devonian conglomerate. This feature is irregular in the topographic map, its origin is unclear. Considering its morphological characteristics (an elongated and plateau with irregular edges), it is not considered as plausible candidate for an impact structure.

Bou Jertala 1 (1.70 km), Bou Jertala 2 (1.64 km) and Bou Jertala 3 (1.34 km) are circular depressions, located on Bou Jertala trough (Institut Géographique National, Annexe, Centre de l'Afrique Occidentale, 1980; Fabre, 1997) formed in Cambrian sandstones of the Oujeft Group, exposed as a plateau surrounded by Quaternary sediments (sands and dunes). It is of note that Aouelloul was formed in the same geological unit. They are aligned over a distance of less than 20 km. The floors of the depressions are flat and the edges of the depressions are at the same level as the plateau (no raised rims). The absence of raised rims, the geographic proximity of the three structures and the presence of other irregular depressions in this unit argue against an impact origin, but the likely common origin of these three features would need further studies to be elucidated.

Rachid (1.50 km) is a topographic ring composed of Ordovician quartzites and sandstones (Fig. 9e). In the absence of ubiquitous alternative hypotheses (absence of volcanic/magmatic intrusion in the area), this structure is a good candidate for an impact structure. The topographic ring may correspond to an eroded rim of a small impact crater, or to the central peak/peak ring of a large complex impact structure. It was already mentioned on the Tidjikja topographic map (Institut Géographique National, Annexe, Centre de l'Afrique Occidentale, 1964).

Semsiyat Dome (4.35 km) is a peculiar morphological feature formed in the Oujeft Group (quartzose sandstones). It has a circular moat bounding a wide annular plateau. At the center of the annular plateau, there is an irregular depression, about 1.2 km in diameter, bounded by a raised rim. This feature was briefly mentioned by Dietz et al. (1969), and was considered to have a common non-impact origin with the Richat dome, which is only 45 km to the north-east, but further work, dedicated directly to the dome, is warranted to confirm its origin.

Tergit 1 (1.34 km), Tergit 2 (1.54 km) are elongated plateaus with a knob at their centers. They occur in the sandstones of the Oujeft Group. The two structures are 2 km apart and are probably formed by erosion of the sandstones.

Tichit (5.4 km) is the third largest of our list of circular features. It occurs in the Oj and Ti units (Cambrian to Ordovician sandstones) (Fig. 9f). Its morphology is composed of an incomplete raised rim surrounding an annular moat, and a central peak. These morphological characteristics are compatible with a complex impact structure. This structure should be targeted in priority for fieldwork.

Ntakat (7.98 km), Taghader (7.5 km) are elongated plateaus, named after Institut Géographique National, 1978. The top of the plateau being composed of the sandstone of the Ti unit. The two structures are the largest in our list. The edge of each plateau is irregular, with the elliptical feature observed on satellite imagery being formed by debris in the talus slope. The two objects are only 4 km apart and appear to be erosional remnants.

6.4. *Circular structures entirely covered by or occurring in quaternary sediments*

Gourfafié (0.95 km) appears in visible imagery as a circular area with denser vegetation compared to the surrounding. On the topographic map, the structure forms a dome with a subtle raised rim. The circular depression lies only a few meters below the raised rim. On the geological map, the depression is indicated to be filled up with lacustrine deposits surrounded by Quaternary desert pavement gravels. Radial drainage has developed on the outward faces of the raised rim. The structure was actually mentioned on an ancient topographic map of the area (Institut Géographique National, 1961). The nearby (2–3 km) presence of Jurassic intrusion could offer an explanation for this feature, but an impact origin remains possible.

Bassikounou 1 (1.94 km) and Bassikounou 2 (400 m) are circular depressions, without raised rims, that are 5 km apart. As mentioned above, the cluster of Bassikounou structures similar in morphology could share the same non-impact origin (dissolution processes).

Chegga 1 (800 m) is barely visible in satellite imagery as concentric features that are partially covered by a field of dunes. The feature is associated with a subtle circular dome in the topographic map. It is entirely covered by Quaternary sediments. A magmatic intrusive origin is possible, given the proximity of Paleoproterozoic granites.

Hassi Djebilet 2 (2.10 km) is a circular depression with a possible raised rim marked by gullies visible on satellite imagery. Its morphology is compatible with that of an eroded simple impact crater. It was already reported on the Hassi Djebilet topographic map (Institut Géographique National, Annexe, Centre de l'Afrique Occidentale, 1969). This feature is

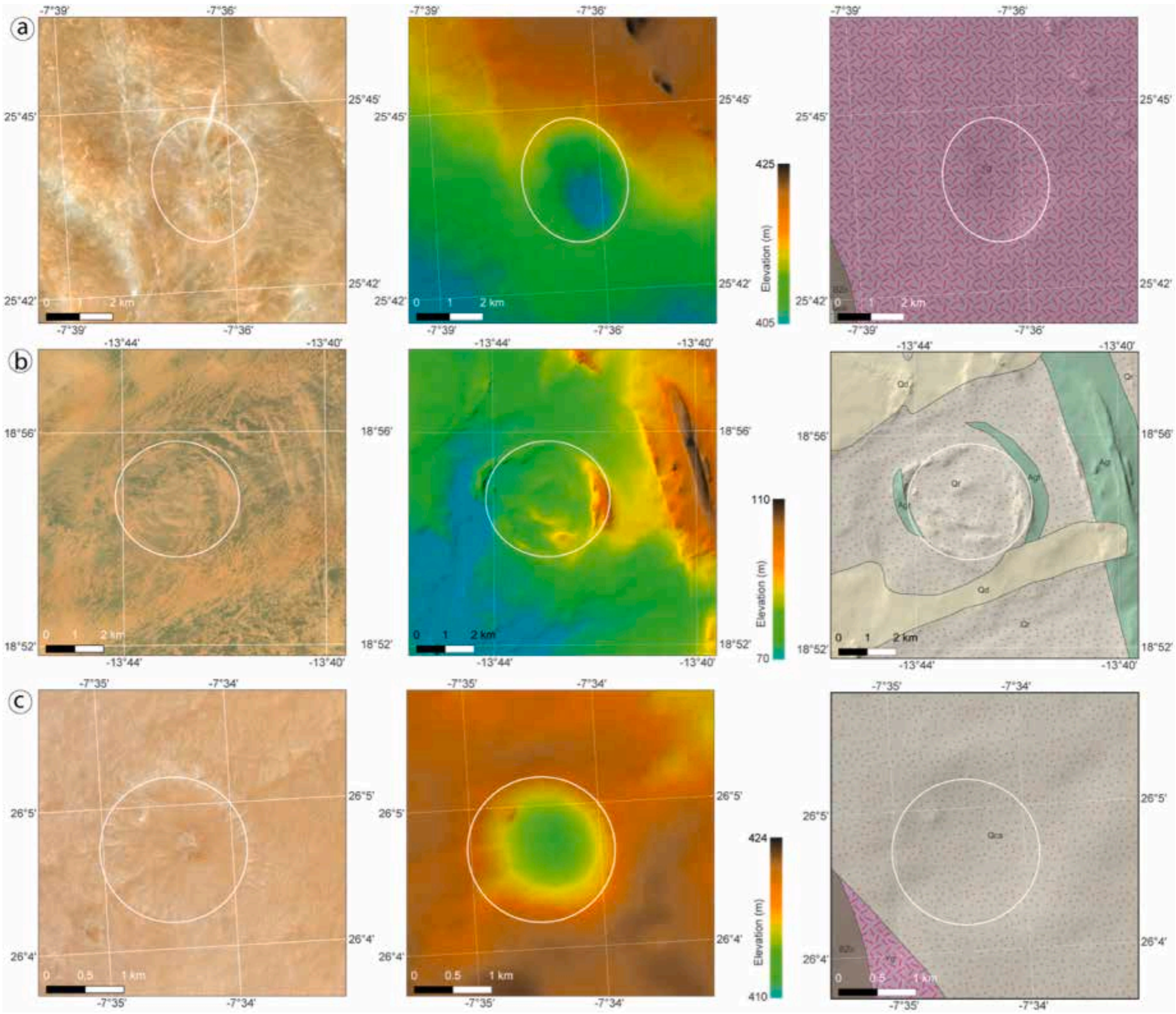

Fig. 9. Aerial view (left), topographic map (middle) and close-up view of the geological maps for 6 structures, considered to be the most promising prospects in terms of possible impact origin. From top to bottom, Chegga 2 (a), Dio Bou Guedra (b), Hassi Djebilet 2 (c). See Supplementary material (Baratoux, 2023) for the complete legend (SM_Legend.pdf) of the geological units. See Table 2 for definition of map units or data set provided by Baratoux (2023).

also close (2 km) to exposures of Paleoproterozoic granites and deserves further attention to discriminate between an impact and a magmatic origin (Fig. 9c).

Koumbi Saleh defines a circular moat, 1.30 km in diameter. It is of note that the circular moat is surrounded by a subtle and incomplete raised rim, eroded in its southern part. The moat is marked by denser vegetation and present or past human settlements in satellite imagery.

Fig. 9 (continued) – Aerial view (left), topographic map (middle) and close-up view of the geological maps for 6 structures, considered to be the most promising prospects in terms of possible impact origin. From top to bottom, Temimichat-Ghallaman (d), Rachid (e), and Tichit (f). See Supplementary material for the complete legend of the geological units.

7. Conclusion

Satellite imagery of Mauritania has been scrutinized to search for circular structures and potential meteoritic impact structures. Whereas previous explorations of the country reported 4 potential impact structures, 50 new circular structures have been discovered in this investigation. Among these structures, a non-impact origin appears to be most plausible for 48 features. We are therefore left with 6 structures that deserve further attention, and investigations in the field: Chegga 2, Dio Bou Guedra, Temimichat-Ghallaman, Rachid, Tichit, and Hassi Djebilet 2. The preliminary assessment of the possible origins of these circular features was facilitated by the existence of recent and homogenized geological mapping of Mauritania. The study shows that a large number of circular features may be detected from careful examination of satellite imagery and topographic data sets. From a simple ratio of the area of Mauritania to the area of Africa, the extension of this study to the entire continent may lead to the discovery of more than 1000 new circular features. The examination of satellite imagery should be therefore followed by a careful examination of each structure against geological maps and other available data, which may be not as homogeneous and reliable as in Mauritania. The examination of these structures could represent small research projects for students, which would not necessarily lead to discoveries of new impact structures, but could lead to various insights into the tectonic, magmatic, and metallogenic history of Africa. Finally, the main caveat of this approach is its inability to detect circular structures buried under recent sediments (which was expected) and its low capacity to detect large circular structures, which is more problematic to address the question of missing large impact structures in Africa. Other approaches, combining satellite imagery and topography with gravity, airborne magnetic and radiometric data shall be developed for this purpose.

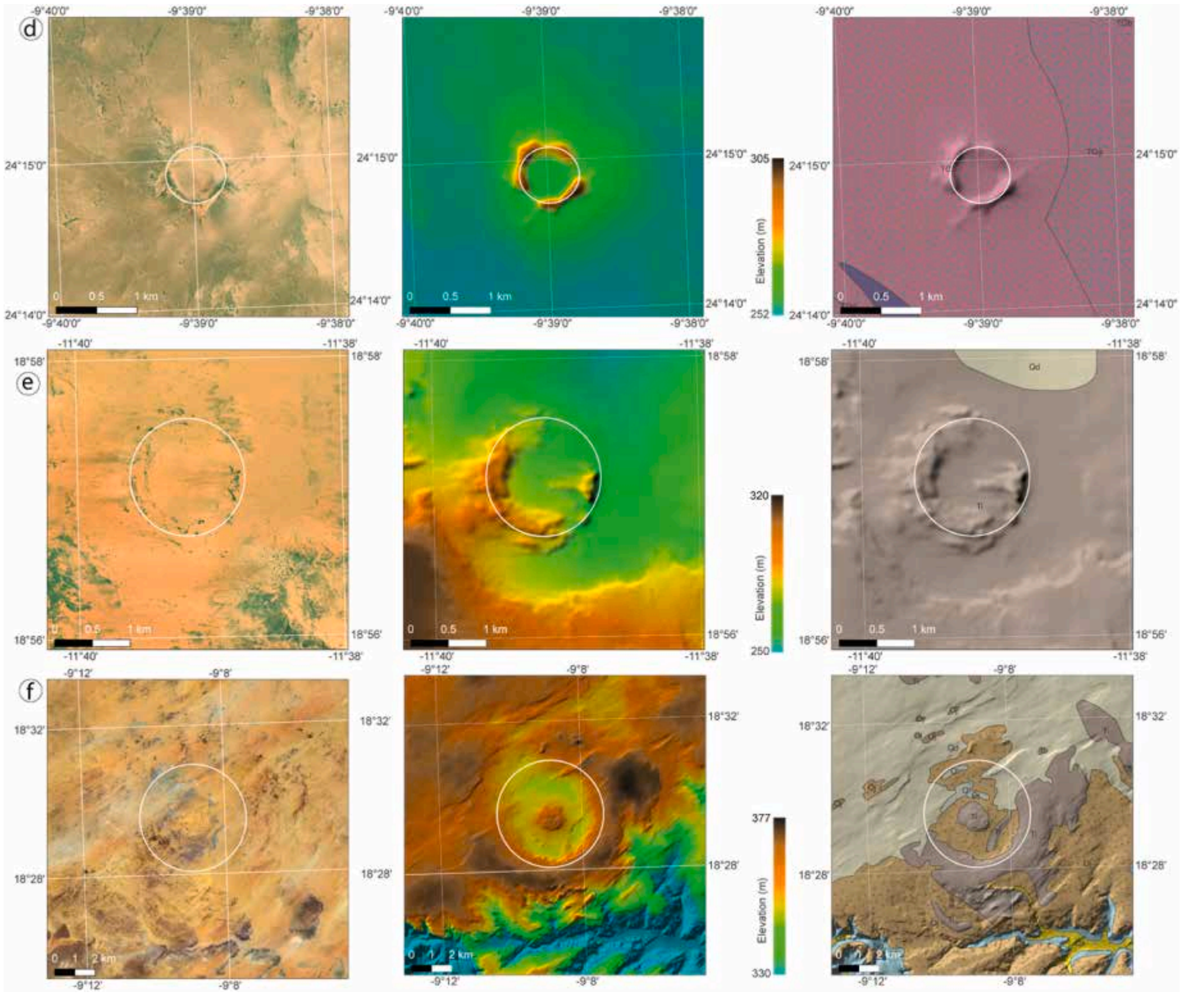

Fig. 9. (*continued*).

CRediT authorship contribution statement

E. Ould Mohamed Navee: Investigation, Funding acquisition. **D. Baratoux:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **H. Chennaoui Aoudjehane:** Validation, Project administration, Funding acquisition, Conceptualization. **H. Si Mhamdi:** Supervision, Investigation. **M. Raji:** Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The raw data are publicly available and the maps produced in this study are made available on a public data repository

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