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The Impact Crater Bandwagon (Some problems with the terrestrial impact cratering record)

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This editorial provides a discussion of some problems concerning the current record of terrestrial impact structures, and the recognition and confirmation of new impact structures. According to the well-appreciated Earth Impact Database of the University of New Brunswick, Canada (www.unb.ca/passc/ImpactDatabase), currently (28 July 2007) 174 impact structures are known on Earth. Unfortunately, this list does seem to contain at least two structures that cannot be considered confirmed impact structures: the two Arkenu structures in Libya that were proposed as impact structures by Paillou et al. (2003), but which have been debated in Libya as likely carbonatite complexes of endogenic origin (M. Baegi, Remote Sensing Authority, Tripoli, personal communication, October 2006). The evidence cited by Paillou et al. (2003)—alleged presence of shatter cones, impact breccia, and a report of planar fractures in quartz—does not stand up to scrutiny. The proposed shatter cones resemble wind ablation features well known from desert terrains, the proof for the presence of impact breccia is missing, and the reported planar fractures in quartz crystals are clearly not planar (their Fig. 8) and would not constitute unambiguous shock deformation anyway.

Another controversial example from the Earth Impact Database is the alleged Suavjärvi impact structure of ~2400 Ma age that was listed based on minimal information reported in a short abstract by Mashchak and Naumov (1996). In my opinion, the pictorial evidence given in this abstract for the presence of shock-diagnostic microdeformation in quartz is less than convincing, and the age constraints provided are unsupported by radiometric dating. No follow-up peer-reviewed publication has since been published in the international literature.

The Earth Impact Database reveals another serious issue: out of the 174 impact structures listed, 10 impact structures younger than 1 Ma have well-defined ages compared to 13 other in that category, whose ages are ill-defined. Sixty-nine structures older than 1 Ma have errors <15% on their ages, but 33 of these ages have errors >5 Ma (in many cases >10 Ma). All other impact ages are even less constrained. In addition to this problematic statistic, it was shown recently by Reimold et al. (2005) that even seemingly excellent ages with errors of just a few million years may have to be revised, as in the case of the Siljan age which was corrected from 362.7 ± 2.2 to 377 ± 2 Ma [2σ errors]). For many of these published ages, one also does not know whether errors on the ages are reported at the 1 or 2σ level. Clearly, the impact age statistic requires improvement, especially in the light of the widespread interest in the correlation between large impact events and important breaks in the biostratigraphic record.

On the occasion of the 2006 Workshop on Impact Craters as Indicators for Planetary Environmental Evolution and Astrobiology held in Östersund (Sweden), a presentation by Wall et al. (2006) on the Silverpit structure in the North Sea—originally proposed as an impact structure by Stewart and Allen (2002)—triggered an animated debate. The repeated reference to a "Silverpit impact structure" raised the question about the evidence to support an impact origin of Silverpit (also in the light of a failed search for shock metamorphic deformation in, admittedly limited, drilling product from the site [Koeberl and Reimold 2004]). The response was divided: a group of impact workers maintained that in the complete absence of bona fide evidence in favor of an impact, whether in the form of either shock metamorphic evidence or traces of an extraterrestrial projectile, i.e., either physical remnants of the projectile or chemical or isotopic traces of it (e.g., Koeberl 2002; Montanari and Koeberl 2000), one could only speak of a possible impact structure. This view was opposed by others who pointed out that once a crater-like morphological feature had been observed, for which no other likely endogenic origin could be proposed, it was justified to describe it as of "impact origin." An argument supporting this opinion was that "we do not require shock metamorphic or geochemical evidence of impact to designate the obvious impact origin of the numerous crater features on the Moon and other planetary bodies." This opinion ignores the fact that crater structures on Earth generally have been subject to erosion and degradation within geologically short periods of time, and also that there are many other geological processes that can result in circular structures on Earth. No consensus was reached at Östersund, but I believe that an "apparent" impact origin for a terrestrial crater structure does not replace objective evidence. This is supported by ample evidence of the past when "apparent" endogenic structures had to be reassessed as impact structures. The classification into "possible" and "confirmed" impact structures has served us well—and in my view has never been as important as nowadays.

The recent easy access to satellite imagery and software, such as Google Earth or World Wind, has precipitated a deluge of new "discoveries" of supposed impact structures. While many of the proposed features are quickly recognized as volcanic structures, pans, wind deflation sites, or other types of "normal" geological structures, a large number of other proposals has remained that, at least in part, cannot be readily distinguished from bona fide impact structures on morphological grounds alone. Reports of remote sensing observations of possible new impact structures commonly, and generally when they are made by non-specialists, suffer from insufficient knowledge of the available literature. Especially in South America, a continent where to date only nine impact structures have been confirmed and where awareness of impact cratering as a fundamental geological process is slowly gaining foothold, a number of apparent crater structures have been proposed to be of a possible impact origin; in each of these cases, detailed "ground-truthing" remains to be done.

From a satellite image, El Baz and Ghoneim (2006) proposed the existence of a large (34 km in diameter) impact structure near the Libyan-Egyptian border and, furthermore, they proposed that this could be the source crater of the Libyan Desert Glass strewn field in the Great Sand Sea of southwest Egypt, which is why this report resulted in much interest in the geo- and planetary community. Also, the El Baz and Ghoneim (2006) article followed immediately on a BBC documentary about the "mysterious" Libyan Desert Glass, ensuring that maximum public attention was guaranteed when the alleged impact crater discovery was reported. However, up to now no supporting evidence of the presence of this alleged crater structure, and certainly not for the presence of an impact structure, or any age information that would provide a link to the ~29 Ma Libyan Desert Glass has been produced.

The Egyptian Desert has achieved further "impact" notoriety with a recent report of no less than some 1300 crater-like features in the Gilf Kebir region (Paillou et al. 2006), with these authors discussing a possible impact origin or formation of these features by a hydrothermal venting process (yes, I was a co-author of this paper, and I cannot exclude that the experience of moderating the original "strewn field of 1300 impact structures" to the final discussion has contributed to the idea of writing this editorial). While I do not see some 1300 circular or even near-circular features in the imagery provided, there are a handful of structures that seem to deserve closer attention due to their resemblance of, for example, the BP and Oasis (named after the respective oil companies) structures in eastern Libya. As in the case of the Arkenu structures, the researchers at first suggested the presence of shatter cones and impact breccia with planar deformation features (PDFs) in quartz at several of the Gilf Kebir structures—claims that have not been confirmed yet (e.g., L. Ferrière, Vienna, personal communication 2007).

Shatter cones, in particular, seem to have become a matter of contention with respect to impact structures proposed in desert terranes. Our group once travelled to Morocco to follow up on a report of shatter cones in the Sahara. In that case, the alleged shatter cones were identified as sedimentary cone-in-cone structures (Lugli et al. 2005). However, a number of confirmed (e.g., Roter Kamm, Namibia) and proposed (Arkenu structures, Libya) impact structures have wind abrasion features (ventifacts), that is, striations formed due to sand blasting under persistent wind direction and possibly superposed on mineral lineations in the rocks concerned. It does not suffice to obtain a photograph or two of shatter cone–like features, but a full analysis of such phenomena, including their relationship to host rock and regional fabrics, as well as ascertaining that the fracture phenomenon in question is penetrative and not purely superficial, is required to differentiate between bona fide shatter cones and other cone-like features.

On March 16, 2007, BBC News (http://news.bbc.co.uk/2/hi/science/nature/6458841.stm) reported on a "possible space impact crater uncovered" in California's Central Valley, a possibility that had just been reported by Spevack et al. (2007) at this year's Lunar and Planetary Science Conference. This episode demonstrates the public's ongoing interest in impact cratering and discoveries of possible new impact structures. However, the Spevack et al. (2007) abstract also raises the question whether the seismic and well log evidence reported constitutes "documented, diagnostic characteristics of impact structures" (ibid). This is in contrast to the widely held standard, which is also supported by MAPS, that only evidence of shock metamorphism or of projectile traces constitutes diagnostic evidence for impact. Another example of "impact structure discovery" based on geophysics is the report by Becker et al. (2004) of a huge impact structure known as Bedout off the western coast of Australia. This initial report contained argon chronological results that suggested an age of 251 Ma for the alleged structure—coincident with the Permian/Triassic (P/Tr) boundary and the associated enormous mass extinction. However, this interpretation of the age data was questioned (Renne et al. 2004) and, based on the detailed reassessment of the geophysical data by Müller et al. (2005), the existence of a crater structure at Bedout has remained highly unlikely.

The Bedout story was subject to much media hype. Impact and mass extinction are still a huge news item. Consequently, the idea by Von Frese et al. (2006) of a huge impact structure of P/Tr boundary age located under thick ice cover in East Antarctica, indicated solely by a gravity anomaly, again caused a surge of public attention. Although, how anybody could accept the claim that an impact structure had been identified by a geophysical anomaly alone, especially when the feature in question is known to be covered by kilometers of ice, is beyond belief. In this context, we should recall that the earlier report of shock deformation in quartz from P/Tr boundary sections (Retallack et al. 1998) in Australia and Antarctica could not be substantiated (Langenhorst et al. 2005). Numerous other P/Tr sections have been studied and no evidence of shock was ever found. Thus, a firm link between impact and the P/Tr mass extinction remains unsupported.

Besides geophysical evidence, several other types of observation have been termed "impact-diagnostic criteria" in recent years. This includes repeated reference to "pseudotachylite," a melt breccia resulting from frictional melting known also from numerous tectonic occurrences (see, e.g., discussion of this problem in Reimold and Gibson 2005), occurrences of "agate" (e.g., Kinnunen and Lindqvist 1998), and so-called "bleaching, i.e., partial resetting, of optically stimulated luminescence and thermoluminescence" (Stankowski 2007).

Also "planar features" are mentioned frequently in the literature, which is ambiguous in the impact context, as it could pertain to either planar deformation features (PDFs) or planar fractures (PFs). The description of planar features in quartz and other minerals from structures proposed to be of impact origin has remained a matter of concern. Much is presented as "planar" that can hardly be termed "subplanar." The strict geometric constraints in the definition of PDFs (spacings between individual features <5–10 µm, width of individual PDF of the order of 1–2 µm, features have to be parallel to important crystallographic orientations) often remain unconsidered, or may be unknown to the authors. Where only single sets per host grain are reported, it is particularly important to ascertain that PDFs and not other tectonic deformation (e.g., Böhm lamellae) is recorded. Often wavy and non-parallel features are wrongly called "PDFs," obviously ignoring the meaning of the word "planar." For example, an, in my opinion, incorrect identification of PDFs was recently published by Sisodia et al. (2006a) in an Indian journal, claiming to confirm that the Ramghar structure was of impact origin. A comment by Reimold et al. (2006) solicited a reply (Sisodia et al. 2006b) that presented further pictorial material—none of which only closely resembles PDFs. What is more, recently I was able to study several specimens from Ramghar, but was not able to identify PDFs in quartz.

In several recent cases, "planar fractures" (also the so-called "planar fractures with feather features") described from optical studies have been given status of impact-diagnostic evidence (e.g., some contributions to Glikson and Haines 2005), the validity of which, in the absence of further impact-supporting evidence, I would like to question. Haines (2005) states: "Also significant, though considered less definitive, are planar fractures (PFs) . . . ", but then proceeds to declare the alleged "PFs" described from several structures in Australia "low-level petrographic shock effects." A very detailed study of planar fractures and a type of planar microdeformation termed "possible incipient planar deformation features" in quartz was reported by French et al. (2004), who concluded that this, together with other evidence of highly deformed rocks in an otherwise undisturbed region, and stratigraphic uplift in the center of the structure, established Rock Elm as an impact structure. Planar features of the kind shown by these authors (e.g., their Fig. 3), especially when occurring in multiple orientations per host grain, are seemingly distinct from tectonic microdeformation. However, single sets of subplanar to planar, even "feathered" features, in my opinion, do not by themselves constitute a sufficient diagnostic shock deformation and thus are not reliable evidence for an impact. The nature of planar fractures/features does require more microstructural analysis, including both the petrographic study of samples from confirmed impact structures and shock experimental analysis. Indeed, the nature of shock microdeformation in sedimentary rocks, in general, requires further dedicated analysis, and, in particular, the microdeformation produced in the low-level (<10 GPa) shock regime. In addition to planar microdeformation, larger-scale rock deformation and stratigraphic evidence, and the relationship of the investigated structure to the surrounding geology must be investigated and discussed in detail to support any impact claim.

Sisodia et al. (2006b) based their alleged identification of PDFs in Ramghar quartz on a comparison with optical microscopic images published on the Chiemgau Impact Research Team's website (www.chiemgau-impact.com). This group of mainly nonscientists, but also including a geophysicist and a paleo-astronomer, has for several years claimed that an impact of cometary fragments some 2500 years ago in the Chiemgau region of Bavaria, southern Germany, formed a strewn field of crater structures (the largest one being Lake Tüttensee) and led to the demise of the Celtic people in this part of Central Europe and the simultaneous strengthening of the Roman Empire due to the sudden availability of C-hardened "steel." There has been enormous media attention to this so-called "Chiemgau comet impact," with local authorities being excited about the likely windfall of income from tourism. On the other hand, the German and the international planetary and geological communities (e.g., http://idw-online.de/pages/de/news185966; Wünnemann et al. 2007) have repeatedly highlighted the lack of definitive evidence for an impact in the Chiemgau region (and for impact of a comet in particular), as well as for the impact origin of Lake Tüttensee, other lakes, and crater-like depressions in this glacially overprinted region in the foreland to the Alps. This episode highlights how important it is to maintain firm standards regarding the acceptance of confirmed impact structures, but also how the current widespread accessibility of web-based information can lead to serious misperception (Chiemgau evidence interpreted in India as impact evidence; non-peer-reviewed claims of alleged pro-impact findings taken at face value by the public).

The popularity of impact cratering and the rapid invoking of this process without proper supporting evidence is further exemplified by the following recent publications: 1) an entirely unsubstantiated claim of recognition of a meteorite impact site at Luna in the Kachchh district of Western India by Karanth (2006) and Karanth et al. (2006); 2) the report of a controversial hypothesis that impact of a large comet or asteroid could have been responsible for the demise of the Clovis culture in North America (Dalton 2007; Firestone et al. 2007); 3) the claim by Gasperini et al. (2007) that a so-called Lake Cheko impact crater related to the Tunguska blast event had been discovered in Siberia; this claim has been refuted by Collins et al. (2008); 4) speculations (the actual authors' choice of word) concerning multiple impact events in Antarctica by Weihaupt and Rice (2007); 5) the reference to a "High Rock Lake impact" by Leybourne et al. (2007), for which, to my knowledge, no impact-supporting evidence has been provided by these authors nor by Kohn et al. (1995) whom they cited.

Contrary to the impression that I may be making in this article (that I might feel discontent about the widespread attention that impact cratering is enjoying), I am actually delighted about it. It has been some 50 years that impact cratering had to wait for wide acceptance in the geoscience community and to gain entry into textbooks. Today, impact cratering is an established aspect of geo-discussion throughout the subdisciplines of our field—from Archean to Quaternary geology, from mineralogy to geochemistry to geochronology, and from hard rock geology to sedimentology and stratigraphy. And yet, there is only a rather limited terrestrial impact record, with less than 174 impact structures confirmed on Earth. Most of these are concentrated in North America, Eurasia, and Australia, whereas central Africa, much of South America, and large parts of Asia are underrepresented (see world map on www.unb.ca/passc/ImpactDatabase). The reasons for this are multiple, including limited access to English impact literature or remote sensing and regional geophysics in rainforest terrains and civil strife, especially in parts of central Africa, having hindered the "ground-truthing" of possible target structures. It is also rather strange that not a single impact structure is known from the vast terrain of China, only two impact structures have been confirmed in India, and only one impact structure is known from Mongolia. Clearly, studies of impact cratering have not been performed yet in several Asian countries, but there is also scope for further discoveries in South America and in parts of Africa.

Evidence for impact in the stratigraphic record is still scarce. A good review was recently published by Simonson and Glass (2004), and the reader could also refer to Montanari and Koeberl (2000) and papers in Peucker-Ehrenbrink and Schmitz (2001). Only continuing exposure of impact science to the wider geological community will result in more emphasis on search for impact indicators (shock deformation) in sedimentary strata. Mass extinction horizons and impacts of large extraterrestrial projectiles as possible causes for global catastrophes are being investigated. However, only few workers have so far attempted to enlarge the distal impact record through dedicated search for impact tracers. In this context, a positive development has been the identification of the ejecta from the Sudbury impact structure in distal sedimentary sections in western Ontario and Minnesota (Addison et al. 2005), and in Michigan (Kring et al. 2006; Pufahl et al. 2007). The ejecta of the Vredefort event that have been searched for in the Waterberg Group strata of northern South Africa are, however, still elusive (Reimold 2007). The huge drill core record from supracrustal strata remains essentially unexamined for impact ejecta.

It has become fashionable to identify impact structures, and the fact that some science organizations as well as lay websites have been heavily punting such "discoveries" has further populated the bandwagon. Therefore, the impact cratering community has the obligation to continue the promotion of our science throughout the world with special attention to the education about the firm criteria that need to be met in order to classify geological forms as impact structures. It must be concluded that where geological-geophysical features consistent with the character of confirmed impact structures are present but are not supported by unambiguous shock deformation evidence, the presence of a "possible" or "probable" impact structure ought to be reported—but not the presence of a "confirmed" impact structure.

Besides the widely recognized and extremely valuable Earth Impact Database, several other so-called impact statistics feature many more structures that have been, at times, likened to impact structures (e.g., Rajmon 2006, including 389 possible ones; www.somerikko.net/old/geo/imp/impacts.htm featuring 205 structures). These databases may contain valuable information, but it is imperative to carefully distinguish confirmed impact structures and those of uncertain origin (as is done by David Rajmon!). This can only be achieved through the application of firm diagnostic criteria that all of us can subscribe to.

Editors, associate editors, and reviewers have the responsibility to adhere to the strictest quality control regarding the evidence presented in support of new impact structure discoveries through rigorous peer-evaluation of manuscripts. As demonstrated above, misleading, incomplete, or incorrect information can find its way quickly into the mainstream science (and even faster into the public domain) via the internet. Instead of improving our terrestrial impact crater record, misleading information may be rapidly absorbed into valuable databases and thereby making them unreliable.

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REFERENCES

Addison W. D., Brumpton G. R., Vallini D. A., McNaughton N. J., Davis D. W., Kissin S. A., Fralick P. W., and Hammond A. L. 2005. Discovery of distal ejecta from the 1850 Ma Sudbury event. *Geology* 33:193–196.

BBC News, "Oil exploration work in California's Central Valley region has uncovered a possible space impact crater." http://news.bbc.co.uk/2/hi/science/nature/6458841.stm. Accessed October 10, 2007.

Becker L., Porada R. J., Basu A. R., Pope K. O., Harrison T. M., Nicholson C., and Lasky R. 2004. Bedout: A possible end-Permian impact crater offshore of northwestern Australia. *Science* 304:1469–1476.

The Chiemgau Impact Research Team. The Chiemgau impact. http://www.chiemgau-impact.com. Accessed October 10, 2007.

Collins G. S., Artemieva N., Wünnemann K., Bland P. A., Reimold W. U., and Koeberl C. 2008. Evidence that Lake Cheko is not an impact crater. *Terra Nova* (Forthcoming).

Dalton R. 2007. Archaeology: Blast in the past? *Nature* 447:256–257.

Earth Impact Database. http://www.unb.ca/passc/ImpactDatabase. Accessed October 10, 2007.

El Baz F. and Ghoneim E. 2006. Veiled crater in the Eastern Sahara. *The Planetary Report* 4:10–15.

Firestone R. B., West A., Kennett J. P., Becker L., Bunch T. E., Revay Z. S., Schultz P. H., Belgya T., Kennett D. J., Erlandson J. M., Dickenson O. J., Goodyear A. C., Harris R. S., Howard G. A., Kloosterman J. B., Lechler P., Mayewski P. A., Montgomery J., Poreda R., Darrah T., Que Hee S. S., Smith A. R., Stich A., Topping W., Wittke J. H., and Wolback W. S. 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctuions and the Younger Dyas cooling. *Proceedings of the National Academy of Sciences* 104:16,017–16,021, doi: 10.1073/pnas/.0706977104.

French B. M., Cordua W. S., and Plescia J. B. 2004. The Rock Elm meteorite impact structure, Wisconsin: Geology and shock-metamorphic effects in quartz. *Geological Society of America Bulletin* 116:200–218.

Gasperini L., Alvisi F., Biasini E., Monatti E., Longo G., Pipan M., Ravaioli M., and Serra R. 2007. A possible impact crater for the 1908 Tunguska event. *Terra Nova* 19:245–251, doi:10.1111/j.1365-3121.2007.00742.

Glikson A. Y. and Haines P. J. 2005. Shoemaker Memorial Issue of the Australian impact record: 1997–2005 update. *Australian Journal of Earth Sciences* 52:475–798.

Haines P. W. 2005. Impact cratering and distal ejecta: The Australian record. *Australian Journal of Earth Sciences* 52:481–507.

Humboldt-Universität zu Berlin, "Vermeintlicher Einschlag eines Kometen im Chiemgau entbehrt wissenschaftlicher Grundlage," news release, November 21, 2006. http://idw-online.de/pages/de/news185966. Accessed October 10, 2007.

Karanth R. V. 2006. The unusual impact crater of Luna in Kachchh, western India. *Journal of the Geological Society of India* 68:927–928.

Karanth K. V., Thakker P. S., and Gadhavi M.S. 2006. A preliminary report on the possible impact crater of Kachchh. *Current Science* 91:877–879.

Kinnunen K. A. and Lindqvist K. 1998. Agate as an indicator of impact structures: An example from Sääksjärvi, Finland. *Meteoritics & Planetary Science* 33:7–12.

Koeberl C. 2002. Mineralogical and geochemical aspects of impact craters. *Mineralogical Magazine* 66:745–768.

Koeberl C. and Reimold W. U. 2004. Silverpit structure, North Sea: Search for petrographic and geochemical evidence for an impact origin (abstract). *Meteoritics & Planetary Science* 39:A53.

Kohn B. P., Osadetz K. G., and Bezys R. K. 1995. Apatite fission-track dating of two crater structures in the Canadian Williston Basin. *Bulletin of Canadian Petroleum Geology* 43:54–64.

Kring D. A., Horton J. W., Jr., and Cannon W. F. 2006. Discovery of the Sudbury impact layer in Michigan, USA (abstract). *Meteoritics & Planetary Science* 41:A100.

Langenhorst F., Kyte F. T., and Retallack G. J. 2005. Reexamination of quartz grains from the Permian-Triassic boundary section at Graphite Peak, Antarctica (abstract #2358). 36th Lunar and Planetary Science Conference. CD-ROM.

Leybourne M. I., Denison R. E., Cousens B. L., Bezys R. K., Gregoire D. C., Boyle D. R., and Dobrzanski E. 2007. Geochemistry, geology, and isotopic (Sr, S, and B) composition of evaporates in the Lake St. Martin impact structure: New constraints on the age of melt rock formation. *Geochemistry, Geophysics, Geosystems* 8. 22 p.; doi:10.1029/2006GC001481.

Lugli S., Reimold W. U., and Koeberl C. 2005. Silicified cone-in-cone structures from Erfoud (Morocco): A comparison with impact-generated shatter cones. In *Impact tectonics*, edited by Koeberl C. and Henkel H. Impact Studies Series, vol. 6. Berlin-Heidelberg-New York: Springer-Verlag. pp. 81–110.

Mashchak M. S. and Naumov M. V. 1996. The Suavjärvi structure: An Early Proterozoic site on the Fennoscandian Shield (abstract). 27th Lunar and Planetary Science Conference. pp. 825–826.

Moilanen J. List of impact structures of the world. http://www.somerikko.net/old/geo/imp/impacts.htm. Accessed October 10, 2007.

Montanari A. and Koeberl C. 2000. *Impact stratigraphy—The Italian record*. Lecture Notes in Earth Sciences, vol. 93. Berlin-Heidelberg-New York: Springer-Verlag. 364 p.

Müller R. D., Goncharov A., and Kritski A. 2005. Geophysical evaluation of the enigmatic Bedout basement high, offshore northwestern Australia. *Earth and Planetary Science Letters* 237:264–284.

Paillou P., Rosenkvist A., Malezieux J.-M., Reynard B., Farr T., and Heggy E. 2003. Discovery of a double impact crater in Libya: The astrobleme of Arkenu. *Comptes Rendus Geoscience* 335: 1059–1069.

Paillou P., Reynard B., Malezieux J.-M., Dejax J., Heggy E., Rochette P., Reimold W. U., Michel P., Baratoux D., Razin P., and Colin J.-P. 2006. An extended field of crater-shaped structures in the Gilf Kebir region, Egypt: Observations and hypotheses about their origin. *Journal of African Earth Sciences* 46:281–299.

Peucker-Ehrenbrink B. and Schmitz B, eds. 2001. *Accretion of extraterrestrial matter throughout Earth's history.* New York: Kluwer Academic/Plenum Publishers. 466 p.

Pufahl P. K., Hiatt E. E., Stanley C. R., Morrow J. R., Nelson G. J., Edwards C. T. 2007. Physical and chemical evidence of the 1850 Ma Sudbury impact event in the Baraga Group, Michigan. *Geology* 35:827–830, doi:10.1130/G23751A.1.

Rajmon D. 2006. Suspected Earth impact sites (abstract #2372). 37th Lunar and Planetary Science Conference. CD-ROM.

Reimold W. U. 2007. 29th De Beers Alex L. Du Toit Memorial Lecture "Revolutions in the earth sciences: Continental drift, impact, and other catastrophes." *South African Journal of Geology* 110:1–46.

Reimold W. U. and Gibson R. L. 2005. "Pseudotachylite" in large impact structures. In *Impact tectonics*, edited by Koeberl C. and Henkel H. Impact Studies Series, vol. 6. Berlin-Heidelberg-New York: Springer-Verlag. pp.1–53.

Reimold W. U., Kelley S. P., Sherlock S. C., Henkel H., and Koeberl C. 2005. Laser argon dating of melt breccias from the Siljan impact structure, Sweden: Implications for a possible relationship to Late Devonian extinction events. *Meteoritics & Planetary Science* 40:591–607.

Reimold W. U., Trepmann C., and Simonson B. 2006. Discussion: Impact origin of the Ramgarh structure, Rajasthan: Some new evidences by M. S. Sisodia et al. *Journal of the Geological Society of India* 68:561–563.

Renne P. R., Farley K. A., Reimold W. U., Koeberl C., Rampino M. R., Kelley S. P., and Ivanov B. A. 2004. Is Bedout an impact crater? Take 2. *Science* 306:610–612.

Retallack G. J., Seyedolali A., Krull E.S., Holser W. T., Ambers C. P., and Kyte F. T. 1998. Search for evidence of impact at the Permian-Triassic boundary in Antarctica and Australia. *Geology* 26:979–982.

Simonson B. M. and Glass B. P. 2004. Spherule layers—Records of ancient impacts. *Annual Reviews in Earth and Planetary Science* 32:329–361.

Sisodia M. S., Lashkari G., and Bhandari N. 2006a. Impact origin of the Ramghar structure, Rajasthan: Some new evidences. *Journal of the Geological Society of India* 67:423–431.

Sisodia M. S., Lashkari G., and Bhandari N. 2006b. Reply to Reimold et al. (2006), Discussion of impact origin of the Ramghar structure, Rajasthan: Some new evidences. *Journal of the Geological Society of India* 68:563–565.

Spevack S. C., Morrow J. R., and Spevack B. Z. 2007. 3-D seismic and well log analyses of the Victoria Island structure, a potential buried impact crater, San Joaquin County, California (abstract #1033). 38th Lunar and Planetary Science Conference. CD-ROM.

Stankowski W. T. J. 2007. Luminescence dating as a diagnostic criterion for the recognition of Quaternary impact craters. *Planetary and Space Science* 55:871–875.

Stewart S. A. and Allen P. J. 2002. A 20-km-diameter multi-ringed impact structure in the North Sea. *Nature* 418:520–523.

Von Frese R. R., Potts L., Wells S., Gaya-Piqué L., Golynsky A. V., Hernandez O., Kim J., Kim H., and Hwang J. 2006. Permian-Triassic mascon in Antarctica (abstract #T41A-08). 2006 Fall Joint Assembly of the American Geophysical Union. *Eos Transactions* 87(36).

Wall M., Davies R., Stewart S., and Cartwright J. 2006. Burial of the Silverpit meteorite crater (abstract). Workshop on Impact Craters as Indicators for Planetary Environmental Evolution and Astrobiology, Östersund, Sweden, 8–14 June 2006, Abstract and Program Volume, edited by Deutsch A. and Ormö J. 2 p.

Weihaupt J. G. and Rice A. 2007. Suggestions of multiple meteoroid impact in Antarctica: How do we sort it out? (abstract). 31st Symposium on Antarctic Meteorites. Tokyo: National Institute of Polar Research. p. 103.

Wünnemann K., Reimold W. U., and Kenkmann T. 2007. Postuliertes Impaktereignis im Chiemgau nicht haltbar. *GMIT-Geowissenschaftliche Mitteilungen* 27:19–21.