The Kamil Crater in Egypt

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Impact craters up to a few hundreds of meters in diameter are common structures of solid surfaces of planetary bodies in the solar system. Statistics predict that impacts producing small craters on Earth occur on decadal to secular time scales (*1*, *2*). However, small craters are rare on Earth because they are rapidly eroded, and the few identified so far [15 <300 m in diameter out of 176 craters up to 300 km in diameter (*3*)] have lost most of their primary features.

We report the detection in southern Egypt of a rayed impact crater 45 m in diameter (Fig. 1A) on a Cretaceous sandstone target. The ejecta rays highlight the exceptional freshness of the structure. The crater was identified by V. De Michele during a Google Earth survey and named Kamil Crater after nearby Gebel Kamil. A geophysical expedition undertaken [supporting online material (SOM)] in February 2010 revealed that the crater is bowl shaped and has an upraised rim (~3 m above preimpact surface) (figs. S1 and S2) typical of simple craters (*4*). The true crater floor depth is 16 m and is overlain by ~6-m-thick crater-fill material (fig. S2). Morphometric parameters agree with those predicted by models (*5*) for a transient crater generated by an iron meteorite 1.3 m in diameter (equivalent to 9.1×10^3 kg) impacting at a velocity of 3.5 km s^{-1}, assuming an average meteoroid entry velocity and entry angle of 18 km s^{-1} and 45°, respectively. Centimeter-scale masses of scoriaceous impact melt glass (fig. S3) occur in and close to the crater and indicate local shock pressures >60 GPa (*4*). We identified 5178 iron meteorite specimens totaling ~1.71 tons in the crater and surrounding area during systematic searches (SOM). They consist of <34-kg shrapnel produced by the explosion of the impactor upon hypervelocity collision with the target (Fig. 1B), except one individual fragment of 83 kg (fig. S4). This evidence indicates that the Kamil Crater was generated by an impactor that landed nearly intact without substantial fragmentation in the atmosphere. The meteorite is classified as an ungrouped Ni-rich ataxite [Ni = 19.8 weight % (wt %), Co = 0.75 wt %, Ga = 49.5 $\mu g\ g^{-1}$, Ge = 121 $\mu g\ g^{-1}$, Ir = 0.39 $\mu g\ g^{-1}$; data following (*6*); fig. S5]. Magnetic anomaly data show no evidence of buried meteorites larger than some tens of centimeters (fig. S1).

On the basis of systematic meteorite searches, the estimated total mass of the impactor is of the order of 5×10^3 to 10×10^3 kg, corresponding to a preatmospheric mass of $\sim 20 \times 10^3$ to 40×10^3 kg (*2*). According to geophysical models (*2*, *7*), iron masses $<3 \times 10^6$ kg normally fragment upon impact with Earth's atmosphere, thereby reducing the energy of the impact at Earth's surface. However, the present statistics, which include the recently discovered Whitecourt Crater (*8*) and the Kamil Crater, suggest that ~35% of the iron meteorites in the above mass range are not disrupted in the atmosphere.

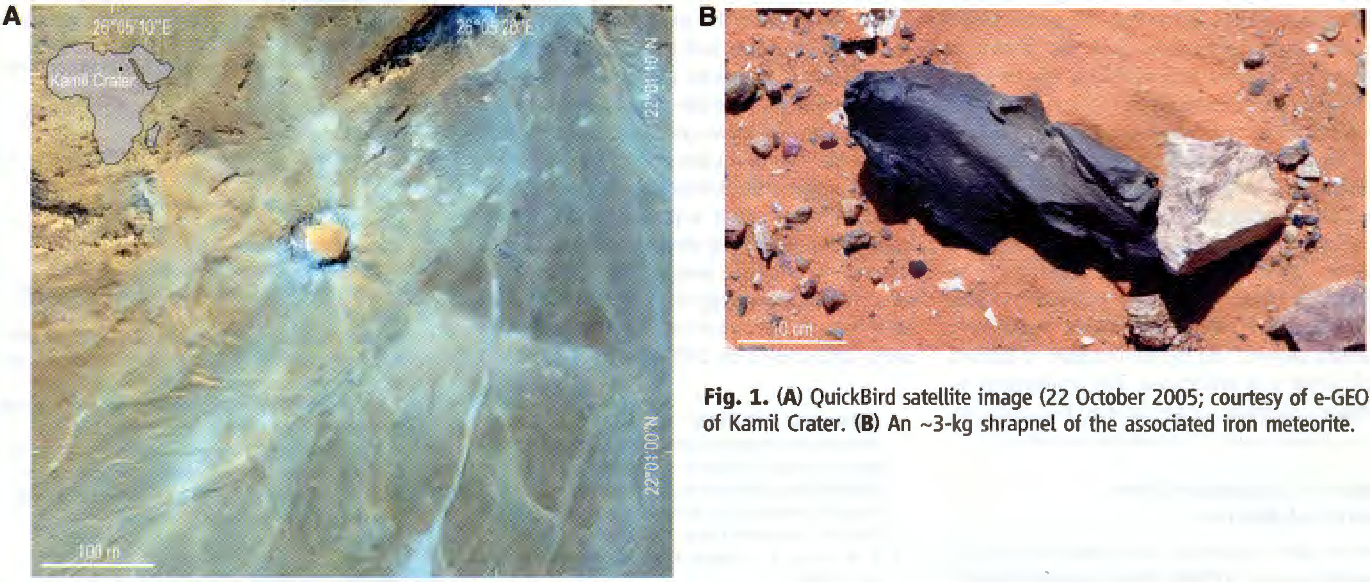

Fig. 1. **(A)** QuickBird satellite image (22 October 2005; courtesy of e-GEOS) of Kamil Crater. **(B)** An ~3-kg shrapnel of the associated iron meteorite.

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Supporting Online Material

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Materials and Methods
Figs. S1 to S5

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unconventional uranium will yield a price cap to conventional nuclear fuel. That maximum price is likely, however, to be prohibitively high, and other options may be more attractive.

Option 2: Reprocessing Spent Fuel for Multiple Mixed U-Pu Oxide Fuel Recycle

This potentially long-lived fuel cycle has been developed over many decades in several countries (especially France, United Kingdom, and Russia). It involves the chemical separation of plutonium, in order to fabricate fuel from mixed U-Pu oxide powders (MOX) (*24*). However, because Pu separation is a proliferation-sensitive technology, MOX fuel fabrication is likely to be restricted to the nuclear weapons states, although perhaps with increasing international access to such fuels via appropriate global agreements.

Option 3: Critical Fast Reactors

These reactors are more compact and have much higher energy density than today's nuclear power systems. Consequently the rate at which the neutron density or temperature can change in the event of an accident is faster and therefore a greater engineering challenge. As such, critical fast reactors raise safety and reliability issues beyond those typical of today's nuclear power plants, especially in the event of a loss-of-coolant accident. Also, because of the greater potential for production of fissile material ("breeding"), such technologies raise security concerns. A substantial advantage is that both ^{235}U and ^{238}U isotopes undergo fission in these reactors, thereby using a much greater proportion of the uranium.

Option 4: Thorium Fuel Cycle

Thorium has the potential to become an important nuclear fuel. It is not fissile itself, but in a reactor, thorium-232 can capture neutrons to yield fissile uranium-233. The thorium fuel cycle can then proceed by either (i) fabricating fuel pellets that contain a mix of thorium-232 and a fissile element (such as uranium-233), (ii) placing a blanket of thorium fuel around a reactor core containing fissile material, or (iii) injecting extra neutrons from a particle accelerator (see option 5). Thorium is several times more abundant than uranium, and a thorium fuel cycle can be developed that produces negligible amounts of plutonium and fewer long-lived minor actinides than a uranium cycle. However, fissile uranium-233 is difficult to extract and handle, because it is produced together with other highly radioactive uranium isotopes, and the performance of thorium fuels is not well understood. The proliferation resistance credentials of the thorium fuel cycle deserve greater scrutiny but appear promising.

Option 5: Accelerator-Driven Subcritical Reactors

Despite their complexity, accelerator-driven subcritical reactors (ADSRs) have potentially useful advantages over conventional critical reactor systems. ADSRs can, in principle, produce thorium-fueled nuclear energy, avoiding the need for fissile materials supplied from other sources. In addition, ADSRs show promise for waste treatment. The process of nuclear transmutation using an ADSR has the potential to reduce quantities of long-lived and highly toxic radioactive wastes quite substantially (*25*). Lastly, ADSRs offer improved safety and fuel utilization compared with other sustainable second-phase nuclear options.

Option 6: Nuclear Fusion Energy

Nuclear fusion could provide clean energy with enhanced intrinsic safety and abundant fuel resources. However, the technology has not been demonstrated at industrial scale and reliability. Furthermore, it relies on helium coolants (a coproduct of nonrenewable natural gas), although various measures such as cooling with liquid hydrogen have been suggested (*26*, *27*). Fusion is unlikely to move toward commercialization until after 2050. Furthermore, the many commonalities between fusion and fission research—high temperature materials for high radiation environments, fast neutron physics, structural integrity issues—favor a collaborative approach between the fusion and fission communities. Fusion-fission hybrids and fusion-driven fission fuel breeders (*28*, *29*) have been suggested as a route to early commercialization of fusion energy.

Outlook

Nuclear technology is at a crossroads. The community has been tested in recent years as it gears up to renew existing facilities in Europe and North America while continuing or initiating an expansion in other regions. It seems ever more likely that a second larger phase of nuclear development will be required beyond the 2030s to ensure a low-carbon energy future that makes maximal efficient use of nuclear plants and resources. Energy and research policy decisions made now will determine whether we have the capacity to design and develop innovative new systems that contribute to sustainable flexible nuclear energy generation.

Although we are developing other energy generating systems and it is possible that a second larger phase of nuclear development will not be required, it would be unwise at this stage to assume that nuclear energy will not be needed. If we are to generate that option for policy-makers and the energy industries of the 2030s, we must act now.

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