Available online at www.sciencedirect.com
SCIENCE DIRECT®
C. R. Geoscience 336 (2004) 1491–1500
COMPTES RENDUS GEOSCIENCE
http://france.elsevier.com/direct/CRAS2A/

Surface Geosciences

Discovery of the largest impact crater field on Earth in the Gilf Kebir region, Egypt

Philippe Paillou[a,*], Ahmed El Barkooky[b], Aly Barakat[c], Jean-Marie Malezieux[d], Bruno Reynard[e], Jean Dejax[f], Essam Heggy[g]

[a] *Observatoire aquitain des sciences de l'Univers, UMR 5804, 2, rue de l'Observatoire, BP 89, 33270 Floirac, France*
[b] *Cairo University, Department of Geology, Giza, Egypt*
[c] *Egyptian Geological Survey and Mining Authority, Cairo, Egypt*
[d] *Institut « Environnement, Géo-Ingénierie, Imagerie et Développement » (EGID), université Bordeaux-3, 1, allée Daguin, 33607 Pessac cedex, France*
[e] *Laboratoire de sciences de la Terre, UMR 5570, École normale supérieure, 46, allée d'Italie, 69364 Lyon cedex 07, France*
[f] *Département « Histoire de la Terre », UMR 5143, Muséum national d'histoire naturelle, 8, rue Buffon, 75005 Paris, France*
[g] *Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX, 77058, USA*

Received 9 April 2004; accepted after revision 21 September 2004

Available online 6 November 2004

Presented by Jacques Angelier

Abstract

Using orbital imaging radar, we have detected a large number of circular structures in the southwestern Egyptian desert, covering more than 4500 km^2 close to the Gilf Kebir plateau in sandstones of Upper Cretaceous. Fieldwork confirmed that it is a new impact crater field: 13 craters from 20 m to 1 km in diameter were studied. The impact origin is confirmed by the observation of shock-related structures, such as shatter cones and planar fractures in quartz grains of breccia. Considering the extension of the crater field, it was possibly created by several meteorites that broke up when entering the atmosphere. ***To cite this article: P. Paillou et al., C. R. Geoscience 336 (2004).***

Résumé

Découverte du plus grand champ de cratères d'impact sur Terre dans la région du Gilf Kebir, Égypte. À partir d'images satellites issues de systèmes radar, nous avons détecté un grand nombre de structures circulaires dans le Sud-Ouest du désert égyptien, s'étendant sur plus de 4500 km^2 à l'est du plateau du Gilf Kebir, dans des grès du Crétacé supérieur. Une étude sur le terrain a permis de vérifier qu'il s'agit d'un champ d'impacts météoritiques jusque là inconnu : 13 structures, d'un diamètre compris entre 20 m et 1 km, ont été reconnues comme cratères d'impact. La présence d'un grand nombre de cônes de percussion

* Corresponding author.
E-mail address: paillou@obs.u-bordeaux1.fr (P. Paillou).

1631-0713/$ – see front matter © 2004 Académie des sciences. Published by Elsevier SAS. All rights reserved.
doi:10.1016/j.crte.2004.09.010

et de brèches dans lesquelles des quartz choqués à structures planaires ont été observés confirment l'hypothèse de l'impact. Considérant l'extension du champ d'impact, il a probablement été créé par plusieurs météorites qui se sont fragmentées dans l'atmosphère terrestre. ***Pour citer cet article : P. Paillou et al., C. R. Geoscience 336 (2004).***

Keywords: impact; crater field; Egypt; radar; Gilf Kebir

Mots-clés : impact ; champ de cratères ; Égypte ; radar ; Gilf Kebir

Version française abrégée

1. Introduction

Plus de 160 structures d'impacts météoritiques sont connues sur Terre [11], parmi lesquelles seulement neuf champs d'impacts : Kaali [34,35] en Estonie, Rio Cuarto [27,28] et Campo del Cielo [3,26] en Argentine, Macha [9] en Yakoutie, Henbury [1,16] en Australie, Morasko [14,31] en Pologne, Odessa [2, 29] au Texas, Wabar [10,23] en Arabie Saoudite et Sikhote-Alin [15] en Sibérie. Deux autres champs de cratères, Sirente [18,19,30] en Italie et Elko [17,36] au Texas, font encore l'objet de débats quant à leur origine. Nous présentons ici la découverte d'un nouveau champ de cratères d'impacts dans le Sud-Ouest de l'Egypte, qui dépasse de plusieurs ordres de grandeur, par ses dimensions, le plus grand champ d'impacts connu à ce jour.

2. Imagerie satellite radar du champ de cratères

L'imagerie par satellite radar permet d'explorer le sous-sol des régions arides jusqu'à quelques mètres de profondeur [20]. Nous avons réalisé une mosaïque radar du Sahara oriental à partir des images du satellite japonais JERS-1, qui nous a déjà permis de découvrir deux nouveaux cratères d'impact dans le Sud-Est de la Libye [21]. Nous étudions ici un site localisé 115 km à l'est du plateau du Gilf Kebir, s'étendant sur 4500 km^2 entre les latitudes 23°10′N–23°40′N et les longitudes 26°50′E–27°35′E. On observe, sur les images radar, plus de 50 structures circulaires d'un diamètre maximum de 2,5 km (Fig. 1) dans une étendue de grès grossiers du Crétacé supérieur, la formation de Sabala, partiellement recouverts de dépôts éoliens du Quaternaire. Plusieurs *circular features* sont mentionnées sur la carte géologique de Klitzsch et al. [13], accompagnant des affleurements de basalte doléritique du Tertiaire dans la partie nord-ouest. Issawi [12] avait étudié auparavant cette région : il a mentionné des structures bréchifiées et déformées, ainsi que des collines de grès ferrugineux (les *Black Hills*). Aucune explication claire n'a été proposée à ce jour quant à l'origine du fer dans la région. Des structures circulaires dans l'Ouest du désert Egyptien avaient déjà attiré l'attention de plusieurs scientifiques, qui avaient également observé des ressemblances avec les paysages lunaires et martiens [6,7].

3. Observations sur le terrain et preuves d'un impact

Nous avons pu étudier 13 cratères (Tableau 1), tandis que plusieurs autres ont été observés lors de trajets en voiture à travers le site. La Fig. 2 montre une image Landsat-TM5 indiquant la localisation des cratères étudiés, leur diamètre variant entre 20 et 1300 m. Ils présentent tous une morphologie circulaire, leurs bords pouvant atteindre 80 m de haut : c'est le cas du cratère GKCF13, présenté sur la Fig. 3. L'état de fraîcheur des structures, ainsi que la présence de petits cratères, indiquent qu'elles sont probablement récentes. De grandes quantités de brèches polymictes [32] ont été observées le long des bords de tous les cratères, formant des couches d'épaisseur métrique, parfois intercalées avec des grès. Les brèches sont constituées de fragments irréguliers de taille pluricentimétrique, dans une matrice contenant des grains de quartz (Fig. 4c et d). Ces brèches pourraient résulter d'éboulis d'éjectats. Des cônes de percussion [25] ont également été découverts sur le bord des cratères GKCF01, GKCF02 et GKCF12 : la Fig. 4a montre des structures caractéristiques en *horsetail* [24] produites par l'onde de choc de l'impact. Nous avons pu aussi observer des structures tectonisées, qui ont pu être produites par des impacts (Fig. 4d). D'autres indices d'impact ont également été fournis par les brèches et grès échantillonnés sur le site, qui contiennent essentiellement du quartz, associé à quelques zircons

et oxydes de fer. Plusieurs grains de quartz, issus d'échantillons des sites GKCF02, 07, 08, 09, 12, et 13, présentent des structures planaires ou PFs [8,33], associées parfois à une extinction roulante (Fig. 5a–d). La plupart des grains de quartz présentent une seule famille de PFs, mais quelques grains comptent deux familles de structures planaires (Fig. 5e).

4. Discussion

L'origine des champs de cratères d'impact est expliquée par la fragmentation d'une météorite à son entrée dans l'atmosphère terrestre : les fragments produisent alors un champ de cratères, orienté suivant la trajectoire du bolide [5]. Des modélisations numériques du phénomène indiquent que le champ d'impacts créé par un seul corps s'étend au maximum sur quelques dizaines de kilomètres carré [4,22] : c'est le cas des champs d'impacts connus jusqu'alors sur Terre, dont le plus grand couvre 60 km^2. Étant donné la très grande étendue du champ d'impacts découvert en Égypte (supérieure à 4000 km^2), il faut ici invoquer l'hypothèse de plusieurs météorites pénétrant l'atmosphère terrestre.

1. Introduction

More than 160 impact structures are known on Earth [11], among which most are single craters and very few impact fields. Impact crater fields result from meteor showers that can produce tens of kilometer-size impact structures in a single event. Nine impact fields are nowadays known on Earth, the impact origin of two being still unconfirmed.

The crater group of Kaali [34,35] is located on the Island of Saaremaa, in Estonia (N58°24′, E22°40′). It covers 1 km^2 and consists of nine craters, the largest one having a diameter of 110 m and the others ranging from 5 to 44 m. They were formed about 3700 yr ago and meteorite fragments (coarse octahedrite class) were found in the smallest craters.

The Rio Cuarto field [27,28] is located in central Argentina around coordinates (S30°52′, W64°14′). It is the first terrestrial example of oblique impact, forming a 30-km-long crater chain. Around 10 elliptic impact structures were observed, the biggest covering 4.5 km × 1.1 km. Impactites, breccias and meteorite fragments (chondritic impactor) were found on the site. The impact is younger than 3500 yr.

The Campo del Cielo crater field [3,26] is also located in Argentina (S27°35′, W61°40′). It contains at least 20 small craters, the largest being 103 m in diameter, and covers a 19 km × 3 km area. These craters were formed by fragments of an IA-type meteorite about 4000 years ago.

The Macha impact crater field [9] was discovered in western Yakutia at the location (N60°06′, E117°35′). It is formed by five craters from 60 to 300 m in diameter, covering less than 10 km^2. Shock metamorphic effects (planar fractures in quartz) were observed in breccias and the age of the craters is around 7300 yr. They could have been produced by iron meteorites.

The Henbury field in central Australia [1,16] is formed of 13 small craters, ranging from 5 to 145 m in diameter, which cover an area of 1.25 km^2. They are distributed in a scattering ellipse centered at coordinates (S24°34′, E133°08′). Iron meteorites and impact glass were found on the site and the event is dated at 4200 yr [16].

The Morasko [14,31] crater field is located in Poland, at coordinates (N52°30′, E16°55′). It is a group of eight craters, covering 2.5 km^2, the largest being 100 m in diameter, with a depth of 13 m. Iron meteorites of octahedrite class have been found in the area and the field is dated between 3500 and 5000 yr.

The Odessa crater field [2] in Texas, USA (N31°43′, W102°25′), consists of one main crater of diameter 170 m, surrounded by four smaller craters of diameter ranging between 6 and 21 m. It extends over less than 0.5 km^2 and was produced by a 300 tons iron meteorite of octahedrite class. Impactites were found on the site [29].

The Wabar crater field [10] is located in southern Saudi Arabia, in the Rub'al Khali desert (N21°29′, E50°28′). A group of four craters, of diameter between 17 and 100 m, lies in a 400 m × 200 m area. Fragments of meteoritic iron (octahedrite class) have been found on the site. Luminescence dating allowed one to obtain a very young age of 290 years for the event [23].

The Sikhote-Alin strewn field [15] was produced by a meteorite fall on February 12th, 1947 in Siberia (N46°06′, E134°42′). Thousands of iron meteoritic fragments were found in about 150 craters, ranging in diameter from less than one meter to 27 m. They cover a region of 1.7 km^2 and the total mass of the fall has been estimated to be about 70 tons.

The Sirente field [18,19] was recently discovered in central Italy within the mountains of the Abruzzo region (N42°10′, E13°35′). It covers 450 m × 400 m and contains 17 small craters close to a main crater of diameter 140 m. Radiocarbon dating of the target surface preserved below the rim gave an age of 1650 yr, but neither shocked material (shatter cones, breccias) nor meteoritic components were found until now. Recent work shows that it could be of anthropogenic origin [30].

About 300 crater-like depressions ranging from 5 to 250 m in diameter are located in northern Elko County, Nevada, USA. They cover an area of 10 km × 25 km. Although an impact origin was initially proposed, neither ejecta nor meteoritic material were found on the site and inspection of the stratigraphy of the crater rims did not reveal any evidence of disturbed layering. Subsidence by groundwater sapping [17,36] is now proposed as an alternative to the impact origin.

We report here on the discovery of a new and large impact crater field in southwestern Egypt, which increases by several orders of magnitude the size of strewn fields known on the Earth's surface.

2. Space-borne radar imaging of the crater field

Radar remote sensing allows a unique access to subsurface information down to a depth of several meters in arid regions [20]. We have produced a global radar mosaic of East Sahara (Egypt, Libya, northern Sudan, northern Chad) using archives of the Japanese JERS-1 radar satellite, for mapping the hidden hydrological and tectonic structures in eastern Sahara. This radar mosaic already permitted the discovery of a double impact crater in southeastern Libya [21]. It was used to explore Egypt where no impact craters have been so far discovered.

We focused on a region located 115 km east of the Gilf Kebir plateau, in the western Egyptian desert. This region presents at least 50 small circular features (maximum diameter of 2.5 km) in JERS-1 radar images (Fig. 1) and extends over 75 km × 60 km (i.e. 4500 km^2) between latitudes 23°10′N–23°40′N and longitudes 26°50′E–27°35′E. The exposed rocks belong mainly to the Sabala Formation of Upper Cretaceous. It consists of medium- to coarse-grained fluvial sandstone, interbedded with muddy paleosoil horizons. The area is partially covered with Quaternary aeolian sand deposits. The southern limit of the studied region also exhibits outcrops of the Aptian Abu

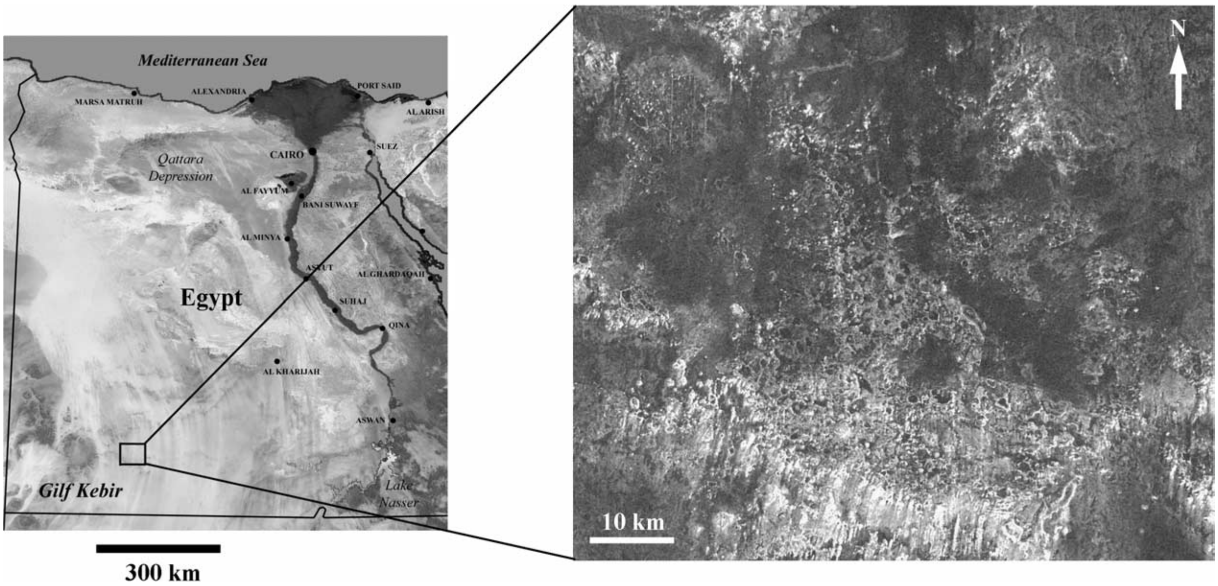


Fig. 1. Gilf Kebir crater field located on a map of Egypt (left) and observed by the imaging radar of JERS-1 (right).
Fig. 1. Champ de cratères du Gilf Kebir localisé sur une carte d'Egypte (gauche) et vu par le radar de JERS-1 (à droite).

Ballas Formation, constituted of shallow near-shore marine to coastal siltstone and fine-grained sandstone. Several 'circular features' are mentioned on the geological map of Klitzsch et al. [13], while few small Tertiary alkali olivine basalt (59 Ma [13]) outcrops are reported in the northwestern part of the region. Issawi [12] previously studied this area and reported the brecciation, ferruginisation and deformation of the bedding. No clear explanation for the iron origin in ferruginous sandstone formations (the so-called Black Hills) was proposed so far. Crater structures in the western Egyptian desert already attracted the attention of several scientists who also noticed some similarities with the Lunar and Martian landscapes [6,7].

3. Fieldwork results and evidences for an impact origin

We were able to study several circular structures on the field, a few of them being of volcanic origin. We could check 13 craters located in Fig. 2 over a Landsat-TM5 image and described in Table 1, but we observed much more similar structures while driving on the site. Their diameter ranges from 20 to 1300 m and they present a circular morphology with low (a few meters) to high rims: more than 80 m high for crater GKCF13 shown in Fig. 3. The height of the rims of the largest craters and the frequent presence of small ones indicate that these structures are probably quite young. Some crater depressions (e.g., GKCF13) are very marked with little post-shock sedimentary deposits, while others (generally the small ones with the lowest rims) are filled with Quaternary Aeolian deposits.

Abundant polymict breccias [32] were observed along the rim of all craters, forming pluri-decimetric to metric beds, sometimes interbedded with sandstones. They consist of centimeter- to decimeter-sized irregular fragments, embedded in a fine-grained quartz matrix (Fig. 4c and d). Beds are systematically dipping inwards the crater, with a steep dip close to vertical on the highest rims down to about 30° on the lowest observable rims. Their exact mode of formation is debatable, but they rather originated from slope deposits of the rims of the newly formed crater rather than from direct re-deposition of ejected material, because of the interbedding with sandstones and rounded shape of some fragments, implying slight erosional reworking. This idea is also supported by the absence of impact breccias on the slopes of similar size recent craters, such as Meteor Crater in Arizona. Shatter cones [25] were found on the border of craters GKCF01, GKCF02 and GKCF12. Fig. 4a shows shatter cones found on site GKCF01: it presents conical patterns, with 'horsetail' markings [24] produced by the impact shock waves. Finally, faulted zones with

Fig. 2. The Gilf Kebir crater field imaged by Landsat-TM5 with the 13 studied craters.

Fig. 2. Le Champ de cratères du Gilf Kebir vu par Landsat-TM5 avec les 13 cratères étudiés.

Table 1
List of the 13 craters studied (GKCF: Gilf Kebir Crater Field)

Tableau 1
Liste des 13 cratères étudiés (GKCF : Gilf Kebir Crater Field)

Crater's name	Latitude N	Longitude E	Diameter (m)	Observations
GKCF01 (Ahmed)	23°14′37″	27°27′37″	630	breccia shatter cones
GKCF02 (Nessim)	23°27′10″	27°19′18″	1000	breccia shatter cones
GKCF03 (Gihan)	23°28′33″	27°12′26″	1300	breccia
GKCF04 (Bruno)	23°29′05″	27°11′12″	950	tectonic breccia
GKCF05 (Virginie)	23°32′42″	27°09′33″	450	breccia
GKCF06 (Roxane)	23°31′45″	27°11′05″	20	breccia
GKCF07 (Nathan)	23°31′49″	27°10′57″	40	breccia
GKCF08 (Sarah)	23°31′45″	27°11′17″	75	breccia
GKCF09 (Jean-Marie)	23°31′13″	27°10′59″	710	breccia
GKCF10 (Jean)	23°32′01″	27°11′20″	370	breccia
GKCF11 (Aly)	23°28′15″	27°02′38″	1200	breccia
GKCF12 (Ragab)	23°24′50″	26°57′04″	500	breccia shatter cones
GKCF13 (Rahman)	23°18′23″	26°55′28″	950	breccia

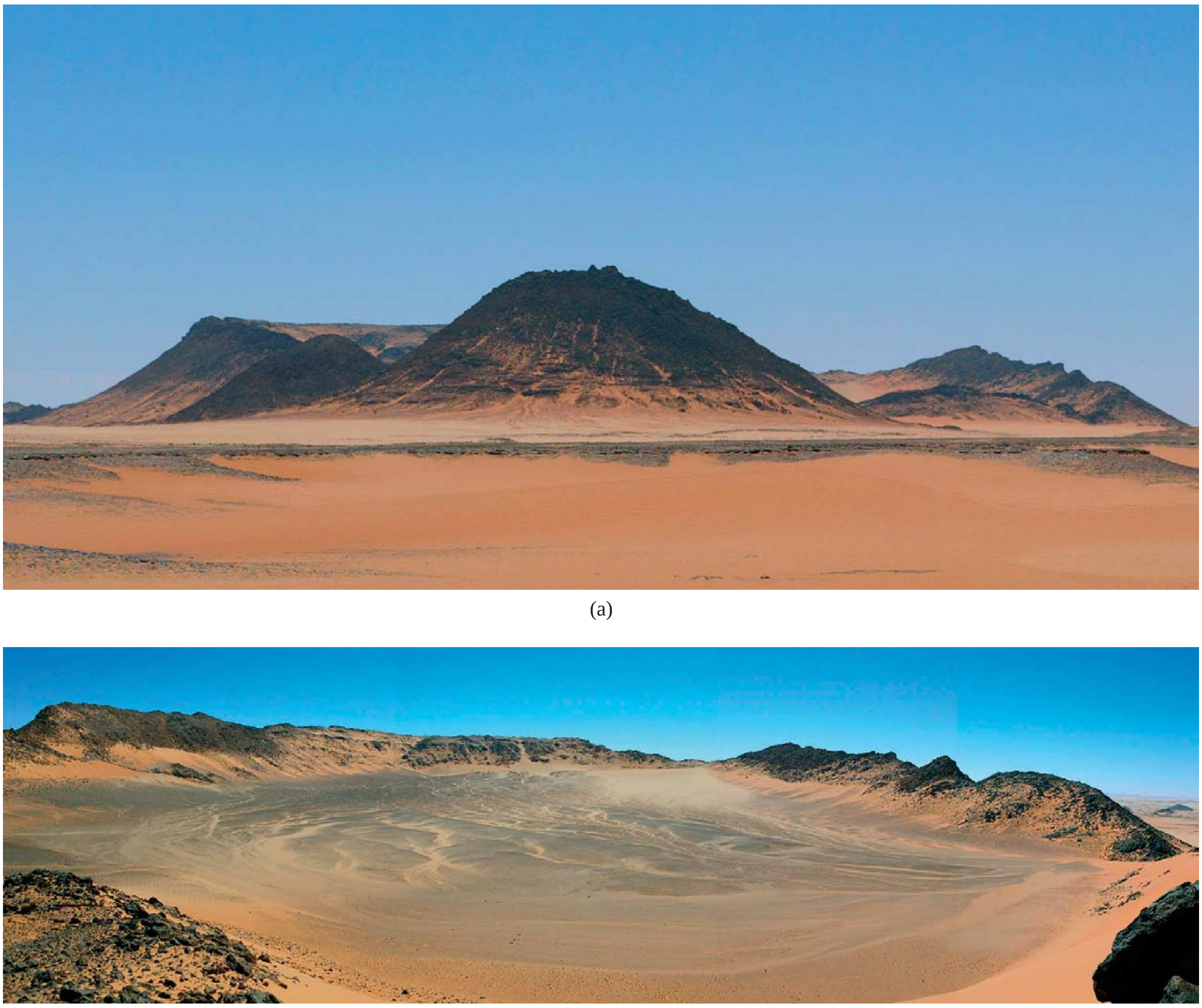
decimeter-sized tilted domains of originally cross-bedded sandstones are sometimes observed in the vicinity of crater rims (Fig. 4b). These deformations may be related to an impact, although a classical tectonic origin cannot be ruled out.

We prepared thin sections cut in the breccias and sandstones from crater rims. These samples were studied by optical microscopy and Raman micro-spectrometry. Both sandstones and breccias consist mostly of quartz, with very few zircons and other accessory minerals. Grain size ranges from about 3 mm down to very fine grains (about 50 µm in average) in the matrix of the breccias, associated with minor iron oxides and hydroxides, and possibly clay minerals. One of the sandstones consists of round quartz grains cemented by continuous 100- to 300-µm-thick layers of hematite and goethite. Quartz morphology is very varied from rounded to sharp angular grains. In sandstones and breccias from various craters (GKCF02, 07, 08, 09, 12, and 13), several quartz grains, generally over the millimeter in size, contain parallel features that are very likely to be planar fractures – PFs [33] –, sometimes associated with undulatory extinction (Fig. 5a–d). Such regular planar microstructures result from shock metamorphism in a pressure range from 5 to 20 GPa [8]. Micro-Raman profiles performed across these deformation features did not reveal the presence of glassy material, whose occurrence cannot be ruled out because of the low signal of glass in Raman spectroscopy. Most of these grains contain a single family of PFs, but a few grains present two different sets of PFs (cf. Fig. 5e).

Observation of shatter cones and breccias together with the discovery of PFs in quartz grains of in situ rock samples lead us to propose that the studied crater field has an impact origin.

4. Discussion

The origin of impact crater fields is explained by the breakup of a meteorite in the upper atmosphere of the Earth: the fall of meteorite fragments produces an impact field, usually distributed over an area elongated in the direction of flight of the meteorite, the largest craters being located near the downrange boundary of the field [5]. The resulting strewn field created from a single meteorite break up is commonly a few square kilometers in area. Numerical modeling of crater field formation indicates that the maximum aerodynamic separation of impactor components is in the order of hundreds of meters for the Earth [4]. The extension of the crater field mainly depends on the breakup altitude



(a)

(b)

Fig. 3. Pictures of crater GKCF13 of diameter 950 m. (**a**) View from outside. (**b**) View from inside.

Fig. 3. Photographies du cratère GKCF13 d'un diamètre de 950 m. (**a**) Vue depuis l'extérieur du cratère. (**b**) Vue depuis l'intérieur du cratère.

(generally between 12 and 30 km) and on the trajectory angle (significant separation is obtained for entry angles less than 30°) and impactor velocity [22]. However, it is very unlikely to obtain impact field extension larger than a couple of hundreds of square kilometers from a single impactor. Such large fields are produced by meteorites with an entry angle less than 5°, but the resulting craters are then elliptical in shape and distributed over an elongated ellipse. All known crater fields on Earth do not extend over more than 60 km^2 and can all be explained by the breakup of a single meteorite.

Considering the very large area covered by the discovered impact field – more than 4000 km^2 – and the spatial distribution of the 13 observed impact craters, showing neither clear main direction nor alignment, it cannot have been produced by the fragmentation of a single body. Such a large strewn field could then have been created by the fragmentation of several meteorites that encountered the Earth atmosphere. More detailed field characterization and modeling of the impact process are needed in order to support this hypothesis.

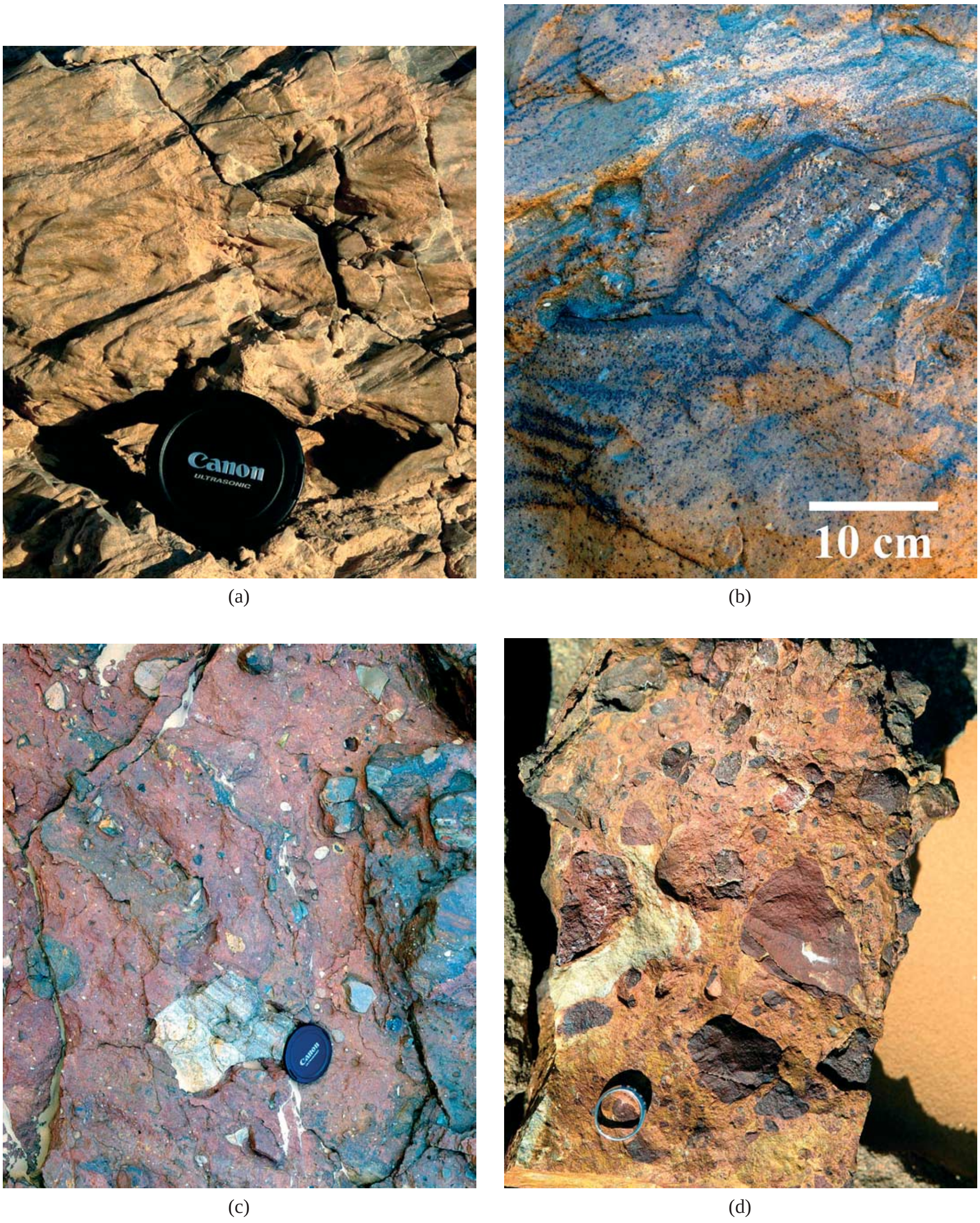


Fig. 4. Impact evidence observed on the field. (**a**) Shatter cones observed at site GKCF01. (**b**) Faulted zones with decimeter-sized tilted domains of originally cross-bedded sandstones found on site GKCF04. (**c**) Polymict breccia sampled on site GKCF01. (**d**) Polymict breccia found on site GKCF05.

Fig. 4. Preuves d'impact observées sur le terrain. (**a**) Cônes de percussion observés sur le site GKCF01. (**b**) Blocs de grès présentant des déformations décimétriques, trouvés sur le site GKCF04. (**c**) Brèche polymicte récoltée sur le site GKCF01. (**d**) Brèche polymicte trouvée sur le site GKCF05.

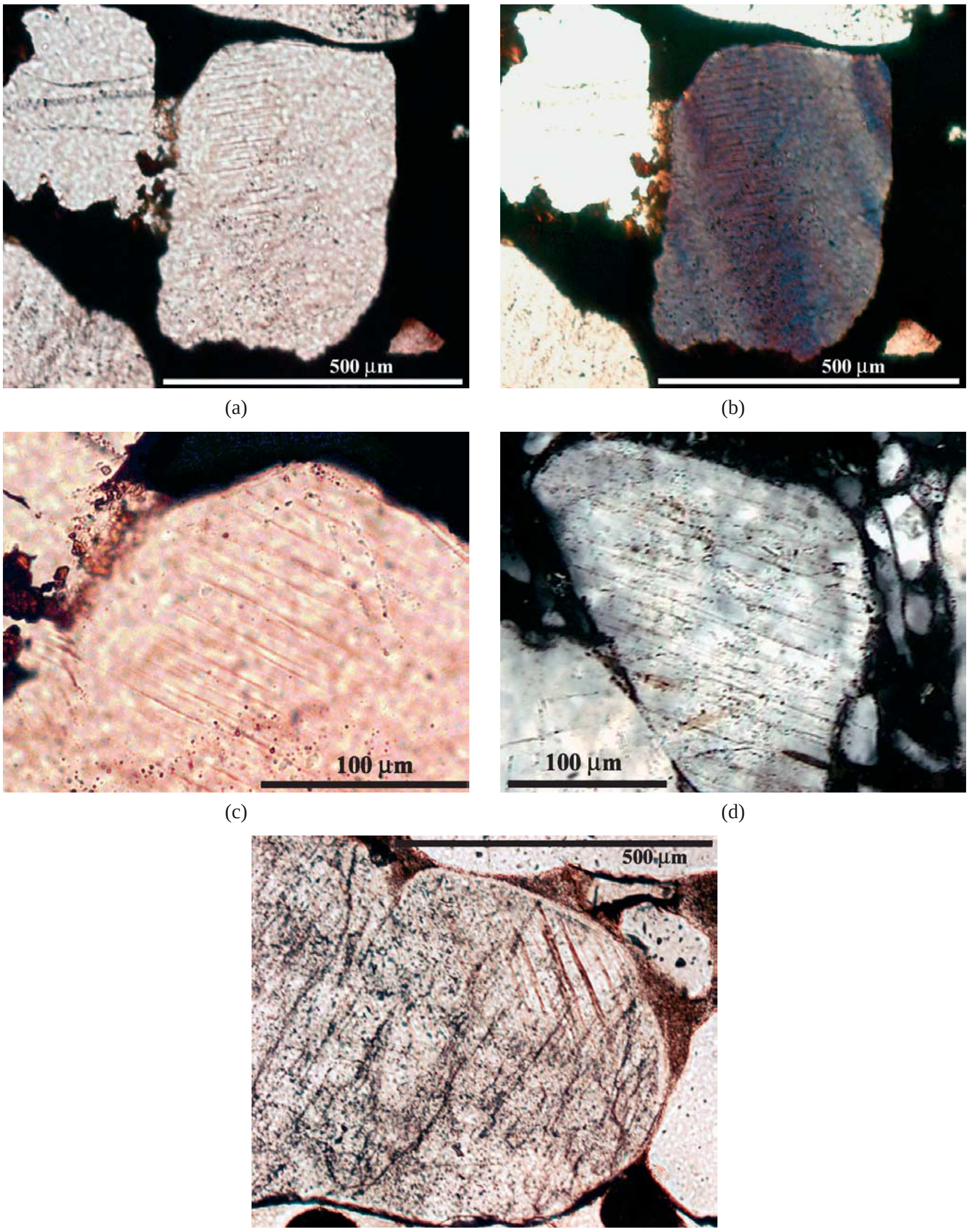


Fig. 5. Examples of shock metamorphism in quartz grain from breccia and sandstone cover of craters. (**a**, **b**) GKCF07, polarized light (**a**) and partially cross-polarized light (**b**), quartz grain showing PFs associated to wavy extinction. (**c**) GKCF07, enlargement of the upper left part of the quartz grain showed in (**a**) and (**b**) (polarized light). (**d**) GKCF12, quartz grain with PFs (polarized light). (**e**) GKCF09, example of quartz grain with two PFs families.

Fig. 5. Exemples de métamorphisme de choc observé dans des grains de quartz issus des couvertures de brèches et de grès des cratères. (**a**, **b**) GKCF07, lumière polarisée (**a**) et partiellement polarisée croisée (**b**), grain de quartz montrant des PFs associées à une extinction ondulatoire. (**c**) GKCF07, agrandissement du coin supérieur gauche du grain de quartz montré en (**a**) et (**b**) (lumière polarisée). (**d**) GKCF12, grain de quartz présentant des PFs (lumière polarisée). (**e**) GKCF09, exemple de grain de quartz avec deux familles de PFs.

Acknowledgements

The authors would like to thank A. Rosenqvist from JAXA, Tokyo, and T. Farr from JPL, Pasadena, for providing satellite imagery. They are also grateful to S. Dubernet from CRPAA, University of Bordeaux-3, France, for Raman analysis and H. Neshim from Aqua Sun Desert Tour for fieldwork support. This work was financially supported by the French ACI for Earth Observation and CNRS/INSU.

References

[1] A.R. Alderman, The Henbury meteorite craters in Australia, Mineral. Mag. 23 (1932) 13.
[2] B. Barringer, Historical notes on the Odessa meteorite crater, Meteoritics 3 (1967) 161.
[3] W.A. Cassidy, M.L. Renard, Discovering research value in the Campo del Cielo, Argentina, meteorite craters, Meteorit. Planet. Sci. 31 (1996) 433.
[4] C.M. Cook, H.J. Melosh, W.F. Bottke, Doublet craters on Venus, Icarus 165 (2003) 90.
[5] M.R. Dence, Meteorite breakup, Nature 289 (1981) 346.
[6] F. El Baz, Circular feature among dunes of the Great Sand Sea, Egypt, Science 213 (1981) 439.
[7] F. El Baz, B. Issawi, Crater forms in the Uweinat region, Ann. Geol. Surv. Egypt 11 (1981) 87.
[8] R.A. Grieve, F. Langenhorst, D. Stöffler, Shock metamorphism of quartz in nature and experiment, Meteorit. Planet. Sci. 31 (1996) 6.
[9] E.P. Gurov, E.P. Gurova, The group of Macha craters in western Yakutia, Planet. Space Sci. 46 (1998) 323.
[10] D.A. Holm, New meteorite localities in the Rub'al Khali, Saudi Arabia, Am. J. Sci. 260 (1962) 303.
[11] http://www.unb.ca/passc/ImpactDatabase/africa.html.
[12] B. Issawi, New finding on the geology of Uweinat Gilf Kebir, Western Desert, Egypt, Ann. Geol. Surv. Egypt 8 (1978) 275.
[13] E. Klitzsch, F.K. List, G. Pöhlmann, Geologic Map of Egypt 1:500 000, Bir Misaha sheet, The Egyptian General Petroleum Corporation, Cairo, Egypt, 1987.
[14] H. Korpikiewicz, Meteoritic shower Morasko, Meteoritics 13 (1978) 311.
[15] E.L. Krinov, Fragmentation of the Sikhote-Alin meteoritic body, Meteoritics 9 (1974) 255.
[16] D. McColl, Distribution and sculpturing of iron meteorites from the major craters at Henbury, Meteoritics 25 (1990) 384.
[17] J.F. McHone, M. Killgore, R.S. Verish, D.J. Roddy, Non-impact origin for Nevada's Elko crater field, in: 34th Lunar Planet. Sci. Conf., Abstr. 1572, Houston, USA, 2003.
[18] J. Ormö, A. Pio Rossi, G. Komatsu, The Sirente crater field, Italy, Meteorit. Planet. Sci. 37 (2002) 1507.
[19] J. Ormö, A. Pio Rossi, G. Komatsu, The Sirente crater field: Outline, age and evidence for heating of the target, in: 3rd Int. Conf. on Large Meteorite Impacts, Nördlingen, Germany, Abstr. 4070, 2003.
[20] P. Paillou, G. Grandjean, N. Baghdadi, E. Heggy, T. August-Bernex, J. Achache, Sub-surface imaging in central-southern Egypt using low frequency radar: Bir Safsaf revisited, IEEE Trans. Geosci. Remote Sensing 41 (2003) 1672.
[21] P. Paillou, A. Rosenqvist, J.-M. Malezieux, B. Reynard, T. Farr, E. Heggy, Discovery of a double impact crater in Libya: the astrobleme of Arkenu, C. R. Geoscience 335 (2003) 1059.
[22] Q.R. Passey, H.J. Melosh, Effects of atmospheric breakup on crater field formation, Icarus 42 (1980) 211.
[23] J.R. Prescott, G.B. Robertson, C. Shoemaker, E.M. Shoemaker, J. Wynn, Luminescence dating of the Wabar meteorite craters, Saudi Arabia, J. Geophys. Res. 109 (2004) E01008.
[24] D.E. Roach, A.D. Fowler, W.K. Fyson, Fractal fingerprinting of joint and shatter-cone surfaces, Geology 21 (1993) 759.
[25] A. Sagy, Z. Reches, J. Fineberg, Dynamic fracture by large extraterrestrial impacts as the origin of shatter cones, Nature 418 (2002) 310.
[26] J. Sanchez, W. Cassidy, A previously undescribed meteorite crater in Chile, J. Geophys. Res. 71 (1966) 4891.
[27] P.H. Schultz, J. Grant, W. Collins, J.P. Lopez, A.J. Toselli, T.G. Castellanos, Rio Cuarto crater field, in: Abstr. 23th Lunar Planet. Sci. Conf., vol. 23, Houston, USA, 1992, p. 1237.
[28] P.H. Schultz, C. Koeberl, T. Bunch, J. Grant, W. Collins, Ground truth for oblique impact processes: New insight from the Rio Cuarto, Argentina, crater field, Geology 22 (1994) 889.
[29] T.R. Smith, P.W. Hodge, Discovery of impactite at the Odessa meteorite crater, Meteorit. Planet. Sci. 32 (1997) A122.
[30] F. Speranza, L. Sagnotti, P. Rochette, An anthropogenic origin of the 'Sirente crater', Abruzzi, Italy, Meteorit. Planet. Sci. 39 (2004) 635.
[31] W.T. Stankowski, The geology and morphology of the natural reserve 'Meteoryt Morasko', Planet. Space Sci. 49 (2001) 749.
[32] D. Stöffler, R.A. Grieve, Classification and nomenclature of impact metamorphic rocks: A proposal to the IUSG subcommission on the systematics of metamorphic rocks, Eur. Sci. Found. Network on Impact Cratering Newslett. 2 (1994) 8.
[33] D. Stöeffler, F. Langenhorst, Shock metamorphism of quartz in nature and experiment: I. Basic observations and theory, Meteoritics 29 (1994) 155.
[34] R. Tiimaa, Kaali craters of Estonia and their meteoritic material, Meteoritics 27 (1992) 297.
[35] R. Tiirmaa, W. Czegka, The Kaali crater field at Saaremaa (Osel), Estonia: Geological investigations since 1827 and future perspectives, Meteorit. Planet. Sci. 31 (1996) A142.
[36] R.S. Verish, Elko crater field revisited, in: Annual Meeting of the Geological Society of America, Abstr. 239-14, Denver, USA, 2002.